PAPERS

THE DEVELOPMENT OF THE AGDRIFT® MODEL FOR AERIAL APPLICATION FROM HELICOPTERS AND FIXED-WING AIRCRAFT

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ABSTRACT
Over the last 25 years, the USDA Forest Service (FS) and its co-operators have been developing computer models to predict the deposition and drift of aerially-released spray material. The two software products developed from this effort are AGDISP and FSCBG. AGDISP, later configured as the aircraft near-wake model in FSCBG, is based on a Lagrangian-solution approach, where spray material from every nozzle on the aircraft is tracked by its own set of equations from release to ground deposition. The spray material is divided into discrete droplet size categories (the droplet size distribution), and each droplet is tracked as it is influenced by the wake of the aircraft, the ambient crosswind, and evaporation. In the last six years the Spray Drift Task Force (SDTF) has been developing the aerial application model AgDRIFT® in response to regulatory needs suggested by the U.S. Environmental Protection Agency (EPA) regarding the off-target drift of agricultural spray material. The computational engine driving AgDRIFT® is the same Lagrangian model originally implemented in AGDISP. In this same time period, the FS recognized the need to convert the existing FSCBG predictive model into a Windows™ - based application. It made sense therefore to draw upon the model development within AgDRIFT® and incorporate forestry spray modelling features already present in FSCBG into AgDRIFT®. In effect, the modelling effort has come full-circle: first developed by the FS into AGDISP and later FSCBG, selected (and expanded upon) by the SDTF/EPA, then re-established by the FS for its present and future needs, resulting in a single model that has application to both agriculture and forestry. This paper summarises the development of the Lagrangian model from start to finish, details model validation by the FS and SDTF, and discusses the tools available within the model with regard to aerial spraying from helicopters and fixed-wing aircraft.

Key words: Modelling, Lagrangian, aerial spraying, drift, deposition

INTRODUCTION
The present paper explains the history of the AgDRIFT® model and its components based on theoretical principles of droplet formation, dispersion, transport and deposition, and validation from experimental studies by numerous researchers in the 1900s. An accompanying paper (Hewitt, this issue) explains the practical use of the AgDRIFT® model for modelling spray applications.

Aerial Spraying, AGDISP, FSCBG and AgDRIFT®

Early 1900s: Aerial Spraying Introduced
The potential usefulness of aerial spraying for pest control was explored in the 1920s (Neillie and Houser 1922). This mode of application was realized in the 1930s as a method of rapidly covering relatively large areas without equipment contact on the ground or canopy. The wake effect of aircraft was an important factor affecting the transport of sprays. Effective modelling of droplet movements required consideration of such wake effects in the application process, but analysing and optimising spray delivery were not yet required.

1950s: Aircraft Wake Effects Modelled
In the 1950s, Reed (1953) developed the equations of motion for material released from nozzles on agricultural aircraft. Reed realized that the wingtip vortices played a significant role in the subsequent behaviour of the released spray. His equations integrated the dynamics of single droplets in a vortex flow field modelled as two counter-rotating irrotational line vortices with separation distance equal to the span of the wing. Image vortices were used to simulate an inviscid ground plane. Resultant trajectories were determined for several droplet sizes released at nozzle positions along the wing. With the droplet size distribution known, an expression for the ground deposition was developed.

Teske (1998) noted that the strength of the Reed model rested in its simplicity – writing equations and computing where the spray material travelled. The equations solved by Reed were formulated as Lagrangian trajectory equations, with one set of equations for the location and speed of the material released from each nozzle on the boom of the aircraft. These techniques lead generally to a Monte-Carlo solution scheme, where particles are released randomly (possibly with statistical direction information), and their accumulated results are summed to recover the ground deposition.

1960s to 1980s: USDA Forest Service Models Initiated
In the 1960s, Dichloro Diphenyl Trichloroethane (DDT) was banned for use in insect control. The United States Department of Agriculture Forest Service (FS) needed to find alternative effective products for pest control in forest canopies. The FS also explored the need to develop a model (including canopy effects) to predict whether aerially sprayed material will reach the targets being sprayed and to assess potential environmental impacts from specific aerial spraying scenarios.

With these goals in mind, Bilanin and Teske (1984) expanded on the work of Reed to include the effects of wake turbulence on the growth of the spray cloud from each nozzle. Equations were written for the ensemble averaged turbulent components, eliminating the

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need for random particle release. Solving these equations with Reed's mean equations, Bilanin and Teske (1984) were able to predict the ground deposition. The mean equations recovered the mean position of the cloud, the turbulent equations recovered the standard deviation of the cloud, and a Gaussian representation of the profile recovered the ground deposition rates. Teske (1998) explained that under proper expansion, the turbulent correlations of particle position and particle velocity with ambient velocity must be obtained from another means. Fortunately, an expression for the needed spectral density function, but only for isotropic (neutral ambient conditions) turbulence, was found (von Karman and Howarth 1938), substituted, and solved. This set of equations is then very compact and complete, being summarized as follows:

$$\frac{d^2 X_i}{dt^2} = [U_i - V_i]\left[\frac{1}{\tau_p}\right] + g_i$$

$$\frac{d X_i}{dt} = V_i$$

$$\frac{d}{dt}\langle x_i x_i \rangle = 2\langle x_i v_i \rangle$$

$$\frac{d}{dt}\langle x_i v_i \rangle = \left[\langle x_i u_i \rangle - \langle x_i v_i \rangle\right]\left[\frac{1}{\tau_p}\right] + \langle v_i v_i \rangle$$

$$\frac{d}{dt}\langle v_i v_i \rangle = 2\left[\langle u_i v_i \rangle - \langle v_i v_i \rangle\right]\left[\frac{1}{\tau_p}\right]$$

where X_i, V_i, and U_i are the ensemble-averaged i^{th} components of droplet position, droplet velocity, and local fluid velocity, respectively. The fluctuating i^{th} components of droplet position, droplet velocity, and local fluid velocity are x_i, v_i, and u_i, respectively, $g_i = (0,0,-g)$ is gravity, and t is time. The mean square turbulence level is $q^2 = \langle u_i u_i \rangle + \langle v_i v_i \rangle + \langle w_i w_i \rangle$.

The first two equations solve for the mean trajectory paths; the next three equations solve for the turbulent correlations, to enable recovery of $\sigma^2 = \langle x_i x_i \rangle$ for the Gaussian ground deposition pattern.

The turbulent equations require the specification of $\langle x_i u_i \rangle$ and $\langle u_i v_i \rangle$ to close the problem. With the form assumed by von Karman and Howarth (1938), it may be shown that:

$$\langle x_i u_i \rangle = \frac{q^2}{3}\left[-\tau_p K + \frac{\tau_t}{2}\right]$$

$$\langle u_i v_i \rangle = \frac{q^2}{3} K$$

where K is a function of the mean relaxation time τ_p (the time for V_i to approach U_i) and the turbulent travel time τ_t (the time for released material to pass through a typical eddy)

$$\tau_p = \frac{4}{3}\frac{D\rho}{C_D \rho_a |U_i - V_i|}$$

$$\tau_t = \frac{\Lambda}{|U_i - V_i| + \frac{3}{8}q}$$

where D is the droplet diameter, ρ is droplet density, ρ_a is air density, C_D is the drag coefficient evaluated empirically for spherical droplets from Langmuir and Blodgett (1946) as

$$C_D = \frac{24}{Re}\left[1 + 0.197\,Re^{0.63} + 0.00026\,Re^{1.38}\right]$$

with

$$Re = \frac{\rho_a D |U_i - V_i|}{\mu_a}$$

and μ_a is air viscosity.

The Lagrangian approach assumes a neutrally buoyant background, and can be solved exactly if a sufficiently small step size is used. The calculation of U_i near the aircraft is based on models described by Bilanin *et al.* (1989) for the aircraft wake flow field.

The FS effort to look at spray dispersal and deposition was driven by John Barry, Robert Ekblad and others from the FS, who funded the H E Cramer Company and others to develop models which would ultimately be available through the public domain for others to build on and benefit from as appropriate.

1980: AGDISP and FSCBG

The efforts described in the previous section led to the development of the Agricultural Dispersal (AGDISP) and Forest Service Cramer Barry and Grimm (FSCBG) models in the early 1980s. Teske *et al.* (2001) explained that the AGDISP model has an extensive history of use and development by several Federal agencies. The initial computational approach for AGDISP was defined under a 1979 grant by the National Aeronautics and Space Administration (NASA) to 'develop and demonstrate a particle dispersion computer code which models deposition on a horizontal surface'. Over nearly twenty years, with continuing support from the FS and the U.S. Army, AGDISP was developed (Bilanin and Teske 1984) and refined, both as a stand-alone code (Bilanin *et al.* 1989) and as the near-wake model in FSCBG (Teske *et al.* 1993). In this same time period, considerable effort has been made toward understanding the spray application problem. This improved understanding has led to extensive data assembly efforts to facilitate use of the model:

1. Defining critical specifications for most agricultural aircraft used in the United States (Hardy, 1987) and testing the sensitivity of deposition to aircraft type;
2. Measuring droplet size spectra for typical agricultural products (Hewitt *et al.* 2001) and investigating their effect on deposition (Bird *et al.* 1996) and atomization modelling (Teske and Bilanin, 1994; Esterly 1998);
3. Performing an extensive series of sensitivity studies of the influence of all inputs into the model (Teske and Barry 1993; Teske, 1996; Teske, Thistle, Barry and Eav 1998; Teske and Thistle, 1999), in an effort to clarify which variables influence field applications; and
4. Evaluating model performance on available field data sets (Teske, Thistle and Eav 1998).

These activities represent many years of extensive research and development toward the on-going refinement of modelling tools that have found application in numerous spray management tools. The AGDISP code has been included in modelling efforts in North America and other countries. In New Zealand, it forms the basis of SpraySafe Manager (Ray *et al.* 1998), which combines drift predictions with efficacy performance for specific herbicides. In North America, it is used for forestry, vector control and other applications. With the development of the AgDRIFT® model described in the following section, AGDISP has found application for agricultural row crop spraying as well as enhanced options for forestry applications (AgDRIFT/FS; Teske *et al.* 1999; Hewitt *et al.* 2000; Thistle *et al.* 2000). The adoption of the AGDISP code within AgDRIFT® by government and industry in the U.S. is discussed in the following section.

1990s: AgDRIFT®

In the 1990s, the Spray Drift Task Force (SDTF), an industry-based consortium of pesticide registrants, identified AGDISP as a valuable tool for substantiating drift data being collected in its extensive aerial field studies (Hewitt *et al.* 2001). Working under a co-operative research and development agreement, the SDTF, EPA and USDA developed the AgDRIFT® model, based on AGDISP and other sources for this purpose. It was soon realized that deposition data from the SDTF field studies could in fact validate the model (Bird *et al.* 2001), and that the model could prove valuable in studying aerial application scenarios which had not been tested in the field, but which were within appropriate model limits.

AgDRIFT® is a Microsoft® Windows™ - based program with a user-friendly interface and extensive help menu. The model operation and features such as toolboxes, screens and droplet size prediction models, are extensively described in an accompanying paper (Hewitt, 2001).

AgDRIFT® includes several enhancements to the previous AGDISP code. These include the provision of extensive libraries for input variables such as droplet size spectra, aircraft characteristics and tank mix physical properties. The model also includes unique evaporation calculations to track the change in droplet size with time following emission from the aircraft nozzles. The evaporation model in AgDRIFT® is based on the D-squared law as suggested by Trayford and Welch (1977).

Analyses of SDTF and other liquid physical property data have shown that aerially applied agricultural materials (in water-based carriers) behave like water under evaporation (Riley *et al.* 1995; Teske and Hill 1995). For water, Trayford and Welch (1977) suggested an evaporation rate of $\lambda_\infty = 84.76\ \mu m^2/(sec\cdot deg\ C)$. Tests by the SDTF showed that the evaporation rate – with flow over the droplet – could be somewhat lower, down to $\lambda_\infty = 70.24\ \mu m^2/(sec\cdot deg\ C)$ for deionized water, well within a ten to fifteen percent variation in the evaluation of thermal conductivity and latent heat, and that the evaporation rate is further reduced as the relative velocity $|U_i - V_i|$ approached zero (Teske, Hermansky and Riley, 1998). This study set a bounding curve to λ_∞ of the following form:

$$\lambda/\lambda_\infty = 0.4 + 0.116\ Re$$

This correction runs counter to scaling laws based on the Sherwood number ($Sh = 1 + 0.27Re^{1/2}$), but, when implemented into AgDRIFT®, reduces downwind deposition by a factor of two and brings model predictions closer to field data measurements. With a reduced evaporation rate, droplet sizes remain larger, and are more likely to deposit closer to the spray block than droplets that experience higher evaporation rate.

Teske *et al.* (2001) described the following additional AGDISP extensions within the AgDRIFT® framework that have improved the accuracy of predictions of downwind drift and deposition:

A more physically correct approximation of the fully rolled up wingtip vortices as generated from an elliptically loaded wing, and experimental recovery of aircraft vortex decay by local turbulence (Teske, Bilanin and Barry 1993);

1. Modification of the helicopter wake model to more nearly approximate the predictions from state-of-the-art wake models;
2. Inclusion of smaller droplet sizes in the droplet size distribution, specifically extending the minimum size class examined to <10 µm, and expressing the droplet size distribution in size classes that each contain no more than two percent of the total volume fraction;
3. Evaporation rates for typical agricultural tank mixes, and the importance of the nonvolatile fraction (Riley *et al.* 1995; Teske and Hill 1995);
4. Reduction in evaporation rate at low relative wind speeds (Teske, Hermansky and Riley 1998); and
5. A significant solution speed increase, incorporating an exact solution to the equations of motion on a step-by-step basis, and an in-memory computation of the smoothed downwind deposition pattern.

These extensions to the aircraft wake model, the droplet size distribution representation, and the evaporation model are now considered essential to the success of any model in accurately predicting downwind drift. In addition, the solution speed increase enables AgDRIFT® to run rapidly in the 32-bit Windows™ environment.

2001 and Beyond: Model Enhancements; Modelling Ground and Orchard Applications

The present paper has described the history of the AgDRIFT® model for studying the transport and deposition of aerially-released sprays. Given the importance of other spray application techniques such as ground rig and orchard airblast spraying, the USDA, FS, SDTF and EPA are exploring the development of analytical models for these modes of application. The mosquito control industry is interested in the development of models for aerosol sprays. A dry deposition model is also being considered by the forestry industry with funding by the National Council for Air and Stream Improvement (NCASI). NCASI is also working on a field study and other data acquisition to validate the stream assessment model (Teske and Ice 2001). Other model enhancements are also being considered, such as expansion of the libraries for input variables, spray filtration by natural or artificial barriers (eg. vegetated buffers), and air stability effects on spray deposition. The evaporation components of the model are being re-examined in light of possible droplet temperature effects on evaporation rates. As previously explained, work by the SDTF, Riley *et al.* (1995) and others showed that the Sherwood number does not exhibit the behaviour previously believed for evaporation effects of all agricultural sprays.

As many groups realize the value of the AGDISP, AgDRIFT® and FSCBG models, the integration of various components such as

AGDISP into other modelling tools is being enthusiastically pursued. The FS is combining drift modelling tools with Geographical Information Systems (GIS), spray coverage and pest/efficacy models to develop total spray decision support tools such as Spray Advisor that will facilitate effective pest management with minimal off-target spray losses (Potter *et al.* 2000a, b). Such efforts build on the success of previous GIS-based integrated modelling developments such as the Gypsy Moth Spray Expert System GypSES.

Additional attention will also be focussed on understanding why the model predictions of deposition agree closely with the 180 SDTF aerial field studies at near-field distances, but over-predict relative to field data by up to four times at distances beyond approximately 800 ft. A wind tunnel study is underway at the time of preparation of the present manuscript to collect data on spray collection efficiency and sampling that may help in understanding this issue.

ACKNOWLEDGEMENTS

The authors wish to acknowledge all of the individuals and organizations who were involved with the development of the AgDRIFT®/FS model and its predecessors. These include personnel from the SDTF, EPA, USDA-FS, USDA-ARS, PMRA Canada, NCASI and many others from industry, academia and government who have been involved with this model or its predecessors.

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