Quantification of Spray Drift from Aerial Applications of Pesticide

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Abstract

With widespread use of pesticides in modern agriculture, the impacts of spray drift have become a topic of considerable interest. The drifting of sprays is a highly complex process influenced by many factors. Advances in aerial application technology and in our ability to measure drift, coupled with the adoption of new technologies for regulating pesticide application have necessitated further research in the pesticide application process. Experiments were conducted to quantify spray drift and describe its movement from aerial applications of pesticide. The effects of spray quality, atomizer type and ground cover were examined. Initial airborne drift amounts were greater than downwind deposits, thus not all of the drifting spray was deposited in the measuring area. Total off-target movement of spray was significantly greater for Fine compared to Coarse sprays. Rotary and hydraulic atomizers, both producing Fine sprays, produced statistically similar off-target movement of sprays. Similarly, no significant statistical differences in spray drift between applications to bare ground and applications to a headed barley crop canopy were not identified. Contrary to expectations, aerial application to bare ground seemed to result in less off-target movement than application to a crop canopy. The vertical spray cloud profiles were similar for all applications with the greatest amount of spray present at the height of release. Spray concentrations diminished from that height upward with diffusion and downward with deposition. The empirical data disagreed with the mechanistic model AgDISP which is currently used in the Canadian regulatory process. The model over-predicted drift deposition by a factor of two to five. Variability in spray deposit values could not be attributed to average

differences in meteorological conditions at the time of application. Experiments with appropriate protocols for increased sensitivity may be required to more accurately report subtle differences in drift at distances greater than 200 m from the target area.

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1.0 Introduction

Environmental impact is an ever increasing consideration in the production of agricultural commodities and pesticide spray drift is one of the most important environmental issues for applicators. Off target losses of pesticide constitute a potential threat to air and water quality (Freemark and Boutin, 1995). In addition, allowing the deposition of pesticide on wildlife habitat, urban, and sub-urban areas has become socially unacceptable.

Pesticide application is said to be a highly inefficient process due to the fact that only a small percentage of what is applied ever actually reaches the target site in the pest organism (Pimentel, 1992). The majority of pesticide applied is deposited on the soil, intercepted by non-target vegetation or is lost from the application area altogether. Knoche (1994) stated that for many active ingredients, the most biologically effective type of spray is one where the majority of the applied volume is contained in small droplets (<200 um diameter). Unfortunately these small droplets are also the most susceptible to off-target losses. Thus, there exists a conflict in requirements for pesticide application between effective, efficient applications and drift reduction.

Aerial application offers several advantages to the producer, the most notable of which include the ability to treat very large areas in a short period of time and to apply pesticides in a timely manner to fields when conditions are unfavorable for application by ground. The application of pesticide by air warrants special consideration with regard to drift. Numerous aspects of aerial application intensify the potential for off target losses of pesticide; these include elevated release height, faster application speed and the generation of a turbulent wake (Frank et al., 1994). While the application of pesticides by air has been an accepted agricultural practice for over half a century, advances in

application technology, changes in the regulatory process and a renewed interest in protecting the environment have necessitated further study of this area by the scientific community.

The objective of this thesis was to quantify the effect of spray quality, atomizer type, and ground cover on the off target movement of pesticides from aerial application. The level of agreement between measured off-target deposits and the predictions of a drift model recently adopted by the Canadian Pest Management Regulatory Agency (PMRA) was also investigated. Airborne drift and the amounts of spray dispersed upward and lost to the atmosphere were studied. These findings could have relevance for the regulation of pesticides and the determination of safe buffer zone distances between applications and sensitive areas.

It is hypothesized that the use of coarser sprays and rotary atomizers will result in lower drift deposits due to their lower volume fraction of drift-prone droplets. It is also predicted that drift deposits will be significantly lower when sprays are applied to a mature crop canopy compared to bare soil due to droplet interception by vegetative elements in the canopy. Finally, it is expected that output from regulatory models will overestimate drift in part due to their oversimplified simulation of atmospheric turbulence.

2.0   Literature Review - Principals Governing Pesticide Spray Drift

2.1   Pesticide Use and Environmental Contamination

It has been estimated that approximately 2.3 billion kg of pesticide active ingredients are applied on a global scale to crops each year (Kiely et al., 2004) . In the absence of pesticide application it is estimated that the production of agricultural commodities would be reduced by 10% with specific crop losses ranging from 0% to 100% (Pimentel, 1992). While the literature does not contain work which examines the total off-target losses of pesticide from large scale aerial spray applications it has been estimated that losses typically range between 20 and 35% of applied sprays (Maybank et al., 1978) and can exceed 50 to 75% of applied amounts for applications where good stewardship is not practiced (Ware, 1983). These off-target deposits of pesticides can result in significant damage to neighbouring sensitive species. For example, there were 18 reported incidents of herbicide drift causing damage to neighbouring crops or vegetation in the province of Alberta in 1997 (Anonymous, 1998).

While the impacts of environmental pesticide contamination on wildlife and natural ecosystems are not well understood there is evidence to suggest that there are significant detrimental consequences for sensitive beneficial insects and microbes, and other wildlife (Freemark and Boutin, 1995). The extent to which the environment has become polluted with pesticides is an area of concern. Commonly used pesticides can be found in almost all of the ecosystems in the world. Concentrations of pesticide are particularly high in marine ice and arctic marine fog (Chernyak et al., 1996). Incidence of pesticide contamination of air and water is also exceptionally high in areas with a great degree of agricultural production. On the Canadian prairies the incidence of contamination of farm ponds and dugouts with 2,4-D ranges between 93 and 100%

depending on the time of sampling (Grover et al., 1997). In another study conducted in the same region by Waite et al. (2004) 2,4-D was detected in between 53 and 63% of air samples collected.

Environmental contamination can occur by several mechanisms including long distance atmospheric transport, volatilization, leaching, erosion and spray drift (Cessna et al., 2005).

2.2   Spray Drift

Spray drift may be defined as that portion of crop protection product carried out of the target area through the air during the application process, or shortly thereafter. It does not include losses from the target area subsequent to the application process in the form of losses due to volatilization, leaching, or erosion (Anonymous, 2001).

2.2.1   Atomization and Spray Quality

Pesticides for agricultural applications are typically sold in concentrated formulations that are diluted in water or another carrier for application to a large area. The pesticide product is usually dispersed in the tank of a spraying implement which atomizes the liquid into small droplets and distributes the chemical evenly over the crop area in a process called dose transfer (Hislop, 1993). This is the process during which spray drift losses can occur.

Atomization is the process by which a stream of liquid is fragmented into small droplets, by the application of energy. For example, this may entail the application of pressure or electricity (Lefebvre, 1993). The process of applying energy and fragmenting a liquid stream is termed primary atomization. This may simply involve emitting the liquid through a small orifice at high pressure, or it may involve the impaction of the liquid at high velocity on a horizontal surface or a rapidly spinning surface (Bouse et al.,

1994). These processes generate instability in the liquid stream and result in fragmentation of the stream into small drops. A spectrum of droplet sizes is generated by agricultural atomizers and may range from very narrow (several hundred μm) to very wide (over a thousand μm) (Kirk, 2001; Teske et al., 2004).

Shear stress is exerted on droplets as they fall through the atmosphere towards the earth's surface. Exposure to the atmospheric flow field (defined as the portion of the atmosphere into which the spray liquid is released) can result in further break up of the spray liquid into smaller drops, in a process called secondary atomization (Schmehl et al., 2000). Shear stress is defined as a state in which the shape of a material changes by transversely-acting forces without a change in volume (Robertson and Crowe, 1997). As the velocity of the flow field is increased relative to the droplet, the disruptive aerodynamic forces exerted on the droplet overcome its forces of surface tension and viscosity which act to stabilise it. Thus, the result of emitting a stream of liquid or a droplet into a high velocity flow field is fragmentation and the creation of many smaller droplets (Pilch and Erdman, 1987). There are several different types of secondary atomization, and the intensity of fragmentation can be defined by the Weber number which represents the ratio of disruptive aerodynamic forces to the stabilizing force of surface tension. The Weber number is arrived at by multiplying atmospheric density, relative droplet velocity and droplet size and dividing by the surface tension of the drop. A larger Weber number is indicative of larger disruptive forces exerted on the drop and a more violent break-up (Pilch and Erdman, 1987).

It is made apparent by the Weber number that the physico-chemical properties of the spray mixture (e.g. dynamic surface tension and liquid viscosity) have a significant impact on the atomization process. The greater the surface tension and the greater the

viscosity of the spray liquid the greater will be its ability to resist shear stress and retain its aerodynamically stable spherical shape. The effects of viscosity on drop break up are characterized by the Ohnesorge number. The Ohnesorge number is arrived at by an equation which determines the response of a droplet to shear stress based on the ratio of resistance of the droplet to change shape and the shape changing aerodynamic forces. A smaller Ohnesorge number is consistent with a more violent droplet fragmentation (Pilch and Erdman, 1987).

Spray quality is a way of describing the droplet size spectra of agricultural sprays. ASAE S572 (Anonymous, 2002) categorizes spray quality into descriptive classes including Very Fine, Fine, Medium, Coarse, Very Coarse and Extra Coarse. The $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$, represent the 10th, 50th, and 90th droplet diameter percentile volume fractions of a spray, respectively. A comparison of the percentile volume fractions produced by a nozzle to that of specific standardized reference nozzles classifies a droplet size spectrum. The $D_{V0.5}$ is also referred to as the volume median diameter (VMD). The VMD is commonly used to characterize the droplet size of a spray, despite the fact that it may not be a good descriptor of drift potential or spray quality due to its disregard for the portion of spray contained in very small and very large droplets (Hewitt et al., 1998). The VMD is the droplet diameter at which 50% of the spray volume is contained in larger droplets and the other half is contained in smaller droplets (Matthews and Thomas, 2000). The $D_{V0.1}$ is the droplet size at which 10% of the spray volume is contained in smaller droplets and 90% of the spray volume in larger droplets. The $D_{V0.9}$ is the droplet size at which 90% of the spray volume is contained in smaller droplets and 10% of the spray volume is contained in larger droplets.

The types of atomizers considered in this study include hydraulic deflection type nozzles and rotary cage nozzles. Hydraulic nozzles use pressure to achieve primary atomization by emitting a high-velocity stream of liquid through a small orifice into the atmosphere where it disintegrates from shear stress (Bouse et al., 1994). Typically, the greater the operating pressure of a hydraulic nozzle the greater will be the velocity at which liquid is emitted, resulting in more shear stress and a more violent fragmentation. However, if the nozzle is oriented backward greater pressure will increase the velocity of the liquid leaving the nozzle, but the result is a relative reduction in the velocity of the droplet in the flow field (Pilch and Erdman, 1987). With this type of nozzle, primary atomization can be made more effective by impacting or deflecting the liquid stream on a surface. Greater secondary atomization is also achieved with a deflection because the liquid is injected into the flow field at a greater angle of incidence (the relative velocity of the flow field is increased) (Kirk, 2001). Atomization with this type of nozzle results in the generation of a wide spectrum of droplet sizes. Models developed by the United States Department of Agriculture (Kirk) show that for the CP-09 nozzle (fixed wing, 0.078" orifice (which converts to a 1.98 mm orifice size), 30° deflection, 240 kPa, 225 km/h) produces a $D_{V0.1}$ of 143 μm, $D_{V0.5}$ of 283 μm, and a $D_{V0.9}$ of 429 μm. This spray has a relative span (which is defined by $(D_{V0.9} - D_{V0.1})/D_{V0.5}$) of 1.01 and 20% of the spray volume is contained in droplets <200 μm in diameter.

Rotary cage atomizers consist of a hollow cylindrical cage into which liquid is injected. The liquid subsequently flows out through the cage openings. This type of atomization utilizes centrifugal energy which is generated by blades attached to the cage for primary atomization. The rate of cage rotation is determined by the speed of the aircraft and can be controlled by the pitch of the blades attached to the cage. This type of

atomizer typically produces a relatively narrow droplet size spectrum (Teske et al., 2001). Models developed by the University of Queensland (Anonymous) show that the ASC A-10 nozzle (fixed wing, 4.4 gpm orifice (which converts to a 16.6 lpm flow rate), 2500 rpm cage speed, 240 kPa, 225 km/h) produces a $D_{V0.1}$ of 84 μm, $D_{V0.5}$ of 213 μm, and a $D_{V0.9}$ of 378 μm, with a relative span of 1.38. Contrary to the expected outcome these models actually show the rotary and hydraulic nozzles to have somewhat similar relative spans.

Matthews and Thomas (2000) described the following factors as contributing to spray quality: atomizer type, flow rate, pattern angle, operating pressure, nozzle orientation with respect to the direction of travel, spray mixture properties, and environmental conditions. Generalizations regarding these parameters of application were: rotary atomizers produce a narrower droplet spectrum than hydraulic atomizers; nozzles with greater flow rates, narrower patterns and lower operating pressures result in coarser sprays; decreasing the angle of incidence of the nozzle backward with regard to the flow field will also result in coarser sprays (Bouse et al., 1994). It is often held that modification of the surface tension and viscosity of the spray liquid by inclusion of adjuvant will result in the generation of a coarser spray (Kirk, 2003), however, there actually exists a high degree of variability in the effect of modified physico-chemical properties of a spray liquid on the droplet size of a spray produced, especially for aerial applications (Kirk, 2000; Wolf et al., 2003).

Environmental conditions at the time of the application influence spray quality as they affect the rate of evaporation of the droplets. Environmental conditions that favour the evaporation of droplets will decrease droplet diameters as the spray cloud travels

through the atmosphere to the target. The result of decreased droplet size due to evaporation is increased potential for drift.

2.2.2   The Physics of Particle Movement

The initial motion of spray droplets immediately subsequent to release from the atomizer is primarily a function of the atomizer and its operating parameters. A short distance from the nozzle the motion of droplets ceases to be governed by the atomizer and becomes a function of physical phenomena in the atmosphere. The transition from motion being governed by the atomizer to being governed by the flow field is conveyed by stop distance or relaxation time (Bache and Johnstone, 1992). The stop distance is the distance away from the nozzle at which droplet motion becomes governed by the flow field. For a droplet released at 20 m/s into air at 20 ºC, stop distances for 50, 200, and 400 μm droplets would be 0.068, 0.75, and 2.26 m, respectively. These values suggest that the initial trajectories of spray droplets become irrelevant a short distance after emission from the atomizer, after which they are subject to movement by the forces of gravity and air turbulence. Relaxation time is defined as the time scale over which the movement of a particle reaches equilibrium within a flow field, subsequent to a disturbance (or its initial state in this case).

Although particle movement in the atmosphere is complex and governed by many variables, some of the basic laws of physics can be used predict particle movement in some circumstances. For example, the motion of large particles is dominated by the force of gravity and in some cases by severe cross flows. In this situation the size and mass of particles can be used (along with density of the flow field) to calculate gravitational forces and drag coefficients, in order that one can arrive at vectors and velocities can be determined for the particle (Galeev and Zaripov, 2003). Additionally,

the settling rate of droplets can be determined from simple mathematical equations for terminal velocity. It has been determined that a 200 μm droplet would take 1.4 s to fall 1 m while a 500 μm droplet would take only 0.6 s to fall the same distance. The dominant force acting on droplets larger than 200 μm in diameter is gravity. These droplets tend to resist the force of wind and quickly fall to the ground without drifting off target (Parkin and Merritt, 1988).

More often an understanding of the movement of smaller droplets is required. Droplets less than 100 μm in diameter are said to be approximately buoyant because gravitational force acting on these droplets is roughly equal to their drag force (Whitney and Roth, 1985). Because movement of these droplets is governed primarily by the flow field, modelling the dispersion of these particles in diluted highly turbulent flow fields is challenging and requires an advanced understanding of physical processes in the atmosphere. Predictions under these circumstances require an in-depth understanding of the turbulence phenomena of the flow field (Shirolkar et al., 1996).

Turbulence in flow fields refers to the non-laminar or non-translational movement of fluid, that is, the rotational motion in the flow field. The transition from laminar flow to turbulent flow is dependent on the viscosity and velocity of the fluid comprising the flow field. The Reynolds number, which refers to the ratio of inertial force to viscous force, can be used to identify whether a flow is laminar or turbulent (Shirolkar et al., 1996).

The rotating structures in turbulent flow fields are called eddies and the rate of rotation in eddies is called vorticity (Robertson and Crowe, 1997). The rotation in flows may appear to be a very disorderly process but it is not a random phenomenon. In fact

turbulence is commonly modelled by general solution of the Navier Stokes equations (Jovanovic and Bamieh, 2001).

Particle movement and dispersion in turbulent flows is dependent on the properties of both the particle and the flow field. The extent to which particles are displaced by turbulence is dependent on their size with respect to the size of the eddy. Particle-eddy interactions are also dependent on flow field viscosity, flow field density and particle density. The movement of very small particles is highly governed by the spatial and temporal distribution of turbulent kinetic energy in the flow field (Shirolkar et al., 1996).

Collection efficiency is the probability that a drop will deposit on a surface located in its path and is dependent on the relative velocity of the drop with respect to the target, wind velocity relative to the target, the size, shape, and orientation of the target, and drop size and drag coefficient (Whitney and Roth, 1985). It is generally accepted that larger drops result in greater collection efficiency on horizontal surfaces. Conversely, smaller drops tend to favour deposition on vertically oriented targets (Zhu et al., 1996).

For this discussion it is useful to re-introduce the concept of relaxation time or stopping distance, as it relates to particle response to a rapid change in the speed and direction of the flow field (Spillman, 1984). The air moving toward an object is able to change direction very rapidly and move around an object but droplets entrained in the flow are less able to do this. An entrained droplet's ability to deposit on a surface increases with droplet size, higher wind speed and smaller collecting objects. Generally small drops have much shorter stopping distance and remain entrained in the flow field that moves around the collecting object (Spillman, 1984). Larger obstacles tend to create

deviations in the flow field which allow particles with longer relaxation time to remain entrained.

Spherical and cylindrical surfaces are better collectors of droplets than flat objects because the flow field follows the cylinder over its sides and reduces the zone of dead air behind the object. Objects oriented at 90° to the flow field have greater collection efficiency than those oriented at lesser angles. Objects oriented at lesser angles generate less severe changes in the flow field; the result is that droplets are less likely to collide with an object (Spillman, 1984).

2.2.3   Impacts of Meteorological Parameters on Spray Drift

The dose transfer process is heavily influenced by atmospheric conditions at the time of application. The major atmospheric factors influencing the transport of a droplet from sprayer to target are wind, turbulence, temperature and humidity (Thistle et al., 1998). The drifting of sprays off target can be either greatly enhanced or reduced depending on the state of the atmosphere at the time of application.

2.2.3.1   Wind

Wind speed and direction are the most powerful influences on the horizontal movement of droplets (Thistle, 2005). The average wind speed and direction determine the horizontal velocity and bearing of droplets. The term "wind" for the purposes of this discussion, refers to the movement of atmospheric air. Generally these currents are generated as air moves from areas of high pressure to areas of relatively low pressure. Wind speed and direction are therefore governed primarily by the distribution and severity of atmospheric pressure gradients. Approximate wind speed can be determined by dividing a pressure difference between two areas by atmospheric density, multiplied by the distance between isobaric surfaces (Barry and Chorley, 2003).

Wind direction and intensity are highly variable. The wind speed near the earth's surface is greatly reduced from that of the free atmosphere due to friction on the earth's surface. The wind speed at 10m above the surface is typically one third of that in the free atmosphere (Bache and Johnstone, 1992). The generation of mechanical turbulence is also a result of surface friction on the surface and on slower moving parcels of air near the surface. The reduction in air velocity caused by drag generates tumbling rotational motion in the airflow (Oke, 1987). There is a continuum of levels of air increasing in velocity with elevation which generates considerable turbulence. The greater the wind speed relative to the surface on which it is dragging on, the greater will be the intensity of the tumbling motion and turbulence generated.

Wind speed and direction are further complicated by the effects of topography and surface roughness. Uneven terrain can significantly alter the properties of airflow over its surface (Bache and Johnstone, 1992). The upwind side of an obstacle or elevated surface may experience higher wind speeds than the fetch area, but the fetch area may experience a more turbulent airflow as a result of the separation caused by the obstacle. Surface roughness also influences wind speed. It is defined by the presence of smaller obstacles or vegetation on the surface. Roughness length is defined as the height above ground where the logarithmic wind velocity profile reaches zero, and can be approximated by 1/10 to 1/30 of the height of the roughness elements (Teske et al., 2002). These surface features alter the wind speed by increasing the effect of friction or drag on the surface. Surface roughness is established based on the height and porosity of objects on the surface and can influence the air flow above for up to three times their height.

Research has shown the relationship between wind speed and initial airborne spray drift to be approximately linear. Grover et al. (1997) showed that total initial airborne drift increased from less than 2% of that emitted at a wind speed of approximately 10 km/h, to greater than 10% at approximately 25 km/h. Research to determine the effect of wind speed on spray drift can sometimes be difficult to interpret. For example, Yates et al. (1974) measured found decreased spray drift deposits with increasing wind speed. This phenomenon was also observed by Threadgill and Smith (1975). This trend was probably observed because the samplers utilized in the experiment could only measure off target horizontal deposits and not total off target losses. In this situation total drift losses are likely to increase, however drift deposition at the ground level may actually decrease due to a greater proportion of the spray cloud being dispersed upward into the atmosphere and becoming available for long distance transport. Despite the uncertainty in the interpretation of earlier experiments it is commonly held that increased wind speed results in greater drift losses (Thistle et al., 1998).

2.2.3.2 Temperature and Humidity

The importance of temperature and humidity with regard to spray drift relates to their influence on droplet size (Thistle et al., 1998). Low relative humidity and high temperature during application promote evaporation of the carrier solution during dose transfer. High temperatures may also result in increased volatilization of the pesticide product. The result is generation of a continuously finer droplet spectrum for as long as the spray cloud remains aloft. Luo et al. (1994) observed that at a constant temperature of 25 °C and speed of 2.0 m/s, a 1070-μm droplet took 300 s to completely evaporate at 20% RH and 540 s to completely evaporate at 60% RH. Luo et al. (1994) also

demonstrated that a 910-µm droplet at 60% RH took 780 s to evaporate at 10 °C, but only 420 s to evaporate completely at 25 °C. It has also been demonstrated that smaller droplets experience greater rates of evaporation due to their larger ratio of surface area to volume compared to larger droplets(Luo et al., 1994).

Understanding droplet size reduction rates is an important principle in modelling the drifting of sprays. For that reason, a series of mathematical procedures has been developed to predict rates of evaporation from falling droplets. The first work towards modelling drop evaporation was conducted by Ranz and Marchall (1952). Their work was elaborated on by Williamson and Threadgill (1974) whose model is utilised by the AgDISP model commonly used today. An example of the application of this model is provided by Picot et al. (1981) who demonstrated that an 85-µm water droplet falling at its terminal velocity through air at 10 °C and 60% RH would reduce to one half of its original size in 107 s.

2.2.3.3 Atmospheric Stability

Atmospheric stability depends on the change in air temperature with height. It is relevant to the dispersion of droplets as temperature gradients govern thermal atmospheric mixing. Thermal atmospheric mixing refers to vertical movement of air that is governed by its temperature and buoyancy.

There are three phases of atmospheric stability. In a neutral atmosphere the temperature change with height follows the adiabatic lapse rate. The adiabatic lapse rate refers to the drop in air temperature that occurs with elevation as a result of decreasing air pressure. This reduction in air temperature is 1 °C per 100 m for dry air and decreases with increasing humidity because water vapour is less subject to expansion and compression. Neutral atmospheres are not common, but do occasionally occur and are

characterised by cool days with overcast skies and slight winds. This situation may be the most desirable for pesticide applications, as very little drift would occur due to the low wind speeds, lack of droplet evaporation and lack of vertical mixing (Bache and Johnstone, 1992).

In an unstable atmosphere, the rate of cooling with elevation is greater than the adiabatic lapse rate. This elevated rate of cooling is the result of surface heating from incoming long wave solar radiation. The warmer air at the surface is less dense than the cooler air above it, consequently it rises up in the atmosphere and is replaced by cooler air, which is heated at the surface and the cycle continues. This vertical mixing in an unstable atmosphere can effectively disperse clouds of pesticide drift (Thistle, 1996). An unstable atmosphere is common on days with very little cloud cover and substantial and variable winds. This atmospheric situation is suitable for pesticide applications provided the wind speeds are not excessive. In an unstable atmosphere the total amount of drift maybe greater than in a neutral atmosphere due to increased evaporation and the creation of smaller more drift prone droplets. However, vertical mixing that occurs effectively disperses the spray cloud upward into the atmosphere, thereby diluting the spray cloud to very low concentrations that are not likely to do damage downwind of the application. The combined vertical movement caused by atmospheric mixing and horizontal movement caused by wind results in the generation of considerably intense turbulence (Bache and Johnstone, 1992). Although the dispersion of a pesticide spray cloud is beneficial for the reduction of local pesticide drift damage, it is offset by the increased levels of pesticide in the atmosphere. Once in the atmosphere, pesticides can be transported large distances on atmospheric currents or they may be deposited locally (Waite et al., 2004).

A stable atmosphere exists when the rate of cooling with elevation is less than the adiabatic rate. This situation, often called a temperature inversion, frequently begins just prior to sunset and can persist until after sunrise. It is characterized by the absence of wind on clear summer nights. In this condition the air at ground level is cooler than the air above it, resulting in an absence of vertical mixing of the atmosphere. In a stable atmosphere there is warming with increasing elevation up to a certain height after which cooling begins with increasing elevation. This point where warming stops and cooling begins is called the inversion cap (Bache and Johnstone, 1992).

A stable atmosphere has very little mixing and is least desirable for the application of pesticides. The droplets do not settle into the cooler air below nor are they dispersed and diluted upward, rather they tend to remain suspended and concentrated below the inversion cap (Thistle et al., 1998). The concentrated pesticide cloud could then slowly move in any direction into a sensitive area where it has the potential to be deposited once the inversion breaks (Miller and Stoughton, 2000).

2.2.4 Implications for Aerial Applications

The application of pesticides to farmland from aircraft has been practiced for over half a century. While this method of application offers several advantages with regard to productivity and efficiency, several aspects of aerial application may exacerbate the drift problem (Frank et al., 1994). In fact work by Maybank et al. (1975) have shown that initial drift from aerial applications can be 10 times greater than that from ground rigs. The researchers (1975) also reported that drift deposition from aerial application was 6 times greater at 30 m downwind and 4 times greater at 60 m downwind than applications by ground. The same studies showed that, on average, 12% of the applied dose remained aloft at 25 m downwind of the application. Another study

conducted by Maybank et al. (1978) showed that for aerial applications, depending on application parameters, 3 to 8% of the applied amount may still be aloft between 200 and 400 m downwind of the application.

2.2.4.1   Application Speed

Aerial applications can be made at speeds in excess of 225 km/h. At these speeds, the aerodynamic characteristics of the application implement become relevant due to the generation of a turbulent wake. The entrainment of droplets in this turbulent wake may result in non-uniformity in deposition under the plane and may also result in greater off target movement of the spray (Raghavan, 1987). The secondary atomization process takes place to a greater extent when applications are made at high speed due to the increased shear stress droplets are subjected to when injected into the relative high speed of the flow field (Pilch and Erdman, 1987).

The major aerodynamic characteristics under consideration when pesticides are applied by air include wing-tip vortices and prop-wash. The wing tip vortices rotate clockwise on the port side of the plane and counter-clockwise on the starboard side. Droplets entrained in these vortices may be displaced from underneath the plane and can move off-swath in the horizontal direction. These vortices may also elevate small droplets above the height of release making them very susceptible to drifting off target. The entrainment of droplets in wing-tip vortices can be managed by shortening the length of the spray boom relative to the wingspan (Raghavan, 1987). It has been recommended that modern aircraft employ a spray boom that is less than 70% of wingspan (Anonymous, 1997). The rotational motion of the plane's propeller also generates a large vortex around the plane's fuselage which rotates in the clockwise direction. This prop-wash can displace some of the spray emitted on the starboard side

of the plane and deposit it under the portside. This effect can be countered by adjusting the arrangement of nozzles around the fuselage (Raghavan, 1987).

The majority of aerial sprayers use drop booms which lower the release height some distance below the wings in order to avoid some of the smaller scale turbulence generated by the less pervasive aerodynamic characteristics of the plane (Hoffmann and Tom, 1999).

2.2.4.2 Release Height

The elevated release height of aerial application exacerbates the drift problem. The greater the distance between the point of release and the ground the longer it will take for the emitted droplets to travel to target. The emitted spray is subjected to the atmospheric conditions for a longer period of time which means there is a greater potential for the droplets to evaporate and become entrained in convective or horizontal airflows (Anonymous, 1997).

2.2.5 Effect of Spray Quality, Atomizer Type and Ground Cover on Spray Drift

2.2.5.1 Effect of Spray Quality on Spray Drift

The spray quality of a pesticide application is the most influential parameter determining the quantity which moves off-target. In fact research has shown the spray quality of aerial applications to be the only parameter which consistently has a significant impact on drift (Bird et al., 1996). This is an expected trend since the movement of larger droplets is dominated by gravity. Sprays which have most of their volume in large droplets will tend to be deposited mostly on target.

A review of previous findings shows that applications involving the release of very small droplets (VMD < 200 μm) can increase drift potential 5-10 times. Conversely, the release of very large droplets (VMD > 500 μm) can reduce the drift

potential of aerial applications to that of conventional ground applications (Bird et al., 1996). Yates et al. (1967) reported horizontal drift deposits from an application of relatively small droplets (VMD = 290 μm) was over twice as much as the drift deposits from an application of spray containing larger droplets (VMD = 420 μm). Further work by Yates et al. (1974) showed that downwind drift deposition was approximately 3 times greater for the application of a fine spray (VMD = 175 μm) compared to a coarser one (VMD = 450 μm) and in certain cases, drift deposits from the fine spray were as much as 5.5 times greater. In both these studies spray quality was manipulated by altering the orientation of the nozzles. Womac et al. (1993) manipulated droplet size by changing the speed of the aircraft. Increasing the aircraft speed from 218 to 241 to 265 km/h resulted in the production of sprays with VMD of 247 μm, 218 μm, and 189 μm, respectively. However, there was no significant effect of treatment observed in the drift measurements on high volume air samplers downwind.

A similar effect of spray quality on drift can be seen from ground applications. Goering and Butler (1975) reported a drift reduction of 17% associated with the generation of larger droplets from reducing nozzle pressure from 275 to 172 kPa. Threadgill and Smith (1975) found in working with mono-dispersed droplets from ground applications that drift potential decreased with increasing droplet size up to 140μm at which point drift became negligible. Grover et al. (1997) found total airborne drift ranges reduced by half in when spray droplet size increased from 169 μm to 258-μm in diameter. The same experiment also showed that downwind deposits were reduced from 10% of applied spray to 8% of applied spray by using a coarser spray.

2.2.5.2   Effect of Atomizer Type on Spray Drift

Few studies have compared actual drift deposits of sprays from rotary and hydraulic atomizers. However, the droplet size spectra generated by the nozzles and their drift potential are well documented. The objective of utilizing rotary atomization for pesticide application is to narrow the droplet spectrum around a target VMD. It has been shown that rotary atomizers offer more control over the primary atomization process so that less of the spray liquid is contained in very large drops which are not as biologically effective, and less spray liquid is also contained in very small drops which tend to drift off target (Spillman, 1982). The potential result is a spray that is both more biologically efficient and safer from a drift perspective. For example, Spillman (1982) chose 225 μm as a target VMD and stated that the ideal sized droplets should fall within 25% of this size. It was then shown that for a hydraulic nozzle 33% of total spray volume was contained in droplets in the ideal size range but for the rotary nozzle 70% of the total spray volume was contained in droplets in the ideal size range. Spillman (1982) also noted that for the rotary nozzle, less than 5% of the spray volume was contained in droplets smaller than 150 μm in diameter. The importance of generating a droplet spectrum with a narrow distribution of droplet sizes around a target VMD of 200 μm was also expressed by Akesson and Yates (1984). However, Bouse et al. (1994) showed that hydraulic nozzles could also produce a droplet size spectra with ideal target VMDs and with small percentages of spray volume contained in droplets less than 100 μm in diameter.

In a study conducted by Maybank et al. (1980) a rotary spinning disc sprayer for ground application was compared to a flat fan nozzle and it was found that the rotary atomizer produced significantly less initial airborne drift and significantly lower drift

deposits downwind than the hydraulic nozzle, despite having a much smaller VMD (VMD = 350 μm for the rotary atomizer and VMD = 600 μm for the hydraulic atomizer). In a bystander exposure study conducted by Gilbert and Bell (1988), it was reported that persons located 50 m downwind of the target area collected 36 times more spray from applications with a hydraulic nozzle than from applications with a rotary nozzle.

2.2.5.3 Effect of Ground Cover on Spray Drift

Many studies have documented the interception of drift by vegetation at the edges of fields. It has been demonstrated that vegetation or other obstacles in the path of drifting sprays tend to collect the spray droplets and by scrubbing the atmosphere effectively reduce the amount of off-target drift. Certain types of vegetation can have very high collection efficiency (approaching 100%) depending on their porosity, size and orientation. Richardson et al. (2004) showed airborne drift reductions from >75% of applied quantities on the windward side of a shelterbelt to <5% of applied amounts on the leeward side. Airborne drift below 2 m was greatly reduced when spray from ground applications was filtered by a tall stand of mixed grass species (Miller et al., 2000). Other work by Longley and Sotherton (1997) has shown that buffer zone distances can be decreased if a crop canopy is present in the un-sprayed area. Van de Zande et al. (2000) observed that spray drift was reduced by 70 to 90% on the downwind side of hedges at the field edge.

The work with greatest relevance in investigating the effect of crop characteristics on the drifting of spray into the far field was conducted by Lawson and Uk (1979). In this experiment the amount of drift from aerial applications was evaluated as influenced by the presence or absence of a wheat canopy (early stages of anthesis). It

was found that the wheat canopy was 100% effective in removing droplets >50 μm in diameter while the application to bare ground was only 60% effective in removing droplets of that size. It was also found that the total amount of airborne drift over the bare ground was 70% greater than the amount over the crop canopy.

2.3   Drift Modelling and Buffer Zones

2.3.1   AGDISP

Mechanistic models have been developed which can be used to predict the movement of aerially applied sprays. In order to model the movement of spray, one must account for droplet size distributions, evaporation rates, ambient winds, atmospheric- and aircraft-generated turbulences, and the collection efficiency of the target (Teske et al., 1998). AgDISP is one such model used by the PMRA of Canada for aerially applied crop protection products (Kuchnicki et al., 2004). The AgDISP program was initially developed by the USDA, U.S. Forest Service and the U.S. Army and requires the input of aircraft (make and model) and aircraft set-up (nozzle, nozzle spacing, application volume and operating pressure), operating parameters of the aircraft (speed and release height), atmospheric conditions (wind speed, temperature, RH, and atmospheric stability), and characteristics of the target (surface roughness) to calculate downwind deposits (Teske et al., 2002).

Comparison of AgDISP predictions to empirical data has been conducted in several different studies. The most rigorous of these studies was conducted by Bird et al. (2002) where 161 aerial applications were made and the empirical data were compared to AgDISP predictions. It was observed that the model tended to underestimate deposition in the near field and overestimate deposition in the far field. The model predictions of spray drift at 305 m downwind of the application were found on average

to be overestimated by a factor of approximately two. It was also noted for the application of coarser sprays that the model tended to underestimate drift to a greater extent in the near field and overestimate to a lesser extent in the far field for the application of courser sprays (VMD > 350 μm). When considering the applications of finer spray qualities, the model overestimated deposition at the 305-m distance by a factor closer to five. Duan et al. (1992) also noted similar results, with AgDISP over predicting deposition on average by a factor of two. On an individual application basis the model occasionally over predicted deposition by a factor of three. Reasons suggested by Bird et al. (2002) for the over prediction of the model included over-sensitivity to evaporative effects, the assumption of perfectly flat terrain and the assumption of a near neutral atmosphere.

Work by Bilanin et al. (1989) made qualitative comparisons between predicted deposition curves with distance from the target area and previous drift studies and noted good agreement between the shape of deposit curves with distance and magnitude of spray deposits. Similar comparisons and findings were noted by Woods et al. (2001).

2.3.2 Buffer Zone Determination

A buffer zone is an area downwind of a pesticide application that is not directly sprayed in order to mitigate the deposition of spray on a sensitive area (Payne et al., 1988). Sensitive areas are determined by the presence of species that may be harmed by the applied pesticide. Buffer zone distances vary depending on the relative toxicity of a particular pesticide on a specific sensitive species. Buffer zones are established by comparing toxicological data for each pesticide to expected environmental concentrations (Kuchnicki et al., 2004). Toxicological studies identify the most susceptible species to the active ingredient of a pesticide from among approximately ten

tested. A dose response experiment then determines the environmental concentration at which there is no observable effect (NOEC) on aquatic organisms and the concentration at which there is a 25% inhibitory effect (EC_{25}) on terrestrial plant life. For aerial applications, the mechanistic model AGDISP is used to determine the environmental concentrations of pesticide downwind of a pesticide application. The distance at which the NOEC or EC_{25} occurs for the most susceptible organism then becomes the buffer zone for that particular application (Anonymous, 2002).

3.0   Materials and Methods

Experiments were conducted to quantify drift from aerial applications of pesticide and describe its movement. The effects of spray quality, atomizer type and ground cover were examined. The AgDISP model was evaluated by direct comparison of its output to empirical data. Efforts were made to account for variability attributed to meteorological conditions for each application.

3.1   Experimental Design

The experimental design for this project was a completely randomized design with four treatments and three replicates in time. Treatments in the experiment were intended to examine the effects of application parameters on the generation of spray drift. Application parameters considered in the study included spray quality, method of atomization, and the type of ground cover. The application treatments allowed for the comparison of Fine vs. Medium spray qualities, hydraulic-deflection vs. rotary atomizers, and application to bare ground vs. a mature crop canopy.

3.2   Site Description

The study was conducted near Indian Head, SK, in August of 2004. The experimental site was the northern third of a field measuring approximately 600 m by 1600 m seeded to barley and an adjacent field to the west measuring approximately 800 m by 800 m seeded to peas (Figure 3.2.1). The barley crop was approximately 1m tall and in the late stages of anthesis (Zadoks 65, (Zadoks et al., 1974)) at the time of application. The pea field had been harvested at the time of application leaving minimal residue on the soil surface.
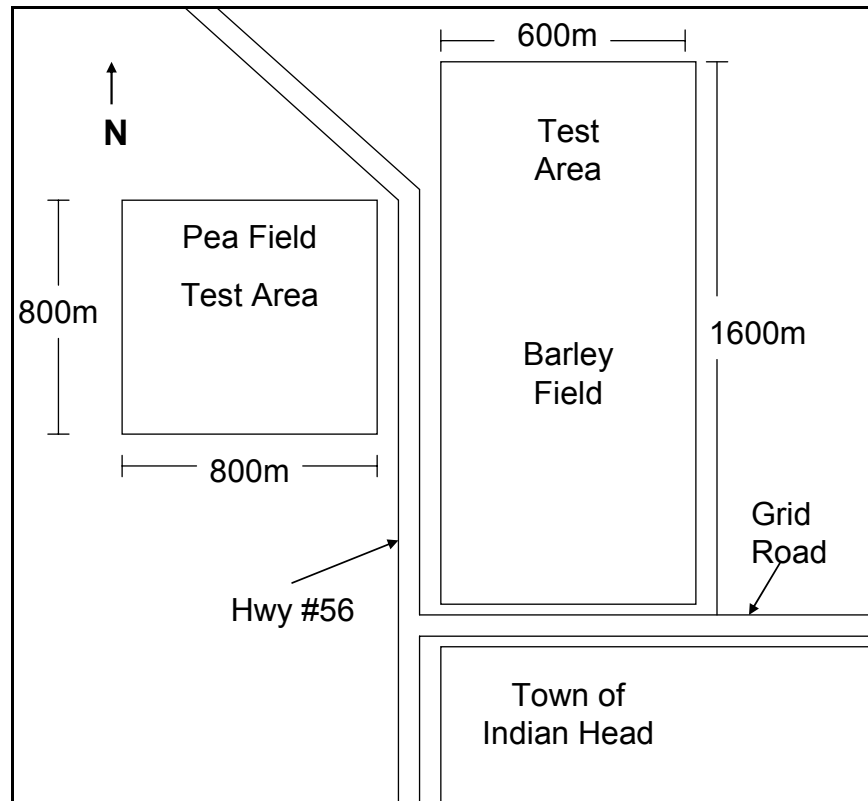
Figure 3.2.1. Experimental test site.

The field was measured and the flight path was marked off perpendicular to the wind direction on the windward side of the field (Yates et al., 1974) and (Goering and Butler, 1975). A sampling line was then marked perpendicular to the flight path. Sampling stations for drift measurement were placed at 12.5 m, 25 m, 50 m, 100 m, 200 m and 400 m on the sampling line (Figure 3.2.2). The off-swath samplers were placed at these stations. Sampling stations were also placed directly on the flight path and upwind of the application area. The on-swath samplers and upwind background samplers were placed at these respective locations. The test site and field measurements were made in similar fashion to the guidelines set forth in ASAE Standard S561 for measuring drift deposits from spray applications (Anonymous, 2003)
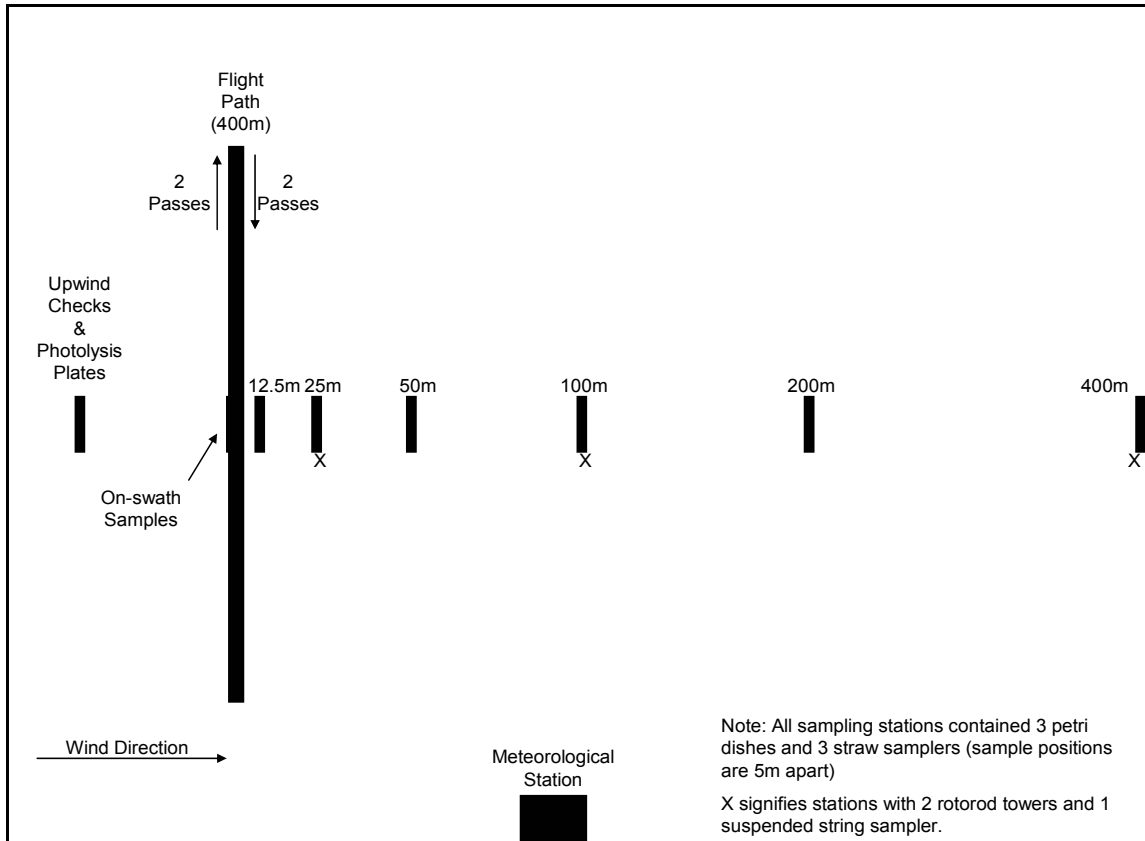
Figure 3.2.2. Field setup and sample station distribution

3.3 Collectors of Spray Drift

Samplers utilized in this experiment were selected based their ability to collect both deposited drift and airborne drift (Figure 3.3.1). Horizontal samplers (three 15-cm diameter petri dishes positioned 5 m apart at each sampling station) were employed to assess drift deposition in a similar approach to the setup used in the drift experiments conducted by Yates et al. (1974); this type of sampler is still commonly used in modern experiments (Hoffmann et al., 2003).

Several types of vertically oriented samplers were used to measure airborne drift at different heights and with different collection efficiencies. Plastic drinking straws 0.6 cm in diameter and 12 cm long were placed vertically at each sampling station immediately beside the horizontal samplers. These provided a direct comparison of drift

Figure 3.3.1. Samplers utilized in the experiment included petri dishes (upper left), plastic straws (upper right), rotorods (lower left) and strings suspended from blimps (lower right)

fallout vs. horizontally moving droplets at ground level (Parkin and Merritt, 1988). Monofilament plastic strings sampled the spray cloud with height in similar fashion to the setup of Woods et al. (2001). In this experiment the strings were suspended by helium blimps elevated to a height of 30 m. The strings were 2 mm in diameter and processed in 1m sections to yield a total of 30 samples per string. A single blimp was placed at the 25 m, 100 m and 400 m downwind stations. The string samplers were included in the study to describe the change in spray cloud concentration with height as it traveled downwind of the application. The spray cloud profiles obtained from the

string provided an understanding of the extent to which spray was dispersed upward in the atmosphere.

Rotorod air samplers (Model 92, Sampling Technologies Inc., Minnetonka, MN) were employed to actively sample the spray cloud at a rate of 120 l per minute. A rotorod sampler consists of two rapidly spinning brass arms which impact upon particles suspended in the atmosphere. The towers sampled air at 1 m, 2 m, 3 m, and 4 m height. A pair of towers positioned 10 m apart were placed at the 25-m, 100-m and 400-m stations. The suitability of these vertical samplers for measuring airborne drift and the procedures for utilizing them is described in detail by Bui et al. (1998).

3.4   Application Equipment

All treatments were made with a fixed wing, turbine powered monoplane. The plane was an Air Tractor model AT502 (Figure 3.4.1). The plane had a wingspan of 15.2 m and weighed approximately 3000 kg. The applications were made at a travel speed of approximately 225 km/h with a release height of 3 m above ground. For applications with the deflection atomizer, the sprayer boom was 78% of wingspan, with 38 nozzles spaced at 28-cm intervals with a gap of 1.8 m under the fuselage. For applications with the rotary atomizer the sprayer boom was 64% of wingspan with 10 nozzles spaced at 88-cm intervals and a gap of 2.8 m under the fuselage.

Figure 3.4.1. AT502 applying Rhodamine dye at test
site near Indian Head, Saskatchewan

3.5　Application Scenarios

The application scenarios performed in this study make up the treatments which were evaluated. The treatments were designed to test the effects of spray quality, atomizer type and ground cover on the off-target movement of sprays. A total of four treatments were utilized to test the desired parameters (Table 3.5.1).

Treatments to test the effect of spray quality were generated using the same hydraulic CP-09-3P nozzles set at the 0.078" orifice size (which converts to a 1.98 mm orifice) and at an operating pressure of 240 kPa. A straight stream without deflection was used to generate a Medium spray (Treatment 1) and a deflection setting of 30° was used to generate a Fine spray (Treatment 2) (Table 3.5.2). To study the effect of atomizers, Treatment 2 was compared to an ACS rotary-cage type nozzle set at the #12 orifice (4.4 gpm, or 16.6 lpm)with an operating pressure of 240 kPa and a cage speed of 2500 rpm (Treatment 3). The first three treatments were applied over the barley crop. The effect of ground cover was tested by comparing Treatment 2 to the same atomizer applied over a harvested pea field with minimal residue on the surface.

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Table 3.5.1. Treatment application scenarios.

Trt	Atomizer	Spray Quality	Target
1	Hydraulic	Medium	Crop
2	Hydraulic	Fine	Crop
3	Rotary	Fine	Crop
4	Hydraulic	Fine	Bare Soil

Table 3.5.2. Treatment nozzles and spray quality parameters.

Trt	Atomizer	$D_{V0.1}$ (μm)	$D_{V0.5}$ (μm)	$D_{V0.9}$ (μm)	Relative Span	%<100 μm
1	CP-09-3P (0°)	175	345	594	1.21	5.06
2	CP-09-3P(30°)	143	283	429	1.01	6.8
3	ASC A-10	84	213	378	1.38	NS*
4	CP-09-3P(30°)	143	283	429	1.01	6.8

* Not Specified

Upon completion of the field trials, the measurements taken during treatments 1, 2 and 4 were entered into the AgDISP model. Treatment 3 was omitted due to the unavailability of its droplet size spectrum within the AgDISP model. Each set of treatment conditions was entered and the model was executed three separate times, using the meteorological data taken from the three trial replicates. The model output was formatted to allow comparison with the deposit data collected during the field trial at each of the sampling distances (Duan et al., 1992). AgDISP input parameters which were held constant are summarized in Table 3.5.3.

Table 3.5.3. AgDISP parameters used in model output analysis.

Parameter Description	Value	
	Treatments 1 & 2	Treatment 4
Boom Height	4 m	4 m
Flight Lines	1	1
Nozzle Placement	38 nozzles, 78% of wingspan	38 nozzles, 78% of wingspan
Droplet Size Distribution	USDA Model	USDA Model
Swath width	18.3 m	18.3 m
Swath Displacement	0	0
Metoerology	As per actual trial	As per actual trial
Spray Material		
Volume	18.7 L/ha	18.7 L/ha
Active Fraction	0.003	0.003
Non-volatile fraction	0.003	0.003
Stability	Overcast	
Canopy Height	1 m	n/a
Surface roughness	0.1 m	0.01 m
Canopy Roughness	0.0937	n/a
Canopy Displacement	0.0656	none
Upslope angle	0	n/a
Sideslope angle	0	n/a
Flux Plane Distance	0	n/a

3.6 Spray Solutions and Tracers

The tank solution consisted of Rhodamine WT (A.S. Paterson Co. Ltd., 1110

Sheppard Avenue East, North York, ON) at a concentration of 2 ml/l. It also included

the non-ionic surfactant, AgSurf (Inter-provincial Cooperative Limited, Saskatoon, SK),

at a concentration of 0.1% volume to volume and an optical brightener, Tinopal CBS-X

(Ciba Specialty Chemicals Canada Inc., Mississauga, ON), at a concentration of 3 g/l.

The surfactant was included in the tank mix to more accurately simulate the

physical/chemical characteristics of a pesticide solution and the optical brightener was

included in the tank mix in an attempt to reduce photolysis of the Rhodamine WT by

quenching the energy from UV light (Pergher, 2001). At the target tank concentrations,

Rhodamine WT was applied at a rate of 3925 $\mu g/m^2$ with a carrier volume of 18.7 l/ha

per spray pass. For each treatment, four passes were made along the same flight path to moderate instantaneous variability in atmospheric conditions (EPA, 1998). The total application rate to the flight path for each treatment was 15700 μg/m^2 Rhodamine WT with a carrier volume of 74.8 l/ha.

In order to account for the photolytic breakdown of the tracer dye in the presence of ultra violet light, eight petri dish samples were sprayed in a cabinet sprayer with the same Rhodamine WT dye solution used in the experiment for each trial run prior to the experiment and stored without exposure to light. When the trial commenced, four samples were exposed to ambient environmental conditions upwind of the application area. As samplers were picked up from the field, the exposed samples were returned to dark conditions. The remaining four samples stayed in dark storage until the time of extraction and analysis. The ratio of the deposit on unexposed samplers to deposit on exposed samplers provided a multiplier to account for the photolytic breakdown of tracer over the period of time that the application and sample collection took place. This procedure for measuring dye degradation was first set forth by (Goering and Butler, 1975) and is still common in modern experiments (Kramer et al., 2002).

3.7   Sample Collection and Extraction

Once the pesticide application had been completed, at least 3 minutes was allowed for the spray cloud to move out of the test area. The samplers were then collected in a sanitary manner and placed in dark storage. In order to prevent contamination of the samples, care was taken to ensure off-swath samples were not handled near or stored with on-swath samples. Samples were processed by washing in 95% ethanol (Staniland, 1959). The suspended string samples were processed in 1 m sections by passage through a U-tube which contained 20 ml of ethanol per 1 m section.

The U-tube was 50 cm in length and thus could only process one half section of the sample at a time. Each string section was submersed in the U-tube for 1 min (2 min per sample). The U-tube was placed in a sonicated bath to enhance the extraction process. The straw samples were submersed in test tubes which contained 20 ml of ethanol and were allowed to sit for a period of at least 24 h. The rotorod samplers were submersed in test tubes which were in a sonicated bath similar to the setup for the string samplers. Each arm of the rotorod was submersed in a test tube containing 7 ml of ethanol and sonicated for 1min. The petri dish samples were rinsed 3 times with 15 ml ethanol and the total wash volume was then brought up to 50 ml.

Deposits extracted from collection samplers were analyzed on a fluoro-spectrophotometer (Shimadzu Corporation, model RF-1501, Kyoto, Japan) which measured the fluorescence intensity of a particular solution for a specific excitation and emission wavelength. The fluorescence intensity is a unitless value which is compared to a regression curve generated from the fluorescence intensity of standard solutions of known concentration.

The lowest non-zero standard utilised in the generation of standard curves in this study was 1 ppb of Rhodamine WT dye, even though subsequent work has shown the instrument to be capable of accurately detecting the tracer to 0.1 ppb. The measurement of 1 ppb is 5% of full scale for the instrument and all accounts of noise or anomalies in detection were lower than 5% of scale. In this study all concentrations below 1 ppb were statistically analyzed as determined by the fluoro-spectrophotometer. However, for the purposes of interpretation, all deposits which generated concentrations below 1 ppb were taken to be below the limits of detection (Table 3.7.1).

The wash concentrations from the fluorescence spectrophotometer were converted to μg of dye deposited per m^2. These conversions were made based on the concentration of the dye in the spray tank solution, surface area of the sampling device, volume of ethanol used to extract from the sampling device, photolytic multipliers, and the conversion of ppb to μg.

Table 3.7.1. Detection limits from spray collection samplers (μg/m^2) based on the lowest non-zero standard of 1ppb.

Sampler	Limit of Detection (μg/m^2)
Petri Dish	3.20
Drinking Straw	27.78
String	10.00
Rotorod	37.14

Environmental background fluorescence was measured by control samplers placed upwind of the application area. Petri dishes and rotorod samplers were placed upwind to account for both horizontal deposition and airborne movement of any potential contaminants which may contribute to the fluorescence of downwind samplers. These samples also provide an understanding of the levels of experimental cross-contamination and degree of sanitation in the experimental procedure.

3.8   Meteorological Conditions

A detailed account of the meteorological conditions was recorded for each application in accordance with the guidelines set forth by Thistle et al. (1998). The wind speed measurements were taken at heights of 1 m, 2 m, 3 m, and 4 m (reported values were from the 4-m height) using cup anemometers (Model 014A Met One Wind Speed Sensor, Campbell Scientific Canada Corp., Edmonton, AB). These measurements were taken at both the 25-m and 400-m downwind sampling stations. Relative humidity and temperature were measured at 1-m elevation with a humidity sensor and temperature

probe enclosed in a radiation shield (Model HMP45C212 Relative
Humidity/Temperature Probe, Campbell Scientific Canada Corp., Edmonton, AB).
Temperature differential between 1 m and 5 m heights was also measured using a
copper-constantan thermocouple. All meteorological data were collected on data loggers
(Model CR10 data logger, Campbell Scientific Canada Corp., Edmonton, AB) and
measurements were time averaged from 1 min prior to the application to 2 min after the
application. Efforts were made to ensure the meteorological parameters were similar
across treatments.

To aid in the interpretation of results observed, Richardson numbers and friction
velocities were calculated for each application. The Richardson number identifies the
relative importance of thermal and mechanical turbulence and is derived by;

$$\text{Ri} = \frac{\text{g}}{\text{T}} \cdot \frac{(\Delta \text{T} / \Delta \text{z})}{(\Delta \text{u} / \Delta \text{z})^2} \text{,}$$

where g is acceleration due to gravity (9.81m/s^2), T is mean temperature, z is height (m)
and u is mean wind speed (m/s). Friction velocity is an indicator of mechanical
turbulence relating to the transfer of material between atmospheric layers. It can be
derived by;

$$\text{u*} = \frac{\text{u(z)} \cdot \text{k}}{\ln\left(\dfrac{\text{z}}{\text{z}_o} \right)} \text{,}$$

where u(z) is wind velocity at height z (m/s), k is von Karman's constant (0.4) and z_o is
roughness length (Oke, 1987).

3.9 Analysis Techniques

The three sub samples of deposits on the petri dish and straw samplers were averaged. Original and base-10 logarithm transformed data were then fit to regression curves to identify best fits. Models tested included inverse power functions, 2nd order polynomials and linear. Many of the regressions provided adequate accounts of the variance in the data set and satisfactory residual sums. A linear regression of the base-10 logarithm of the deposit data provided a superior account for variance, satisfactory residual sums and meaningful parameters for analysis (slope and intercept). Regressions of the logarithm of deposit vs. the logarithm of distance downwind were developed for every replicate of each treatment for the empirical data and AGDISP output. The regression analysis allowed for interpretation and analysis of the relationship between spray drift deposit and airborne drift concentrations at the ground level with distance from the target area.

The slope and intercept of each replicate were analyzed using analysis of variance (ANOVA). Means of significant effects were separated using the Least Significant Difference Test (LSD) at 5% significance. ANOVA and LSD means separation were also conducted on a point by point basis for the specific distances of 25 m 100 m and 400 m downwind of the application area. These points were chosen to represent deposition in the near-field (25 m downwind), deposition in the far-field (400 m) and a point intermediate between the two (100 m). These points are also logical points to investigate in detail because they can be compared to the airborne drift data at the same distance.

A mass balance account for the fate of the entire spray cloud was developed by integrating horizontal deposition over distance using Simpson's Rule at 0.5 m intervals.

Deposits on the suspended string were integrated using the trapezoid rule at 1m intervals. This provided not only insight into the portion of spray deposited with distance and the amount still moving in the horizontal direction at ground level, but could also be used to establish the quantity of spray that was dispersed upward into the atmosphere similar to that method employed by Grover et al. (1997). The total integrated deposit from the suspended string at the 25 m distance was taken as the initial airborne drift amount. This value could then be expressed as the proportion of spray available for dispersion and deposition downwind. Reductions in total airborne drift downwind could be accounted for by the integration of the horizontal deposit data with distance. The amount of spray dispersed above the sampling area was calculated by subtracting the total amount deposited between 25 m and 100 m, and by subtracting the total amount still aloft at 100 m from the initial amount of airborne drift. The same process was then used to determine the amounts dispersed above the sampling area between 100 m and 400 m

The effect of atmospheric conditions on drift was investigated using covariate analysis where individual meteorological parameters (wind speed, RH, temperature, and temperature difference) were analyzed as a covariate of deposit. The response of the deposit on the petri dish samplers at the 100-m downwind site to meteorological conditions was assessed by regressing the deposits for all applications against the data collected for each meteorological parameter during all of the applications. The 100-m downwind site was chosen for being intermediate between the near-field (which experienced a great deal of variability associated with large deposits and swath displacement) and the far-field (where detection limits became an issue of concern).

4.0 Results

4.1 Experimental Conditions

4.1.1 Recorded Meteorological Conditions

A detailed account of the meteorological conditions was recorded for each application (Table 4.1.1). The wind speeds over the course of the study ranged from 14 km/h to 25 km/h. All applications were made during times of variable cloud cover. The majority of applications were made under strongly convective conditions. However, a nearly neutral atmosphere was observed during the third application from the rotary atomizer, where an environmental lapse rate of -0.01 °C was measured between 1 m and 5 m.

Table 4.1.1. Meteorological conditions recorded during each application.

Application Scenario	Replicate	Windspeed (km/h)	Temperature (°C)	RH (%)	Δ Temperature (°C 1 to 5 m)
Medium Spray Quality	1	18.0	22.7	45.5	-0.22
	2	21.6	15.5	67.2	-0.14
	3	19.2	15.2	65.7	-0.07
Fine Spray Quality	1	21.6	23.4	49.2	-0.50
	2	17.3	16.0	66.0	-0.23
	3	14.7	15.0	65.7	-0.06
Rotary Atomizer	1	25.7	23.4	44.3	-0.18
	2	14.2	16.1	69.0	-0.37
	3	14.5	14.5	70.4	-0.01
Application to Bare Ground	1	19.5	18.6	29.2	-0.81
	2	23.8	17.5	30.7	-0.09
	3	19.4	17.4	45.4	-0.28

4.1.2 Photolysis Account and Upwind Controls

4.1.2.1 Photolysis Account

Average photolytic degradation of the tracer dye over the course of the

application and sample collection procedure for each treatment ranged between 5.7%

and 16% (Table 4.1.2).

Table 4.1.2. Photolysis accounts of percent reduction of fluorescence activity during
treatment applications.

Trt	Application Parameters	Photolytic Reduction (%) (St. Dev.)
1	CP nozzle	5.7
	Medium Spray	(5.5)
2	CP nozzle	16.0
	Fine spray	(16.5)
3	ASC nozzle	12.3
	Fine spray	(17.1)
4	CP nozzle	15.0
	Bare Ground	(4.6)

4.1.2.2 Upwind Controls

The majority of upwind check samples generated deposit values lower than

detection limits, indicating that environmental factors and cross contamination were not

significant contributors to the measurements taken downwind of the application area

(Table 4.1.3). Pure ethanol blanks were analyzed accompanying each upwind check

sample so that any anomalies could be identified. The measurement 6.36 $\mu g/m^2$ for the

upwind petri dishes of Treatment 2 differed from the upwind rotorod samplers where

deposits were not detected. This may have been due to contamination.

Table 4.1.3. Upwind control sample deposits for rotorods and petri dishes and accompanying ethanol blanks.

Treatment	Up-wind Rotorod (μg/m^2)	Ethanol Blanks[1] (μg/m^2)	Up-wind Petri Dish (μg/m^2)	Ethanol Blanks[2] (μg/m^2)
1	<37.14	<37.14	<3.20	<3.20
2	<37.14	<37.14	6.36	<3.20
3	<37.14	<37.14	<3.20	<3.20
4	<37.14	<37.14	<3.20	<3.20

[1] Ethanol blanks run in accompaniment with up-wind rotorods
[2] Ethanol blanks run in accompaniment with up-wind petri dishes

4.2 **Influence of Spray Quality on the Generation and Movement of Spray Drift**

This chapter will present and examine the results of the applications which were included to determine the effects of spray quality on the generation of spray drift. Treatment 1 (CP nozzle, Medium spray quality) and Treatment 2 (CP nozzle, Fine spray quality) are the focus of this section.

4.2.1 **Regression Analysis**

4.2.1.1 **Horizontal Sampler**

Linear regressions of the response of the logarithm of spray deposit to the logarithm of distance downwind of the application were fitted to the data obtained from the petri dish samplers (Figure 4.2.1).
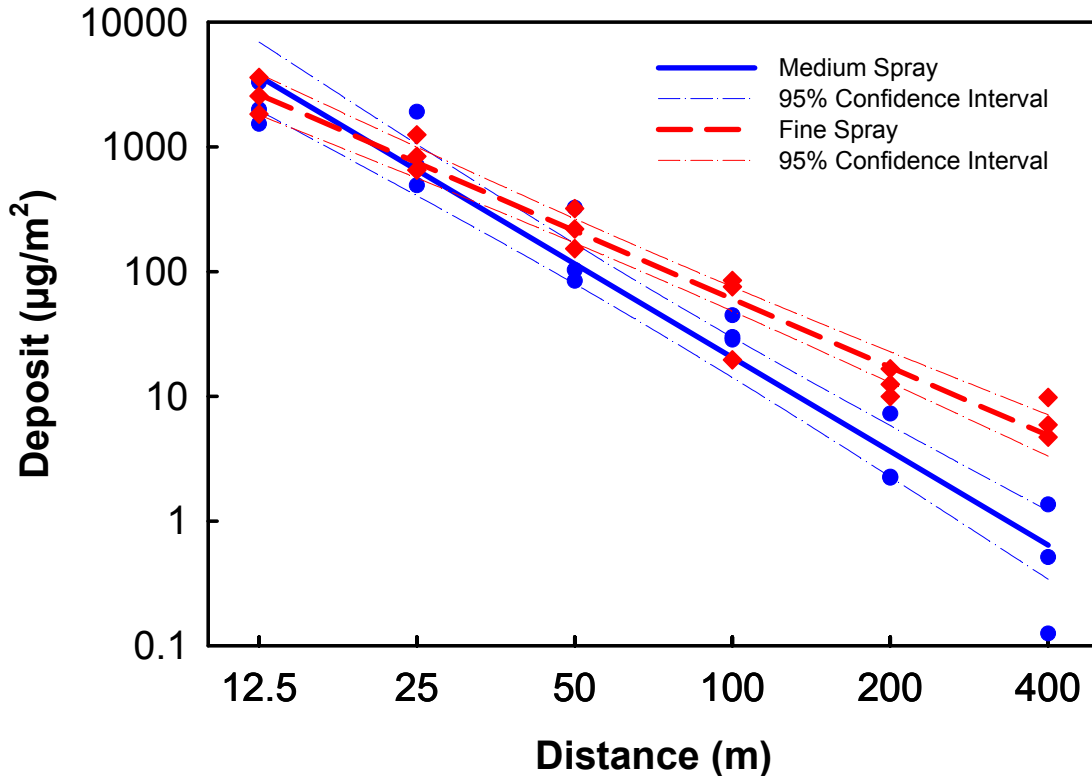
Figure 4.2.1. Linear regressions of the response of the logarithm of spray deposition to the logarithm of downwind distance on petri dish samplers for Medium and Fine spray qualities from hydraulic nozzles ($P_{0.05}$).

On average, the linear models accounted for 98% of the variability in the data set (Table 4.2.1). ANOVA on the slopes for all treatments indicated significant treatment effects (p=0.0029). ANOVA on the intercepts for all treatments also indicated significant treatment effects (p=0.0078). Means comparison for both of these regression parameters showed that spray quality had a significant impact on the downwind spray drift deposits arising from the applications.

Table 4.2.1. Linear regression parameters of the effect of the logarithm of downwind distance on the logarithm of deposit for horizontal samplers.

Trt	Parameters	Slope	Intercept	r^2
1	Medium Spray	-2.47 a[1]	6.25 a	0.97
2	Fine Spray	-1.80 b	5.38 b	0.98
3	Rotary Nozzle	-1.96 b	5.44 b	0.99
4	Ground Cover	-2.05 b	5.56 b	0.98

[1] numbers in column followed by the same letter are not statistically different ($LSD_{(slope)}$ = 0.28, $LSD_{(intercept)}$ =0.44, $\acute{\alpha}$= 0.05)

The linear model describing the change in spray drift deposition with distance from applications with the Medium spray quality (Treatment 1) had a significantly steeper slope than the model developed from the applications with the Fine spray quality (Treatment 2). The slopes of these regressions were associated with the rate of spray deposition. Given the same initial off-swath deposits, a greater rate of spray deposition can be interpreted to mean that a greater proportion of the spray cloud was deposited in the near field, resulting in a reduced amount available to be deposited in the far field.

The regression developed from the application with a Medium spray quality had a significantly larger intercept than the regression developed from the application with a Fine spray quality. This observation, that initial off-target deposition was greater for the Medium spray, is contrary to the expected result and may be attributed to a combination of swath displacement and limitations of the regression approach in this context. The linear regressions of the logarithm of deposit vs. the logarithm of distance overestimated deposition at the 0 m distance, because deposit quantities were asymptotically predicted to be increasing, while approaching the position 0-m from the application site. Therefore, the intercept parameter should not be used to calculate a predicted on-swath deposit or a deposit at 0 m.

4.2.1.2 Vertical Sampler

Linear regressions of the response of the logarithm of spray deposit to the
logarithm of distance downwind of the application were fitted to the data obtained from
the vertically oriented drinking straw samplers (Figure 4.2.2).
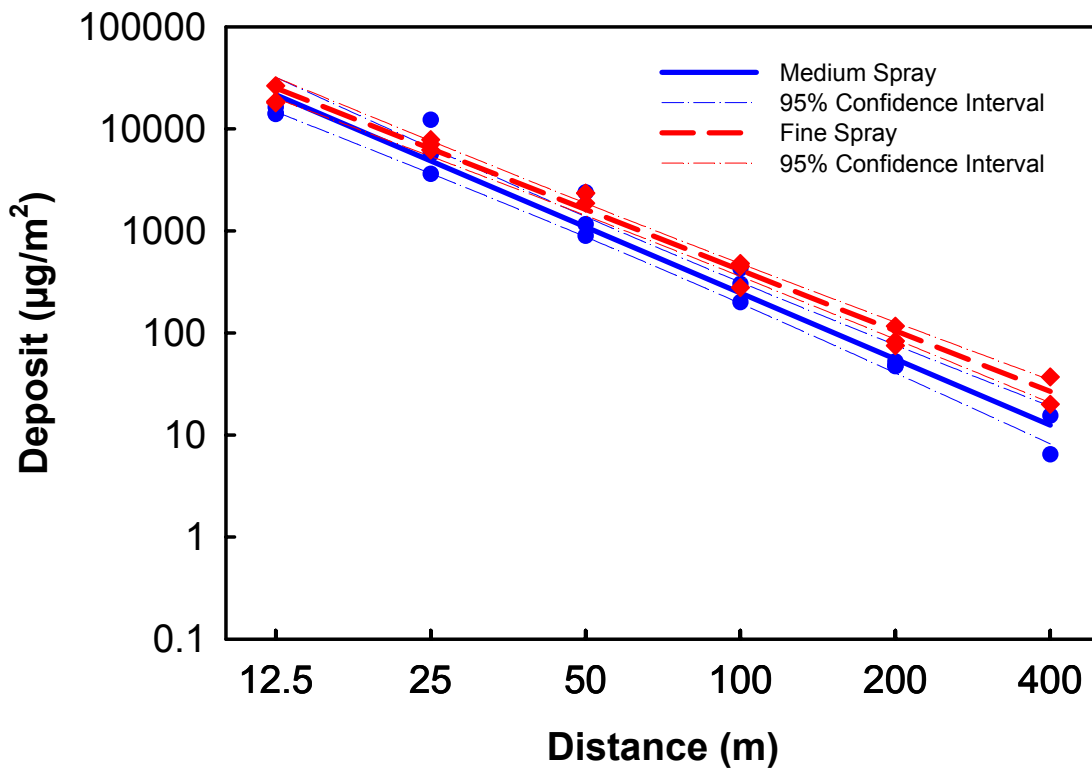
Figure 4.2.2. Linear regressions of the response of the logarithm of spray deposition to
the logarithm of downwind distance on straw samplers for Medium and Fine spray
qualities from hydraulic nozzle. ($P_{0.05}$).

On average the linear models accounted for 98% of the variability in the data set
(Table 4.2.2). ANOVA conducted on the regression parameters indicated that treatments
did not have a significant impact on the amount of spray drift arising from the
applications (p=0.0655 for slope and p=0.2353 for intercept).

Table 4.2.2. Linear regression parameters of the effect of the logarithm of downwind distance on the logarithm of deposit for vertically oriented samplers.

Trt	Parameters	Slope	Intercept	r^2
1	Medium Spray	-2.33	6.95	0.98
2	Fine Spray	-1.99	6.60	0.99
3	Rotary Nozzle	-2.04	6.52	0.99
4	Ground Cover	-2.54	7.22	0.97

(P= 0.05)

The regressions developed from the vertically oriented samplers from the applications of Medium and Fine sprays did not differ significantly in either slope or intercept, despite the fact that the vertically oriented sampler tended to be a better collector of spray drift than the petri dish samplers.

4.2.2   Deposit Analysis

4.2.2.1   Horizontal Sampler

ANOVA on the petri dish deposits at 25 m, 100 m, and 400 m downwind of the application area did not reveal significant treatment effects at the 25 m and 100 m distances (p=0.4671 and p=0.4587 respectively). The Fine spray quality application was the only treatment where deposits were detected at the 400 m distance. At that distance deposits from the Fine spray were significantly greater than those from the Medium spray (p=0.0075) (Table 4.2.3).

Table 4.2.3. Mean deposit ($\mu g/m^2$ and % of applied) on horizontal samplers at 25 m, 100 m and 400 m downwind from the application area.

Treatment	Parameter	25 m		100 m		400 m	
		Mean	% of applied	Mean	% of applied	Mean	% of applied
		(±SD)	(±SD)	(±SD)	(±SD)	(±SD)	(±SD)
1	Medium	1035	0.3297	34	0.0109	<3.20a[1]	<0.0010
	Spray	(±765)	(±0.2437)	(±9)	(±0.0029)	(±0.6)	(±0.0002)
2	Fine	913	0.2908	60	0.0191	6.8b	0.0022
	Spray	(±307)	(±0.0976)	(±35)	(±0.0113)	(±2.7)	(±0.0008)
3	Rotary	544	0.1732	44	0.0109	<3.20a	<0.0010
	Nozzle	(±248)	(±0.0791)	(±24)	(±0.0075)	(±1.3)	(±0.0004)
4	Ground	568	0.1807	33	0.0106	<3.20a	<0.0010
	Cover	(±202)	(±0.0642)	(±16)	(±0.0051)	(±1.1)	(±0.0004)

[1] numbers in column followed by the same letter are not statistically different (LSD $_{(400\ m\ deposit)}$ = 3.0 $\mu g/m^2$)

4.2.2.2   Vertical Sampler

ANOVA evaluating the effect of treatments on drinking straw deposits at 25-m 100-m and 400-m distances downwind of the application area did not reveal significant effects at any distance (p=0.8930 (25 m), p=0.5906 (100 m), and p=0.3913 (400 m)) (Table 4.2.4). The deposits on the drinking straws were similar across treatments at the 25-m and 100-m downwind distances and there were no detectable deposits at the 400-m distance for any of the treatments.

Table 4.2.4. Mean deposit (μg/m^2 and % of applied) on vertically oriented samplers at 25 m, 100 m and 400 m downwind from the application area.

Treatment	Parameter	25 m		100 m		400 m	
		Mean	% of applied	Mean	% of applied	Mean	% of applied
		(±SD)	(±SD)	(±SD)	(±SD)	(±SD)	(±SD)
1	Medium Spray	7159 (±4511)	2.2801 (±1.4365)	310 (±114)	0.0986 (±0.0363)	<27.78 (±0.0021)	<0.0088 (±0.0025)
2	Fine Spray	7013 (±811)	2.2336 (±0.2583)	402 (±108)	0.1281 (±0.0344)	<27.78 (±0.0061)	<0.0088 (±0.0059)
3	Rotary Nozzle	5451 (±1926)	1.7361 (±0.6135)	349 (±148)	0.1113 (±0.0472)	<27.78 (±0.0065)	<0.0088 (±0.0068)
4	Ground Cover	6463 (±3346)	2.049 (±1.0656)	258 (±139)	0.0823 (±0.0444)	<27.78 (±0.0008)	<0.0088 (±0.0009)

4.2.3   Airborne Drift and Drift Profiles

4.2.3.1   Suspended String Samplers

ANOVA evaluating the effect of treatments on the amount of airborne drift integrated from the suspended string samplers did not reveal any significant differences at the 25-m, 100-m, and 400-m distances ($p=0.3184$, $p=0.2477$, and $p=0.1677$, respectively (data not shown)). Although the total amount of drift arising from the Fine spray was nearly double that from the Medium spray, variability in the airborne drift measurements prevented detection of significant effects (Table 4.2.5).

Table 4.2.5. Total amount of airborne drift integrated from the suspended string samplers at 25 m and 100m downwind of application (μg/m).

Treatment	Parameter	25 m		100 m	
		Mean (±SD)	% of applied (±SD)	Mean (±SD)	% of applied (±SD)
1	Medium Spray	22982 (±17391)	7.3 (±)5.5	5811 (±3377)	1.9 (±1.1)
2	Fine Spray	40569 (±8733)	12.9 (±2.8)	13312 (±8532)	4.2 (±2.7)
3	Rotary Nozzle	27472 (±19946)	8.7 (±6.4)	8445 (±3656)	2.7 (±1.2)
4	Ground Cover	15340 (±14134)	4.9 (±4.5)	4198 (±3983)	1.3 (±1.3)

Profiles of the drift clouds at 25 m downwind illustrate the trend for greater amounts of airborne drift arising from the Fine spray treatment (Figure 4.2.3). The drift clouds observed were quite similar in shape, with greatest concentrations of spray present at heights of 2-3 m. Below heights of 2-3 m the spray cloud was probably subject to "scrubbing" by the crop and deposition within the canopy, whereas above heights of 2-3 m the spray cloud was diluted as it dispersed upwards. Measurements taken at increasing heights found the spray cloud to be decreasing in concentration up to the clouds' maximum height of 20 m. Despite general similarity in the shape and distribution of concentrations within the spray clouds, the cloud from the Fine application had greater concentrations of spray at the 25-m downwind distance than the cloud from the Medium application at nearly all heights.
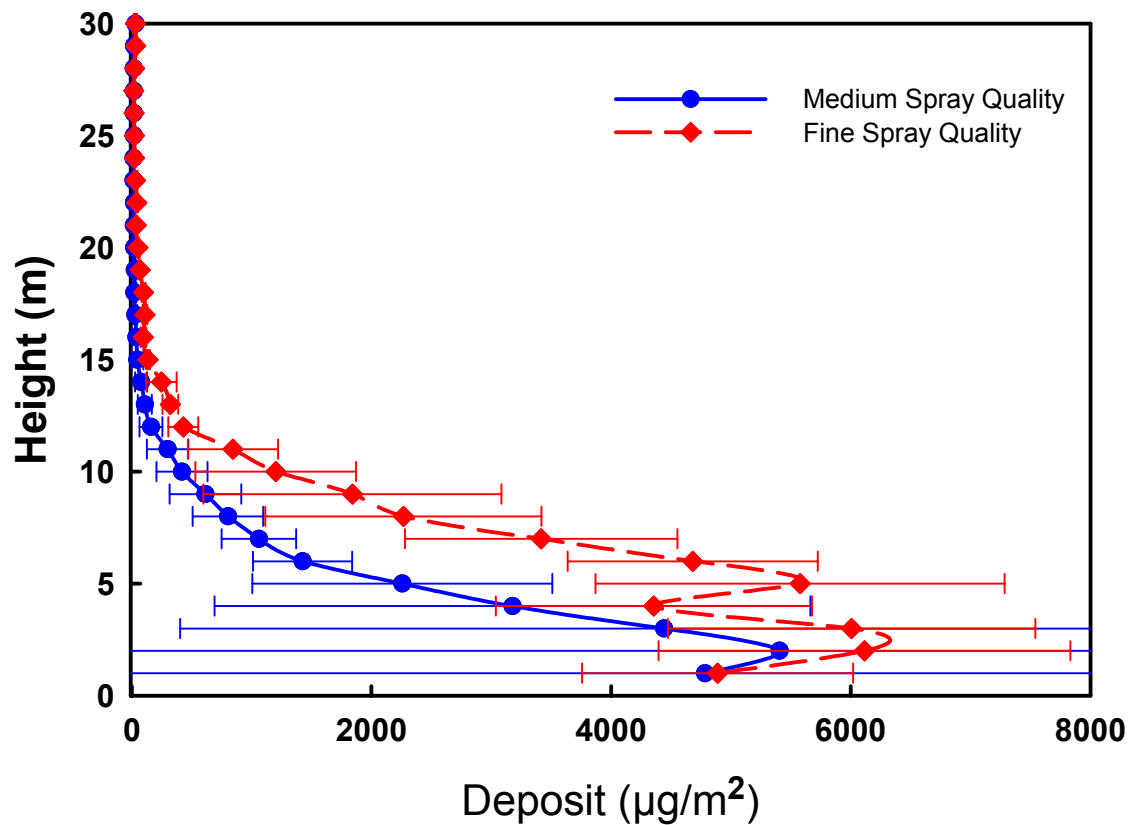
Figure 4.2.3. Variation of spray deposits with height on vertical string samplers positioned at 25 m downwind of the application area for the Fine and Medium spray quality treatments.

Drift cloud profiles at 100-m downwind were similar to those at the 25-m location with greater amounts of airborne drift from the Fine spray treatment (Figure 4.2.4). Drift clouds for the Fine and Medium spray applications maintained similar profiles with maximum deposit concentrations between heights of 4 and 5 m and decreasing concentrations with increasing and decreasing height. The cloud from the Fine spray maintained greater amounts of spray than the cloud from the Medium application at all heights. An interesting development with the Fine spray treatment at the 100-m downwind distance was that the concentration of spray above 20 m was greater than the concentration of spray above 20 m at the 25-m distance. This outcome

was not observed for the Medium treatment. This suggests that a greater amount of

dispersion was taking place for the Fine treatment.
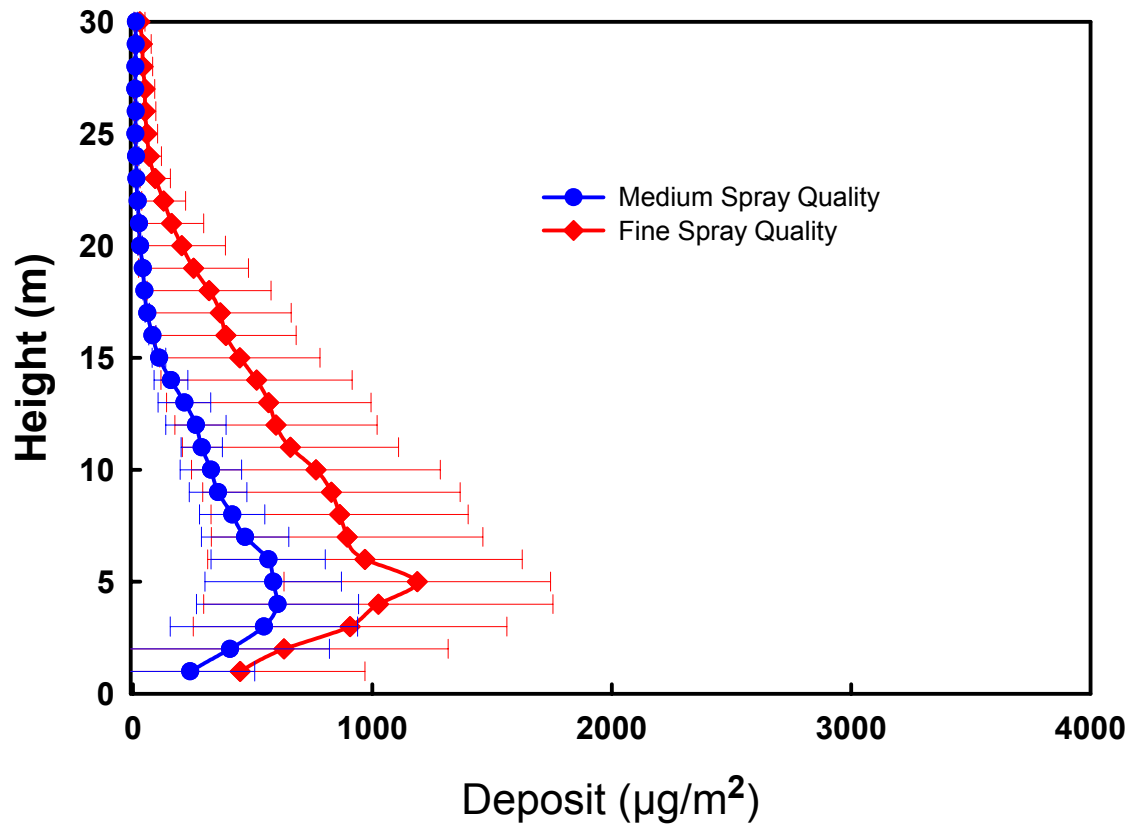
Figure 4.2.4. Variation of spray deposits with height on vertical string samplers positioned at 100 m downwind of the application area for the Fine and Medium spray quality treatments.

Compared to the drift clouds at 25 m downwind, the clouds at 100 m were

similar in shape but the total amount of drift was reduced by approximately 75%. At

100-m downwind the drift clouds existed at higher concentrations above the height of 10

m than they did at 25-m, and existed at much lower concentrations below 10 m.

Assuming no change in collection efficiency by the string sampler, the reduction in total

amounts of drift measured and the changes in concentrations with height indicate that

spray was removed by a combination of dispersion and deposition.

At the 400-m downwind distance the drift cloud for the Fine application exhibited a relatively constant spray concentration with height. The average spray deposit was 22.6 $\mu g/m^2$. Spray deposits were not observed at any height on the string samples at the 400m downwind distance for the Medium spray applications.

4.2.3.2   Rotorod Samplers

Due to their greater sampling rate, the spray deposit collected on the rotorods per unit of sampler area was greater than the deposit collected on the passive vertical samplers per unit of sampler area.

ANOVA on the rotorod deposits at 25 m, 100 m, and 400 m downwind of the application area revealed treatment effects at each distance ($p=0.0037$, $p=0.0011$, and $p=0.0003$, respectively). Deposits for the Fine spray quality treatment were significantly greater than for the Medium spray quality treatment at all distances measured (Table 4.2.6). Similar to the observation made with the suspended string sampler, deposits for the Medium spray quality applications were not detectable 400 m.

Table 4.2.6. Rotorod deposits ($\mu g/m^2$) at 25 m, 100 m and 400 m downwind of application area.

Treatment	Description	Deposit ($\mu g/m^2$)		
		25 m	100 m	400 m
1	Medium Spray	3811 c[1]	337 b	<37 b
2	Fine Spray	8629 a	813 a	47 a
3	Rotary Nozzle	5810 bc	773 a	41 a
4	Ground Cover	7100 ab	578 ab	<37 b

[1] Means in column with same letter are not significantly different ($\mathrm{LSD}_{(25m)} = 2708$, $\mathrm{LSD}_{(100m)} = 245$, $\mathrm{LSD}_{(400m)} = 26$, $\acute{\alpha} = 0.05$)

4.2.4   Spray Accountancy

The fate of spray emitted during each application was determined by integrating the data for horizontal deposits and suspended string deposits (Figure 4.2.5 and Figure

4.2.6). The total initial airborne losses at 25-m downwind were 13% of the total applied

dose for the Fine spray quality and 7.3% of applied for the Medium spray quality.

Between the 25-m and 100-m sampling stations 3.1% of applied quantities was

dispersed above the sampling area for the Fine spray but only 0.7% was lost for the

Medium spray quality. At the 100-m distance, 4.2% of the applied amount remained

aloft for the Fine spray compared to only 1.9% for the Medium spray quality. Between

100-m and 400-m downwind 1.5% of applied spray was deposited and 2.6% was

dispersed for the Fine spray and 0.5% was deposited and 1.3% was dispersed for the

Medium spray quality. The amount of airborne drift at 400-m was 0.0% (not detected) of

the applied amount for the Medium spray compared with 0.2% of the applied amount for

the Fine spray quality. The total losses to dispersion were greater for the Fine spray

quality (5.7% of applied) compared to the Medium spray quality (2.0% of applied).
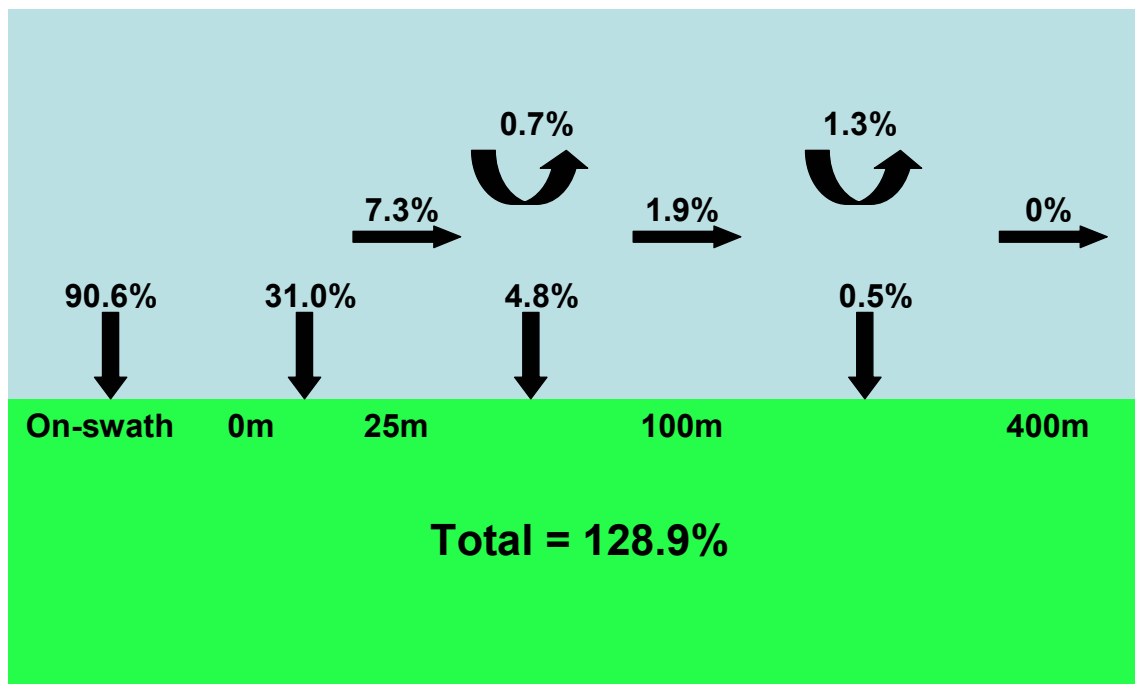
Figure 4.2.5. Fate of spray from the applications with a Medium spray quality.
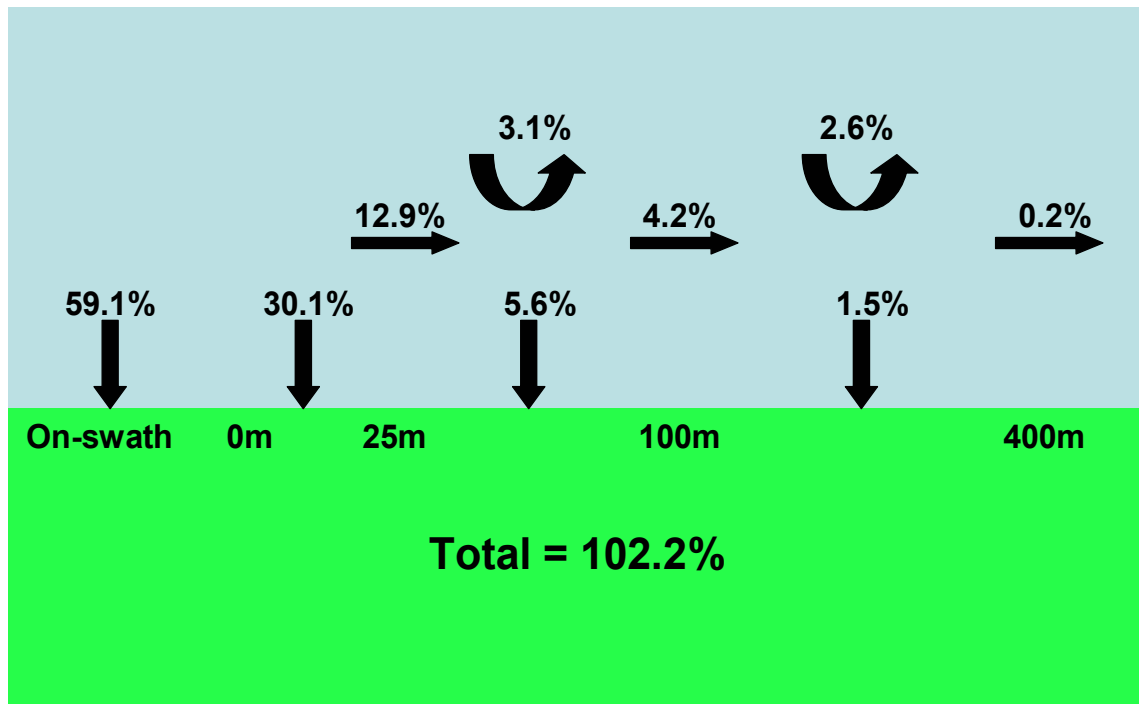
Figure 4.2.6. Fate of spray from the applications with a Fine spray quality.

The integrations allowed for the accounting of 128.9% and 102.2% of the applied amount of spray for the Medium and Fine treatments respectively. The report of measurements exceeding 100% of applied can possibly be attributed to inherent non-uniformity of the dose and release height during application, which introduced variability in the on-swath deposits and the deposits at 25-m. The result is an overestimation not only of the on-swath and 25-m deposits but also in the integration of the area between the two. Swath displacement may have also played a role in the account of more that 100% of applied volume, by elevating the deposits at the 25-m distance.

4.2.5   Discussion

It is well known that spray quality is one of the main variables governing spray drift (Bird et al., 1996; Goering and Butler, 1975; Grover et al., 1997; Threadgill and

Smith, 1975; Ware et al., 1969; Yates et al., 1974). It is less well known whether the benefits of coarser sprays are consistent with distance downwind and whether airborne drift or drift deposition components are equally affected. In general, results of the current study are in agreement with previous research, i.e., that coarser sprays produced less initial off-target drift and had faster rates of deposition with distance than finer sprays (Bird et al., 1996). In comparison to the Fine spray quality applications the Medium spray quality applications exhibited a greater rate of horizontal deposition with distance downwind resulting in a reduced amount of spray available for deposition in the far-field. This trend was confirmed by the fact that detectable quantities of spray were only measured for the Fine treatment at 400 m downwind.

Few studies were published on the relative magnitude of horizontal versus vertical drift at locations downwind. In the present study, horizontal spray movement at ground level was quantified by using vertically oriented drinking straw collectors extending 12 cm above the crop canopy. The quantity of airborne spray deposited per unit area on the drinking straws was approximately 10 times greater than horizontal deposition on the petri plates. Similar differences in horizontal deposition compared to airborne movement have been demonstrated by Woods et al. (2001). However, the horizontal collection technique remains an important component of drift experiments due to its direct application to the regulation of pesticide use and the prediction of environmental contamination (Gilbert, 1999; Kuchnicki et al., 2004). It was expected that the vertical deposition (drinking straws samplers) would be more valuable in identifying treatment differences based on the greater collection efficiency for small droplets moving in the horizontal direction. The inability to identify treatment

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differences in these instances may be attributed to inherent variability in meteorological conditions during the application process (Womac et al., 1993b).

While significant differences in total amounts of airborne drift were not identified on the suspended string samplers, profiles of the drift clouds measured at 25-m and 100-m downwind demonstrate the trend for greater amounts of airborne drift arising from the Fine spray treatment, as expected. The initial amount of spray drift from the fine applications measured on the suspended string samplers was 12.9%. This value is remarkably similar to the findings of Maybank et al. (1975), who also reported 12% of applied spray to be aloft 25-m downwind of the application. The drift clouds observed from both treatments were similar in shape, with the greatest concentrations of spray existing several meters above the ground and then dissipating with height. The total amount of drift arising from the Fine spray was nearly double that from the Medium spray at both the 25-m and 100-m distances, and the Fine spray was present at greater concentrations than the Medium spray at all heights measured. The concentration of the drift clouds at 100-m was reduced to approximately one quarter of the concentration at 25-m. The drift clouds at the 100-m distance were also present at significantly higher concentrations above the 10 m height and concentrations below the height of 10 m were reduced by at least a factor of 0.1. At 400-m downwind the Medium spray treatment did not deposit any detectable amount of spray at any height while the cloud from the Fine treatment existed at a uniform but very low concentration with height.

Results from the rotorod samplers confirmed the trend of increased spray drift arising from the Fine application. Significant treatment differences were observed at all distances measured. Drift from the Fine treatment was present at more than double the concentration of the Medium treatment at the 25-m and 100-m distances. There was no

detectable airborne drift at the 400-m distance for the Medium treatment. The fact that the rotorods detected treatment differences and the string samples did not can be attributed to the greater sampling rate of the rotorod which collected deposits nearly double that of the string sampler most of the time. Such samplers are not easily deployed at great heights on account of their weight and power requirements and this limits their utility.

Spray accountancies considering the fate of the entire spray cloud remain a little-studied area due to difficulties in data collection and reduction. However, mass balance spray accountancy should be included in future work because it summarizes the total movement of the spray cloud and provides an important understanding of the fate of pesticides. In the present study, Fine and Medium sprays differed in the relative amounts of airborne, deposited, and unaccounted-for drift movement. Almost twice as much spray from the Fine spray was airborne and available for movement downwind of the application area. This is in agreement with Grover et al. (1997) who suggested that the initial airborne component of drift represented a greater environmental input than near-field deposition. The accountancy also shows that while the entire spray cloud was either deposited or dispersed within 400 m for the Medium treatment, 0.2% of the amount applied with a Fine spray was still airborne below the height of 30 m and available for deposition and dispersion.

4.3   Role of Atomizer type in the Generation and Movement of Spray Drift

This section will present and examine the results of the data collected to determine the effects of atomizer type on the generation of spray drift. Treatment 2 (CP nozzle, Fine spray quality) and Treatment 3 (ASC nozzle, Fine spray quality) are the focus of this section.

4.3.1   Regression Analysis

4.3.1.1   Horizontal Sampler

Linear regressions of the response of the logarithm of spray deposit to the logarithm of distance downwind of the application were fitted to the data obtained from the petri dish samplers (Figure 4.3.1).
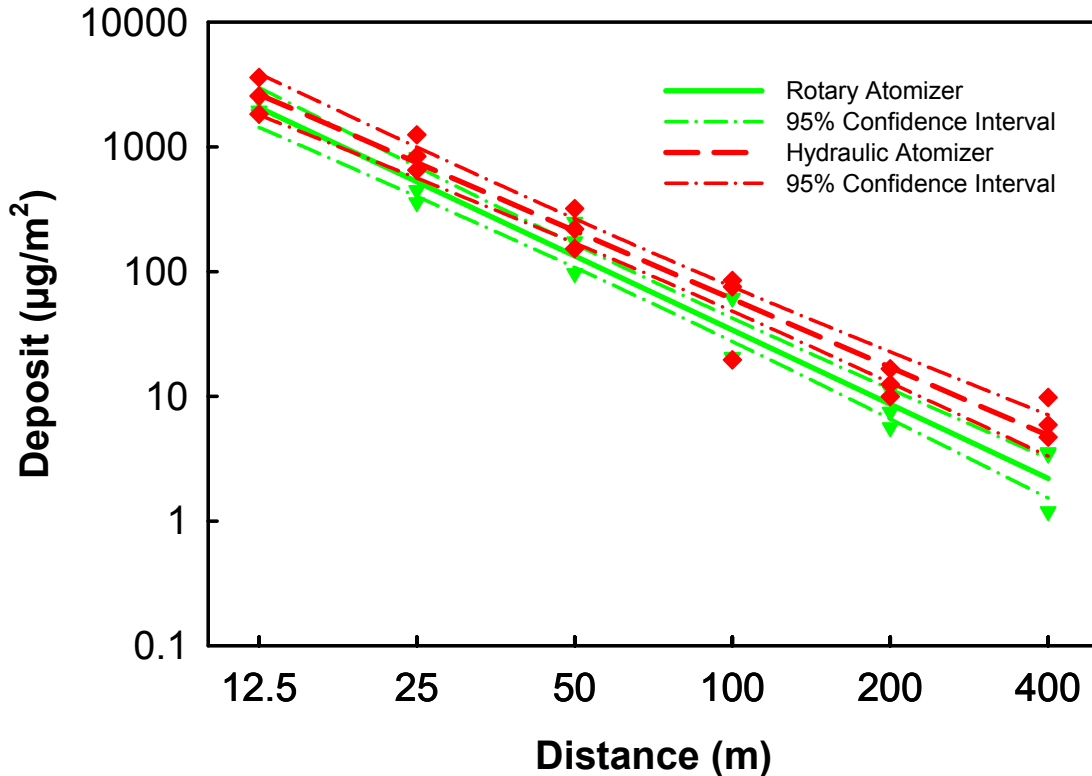
Figure 4.3.1. Linear regressions of the response of the logarithm of spray deposition to the logarithm of downwind distance on petri dish samplers for rotary and hydraulic nozzles producing a Fine spray quality ($P_{0.05}$).

The linear models accounted for approximately 98% of the variability in the data set. ANOVA on the slopes for all applications in the study indicated significant treatment effects (p=0.0029), however, mean comparison showed that the type of atomizer used in the application did not have a significant impact on the slope of the linear model (Table 4.2.1). ANOVA on the intercepts for all applications in the study indicated significant treatment effects (p=0.0066), however, means comparison showed that the type of atomizer did not have a significant impact on the intercept of the linear model (Table 4.2.1). Means comparison for regression parameters show that atomizer type did not have a significant impact on the downwind spray drift deposits arising from the applications.

4.3.1.2 Vertical Sampler

Linear regressions of the response of the logarithm of spray deposit to the logarithm of distance downwind of the application were fitted to the data obtained from the vertically oriented drinking straw samplers (Figure 4.3.2).
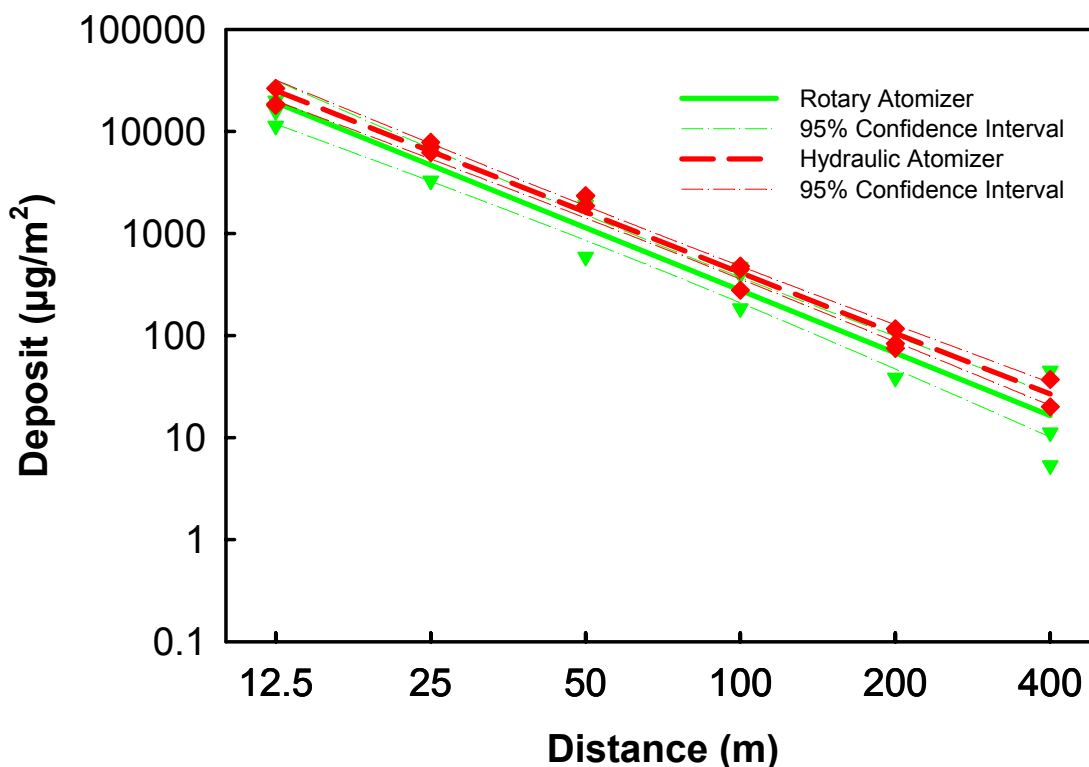
Figure 4.3.2. Linear regressions of the response of the logarithm of spray deposition to the logarithm of downwind distance on drinking straw samplers for rotary and hydraulic nozzles producing a Fine spray quality ($P_{0.05}$).

The regressions accounted for approximately 98% of the variability in the data set (Table 4.2.2). ANOVA on the regression parameters did not identify treatment effects on spray drift for type of atomizer used in the applications (p=0.0655 for slope and p=0.2353 for intercept).

4.3.2   Deposit Analysis

4.3.2.1   Horizontal Sampler

Although there were no significant differences in deposition on the horizontal samplers at 25 and 100 m downwind, the hydraulic atomizer treatment deposited significantly more than the rotary atomizer at the 400 m distance (6.8 $\mu g/m^2$ compared to 2.7 $\mu g/m^2$) (Table 4.2.3). This is an expected observation where, despite the hydraulic atomizer producing a slightly courser spray, it also produces a greater number of very small droplets capable of remaining aloft for movement into the far field.

4.3.2.2   Vertical Sampler

The ANOVA evaluating the effect of treatments on drinking straw deposits at 25-m 100-m and 400-m distances downwind of the application area did not reveal significant treatment effects at any distance (p=0.8930 (25 m), p=0.5906 (100 m), and p=0.3913 (400 m)) (Table 4.2.4). The deposits on the drinking straws were similar across treatments at the 25-m and 100-m downwind distances and there were no detectable deposits at the 400-m distance for any of the treatments.

4.3.3   Airborne Drift and Drift Profiles

4.3.3.1   Suspended String Samplers

ANOVA evaluating the effect of treatments on the amount of airborne drift integrated from the suspended string samplers did not reveal any significant differences at the 25-m, 100-m, and 400-m distances (p=0.3184, p=0.2477, and p=0.1677, respectively (data not shown)). Although the total amount of drift arising from the hydraulic atomizer was slightly greater than from the rotary atomizer (Table 4.2.5).

Profiles of the drift clouds at the 25-m downwind distance displayed greater amounts of airborne drift arising from the hydraulic atomizer compared to the rotary

atomizer (Figure 4.3.3). The drift clouds observed were very similar in shape, with
greatest concentrations of spray present at heights of 2-3 m. Both spray clouds were
found to decrease in concentration up to 25 m, above which the spray deposits were near
detection thresholds.
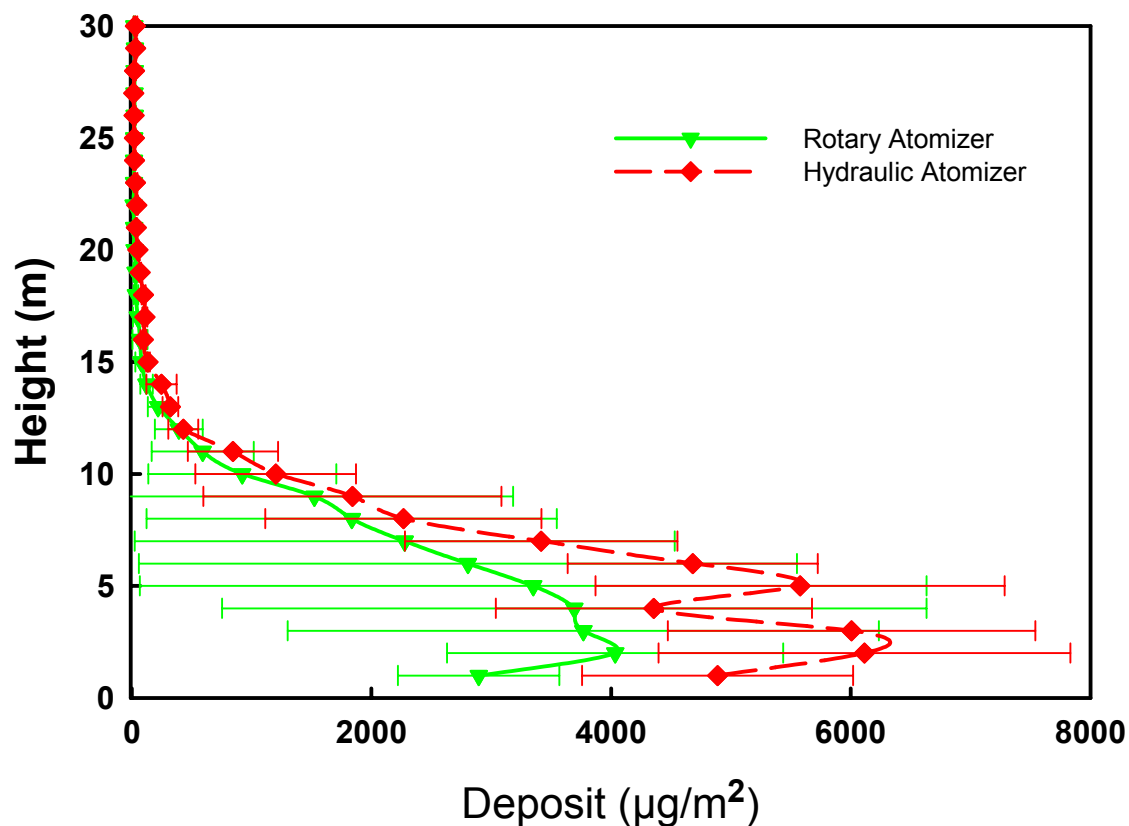
Figure 4.3.3. Variation of spray deposits with height on vertical string samplers
positioned at 25 m downwind of the application area for the rotary and hydraulic
atomizer treatments.

       Profiles of the drift clouds at 100-m downwind also displayed greater amounts of
airborne drift from the hydraulic atomizer (Figure 4.3.4). The clouds of both applications
maintained similar shapes with maximum concentration peaking for the hydraulic
atomizer at the 5-m height and the peak detection for the rotary atomizer occurring
between heights of 3 m and 7 m. The cloud from the hydraulic atomizer contained

greater concentrations of spray than the cloud from the rotary atomizer application at all heights. Greater dispersion occurred for both treatments between the 25-m and 100-m downwind sites since the concentrations of spray present above the 20-m height at 100-m downwind were greater than at 25-m downwind.
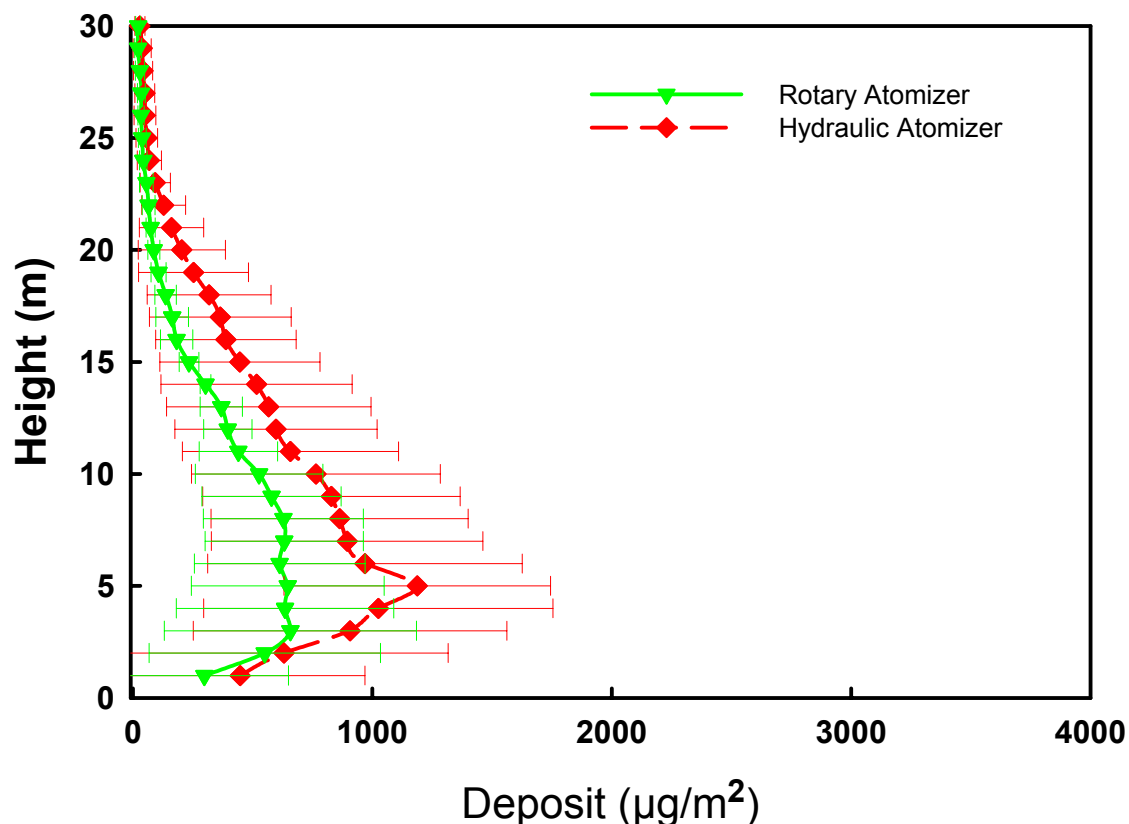
Figure 4.3.4. Variation of spray deposits with height on vertical string samplers positioned at 100 m downwind of the application area for the rotary and hydraulic atomizer treatments.

Compared to the drift clouds at 25-m downwind, the clouds at 100-m were similar in shape but the total amount of drift was reduced by more than 75% compared to 25-m. At 100-m downwind, the clouds existed at greater concentrations above 10 m than they did at 25-m, and existed at much lower concentrations below 10 m.

At the 400-m downwind distance the drift clouds for both applications contained low concentrations that were uniform with height. The average deposit from the rotary atomizer cloud was 5.8 μg/m^2 while the average deposit from the hydraulic atomizer was 22.6 μg/m^2.

4.3.3.2   Rotorod Samplers

Deposits for the hydraulic and rotary atomizer treatments were significantly different from each other at the 25-m downwind distance, where the hydraulic atomizers generated greater amounts of airborne drift (Table 4.2.6). At the 25-m site, deposits for the hydraulic and rotary atomizer were 8629 μg/m^2 and 5810 μg/m^2, respectively. Airborne drift measurements by the rotorods were statistically identical at the 100-m and 400-m downwind distances for both atomizers.

4.3.4   Spray Accountancy

An account for the fate of spray emitted during each application was arrived at by integrating the horizontal deposit data and the suspended string data (Figure 4.2.6 and Figure 4.3.5). The spray accountancy showed very similar off-target losses from the rotary atomizer and hydraulic atomizer treatments.

The on-swath deposits were very similar for both the rotary and hydraulic atomizer treatments, 59.1% and 58.9% of applied, respectively. The total off-target losses beyond 25 m downwind were 12.9% of the total applied dose for the hydraulic atomizer compared to 8.8% of the applied quantity for the rotary atomizer. Between 25 m and 100 m downwind, 3.9% of the applied quantity was deposited and 2.2% was dispersed above the collection area for the rotary atomizer and 5.6% of the applied quantity was deposited and 3.1% was dispersed upward for the hydraulic atomizer. At 100-m downwind, 2.7% of the applied quantity remained aloft and was traveling

horizontally for the rotary nozzle and 4.2% remained aloft for the hydraulic nozzle. Between 100 m and 400 m downwind, 0.8% of the applied quantity was deposited and 1.8% was dispersed above the collection area for the rotary atomizer and 1.5% of applied was deposited and 2.6% was dispersed upward for the hydraulic atomizer.

The amount of airborne drift at 400-m was 0.1% of the applied amount for the rotary atomizer compared 0.2% of applied for the hydraulic atomizer. The total losses to dispersion were also greater for the hydraulic atomizer (5.7% of applied) compared to the rotary atomizer (4.0% of applied). The integrations accounted for 94.6% and 102.2% of the applied amount of spray for the rotary and hydraulic atomizers, respectively.
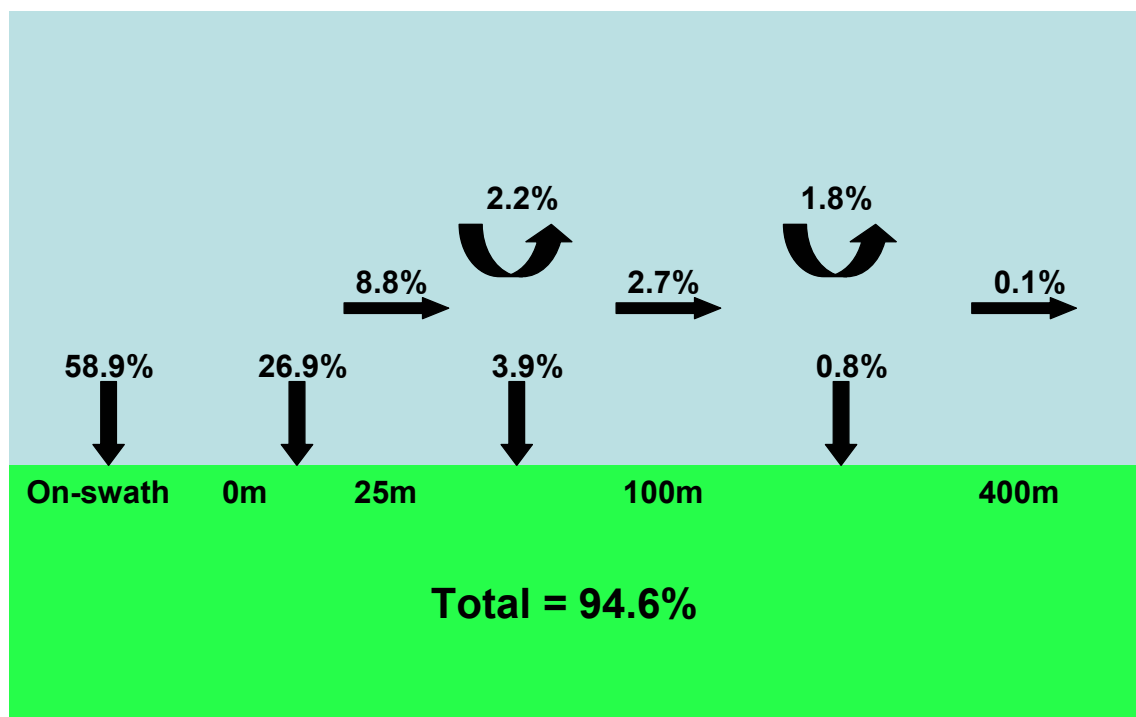
Figure 4.3.5. Fate of spray from the applications made using the rotary atomizer.

4.3.5   Discussion

Actual drift measurements comparing rotary and hydraulic atomizers are not common in the literature. Investigations into the droplet spectra of these atomizers are

well documented and suggest an advantage in drift reduction for rotary atomizers (Bouse et al., 1994, Spillman, 1982, Teske et al., 2005, and Akesson and Yates, 1984). In this experiment both the initial amount of off-target drift and the rates of deposition were found to be similar to the findings of previous research. Analysis of drift deposits showed significant treatment differences only at the 400-m downwind distance and only on the horizontal samplers, where the rotary atomizer produced significantly lower values for deposit.

Significant statistical differences were not identified for total amounts of airborne drift on the suspended string samplers, although profiles of the drift clouds measured at 25-m and 100-m downwind displayed greater amounts of airborne drift for the hydraulic nozzle by approximately one third at 25-m and double at 100-m. The drift clouds observed from both treatments were similar in shape, with the greatest concentrations of spray existing several meters above the ground and then dissipating with height. The concentration of the drift clouds at 100 m was reduced to approximately one quarter of the concentration at 25 m and dispersion had taken place due to the increasing concentrations of spray above the 20-m height. At the 400-m downwind distance both spray clouds exhibited uniform concentrations with height, but the cloud from the hydraulic atomizer was present at slightly greater concentration.

Significant treatment differences in airborne drift measurements from the rotorod samplers were only observed at the 25-m downwind distance, where the hydraulic atomizers showed a greater initial concentration of spray.

The mass balance spray accountancy summarizes the findings of the horizontal deposition and the airborne measurements. The total off-target loss beyond 25 m downwind was 12.9% of applied for the hydraulic atomizer compared to 8.8% of applied

for the rotary atomizer. The hydraulic atomizer treatment displayed greater losses to dispersion above and horizontal movement beyond the experimental area than the rotary atomizer.

Taken as a whole, these results suggest that rotary atomizers result in lower drift potential than hydraulic atomizers providing a similar spray quality. While actual downwind deposits were similar for the two atomizers, the rotary atomizer offered reductions in the initial amount of airborne drift available for movement into the far field. The advantages of a lower proportional volume in small droplets by rotary atomizers may not have been realized in this experiment with the ASC nozzle having a $D_{V0.1}$ of 84 μm compared to the CP nozzle $D_{V0.1}$ of 143 μm. The rotary atomizer actually produced a slightly finer spray compared to the hydraulic nozzle. (VMDs 213 μm and 283 μm, respectively). The elucidation of treatment effects is further complicated in this experiment by the effect of boom width, whereby, the hydraulic nozzles utilized 78% of wingspan while the rotary nozzles utilized only 64%. The potential for drift to become entrained in wingtip vortices may have been greatly increased for the hydraulic atomizer. However, ultimately in this experiment the rotary nozzles demonstrated a somewhat lower drift potential than the hydraulic nozzle despite producing a slightly finer spray.

4.4   Influence of Ground Cover on the Drifting of Sprays

This chapter will present and examine the results of the applications which were included to determine the effects of ground cover on the extent of spray drift. Treatment 2 (CP nozzle, Fine spray quality, applied to a mature cereal crop canopy) and Treatment 4 (CP nozzle, Fine spray quality, applied to bare ground) are the focus of this section.

4.4.1   Regression Analysis

4.4.1.1   Horizontal Sampler

Linear regressions of the response of the logarithm of spray deposit to the logarithm of distance downwind of the application were fitted to the data obtained from the petri dish samplers (Figure 4.4.1).
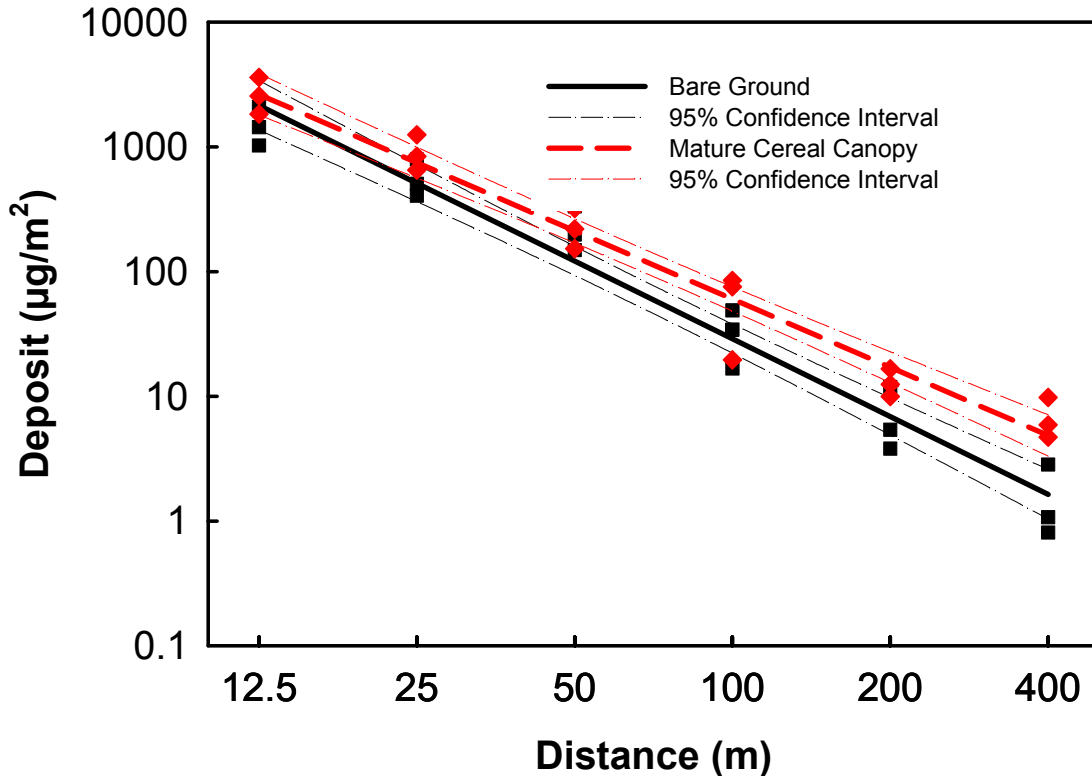
Figure 4.4.1. Linear regressions of the response of the logarithm of spray deposition to the logarithm of downwind distance on petri dish samplers for applications to crop canopy and bare ground using a Fine spray quality ($P_{0.05}$).

On average the linear models accounted for 98% of the variability in the data set (Table 4.2.1). ANOVA on regression parameters identified significant treatment effects but the effect of ground cover did not have a significant impact on the amount of spray drift generated (p=0.0029 for slope and p=0.0066 for intercept). The applications to bare ground resulted in a regression line with a slightly steeper slope and greater intercept than applications to the mature cereal canopy.

4.4.1.2   Vertical Sampler

Linear regressions of the response of the logarithm of spray deposit to the logarithm of distance downwind of the application were fitted to the data obtained from the drinking straw samplers (Figure 4.4.2).
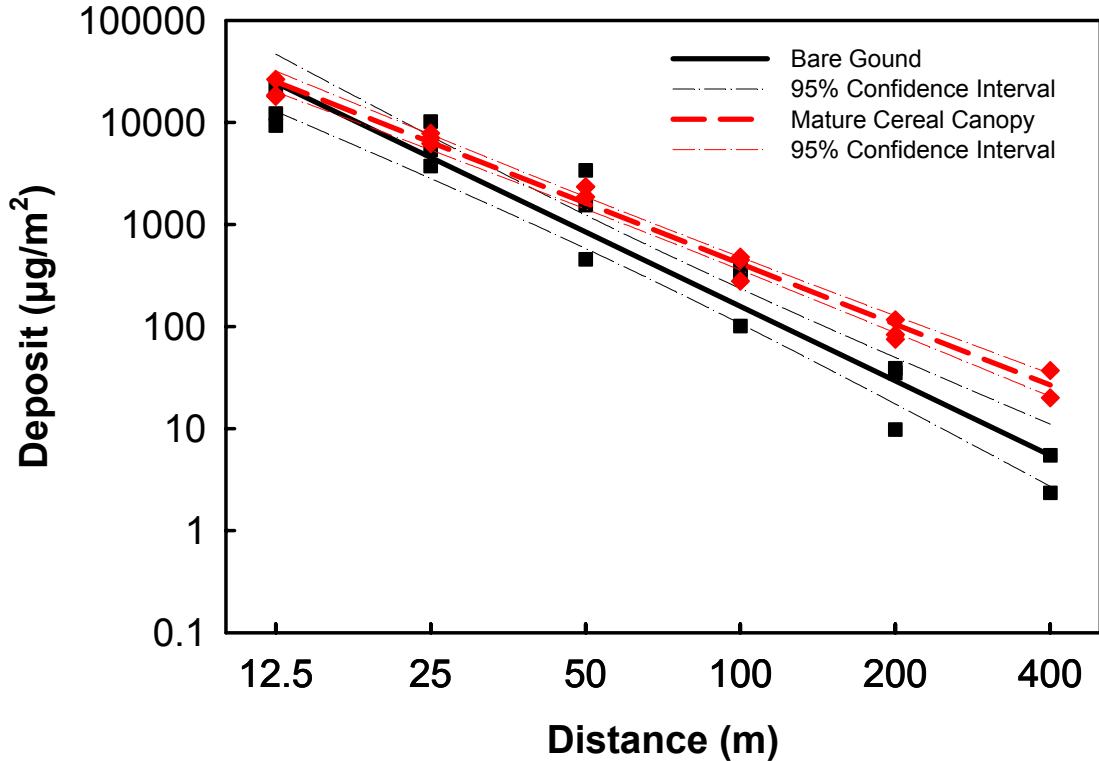
Figure 4.4.2. Linear regressions of the response of the logarithm of spray deposition to the logarithm of downwind distance on drinking straw samplers for applications to crop canopy and bare ground using a Fine spray quality ($P_{0.05}$).

4.4.2   Deposit Analysis

4.4.2.1   Horizontal Sampler

Significant treatment effects were only observed at the 400-m distance downwind where applications over the mature cereal crop canopy resulted in a greater deposit (p=0.0075), with a least significant difference of 3.0 $\mu g/m^2$ (Table 4.2.3).

4.4.2.2   Vertical Sampler

Significant treatment effects were not observed for the vertically oriented samplers at the 25-m 100-m and 400-m distances downwind of the application (p=0.8930, p=0.5906, and p=0.3913, respectively) (Table 4.2.4).

4.4.3   Airborne Drift and Drift Profiles

4.4.3.1   Suspended String Samplers

Significant treatment effects were not observed for the total amount of airborne drift at the 25-m, 100-m, and 400-m distances (p=0.3184, p=0.2477, p=0.1677, respectively (Table 4.2.5)).

Profiles of the drift clouds at the 25-m downwind distance displayed greater amounts of airborne drift from the mature cereal canopy applications (Figure 4.4.3). The drift clouds observed were similar in shape, with greatest concentrations of spray present at heights of 2-3 m. Both spray clouds were found to decrease in concentration up to 25 m, where the spray deposits approached detection thresholds. Although the spray cloud profiles were similar in shape the cloud over the mature cereal crop canopy had greater concentrations of spray than the cloud over bare ground at all heights.
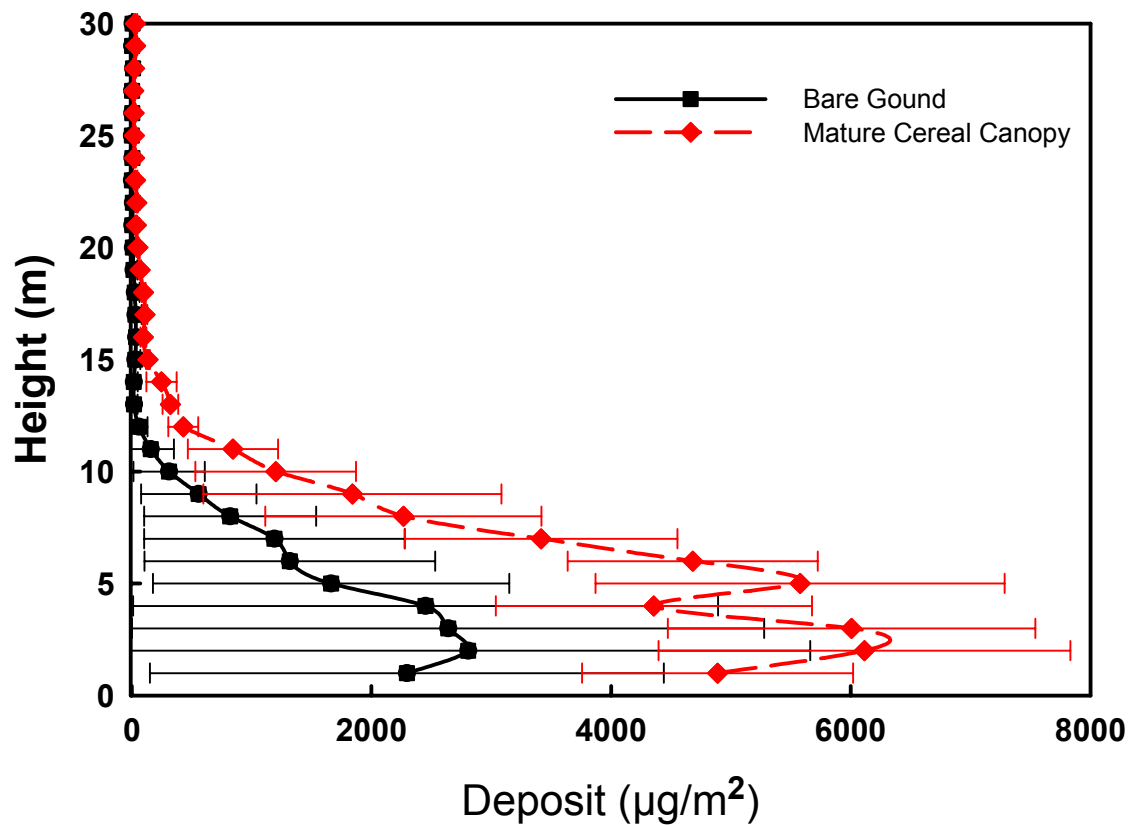
Figure 4.4.3. Variation of spray deposits with height on vertical string samplers positioned at 25 m downwind of the application area for the application treatments to bare ground and mature cereal canopy using a Fine spray quality.

Profiles of the drift clouds at 100 m downwind also displayed greater amounts of airborne drift from the mature cereal crop canopy applications (Figure 4.4.4). The clouds of both applications maintained similar shapes with maximum concentration in the cloud over mature crop canopy at the 5-m height. The cloud from the bare ground treatment was present in uniform concentration from the 1-m to 10-m heights. The cloud over the crop canopy contained greater concentrations of spray than the cloud over the bare ground at all heights. Dispersion seemed to take place for both treatments between the 25-m and 100-m downwind distances because the concentration of spray present above

the 20-m height at 100-m downwind is greater than the concentration above the 20-m

height at 25-m downwind.
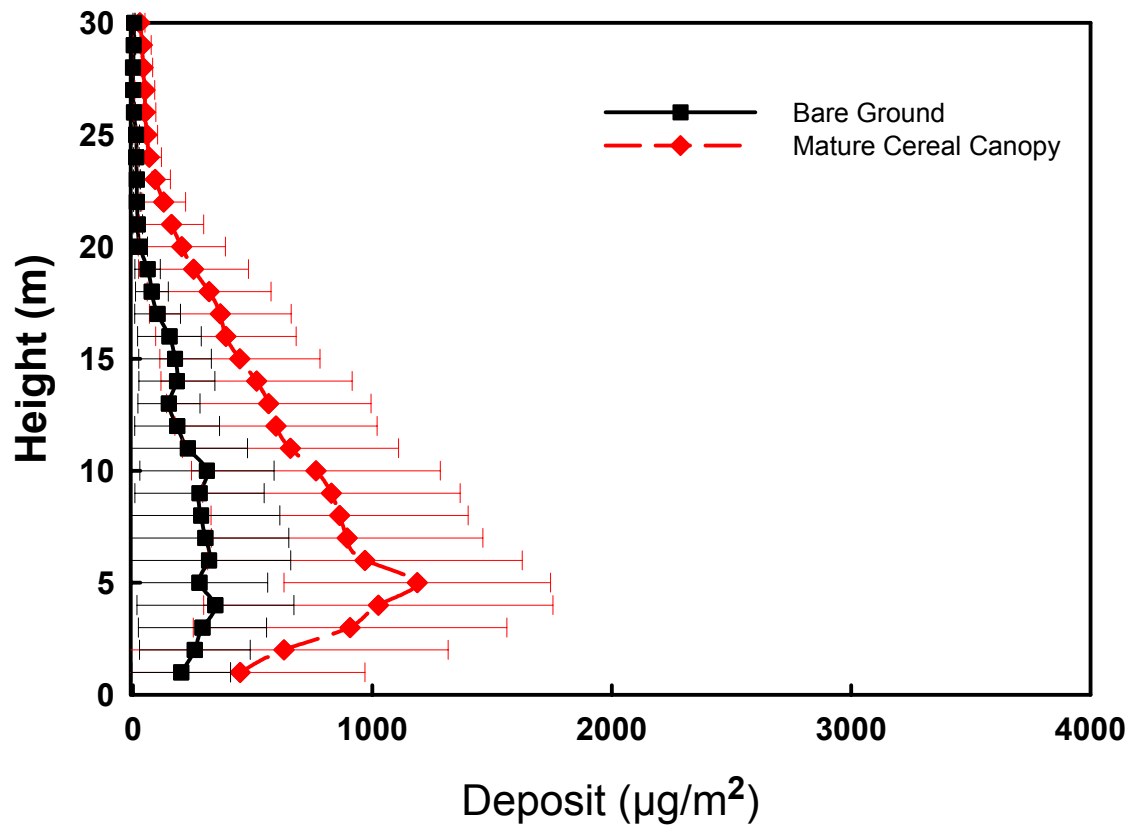
Figure 4.4.4. Variation of spray deposits with height on vertical string samplers positioned at 100 m downwind of the application area for the application treatments to bare ground and mature cereal canopy using a Fine spray quality.

Compared to the drift clouds at 25 m downwind, the clouds at 100-m downwind

were similar in shape but the total amount of drift was reduced by more than 75%

compared to 25 m downwind. At 100 m the clouds existed at higher concentrations

above the 10 m height than they did at 25 m downwind, and existed at lower

concentrations below 10 m.

At 400 m downwind the drift clouds for both applications contained low

concentrations and were uniform with height. The cloud from the bare ground

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applications had an average deposit of 9.8 $\mu g/m^2$ while the average deposit from the
applications to crop canopy was 22.6 $\mu g/m^2$.

4.4.3.2 Rotorod Samplers

ANOVA on the rotorod deposits at 25 m, 100 m, and 400 m downwind of the
application area revealed significant treatment effects at each distance (p=0.0037,
p=0.0011, and p=0.0003). However, means comparison for the deposits showed
significant differences only between application to bare ground and application to crop
canopy at the 400-m downwind distance (Table 4.2.6). At the 400-m distance spray
applications to the crop canopy resulted in a deposit of 47.5 $\mu g/m^2$ compared to no
deposit for applications to bare ground.

4.4.4 Spray Accountancy

The spray accountancy showed greater off-target losses from applications to crop
canopy than from the applications to bare ground (Figure 4.2.6 and Figure 4.4.5).
However, only 74.0% of the total amount applied was accounted for by the integrations.
Perhaps if all of the applied volume was accounted for from the applications to bare
ground, the total amounts of off-target losses might be quite similar. It is unclear
whether measurements under-sampled evenly over all points reported or to a greater
extent at certain points.

The on-swath deposits for the applications to crop canopy and bare ground were
59.1% and 48.8% of applied, respectively. The total off target losses beyond 25 m
downwind were 12.9% of applied quantities for applications to crop canopy but only
4.9% of applied for the applications to bare ground. Between 25-m and 100-m, 4.7% of
applied was deposited and 0.0% was dispersed above the collection area for the
application to bare ground and 5.6% of applied was deposited and 3.1% was dispersed

upward for the application to crop canopy. At 100-m 1.3% of applied remained aloft and was traveling horizontally for the application to bare ground and 4.2% remained aloft for the application to crop canopy. Between 100 m and 400 m, 0.7% of applied was deposited and 0.5% was dispersed above the collection area for the application to bare ground and 1.5% of applied was deposited and 2.6% was dispersed upward for the application to crop canopy. The amount of airborne drift at 400-m was 0.2% of applied for the applications to crop canopy compared with 0.1% of applied for applications to bare ground. The total losses to dispersion were also greater for the applications to crop canopy (5.7% of applied) compared to the applications to bare ground (0.5% of applied).
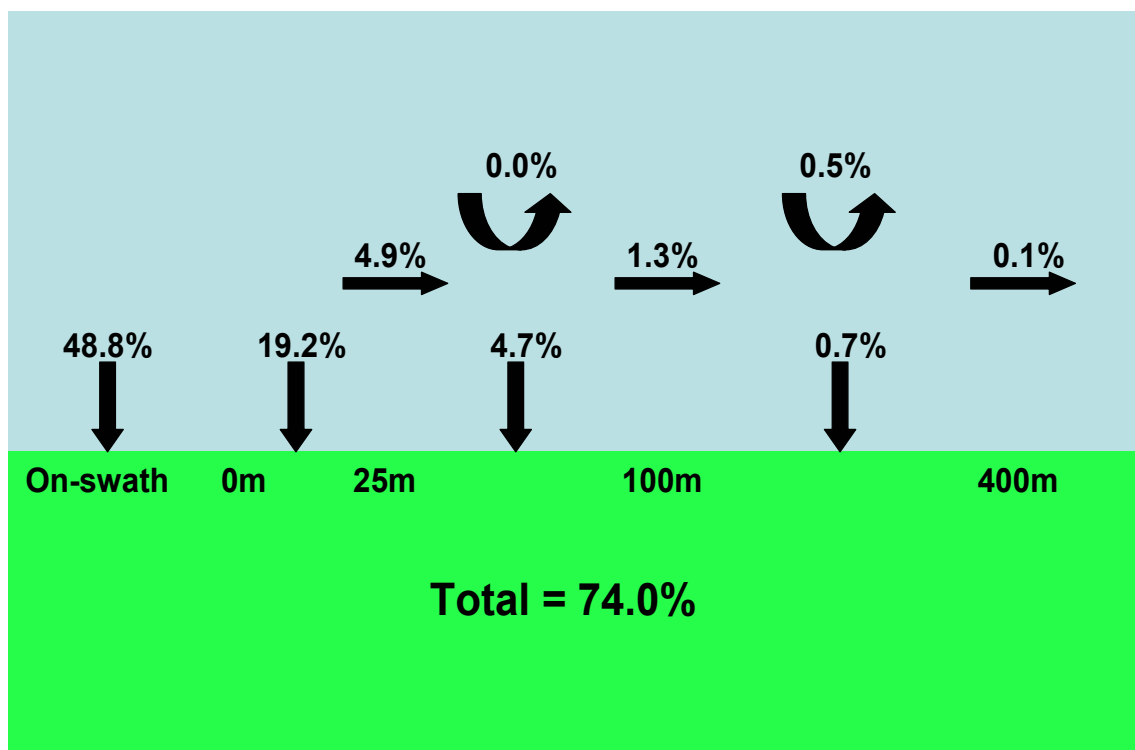
Figure 4.4.5. Fate of spray from the applications made bare ground.

4.4.5   Discussion

The interception of spray droplets as they pass through vegetation has received some attention by researchers who study pesticide application. In fact it has been

suggested that total amounts of drift can be reduced by up to 70% by application to a crop canopy rather than to bare ground (Lawson and Uk, 1979). In this study a comparison of Treatments 2 and 4 did not show a significant effect of ground cover on spray drift. The applications to a mature cereal crop canopy exhibited very similar rates of deposition with distance downwind on both horizontal and vertical samplers. The two treatments only differed in deposition at one point. At 400 m downwind, the applications to the crop canopy resulted in a greater deposit. This observation was in contrast to the expected result, in which lower deposits were expected to be observed for the applications to a crop canopy, as a result of spray interception by the crop (Miller and Stoughton, 2000).

The spray cloud profiles at 25 m and 100 m downwind demonstrated greater amounts of airborne drift arising from the applications to the crop canopy. Results from the rotorod samplers also showed increased spray drift arising from the applications to crop canopy at the 400 m distance. The mass balance spray accountancy showed how dramatic the difference between the two treatments was. The total off-target losses beyond 25 m downwind was 12.9% of applied for the applications to crop canopy but only 4.9% of applied for the applications to bare ground.

While it was expected that the crop canopy would capture spray, especially the airborne fraction of small droplets with the potential to move into the far field, significant treatment differences were not observed for the most part, and in fact the applications to crop canopy saw a greater amount of spray drift into the far field. One notable meteorological phenomenon that may have contributed to these results is the wind speed differences for treatments 2 and 4. Comparison of Richardson Numbers for these two treatments (-0.00001 for Treatment 2 and -0.00002 for Treatment 4) shows

that both treatments were made under fully forced convection and that it was mechanical turbulence and not buoyancy that dominated the dispersion of these sprays. The rate of increasing wind speed with height over the applications to bare ground was much greater than for the applications to crop canopy. While the wind speed for the bare ground treatment was greater at the 4-m height (21 km/h compared to 18 km/h for treatment 2), the wind speeds at the 2-m height were greater for the applications to crop canopy (16 km/h compared to 14 km/h for treatment 4). Z_o (the height at which wind speed equals 0 km/h) was calculated for both treatments. Z_o for the application to crop canopy was 0.32 m and Z_o for the applications to bare ground was 0.27 m. It was considered that the moderate lodging and large amount vegetation present in the crop canopy may have behaved like a floor and not been penetrated by wind. However, these results do suggest that the upper portions of the crop canopy were in fact penetrated by the wind. Comparison of friction velocities for these two treatments shows that the Treatment 2 applications (friction velocity – 1.2 m/s) may have experienced a greater amount of mechanical turbulence than the Treatment 4 applications (friction velocity – 0.6 m/s). These anomalies in the wind speed profiles may have resulted in less filtration of the drift cloud by the crop canopy.

The nature of the crop canopy in the case of this experiment may also have contributed to the observation of more drift arising from the vegetated treatment. In this case the vegetation was an extremely dense stand of barley which was somewhat lodged. This type of vegetation may have behaved like an elevated floor not allowing the passage of air through it and thus not effectively collecting spray drift. This is in contrast with the experiment by Miller et al. (2000) in which the spray application was made into a canopy of intermittently spaced erect culms of grass, which exhibited a high collection

efficiency. One other reason for the disagreement with the observations of Lawson and

Uk (1979) is that in their experiment applications were made with a much finer spray

quality (106 μm compared to 283 μm in the present study).

4.5   Comparison of Horizontal Deposition to Regulatory Models

Application parameters for treatments 1, 2 and 4 (rotary atomizer not represented in the model) were entered into the drift modelling software AGDISP. Model output for horizontal deposition with distance downwind of the application was then compared to the corresponding empirical data generated over the course of this study.

4.5.1   Correlation Analysis

The association between empirical and model predicted deposits was significant with a linear correlation coefficient of 0.79 (p=<0.0001). However, the slope and intercept of the linear regression for model predicted deposits plotted against observed deposits demonstrated disagreement from the ideal parameters of zero for intercept and 1 for slope which would result if the two were in perfect agreement. The regression parameters in this case were 0.35 for slope and 81 for intercept. (Figure 4.5.1).
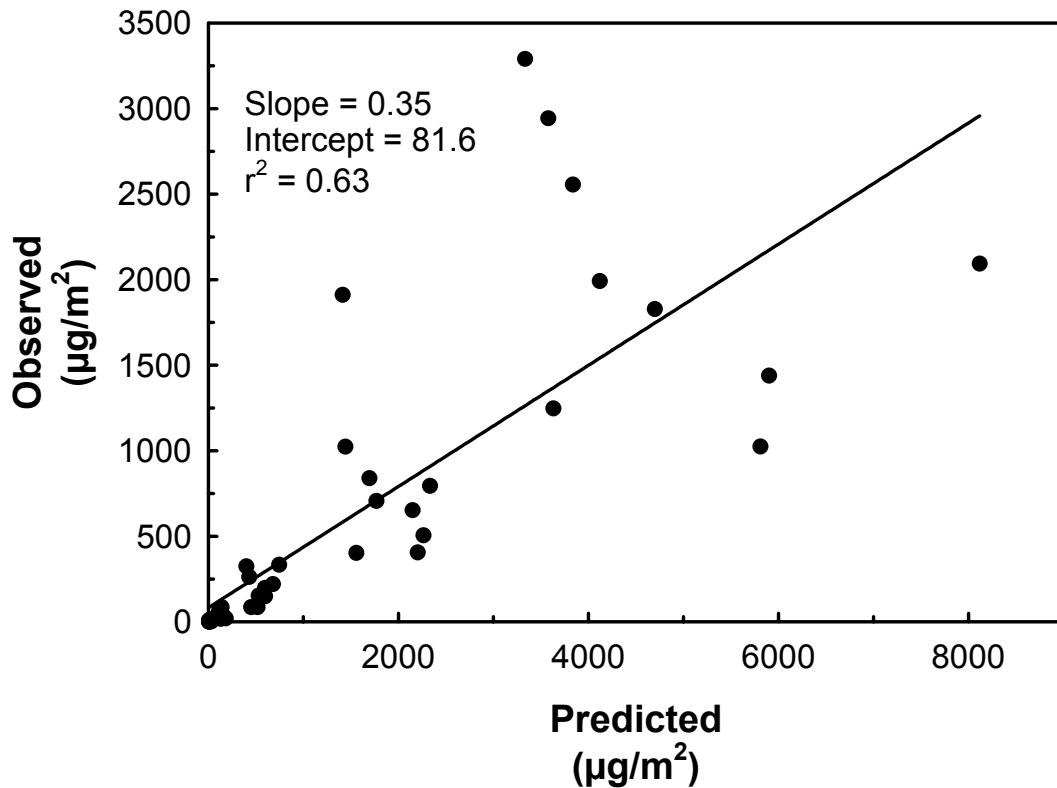
Figure 4.5.1. Linear regression between empirical deposits and AGDISP predicted deposits ($P_{0.05}$)

   An analysis on the deposits in the far field was conducted to remove some of the variability associated with the larger deposits in the near field. The association between empirical and model predicted deposits was significant again with a correlation coefficient of 0.76 (p=0.0001). The regression parameters in this case were for 0.28 slope and 1 for intercept (Figure 4.5.2).
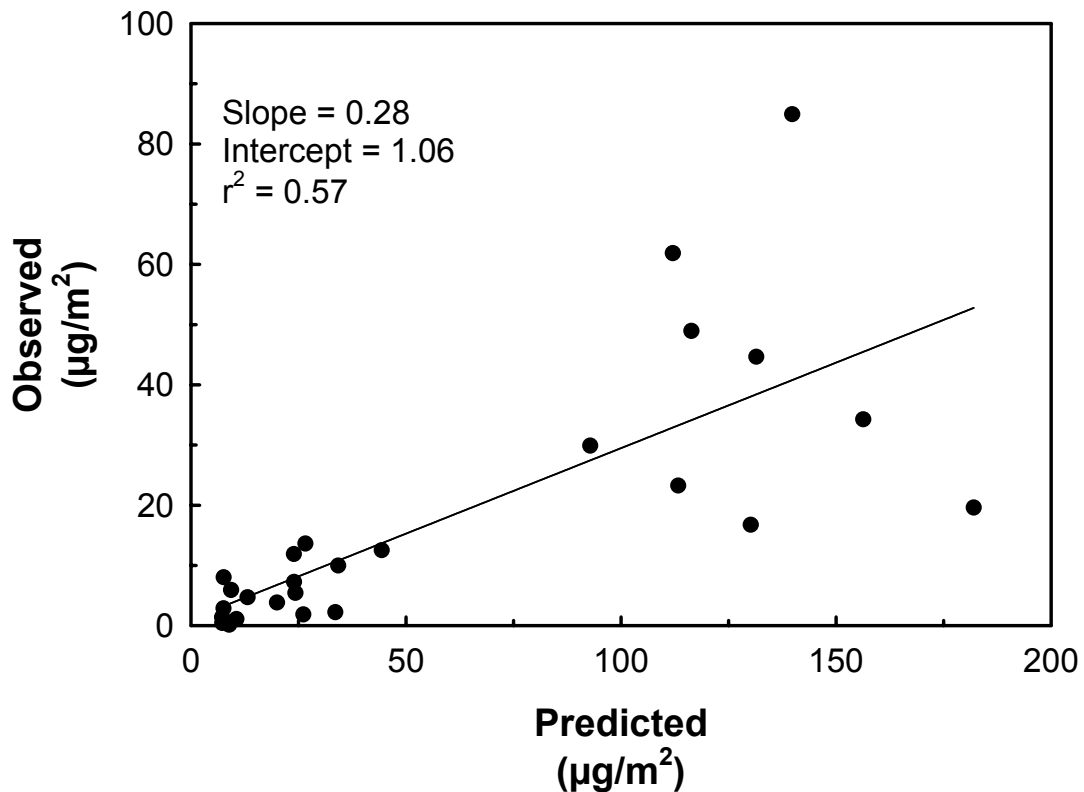
Figure 4.5.2. Linear regresssion between empirical deposits and AGDISP predicted deposits for the 100-m, 200-m, and 400-m distances ($P_{0.05}$).

4.5.2 Regression Analysis

Linear regressions of the logarithm of spray deposit vs. the logarithm of distance downwind of the application were fitted to the data obtained from the petri dish samplers in the treatment applications and their corresponding data generated by the AGDISP model. ANOVA on the regression parameters did identify significant differences between the empirical data collected and the data generated by the AGDISP model for Treatment 1 but not for treatments 2 and 4 (Table 4.5.1). The slopes for all of the regressions developed from the empirical data were steeper than the slopes for the regressions developed from the model output data. The empirical data and model output demonstrated differences in the intercept parameter.

Table 4.5.1. Comparison of the mean empirical and model regression parameters for each treatment.

Treatment	Parameter	Empirical	Model	F-value	P-value
	Slope	-2.4733	-1.8133	30.77	0.0052
1	Intercept	6.2535	5.4447	7.29	0.0541
	Slope	-1.8033	-1.7633	3.79	0.1234
2	Intercept	5.5446	5.4329	21.25	0.01
	Slope	-2.0566	-1.9867	0.78	0.4481
4	Intercept	5.6332	5.8058	15.21	0.0175

$(P_{0.05})$

4.5.3   Deposit Analysis

ANOVA on the petri dish deposits at 25 m, 100 m, and 400 m downwind of the application area identified significant model effects at nearly all points evaluated (Table 4.5.2). The AGDISP model tended to overestimate deposition regardless of distance downwind. On average the model overestimated downwind spray deposition at all distances downwind by a factor of 3 when compared to empirical data. The model was in agreement with the empirical data for the Fine spray quality treatment at the 400 m distance.

Table 4.5.2. Comparison of the mean empirical and model deposits for each treatment at the 25-m, 100-m, and 400-m downwind distances.

Treatment	Distance (m)	Empirical Deposit ($\mu g/m^2$)	Model Deposit ($\mu g/m^2$)	F-value	P-value
	25	1005	1579	1.48	0.2906
	100	33	112	39.04	0.0033
1	400	1	8	100	0.0006
	25	837	1762	15.77	0.0165
	100	56	145	10.21	0.0331
2	400	6	10	4.32	0.1062
	25	568	2267	196.6	0.0002
	100	33	134	45.49	0.0025
4	400	1	9	64	0.0013

4.5.4   Discussion

Previous work to confirm the predictions of the AGDISP model noted underestimation of deposition in the near field and over estimation in the far field. In this study the model overestimated deposition at all distances by a factor of approximately 3. At the 400-m distance results similar to those of Duan et al. (1992) and Bird et al. (2002) were obtained, with the model predictions in these studies fell within a factor of two of empirical data while in this case it fell within a factor of 3. The results of this study are also in agreement with the findings of Bilanin et al. (1989) and Woods et al. (2001) who noted that the model was able to accurately predict trends in deposition although the magnitude of actual predicted deposits was elevated over measured deposits. Explanations for the over prediction of the model in the far-field have been linked to the assumptions of perfectly flat terrain (which has since been improved upon in the current model of AgDISP) and the presence of a neutral atmosphere. Under a neutral atmosphere, the spray cloud would experience less vertical mixing and dispersion,

resulting in greater downwind deposition and over estimation of far-field deposits.

However, there have also been questions raised as to the over-sensitivity of the

algorithms for predicting evaporation rates of droplets, the result is the under prediction

of the amount of spray available for deposition in the far field (Bird et al., 2002).

4.6   Covariate Analysis for Meteorological Parameters on Spray Drift

Significant treatment differences were not detected for either deposit or wind speed (p=0.4643 and p=0.2680, respectively). The absence of significant treatment differences for wind speed and deposit negate the possibility for identifying any response of deposit to wind speed in this experiment (p=0.4761). The lack of significant treatment differences in wind speed may reflect the efforts made to conduct all applications in as uniform environmental conditions as possible.

Treatment differences for temperature were nearly significant at a 95% confidence (p=0.0584). However, there was no response in deposit to the variation in temperature (p=0.2847). The absence of significant treatment differences for RH (p=0.1385) and deposit (p=0.2510) means that a response of deposit to RH cannot be significant (p=0.4761). Similarly, the absence of significant treatment differences for temperature differential (p=0.3706) and deposit (p=0.3470) also negate the possibility of identifying any significant response of deposit to temperature differential in this experiment (p=0.2051).

The overall result of the analysis of meteorological data illustrates that efforts to make the applications in similar environmental conditions were somewhat successful to the extent that none of the variability in the deposit data could be attributed to variability in the meteorological conditions recorded at the time of application. However, it is believed that subtle differences in average environmental conditions and momentary variation in environmental conditions over the course of the applications contributed to the difficulties in identifying treatment differences. Future drift studies should employ a more sophisticated paired application approach for covariate analysis.

5.0   General Discussion

It was understood at the onset of this study that aerially-applied sprays are at a greater risk for drift than the more conventional method of ground application (Frank et al., 1994; Maybank et al., 1975; Salyani and Cromwell, 1992; Ware et al., 1969). This study set out to quantify the amount of drift from modern aerial applications of pesticide. Off-target movement of spray was measured comprehensively with special consideration given to the airborne component of spray drift. Interest was also placed on assessing the accuracy of the model currently used by regulators for predicting environmental contamination downwind of aerial pesticide applications.

An overriding element in this study was the high degree of variability in the spray drift deposits measured, which prevented the elucidation of significant treatment effects in many cases. While a great deal of variability is inherent in the deposition of sprays from aircraft (Maybank et al., 1975; Womac et al., 1993), it is believed that some other contributors to deposit variability could be mitigated with modification to the protocols for studying spray drift. For example, if considerable interest lies in the determination of drift deposits in the far-field, the study should focus solely on that aspect and neglect the near-field collection of spray deposits. Such a protocol would eliminate the complications of swath displacement and the variability associated with on-swath and near-field deposits. In this type of experiment it would be more practical to utilize greater sensitivity because there would be less potential for error stemming from sample cross contamination.

Room for improvement also lies in accounting for variability in meteorological conditions at the time of application. This would involve the simultaneous application of two tracer dyes from two different application systems on the same aircraft (Hewitt et

al., 2002). With this setup one of the application systems would remain constant while the other varied to test the desired application parameters. A covariate analysis could then be conducted with the deposits from the varied parameters using the constant application system as a covariate. With this type of experimental procedure all measurements are made relative to a standard application and the effects of meteorological conditions at the time of application become irrelevant (Woods et al., 2004).

It was noted in this study that the contribution of spray drift to the environment downwind of an application was primarily from horizontally moving airborne droplets. Drift deposits collected by drinking straw collectors extending vertically above the crop canopy were significantly greater per unit area than the deposits quantified by horizontally oriented petri dishes at the top of the crop canopy. Other studies in the area have noted similar observations (Woods et al., 2001).

Airborne quantities of spray were investigated extensively in the experiment with the spray cloud being sampled both actively up to 4m and passively up to 30m. Spray cloud concentrations were profiled with height from suspended string samplers which showed the greatest concentrations of spray occurring at the height of release. Vertical displacement of the spray was observed with decreasing deposits on the string with height. Total amounts of spray dispersed above the collection area were determined by mass balance on average for all applications to be 1.5% between 25-m and 100-m downwind and another 1.5% between 100-m and 400-m downwind. The rotorod samplers actively sampled drift and were the most useful collection device for identifying statistically significant treatment differences.

The effect of several application parameters was examined in this study. Spray quality was found to be the most influential parameter in the off-target movement of sprays. The application of a Medium spray quality displayed a greater rate of deposition of spray with distance from the application area than did the application of a Fine spray quality. The result was that moving from a Fine to a Medium spray quality reduced the amount of spray remaining aloft and available for movement into the far field (Bird et al., 1996). This was confirmed by the deposit data collected on the petri dish samplers at the 400-m downwind distance, which showed significantly greater deposits from the application of a Fine spray. This trend for greater amounts of drift arising from the Fine spray quality applications was verified by the rotorod collectors on which significantly greater deposits were observed for the Fine spray applications at all distances measured.

The off-target movement of spray from a rotary atomizer was compared to that of a hydraulic atomizer. Although statistically significant differences were not identified between these two applications, subtle differences in the deposit data suggest that application with a rotary atomizer may offer slight reductions in drift (Teske et al., 2005).

The role of ground cover was examined by the application to a mature cereal canopy and to bare ground. It was expected that the presence of vegetation would scrub the spray cloud, and result in less total off-target movement (Lawson and Uk, 1979; Miller et al., 2000). However, a significant effect of ground cover was not observed and in fact subtle differences in the data showed a greater amount of drift arising from the applications to crop canopy. This observation is likely the result of average environmental conditions (wind speed and friction velocity) at the time of application

being slightly more conducive to spray drift for the applications to crop canopy and the effect of ground cover was obscured.

All application scenarios were entered in the mechanistic model AGDISP which is used in the regulatory process in the determination of buffer zones. The model output and its corresponding empirical deposit data were compared. Significant disagreement was observed between the model-predicted deposits and the measured deposits. The model seemed to underestimate the rate of deposition with distance. As a result, there was significant over-estimation for deposition at all points, but to a larger extent in the far-field. Thus, regulators of pesticide use should take caution in utilizing this model as a sole means to estimate determine environmental concentrations of pesticide downwind of an application. It is made apparent by this work that empirical data are still necessary to arrive at buffer zone distances that accurately reflect actual environmental contamination from a pesticide application.

As the practice of allowing the deposition of spray on non-target areas becomes less acceptable, greater pressure will be put on applicators to mitigate the drifting of sprays. This work suggests that the application of coarser sprays can significantly reduce the off-target movement of sprays. While the use of rotary atomizers may offer some potential for drift mitigation, the presence or absence of vegetation seemed to have little impact on the drifting of aerially applied sprays. Given the confounding environmental conditions that may have contributed to this result and the contradictions with existing literature, further investigation of crop canopies is necessary.

While future studies are required to confirm the results of this work, it is believed that considerable pressure should be placed on aerial applicators to greatly reduce the potential for off-target movement of sprays and improve the uniformity of deposit on-

swath. Despite the use of modern application equipment in this experiment the mass balance determination of spray drift was remarkably similar to the findings of Maybank et al. (1978). This is possibly due to the faster air-speed and higher boom height associated with modern turbine-powered aircraft such as the AT502 used in this study. As a result, aerial applicators will need to accept more stringent regulatory measures to protect downwind sensitive areas. These measures already include greater buffer zones, but as more information becomes available on the total aiborne losses, measures could necessarily be expanded to account for atmospheric contamination as well.

6.0   Conclusions

Spray drift arising from the aerial application of pesticide was investigated and the impacts of several application parameters were evaluated for their potential to reduce drift. The empirical data collected were compared to the predictions of the AgDISP model. Spray drift deposition was transformed logarithmically and found to decrease linearly with distance from the application area. Airborne spray cloud concentrations were found to be greatest at approximately the height of release and the process of dispersion was found to take place to heights greater than 30 m.

It was found that the application parameter with the most potential for mitigating off-target losses is spray quality. When comparing the application of a Fine spray to a Medium spray it was found that the coarser spray exhibited a significantly greater rate of deposition with distance. This suggests that a greater percentage of the applied volume of the Medium spray was deposited in the near-field, leaving less available for transport into the far-field. This idea is supported by the horizontal deposition data where detectable quantities were only observed for the Fine spray and not the Medium at the 400-m downwind distance. While the spray cloud concentration profiles were similar in shape, the cloud from the Fine spray applications tended to be present in higher concentrations. This trend was confirmed by the rotorod data which revealed significantly greatly airborne amounts of spray from the Fine application. These data showed deposits from the Fine spray to be nearly double that from the Medium spray. Spray accountancy showed that losses to the atmosphere were also greater for the Fine spray applications, where 5.7% of the applied amount was lost compared to only 2.0% for the Medium spray.

Rotary and hydraulic atomizers were found to have similar potential for drift. Rates of deposition with distance were similar for both atomizers. Detectable quantities of spray were found at the 400-m downwind distance for the hydraulic atomizer but not for the rotary atomizer. The applications from both atomizers displayed similar spray cloud concentration profiles, and airborne spray concentrations detected by the rotorods were also similar. Spray accountancy showed losses to the atmosphere to be greater for the hydraulic atomizer applications where 5.7% of the applied amount was lost compared to only 3.0% for the rotary atomizer. In summary, the rotary atomizer offered slight reductions in drift despite producing a slightly finer spray.

The potential for drift mitigation by the presence of vegetation was also investigated and found to have little effect. Similar trends in deposition and airborne concentrations were observed for both applications to bare ground and to mature cereal crop canopy.

Comparison of empirical data to AgDISP predictions showed significant over-estimation of spray drift deposition under all circumstances tested. Regulators should exercise caution in utilizing this model for establishing buffer zone distances.

Future research in the investigation and mitigation of spray drift should continue to look at drift into the far-field and atmospheric losses. Future experiment should utilize dual application systems to reduce deposit variability that is believed to be associated with instantaneous atmospheric variability.

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Appendix A. ANOVA Tables.

Appendix A.1. ANOVA of slope parameter from the regression of the logarithm of deposit vs. the logarithm of distance downwind of the application for treatment application scenarios measured on petri dish samplers corresponding to results reported on page 41.

Source	DF	MS	F-value	P-Value
Treatment	3	0.247	11.41	0.0029
Error	8	0.022		

Appendix A.2. ANOVA of intercept parameter from the regression of the logarithm of deposit vs. the logarithm of distance downwind of the application for treatment application scenarios measured on petri dish samplers corresponding to results reported on page 41.

Source	DF	MS	F-value	P-Value
Treatment	3	0.482	8.26	0.0078
Error	8	0.058		

Appendix A.3. ANOVA of slope parameter from the regression of the logarithm of deposit vs. the logarithm of distance downwind of the application for treatment application scenarios measured on drinking straw samplers corresponding to results reported on page 43.

Source	DF	MS	F-value	P-Value
Treatment	3	0.198	3.6	0.0655
Error	8	0.054		

Appendix A.4. ANOVA of intercept parameter from the regression of the logarithm of deposit vs. the logarithm of distance downwind of the application for treatment application scenarios measured on drinking straw samplers corresponding to results reported on page 43.

Source	DF	MS	F-value	P-Value
Treatment	3	0.32	1.74	0.2353
Error	8	0.184		

Appendix A.5. ANOVA of deposits measured on petri dish samplers at the 25m distance downwind of the application for treatment application scenarios corresponding to results reported on page 44.

Source	DF	MS	F-value	P-Value
Treatment	3	182894	0.94	0.4671
Error	8	195446		

Appendix A.6. ANOVA of deposits measured on petri dish samplers at the 100m distance downwind of the application for treatment application scenarios corresponding to results reported on page 44.

Source	DF	MS	F-value	P-Value
Treatment	3	512.88	0.96	0.4587
Error	8	536.43		

Appendix A.7. ANOVA of deposits measured on petri dish samplers at the 400m distance downwind of the application for treatment application scenarios corresponding to results reported on page 44.

Source	DF	MS	F-value	P-Value
Treatment	3	21.93	8.37	0.0075
Error	8	2.62		

Appendix A.8. ANOVA of deposits measured on drinking straw samplers at the 25m distance downwind of the application for treatment application scenarios corresponding to results reported on page 45.

Source	DF	MS	F-value	P-Value
Treatment	3	1801751	0.2	0.8930
Error	8	8977541		

Appendix A.9. ANOVA of deposits measured on drinking straw samplers at the 100m distance downwind of the application for treatment application scenarios corresponding to results reported on page 45.

Source	DF	MS	F-value	P-Value
Treatment	3	11162	0.68	0.5906
Error	8	16508		

Appendix A.10. ANOVA of deposits measured on drinking straw samplers at the 400m distance downwind of the application for treatment application scenarios corresponding to results reported on page 45.

Source	DF	MS	F-value	P-Value
Treatment	3	254.71	1.14	0.3913
Error	8	224.26		

Appendix A.11. ANOVA of total deposit integrated from suspended string samplers at the 25m distance downwind of the application for treatment application scenarios corresponding to results reported on page 46.

Source	DF	MS	F-value	P-Value
Treatment	3	335775790	1.38	0.3184
Error	8	244106160		

Appendix A.12. ANOVA of total deposit integrated from suspended string samplers at the 100m distance downwind of the application for treatment application scenarios corresponding to results reported on page 46.

Source	DF	MS	F-value	P-Value
Treatment	3	47646853	1.68	0.2477
Error	8	28362887		

Appendix A.13. ANOVA of total deposit integrated from suspended string samplers at the 400m distance downwind of the application for treatment application scenarios corresponding to results reported on page 46.

Source	DF	MS	F-value	P-Value
Treatment	3	244708.1	2.39	0.1677
Error	8	102488.8		

Appendix A.14. ANOVA of amount collected on rotorod samplers at the 25m distance downwind of the application for treatment application scenarios corresponding to results reported on page 50.

Source	DF	MS	F-value	P-Value
Treatment	3	56108174	5.21	0.0037
Error	8	10835802		

Appendix A.15. ANOVA of amount collected on rotorod samplers at the 100m distance downwind of the application for treatment application scenarios corresponding to results reported on page 50.

Source	DF	MS	F-value	P-Value
Treatment	3	570813.9	7.89	0.0011
Error	8	88992.8		

Appendix A.16. ANOVA of amount collected on rotorod samplers at the 400m distance downwind of the application for treatment application scenarios corresponding to results reported on page 50.

Source	DF	MS	F-value	P-Value
Treatment	3	8097.2	7.89	0.0003
Error	8	1026.2		

Appendix B. Covariate Analysis Tables.

Appendix B.1. Covariate analysis of the petri dish deposits at 100m downwind response to wind speed for treatment application scenarios corresponding to results reported on page 85.

Source	DF	MS	F-value	P-Value	RSQ
Model	7	552.8	1.12	0.4861	0.66
Error	4	495.6			
Trt	3	517.1	1.04	0.4643	
Windspeed	1	818.9	1.65	0.2680	
Trt * Windspeed	3	499.7	1.01	0.4761	

Trt	Slope	Intercept
1	4.8	-59
2	-8.9	218
3	-1.7	66
4	0.5	22

Appendix B.2. Covariate analysis of the petri dish deposits at 100m downwind response to temperature for treatment application scenarios corresponding to results reported on page 85.

Source	DF	MS	F-value	P-Value	RSQ
Model	7	685.5	2.6	0.1861	0.82
Error	4	263.3			
Trt	3	577.1	1.96	0.2615	
Temp	1	1816.1	6.9	0.0584	
Trt * Temp	3	477.1	1.81	0.2847	

Trt	Slope	Intercept
1	-0.98	51
2	-7.47	195
3	-3.19	91
4	-21.26	-345

Appendix B.3. Covariate analysis of the petri dish deposits at 100m downwind response to RH for treatment application scenarios corresponding to results reported on page 85.

Source	DF	MS	F-value	P-Value	RSQ
Model	7	691.1	2.73	0.1748	0.83
Error	4	253.6			
Trt	3	517.1	2.04	0.2510	
RH	1	762.8	3.01	0.1579	
Trt * RH	3	841.1	3.32	0.1385	

	Trt	Slope	Intercept
	1	0.41	9
	2	3.65	-160
	3	0.87	-19
	4	-1.67	91

Appendix B.4. Covariate analysis of the petri dish deposits at 100m downwind response to temperature differential for treatment application scenarios corresponding to results reported on page 86.

Source	DF	MS	F-value	P-Value	RSQ
Model	7	636.4	1.82	0.2934	0.76
Error	4	349.2			
Trt	3	517.1	1.48	0.3470	
Temp Diff	1	354.7	1.02	0.3706	
Trt * Temp Diff	3	849.6	2.43	0.2051	

	Trt	Slope	Intercept
	1	1.81	34
	2	137.76	96
	3	110.97	54
	4	-29.11	21