Combining Spray Drift and Plant Architecture Modeling to Minimise Environmental and Public Health Risk of Pesticide Application

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EXTENDED ABSTRACT

Accurate placement of pesticide droplets on to crop and weed surfaces is a key step in guaranteeing high quality food production. Pesticides impact on plant surfaces to give protective coverage for crops and destructive coverage for weeds. Coverage is determined by interactions between the size and density of spray droplets, humidity and turbulence of the air through which the droplets travel, the physical characteristics of the target plant leaves and the architecture of the plant canopy. There are however, increasing concerns over the effect of pesticides in the environment particularly when they move beyond a field boundary.

Droplet movement (spray) models and plant architecture models are being combined using three-dimensional computer modeling techniques to develop a probabilistic model of turbulence-related spray transport around various plant architectures. Measurements of pesticide droplet interactions with the crop canopy from wind tunnel and field studies will be used to refine and validate the combined spray and plant architecture model.

The spraying process can be divided into two zones; close to the nozzle where droplet movement is influenced by the sprayer and at distance from the sprayer where droplet movement is controlled by prevailing meteorological conditions.

Models of droplet movement in the near nozzle region are often ballistic or particle trajectory models and are based around applying Newton's Second Law of Motion (**F=ma**). Velocity can be obtained by integrating the equations developed from Newton's Second Law of Motion and the position can be obtained by a further integration.

The main purpose of models of droplet movement at distance from the spray nozzle is to determine the amount of spray drift moving away from treatment areas. Two main approaches that have been used for these models are Gaussian diffusion theory and random walk.

Plant architectures can be constructed by the repeated production of a relatively small number of different components. The L-system formalism represents plants or parts of plants as an assembly of components, each represented by a symbol (or module). By treating plant geometry as an arrangement of discrete components in space it is possible to keep model specifications concise, even if the simulations eventually yield extensive structures that are made up of many modules (Prusinkiewicz 2004).

In future research, linking the modelling techniques to decision support systems such as the fundamental causal network, FCN, will be investigated, with the aim of assisting growers in evaluating the risk from spraying activities.

By improving our understanding of the complex relationship between the deposition of pesticide droplets on vegetative surfaces it should be possible to improve pesticide application procedures. This will enable the effectiveness of plant protection products to be maximised while minimising risks to public health and the environment from agricultural spraying activities.

1. INTRODUCTION

Pesticides remain an essential tool for agricultural industries in the production of high quality produce and are a key component of integrated crop management (ICM) in most Australian cropping systems. Accurate placement of pesticide droplets on to crop and weed surfaces is a key step in guaranteeing high quality food production. There are however, increasing concerns over the effect of pesticides in the environment particularly when they move beyond a field boundary.

The basic aim of all pesticide application in agriculture is to control pests (weeds, insects or pathogens) and thereby increase yield and farm income. This is generally achieved by producing a uniform coverage of droplets on the target (eg an insect, leaf surfaces or part of a plant). Spray may be lost to non-target areas within a crop such as deposition on to the soil or non-target plant surfaces. The action of wind may result in spray moving from the spray area. By utilising techniques that will maximise deposit on the spray target it is possible to both improve the efficacy of pesticide applications and limit the movement of liquid droplets away from their point of release, both within and outside a target area.

While responsibility for development, registration and labeling of pesticides lies with the registrant/manufacturer, responsibility for efficient and environmentally safe application lies with the applicator and grower. For optimum control of pests and weeds in agricultural cropping situations, the grower is required to take careful consideration of many factors. These include;

- Chemical selection and costs
- Label requirements
- Crop type
- Pest biology and ecology
- Potential revenues (based on price and yield)
- Spray equipment (nozzle selection, droplet size, sprayer type and operating parameters)
- Spray techniques (eg buffer zones, no spray areas)
- Meteorology (wind speed and direction, temperature, relative humidity) before, during and after spraying
- Environmental and public health risk from the spraying operation

Managing these factors in an integrated, holistic manner is often very complex. It requires combining tools, resources and information from several sources in order to optimise the application. Many parameters can also change during application (eg wind speed and direction) and application techniques must then be modified to prevent possible contamination of non-target areas. Failure to rapidly and appropriately manage these complex inter-related parameters has been the reason behind many pesticide drift incidents.

Risks associated with pesticide use can be minimised if correct management decisions are made. Over the last decade, significant research has been conducted overseas and in Australia to establish spray drift profiles and determine the effectiveness of spray drift models (Bird et al. 2002; Woods et al. 2001).

The aim of this project is to combine spray application modeling, plant architectural modeling and risk management tools to develop application procedures that will maximise the effectiveness of plant protection products and minimise risk to public health and the environment.

In this paper we first review spray modelling and plant architectural modelling approaches and then show a combined model. Finally a path to link the model to risk management techniques will be discussed.

2. SPRAY MODELLING

Considerable research has been focused on understanding the movement of sprays from the release point and various computational models have been developed to simulate the spray application process.

In general, spray application can be regarded as two-phase fluid flow where liquid droplets (or occasionally solid particles) are released into an air (gas) flow. To adequately model this situation it is necessary to determine both air flow in the system and spray movement in the prevailing air flow.

The spraying process is complex and not fully understood. It can be divided into two zones; close to the nozzle where droplet movement is influenced by the sprayer and at a distance from the sprayer where droplet movement is controlled by prevailing meteorological conditions.

2.1. Near Nozzle or Spray Vehicle

Close to the spray nozzle the spray is relatively dense and the droplets can influence the local air turbulence (Crowe et al. 1996). The fact that droplets are being propelled from the nozzle in a certain direction causes surrounding air to be entrained into the spray plume (Ghosh and Hunt

1994) (Figure 1). The combination of the high droplet concentration, initial spray sheet and entrained air can provide a blockage to cross flowing air resulting in regions of low and high air pressure leading to the creation of spray induced vortices (Miller and Hadfield 1989; Parkin and Wheeler 1996). The spray vehicle (eg tractor or aircraft and spray structures (eg booms and shields) can also create additional turbulence in the region where the spray is being produced.

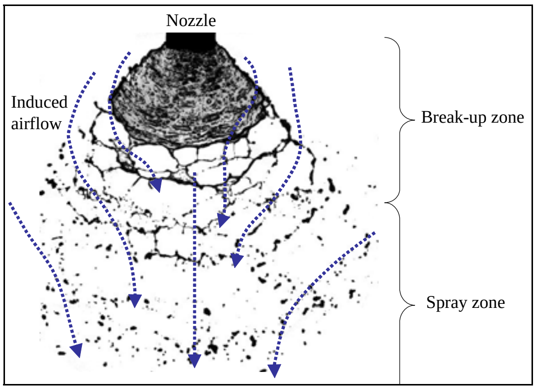

Figure 1. Near nozzle region

Models of droplet movement in the near nozzle region are often ballistic or particle trajectory models and are based around applying Newton's Second Law of Motion (**F=ma**). The two main forces acting on droplets during a typical spraying situation are gravity and drag.

Drag force is in the direction of the airstream relative to the droplet velocity and is a function of the drag coefficient

$$F_d = \frac{1}{2} C_d \rho A V^2 \qquad 1.$$

where F_d = drag force

C_d = drag coefficient

ρ = density of air

A = frontal area of sphere = $\pi d^2/4$

V = relative speed of droplet to the air

The drag coefficient C_d is a function of the dimensionless Reynolds number

$$R_e = \frac{Vd}{\upsilon} \qquad 2.$$

where R_e = Reynolds number

υ = kinematic viscosity of air

d = droplet diameter

The drag coefficient is not a simple analytical function of Reynolds number and it is common to assume that the drag coefficient for a droplet is the same as for a solid sphere as long as Reynolds numbers is less than 1000 (Marchant 1977). Morsi and Alexander (1972) divided the experimental drag curve into a number of regions and fitted a curve to each region. In this way the drag coefficient is always within 2% of the experimental value.

Velocity can be obtained by integrating the equations developed from Newton's Second Law of Motion and the position can be obtained by a further integration (Marchant 1977). Since only empirical equations are available to describe the drag coefficient a numerical solution is required. A fourth-order Runge-Kutta numerical integration technique has commonly been used (Chow 1979; Parkin and Wheeler 1996)

This approach has been used by many researchers (Cox et al. 2000; Hobson et al. 1993; Holterman et al. 1998; Mokeba et al. 1997). The main difference between these models relate to how air flow is characterised in the near nozzle region.

2.2. Distant from Nozzle (Spray Drift)

Once a droplet moves far enough from the spray nozzle it will move entirely under the influence of the prevailing meteorological conditions. At this stage the spray concentration in the air is low so the influence of the droplets on the local air turbulence is negligible (Crowe et al. 1996). The main purpose of these models is to determine the amount of spray drift moving away from treatment areas. The two main approaches used for these models have been Gaussian diffusion theory and random walk.

Gaussian diffusion models

Gaussian plume models make assumptions about the shape of a plume and the distribution of material within a plume (Thistle 2004). A spray nozzle moving along a field (either on a boom spray or agricultural aircraft) is assumed to produce an instantaneous line source of droplets as the time taken to release the spray is short compared to the time scale of the atmospheric turbulence that affects the spray dispersal. A cloud of droplets released from such a line source is subject to the following influences (Lawson 1989).

Diffusion. The action of turbulence causes the droplets to move upwards, downwards, forwards and backwards. This increases the vertical and horizontal dimensions of the spray cloud and results in a corresponding decrease in the maximum droplet concentration. It is usual to assume that the concentration of droplets within the cloud follows a Gaussian distribution with standard deviations in the downwind (x) and vertical (z) direction.

Wind. The spray cloud moves in the direction of the prevailing wind.

Sedimentation. Droplet weight results in a reduction in the height of maximum concentration (initially the release height).

Deposition. Droplets are removed from the cloud at the crop or ground surface.

A downwind moving, sedimenting, diffusing, Gaussian cloud from a short pulse of spray is shown schematically in Figure 2.

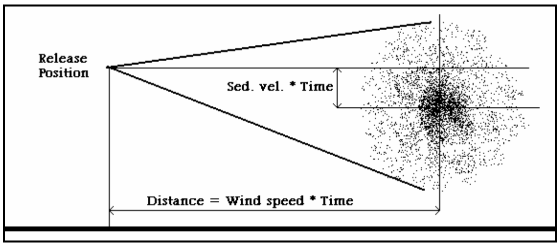

Figure 2. Turbulent dispersal of a spray cloud with a Gaussian concentration distribution (after Lawson, 1989)

Random Walk Models

In random walk models the trajectory of each droplet is followed as it moves through the atmosphere (Hashem and Parkin 1991). A meaningful estimate of dispersal statistics can be obtained by following a large number of trajectories. The trajectory of each fluid element is divided into a large number of small discrete time steps of constant duration, during which the velocity components (u,v,w) of the particle are kept constant. Models based on a random-walk approach have been shown to have good agreement with experimental data close to and distant from the source (Hashem and Parkin 1991; Walklate 1987). A random walk model generally ignores near nozzle effects, however, by tracking the trajectory of droplets in discrete time steps it is possible to account for some near nozzle influences.

3. PLANT ARCHITECTURAL MODELING

Plant architecture may be defined as the structure of a plant at a single instant (Wilson et al. 1999). Above ground, a plant's architecture is determined by the size, shape and variety of their individual components and how these components are connected to each other (Room et al. 1996). Examples of plant components include leaves, internodes, buds, flowers and fruit.

Plants develop and change over time, with individual components changing size and shape, new components being added and the loss of existing components. Plant architectural models may be static (capturing plant form at a point in time) or dynamic (describing the form as a result of growth). Dynamic models may be empirical (integrating the results of measurements of form over time) or mechanistic (attempting to elucidate the development of form by the underlying biological, chemical and physical processes).

Plant architecture is constructed by the repeated production of a relatively small number of components. By treating plant geometry as an arrangement of discrete components (modules) in space it is possible to keep model specifications concise, even if the simulations eventually yield extensive structures that are made up of many modules (Prusinkiewicz 2004). All modules of the same type share the same description, behave according to the same algorithm and may have diverse behaviors defined by changing values of variables associated with the module.

L-systems

Lindenmayer systems (L-systems) were originally developed by Lindenmayer in 1968 using a system of symbols to describe linear or branching linear chains of single-celled organisms (Lindenmayer 1968). L-systems enable the study of dynamic 3D-plant architecture in relation to the environment.

The L-system formalism represents plants or parts of plants as an assembly of components, each represented by a symbol (or module). For example a leaf may be represented by the symbol L, an internode by the symbol I and an apical meristem by the symbol A. Parameters may be associated with each symbol and can be used to set, for example, the surface properties of a leaf or the length and width of an internode. A string of modules captures the architecture of a plant, by positioning the components relative to their neighbors, with a branching topology imposed by a hierarchy of square brackets. A rewriting technique successively replaces parts of a simple initial object using a set of rewriting rules or productions to model development. Figure 3 shows a cotton plant that has been developed using these techniques (Room and Hanan 1995).

Figure 3. Model of Cotton plant

4. COMBINED SPRAY AND PLANT ARCHITECTURAL MODEL

L-systems are the foundation of L-Studio a programming environment well suited for plant architectural modelling (Prusinkiewiez et al. 2000). L-Studio was chosen for this study as it provides a framework that makes it possible to simulate and visualise a wide range of environmental interactions with plant architecture.

A combined ballistic and random walk model based on the approached used by Mokeba et al 1997 has been developed in the L+C programming environment of L-studio (Karwowski and Prusinkiewicz 2003). The velocity of the spray droplets is taken as a weighted sum of their ballistic and random-walk velocities. The ballistic velocity is scaled by a factor (1-β) and the random walk velocity is scaled by β where β is the ratio of the sedimentation velocity (V_s) and the relative velocity of the droplet to air (V). This has currently been linked to simulations of simple plant architecture as shown in Figure 4. An environmental program has been developed to determine when the tracked spray droplets collide with plant components.

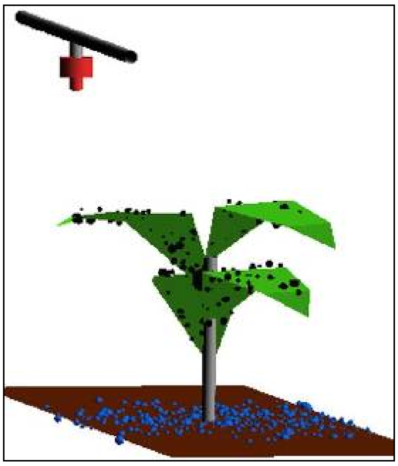

Figure 4. Simulation of the movement of spray droplets around a simple plant structure.

Combined spray drift and plant architectural models such as that proposed in this paper may help to evaluate various spray options to maximize deposit of spray on the target area. Increasing the amount of spray that reaches its target will also reduce the amount of spray that has the potential to cause environmental damage.

Once models have been validated, linking distribution of the spray from the combined spray and plant architecture model to decision support systems could assist growers evaluate the risk from spraying activities. For example if the risk of spray drift is too high, then the droplet size may be increased to reduce the amount of off target movement and the analysis repeated to determine if the risk of spray drift can be reduced to acceptable levels.

5. RISK MANAGEMENT

Risk assessments and management techniques are widely used by regulatory authorities for the registration of pesticides used in agriculture. There is currently a lack of risk management tools available to growers to assist in their decision to spray or not.

The essence of the methodology to minimise risk via managerial actions or procedures is based on the fundamental causal network, FCN (Cox and Ricci 2005).

$$\Delta u \rightarrow \Delta x \rightarrow \Delta r \rightarrow \Delta c \rightarrow \Delta Q \qquad 3.$$

where Δu = risk management act to be evaluated (e.g. change in <u>u</u>se of product or exposure)

Δx = change in e<u>x</u>posure if act Δu is taken

Δr = change in illnesses (the “<u>r</u>esponse” in dose-response models or exposure-response models) caused by Δx,

Δc = change in adverse health <u>c</u>onsequences caused by Δr,

ΔQ = change in a summary measure of risk (e.g., change in expected <u>q</u>uality-adjusted life-years, QALYs, lost per capita-year) caused by Δc.

This sequence of changes in response to Δu may be modified by other variables, for example b affects Δx, s affects Δr and m affects Δc.

Thus, a causal structure based on the FCN can aid decision-makers and stakeholders and should consist of a framework that allows consistent evaluations under risk, updated as additional information becomes available. The characterization of risk can be performed for a proposed risk management intervention Δu, once the exposure modeling and dose-response modeling steps are complete, by “marginalizing out” the remaining variables, i.e., summing (or integrating, for continuous random variables) over their possible values. For example, the composition of the relations $\Pr(\Delta x|\Delta u)$, $\Pr(\Delta r|\Delta x)$ and $\Pr(\Delta c|\Delta r)$ yields the probability density (and thus the expected value) of the human health consequence (c):

$$\begin{aligned}\Pr(\Delta c|\Delta u) &= \Sigma_{\Delta r}\Pr(\Delta c|\Delta r)\Pr(\Delta r|\Delta u) \qquad 4.\\ &= \Sigma_{\Delta r}\{\Pr(\Delta c|\Delta r)[\Sigma_{\Delta x}\Pr(\Delta r|\Delta x)\Pr(\Delta x|\Delta u)]\}\end{aligned}$$

This collapses the entire causal chain ($\Delta u \rightarrow \Delta x \rightarrow \Delta r \rightarrow \Delta c$) to a single but equivalent risk characterization link ($\Delta u \rightarrow \Delta c$) = $\Pr(\Delta c|\Delta u)$ and relates risk management actions to their probable health consequences. More generally, if the main sequence ($\Delta u \rightarrow \Delta x \rightarrow \Delta r \rightarrow \Delta c$) is embedded in a larger directed acyclic graph model with the conditional probability distribution of the value of each node (representing a variable in the model) being determined by the values of the variables that point into it, then the conditional probability distribution for $\Delta c|\Delta u$ can be calculated via computational methods for exact inference in Bayesian networks and causal graphs (Pearl 2000).

Effective computational inference algorithms and software for quantifying $E(\Delta c|\Delta u)$ and $\Pr(\Delta c|\Delta u)$, while conditioning on any relevant data (for individual cases), exist. Therefore, most applied risk assessment effort can focus on using available data to quantify the component causal relations for the nodes, $\Pr(\Delta x|\Delta u, b)$, $\Pr(\Delta r|\Delta x, s)$, and $\Pr(\Delta c|\Delta r, m)$: the exposure, dose-response, and health consequence models. We will investigate how simulation modelling could be used to address the exposure component. These components can then be composed jointly to form the causal path from actions to health consequences and to complete the risk assessment by computing $E(\Delta c|\Delta u)$ or $\Pr(\Delta c|\Delta u)$.

6. FUTURE WORK

It is planned to link the spray model to more complex plant structures such as the cotton model shown in Figure 3 and various other crop and weed species.

A series of trials is planned to measure the deposition of spray droplets on various plant architectures. A range of plant species will be grown and placed in the wind tunnel at the University of Queensland, Gatton campus where they will be spray using a traversing boom. Results from these trials will be used to refine and validate the combined spray and plant architecture model.

The results from the combined spray and plant architectural model can then be used in risk management techniques such as the fundamental causal network outlined above.

7. CONCLUSIONS

By improving our understanding of the complex relationship between the deposition of pesticide droplets on vegetative surfaces, this research seeks to improve pesticide application procedures. The techniques developed in this project may be linked to decisions support systems to maximise the effectiveness of plant protection products and minimise risks to public health and the environment from agricultural spraying activities.

8. ACKNOWLEDGMENTS

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