OPTIMIZING SELECTION OF CONTROLLABLE VARIABLES TO MINIMIZE DOWNWIND DRIFT FROM AERIALLY APPLIED SPRAYS

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ABSTRACT. *Drift of aerially applied crop protection and production materials was studied using a novel simulation-based approach. This new approach first studied many factors that can potentially contribute to downwind deposition from aerial spray application to narrow down the major contributing factors. An optimization process was then applied to reduce the negative impact from one of the main factors, wind speed. With the focus on major contributing factors such as wind speed, release height, and droplet size, the optimization process was performed in AGDISP and MATLAB. This resulted in a near-optimal offset of the flight trajectory in the direction perpendicular to the swath lines to compensate for wind speed. The effect of the near-optimal offset, i.e., the swath offset, was then validated using the Monte Carlo analysis: random values for all the factors were generated; the near-optimal swath offset values were used in comparison to the default one-half swath width offset; the difference between results using the default and the near-optimal offset was analyzed. Statistical analysis of results showed that using the near-optimal offset values can greatly reduce downwind drift as compared to the default offset value. The near-optimal offset values achieved results very close to the optimal ones. For the comparison of application efficiencies, the cumulative downwind deposition between 30.48 and 45.72 m (100 and 150 ft), and the deposition at 30.48, 76.2, and 152.4 m (100, 250, and 500 ft) were used as the performance metrics. The new method can provide some guidance to applicators. For instance, in order to achieve a certain application efficiency value, certain constraints on wind speed, release height, and droplet size must be satisfied.*

Keywords. *Spray drift, Aerial application, Simulation, Optimization, Monte Carlo analysis.*

Minimization of drift, which is the physical movement of aerially- or ground- applied spray away from the intended target (EPA, 2001), is important to reduce damage to off-target crops and to mitigate environmental effects (Cooper and Alley, 1994). Drift minimization practices can also work to increase application efficiency. Research on methods to mitigate off target movement of aerially applied agricultural materials is well-documented (Yates et al., 1966; Yates et al., 1967; Pasquill and Smith, 1983; Bird, 1995; Ganzlemeier et al., 1995; Arvidsson, 1997; Smith et al., 2000; Hewitt et al., 2001a; Maber et al., 2001; Fritz et al., 2008b). Many research efforts focus on the prediction of drift (Turner, 1994; Teske et al., 2002; Teske et al., 2003) from aerial spraying with several standards having been established (EPA, 2000; *ASAE Standards,* 2004).

Movement of aerially applied sprays is influenced by many factors including atmospheric conditions (Munn, 1966; Pasquill and Smith, 1983; Bird et al., 1996; Hoffmann and Salyani, 1996; Seinfeld and Pandis, 1998; Miller et al., 2000b; Thistle, 2000; Fritz, 2006; Fritz et al., 2008a, Fritz et al., 2008b), canopy structure (Praat et al., 2000), droplet size (Hewitt et al., 1996), tank mix (Hewitt et al., 2001b), nozzle type and operation (Bouse, 1994; Hoffmann and Tom, 2000), plant structure (Miller et al., 2000a), and other factors (Hewitt et al., 2001c), all of which applicators must consider when setting up spray equipment and making application treatments. While the applicator can make changes to many of these operational parameters, such as aircraft type, distribution of nozzles, nozzle type and orientation, spray pressure, flight speed, swath offset, and release height, there are other factors such as temperature, relative humidity, atmospheric stability, and wind speed and direction, which must be considered. To this end, knowing how to adjust operational parameters that can be controlled to compensate for the negative impact of the uncontrollable conditions is critical. The research work addressing this tends to be based on either analysis of field collected data (Pasquill, 1961; Yates et al., 1966; Bird, 1995; SDTF, 1997; Praat et al., 2000; Fritz, 2006; Fritz et al., 2008b) or modeling and simulation (Akesson et al., 1981; Walklate, 1987; Bilanin et al., 1989; Turner, 1994; Zhu et al., 1995; Kaul et al., 1996; Potter et al., 2000;

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Hewitt et al., 2002; Teske et al., 2002; Fritz et al., 2008a). Most results in the literature are focused on only one of several factors such as temperature or humidity, with all other factors being fixed. It is difficult, if not impossible, to control some of these variables under field conditions. While a significant effort was made by the Spray Drift Task Force (SDTF) to examine many factors (SDTF, 1997), there has been no systematic approach to indicate the impacts of all factors and their interactions simultaneously. As pointed out in SDTF (1997), "Due to the complexity of evaluating all possible interactions of the numerous application variables, a computer model is the most practical way to conduct spray drift risk assessments."

With simulation tools such as AGDISP, it has become easier to perform sensitivity analysis by which variables that are inputs to simulation models are varied, and the effects on outcomes are determined. Teske and Barry (1993) conducted an extensive study on parametric sensitivity of the FSCBG model. Thirty-seven factors were considered. These factors were varied individually by a certain percentage from a base case. Two metrics were defined to study the parametric sensitivity of the simulation model, these were Figure of Merit (FOM) and Mean Horizontal Position (MHP). The factors were ranked from most sensitive to least sensitive. This work is very important, but the factors were considered one at a time. The impact of interactions among factors was not studied.

Huang et al. (2010) discussed a new approach to identify the main factors and interactions among the factors that have significant influence on drift of aerially applied sprays using the design of experiments (DOE) technique (Taguchi, 1987). DOE is a tool that can be used to systematically study the influence of many factors and their interactions on the outcome. An interaction occurs when the effect of one input variable is influenced by the level of another input variable. Typically, a successful DOE analysis can narrow the factors down to a few important ones. Further detailed study can then be performed by focusing on these factors (Mathews and Mathews, 2004; Montgomery, 2008; Zhan, 2008).

In comparison to the sensitivity analysis conducted by Teske and Barry (1993), where small deviations (~10%) from the base case were considered for individual variables, the DOE analysis can be used to study the sensitivity over a large scale without neglecting the interactions among factors. Huang et al. (2010) selected the application efficiency, the total downwind drift, cumulative downwind deposition between 30.48 and 45.72 m (100 and 150 ft), and the deposition at 30.48, 76.2, and 152.4 m (100, 250, and 500 ft) as metrics for outcome instead of FOM or MHP.

Results in Huang et al. (2010) laid a foundation for aerial spray optimization using simulation tools. Instead of considering every factor, one can focus on the most important factors without causing large errors. With the reduced number of factors, it becomes feasible to conduct a numerical search to select controllable variables to minimize the negative impact of the uncontrollable factors. AGDISP (Agricultural DISPersion) (Teske et al., 2003) was selected as the simulation model. The functionalities and accuracy of AGDISP have been extensively studied in the literature (Bilanin et al., 1989; Hewitt et al., 2002; Teske et al., 2002).

Due to the differences in these two sensitivity analysis approaches (Teske and Barry,1993; Huang et al., 2010), the conclusions were slightly different. For example, Teske and Barry (1993) ranked nozzle extent over release height and wind speed; but Huang et al. (2010) ranked wind speed over nozzle extent and release height. The differences themselves deserve to be studied; but this was not the focus of this study. The DOE analysis result from Huang et al. (2010) is listed in table 1 for reference.

Detailed definitions for variables in table 1 can be found in (Teske et al., 2003; Fritz, 2006; *ASABE Standards,* 2009). Selection of these variables was based on past field experience and related prior research in downwind drift analysis (Bird, 1995; Kaul et al., 1996; Arvidsson, 1997; SDTF, 1997; EPA, 1998; Smith et al., 2000; Hewitt et al., 2002; Teske et al., 2003).

MATERIALS AND METHODS

Following previous research efforts (Huang et al., 2010), a method for determining optimal operational settings based on predetermined environmental conditions and operational parameters is presented. To this end, results from DOE simulations using AGDISP are used, and a search algorithm focusing on a few significant factors is proposed. Statistical analysis will demonstrate that the near-optimal solution derived from this method is very close to the theoretical optimal solution and the DOE analysis provided valid results. After the validation of the near-optimal solution, application of these results are discussed.

Throughout this article, the same metrics used in (Huang et al., 2010) will be used and the same set of parameters, as listed in table 2, will be considered.

Table 1. Significant impact factors on outcomes.[a]

Outcomes/Factors	A	B	C	D	E	F	AB	AC	AD	AE	AF	BC	BD	BE	BF	CD	CE	CF	DE	DF	EF
Total downwind deposition				+												x					
Application efficiency	-		+	-												x					
Deposition between 30.48 and 45.72m	+		-	+					x												
Deposition at 30.48 m	+		-	+					x												
Deposition at 76.20 m	+		-	+												x				x	
Deposition at 152.40 m			-	+												x				x	

[a] A is the release height, B is the nozzle extent, C is the droplet size, D is the wind speed, E is the temperature, F is the relative humidity, and all two letters represent the interaction between the two factors. A "+" in a cell means the larger the factor, the larger the outcome. A "-" in a cell means the larger the factor, the smaller the outcome. Interactions cannot be simply characterized as a "+" or a "-" since they involve more than one factor and the outcome depends on both factors. An "x" in a cell means that the interaction between factors has a significant impact on the corresponding outcome.

Table 2. Factors studied.

DOE Factors	Low Value	High Value
Release height	1.893 m (6.21 ft)	6.1 m (20 ft)
Nozzle extent	50%	80%
Droplet size	ASABE very fine	ASABE very coarse
Wind speed	0.45 m/s (1 mph)	6.71 m/s (15 mph)
Temperature	7.2°C (45°F)	35°C (95°F)
Relative humidity	35%	100%

Selection of these variables and their two extreme values have been discussed (Huang et al., 2010). Other AGDISP simulation parameters were specified in Huang et al. (2010), as illustrated in table 3.

One limitation of the DOE technique is that the impact of any factor should be monotonic (Montgomery, 2008). Nonlinear or non-monotonic impact can lead to erroneous conclusions. In a sense, the success of the DOE method depends on the knowledge of the user. Initial simulation runs were conducted to check that the impacts were not highly nonlinear or non-monotonic between the two extreme values. Since only a limited numbers of runs were simulated, there is always a possibility that such complex interactions could be missed. The solution to this problem is to validate the results using statistical analysis.

Throughout this article, the downwind deposition data were generated using AGDISP; statistical analyses were conducted using Minitab software (Mathews and Mathews, 2004; Meyer and Krueger, 2005); the optimization algorithm was implemented in MATLAB (The MathWorks, Inc., Natick, Mass.).

NEAR-OPTIMAL SOLUTIONS

Optimizing aerially applied sprays by adjusting controllable variables to counter the effects of uncontrollable variables is difficult to realize in practice. The complexity of the theoretical model and the number of variables involved make it virtually impossible to derive a closed form solution. A numerical search algorithm is a more realistic approach. However, if all the variables are considered, the multidimensional search can be too time consuming. This work uses a numerical search that is conducted in the laboratory, which is hereafter referred to as an off-line search, versus real-time while an application is being made. With this off-line search, only the significant factors of release height, droplet size, wind speed, and swath offset are varied. All other factors are assumed to take on nominal values. While greatly simplifying the search algorithm, the trade-off is a near-optimal solution. Numerical search algorithms for finding optimal swath offset require the swath offset value to be searched with a short time step. The smaller the step size is, the closer the result is to the optimal solution. Smaller step size requires longer computational time. This is critical for on-line optimization such as the algorithm used by the Wingman system (ADAPCO, Inc., Sanford, Fla.), where the search time is limited to a few seconds. With the search for a near-optimal solution being conducted off-line, very small step sizes can be used, resulting in computational time of a few minutes to hours. Potter et al. (2000) developed a genetic search algorithm for finding near-optimal solutions. The off-line genetic algorithm typically takes hours to find a near-optimal solution. However, there is no guarantee that a near-optimal solution will be found. The genetic algorithm treats all parameters equally and must be run for a specific set of parameter constraints. This means applicators have to run the genetic algorithm before each aerial spray.

Table 3. Factors not studied, but used in simulation.

Non DOE Factors	Nominal Value
Stability	Day/Moderate
Spray volume rate	46.76 L/ha (5 gal/acre)
Canopy height	0 m
Swath width	18.29 m (60 ft)
Wind direction	-90 deg
Aircraft type	Air Tractor AT-402B
Nozzle number	44
Evaporation calculation	On

One advantage of the approach proposed herein is development of a series of curves representing the near-optimal solution versus the significant parameters that applicators can refer to and use to make in-field adjustments. The generation of such curves may take many hours, but this only needs to be done once. With the help of DOE analysis, parameters involved in the search algorithm are significantly reduced. A near-optimal solution can always be found.

Among the four factors, release height, droplet size, and swath offset are controllable; wind speed is uncontrollable. Therefore, the challenge is to select the three controllable variables to counter the impact of the uncontrollable variable. From table 1, it is clear that the release height should take the minimal value and the droplet size should take the maximum value. The remaining controllable variable, swath offset, will be selected according to the wind speed. This involves a one-dimensional search, thus is numerically feasible for off-line simulation. However, based on the type of the aerially applied sprays and purpose of the sprays, there may be limitations on the release height and/or droplet size. For example, for mosquito control the release height cannot be too low; and the droplet size cannot be too large. The pilot often determines minimum release height in a given spray scenario based on safety considerations. In other words, application efficiency, as defined here, may not be the only requirement in aerial spraying. So instead of using the minimum release height and maximum droplet size, different values for the release heights and droplet sizes will be assumed. For each assumed value for the release height and droplet size, the swath offset will be selected to achieve the best application efficiency.

For a given set of parameters, AGDISP can be used to calculate the deposition at any distance (fig. 1). To improve application efficiency, the swath offset can be adjusted to shift the entire deposition distribution curve (the solid line in fig. 1) to the left or right. Using software such as MATLAB, one can search for the optimal swath offset value such that the application efficiency is maximized (the dashed line in fig. 1).

To reduce computation time, a real-time system such as the Wingman™ GX/AIMMS-20 system (ADAPCO, 2011) can use coarse searching steps in an attempt to find a near-optimal solution by moving the peak value to the middle of the swath (i.e., between 0 and upwind swath). Since an off-line simulation approach is used herein, small searching

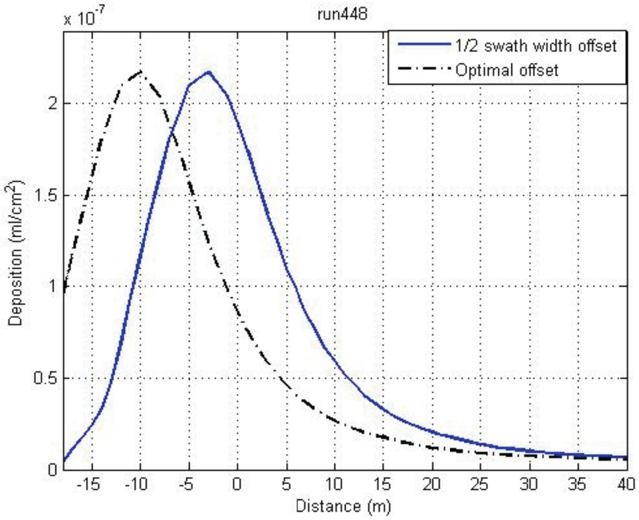

Figure 1. Optimal swath offset selection (In-swath deposition is the deposition between -18 m and 0 m. A positive distance means a downwind location.)

steps and optimal solutions will be sought. This optimal search algorithm can be repeated for different release heights, median droplet sizes, and wind speeds. The resulting optimal swath offset values can be plotted as a function of the wind speed, as illustrated in figure 2. Notice that the curve has a relatively flat area for low wind speed. This is partly affected by the resolution of the AGDISP simulation model, which has a minimum of 1-m resolution. Further improvement in resolution may not be important because when the swath offset is so small, the control accuracy of flight trajectory will become an issue.

One can also use a curve fitting method to generate an implicit function as:

$$y = 0.0941x^2 + 1.4038x - 0.3758 \qquad (1)$$

where x is the wind speed (m/s) and y is the swath off set (m).

Equation 1 provides an optimal solution when other factors are fixed. Of course, in reality all parameters may take different values, thus it requires too much computational time to find the optimal swath offset values for all conditions. However, based on the DOE analysis, the impact of the other factors were not found to be significant. For this work the following nominal values are assumed: nozzle extent is 68% of spray boom width; temperature is 23°C (73.4°F); relative humidity is 70%; stability is Day/Moderate. These nominal values were selected as the midpoints of the two extreme levels. While these factors were determined not to be significant, selecting the midpoint can further reduce their impact. By assuming the nominal values for these factors, one can reasonably assume that equation 1 will provide a near-optimal solution which is close to the optimal result. A statistical analysis method discussed below looks at how close this near-optimal solution is to the optimal one.

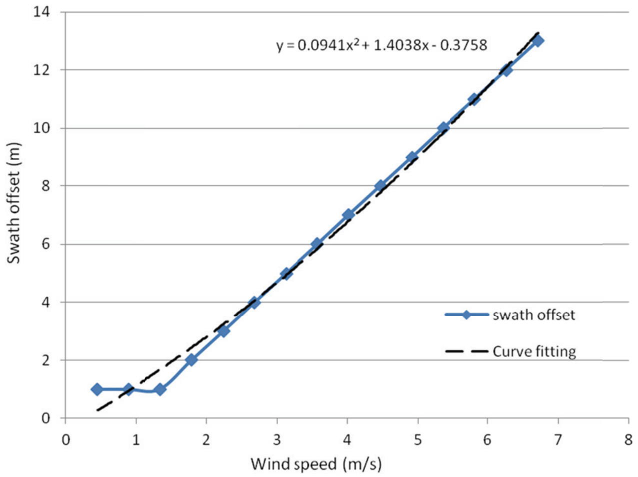

Figure 2. Interpolation: swath offset as a function of wind speed (ASABE fine droplet size and 3-m release height).

It is worth noting that figure 2 only shows the optimal swath offset as a function of the wind speed for an ASABE fine droplet spray released from a height of 3 m. Similar graphs can be generated for different droplet sizes and release heights. They are not included herein because the main purpose is to illustrate the concept and process. To include all simulation parameters in the analysis, instead of limiting to the one considered in this article, computation required would be much more complicated and time consuming.

RESULTS

VALIDATION OF NEAR-OPTIMAL SOLUTION

Earlier a "near-optimal solution" was proposed. To validate that this solution was indeed close to the optimal solution, the Monte Carlo method (Liu, 2001; Casella, 2004) is used. The validation is necessary since the DOE analysis can produce erroneous results when the relationship between the outcome and a certain variable is highly nonlinear.

Values for nozzle extent, temperature, relative humidity, stability, and wind speed are randomly generated under the following assumptions:

- temperature satisfies a uniform distribution from 7.2°C to 35°C;
- relative humidity satisfies a uniform distribution from 35% to 100%;
- nozzle extent satisfies a uniform distribution from 50% to 80%;
- stability satisfies an integer uniform distribution for all the seven options available in the AGDISP software; and
- wind speed satisfies a uniform distribution from 1 to 6.71 m/s.

Uniform distributions are used here for their simplicity, and there is no particular reason to use other probability distributions. However, the validation can be done using any probability distribution. If one has specific knowledge about the probability distribution of each variable, the same validation process can be followed using the specific probability distribution.

Table 4. Statistics for default, near-optimal, and optimal swath offset (ASABE Fine and 3-m release height).

Metric	Setting	Min	Max	Mean	% Change	StDev
Application efficiency (%)	Default	9.81	72.70	37.39	0.00	18.26
	Near-optimal	59.40	84.10	70.10	87.49	6.31
	Optimal	61.30	86.10	72.27	93.31	6.43
Total in-swath deposition (10^{-5} mL/cm²)	Default	1.22	9.17	4.65	0.00	2.29
	Near-optimal	7.15	10.60	8.70	86.98	0.84
	Optimal	7.37	10.80	8.97	92.78	0.85
Deposition at 30.48 m (10^{-8} mL/cm²)	Default	9.89	53.40	28.38	0.00	10.46
	Near-optimal	8.64	36.60	22.47	-20.83	7.92
	Optimal	8.46	35.30	22.21	-21.74	7.88
Deposition 30.48-45.72 m (10^{-7} mL/cm²)	Default	11.70	63.90	35.81	0.00	14.11
	Near-optimal	10.20	45.80	28.38	-20.74	10.73
	Optimal	10.10	45.70	28.05	-21.67	10.61
Deposition at 76.20 m (10^{-8} mL/cm²)	Default	2.65	14.80	8.29	0.00	3.47
	Near-optimal	2.55	11.30	6.99	-15.75	2.56
	Optimal	2.60	11.00	6.93	-16.46	2.53
Deposition at 152.40 m (10^{-9} mL/cm²)	Default	5.96	37.60	22.79	0.00	0.79
	Near-optimal	5.49	36.40	20.46	-10.25	6.84
	Optimal	5.50	36.20	20.36	-10.69	6.80

As discussed earlier, for simplicity of the presentation, the validation will be limited to the case of a 3-m release height and ASABE fine droplet size.

Three swath offsets are used: the default ½ swath width; the near-optimal value calculated from equation 1, and the optimal value calculated in MATLAB. Table 4 lists the min., max., average, and standard deviation in all outcome metrics for the three different swath offset values.

Several conclusions can be drawn from table 4: 1) using either near-optimal or optimal values improves the outcome, regardless of which metric is used; 2) using the near-optimal or optimal values lead to more consistent results as indicated by smaller standard deviations; and 3) the differences between near-optimal and optimal values are relatively small. For example, if application efficiency is used as the metric for outcomes, the default setting has efficiency ranging from 9.81% to 72.7% with an average of 37.39% and a standard deviation of 18.26%; the near-optimal setting has efficiency ranging from 59.4% to 84.1% with an average of 71.1% and a standard deviation of 6.31%; the optimal setting has efficiency ranging from 61.3% to 86.1% with an average of 72.27% and a standard deviation of 6.43%.

Additional statistical analysis was conducted. Summary statistical data for the different outcomes are given in table 5. It can be seen that for all metrics, the near-optimal solutions provide better results than the default swath offset values. Note that the analysis was on the difference between near-optimal and default swath offset. A negative mean implies that the near-optimal swath offset has a lower mean.

Statistical analysis was also conducted to compare the near-optimal solution and the optimal solution (table 6). The average improvement of the optimal solution over the near-optimal solution was only 2.18% for application efficiency, which is much less than the 32.7% difference between the near-optimal and default value solutions.

Based on the statistical analysis, one can conclude that the near-optimal solution is very close to the optimal solution and illustrates significant improvement over the default setting. The result from a typical simulation run is illustrated in figure 3.

Earlier, the assumption that all other factors were insignificant was made when determining the near-optimal solution. This allows one to use nominal values for these factors greatly simplifying the search algorithm. The resulting near-optimal solution was defined by equations such as equation 1, which depends only on the wind speed. This assumption was reasonable based on the DOE analysis, and Monte Carlo analysis in this section confirmed this assumption. When all the factors are allowed to change, equation 1 still provides a near-optimal solution that is very close to the optimal solution.

APPLICATION OF THE NEAR-OPTIMAL SOLUTIONS

The near-optimal solution proposed earlier can provide a useful tool for applicators. For any given droplet size and release height, the application efficiencies can be plotted as functions of wind speed, as shown in figure 4. Though the simulation is time consuming, it can be done off-line allowing for the applicator to refer to a graph to determine the near-optimal application efficiency that can be achieved for a given wind speed. This has an important advantage over a real-time system such as the Wingman™ GX/AIMMS-20 system (ADAPCO, 2011): The applicator would know beforehand if the application efficiency would be acceptable, given that wind speed stays constant, whereas the Wingman system could only provide an optimal or near-

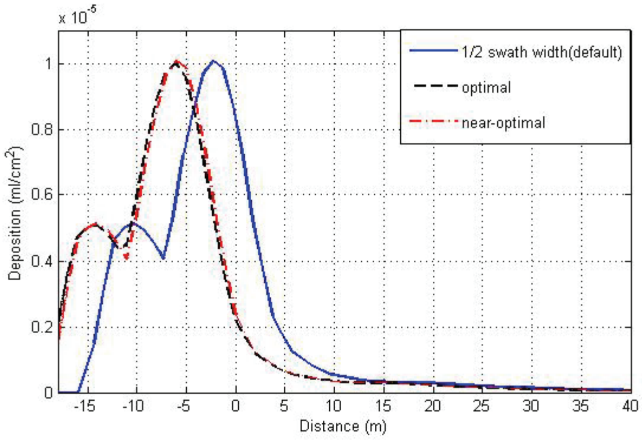

Figure 3. Default, near-optimal, and optimal deposition.

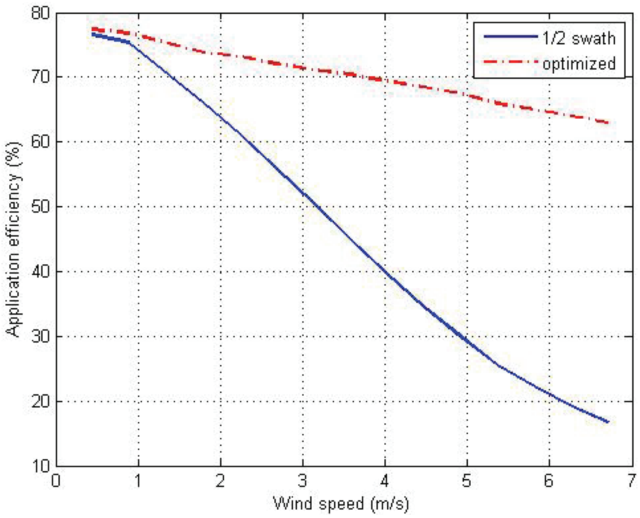

Figure 4. Improvement of efficiency (ASABE fine droplet size and 3-m release height).

optimal result after the aircraft has finished one trajectory along a given direction.

To illustrate how this works, consider certain applications that have to have release heights higher than 3 m and the droplet size equal to or smaller than a FINE spray. The applicator can check weather forecasts to estimate wind speed. Using figure 4, the applicator can conclude that in order to achieve an application efficiency higher than 70%, the wind speed must be lower than 3.6 m/s. In order to achieve the optimal result, equation 1 must be used to calculate the swath offset. For reference, if a swath width of one-half is used, the application efficiency will be below 50% for a wind speed of 3.6 m/s. Similarly, one can generate graphs for other outcome metrics such as deposition between 30.48 and 45.72 m (100 and 150 ft), deposition at 30.48 m (100 ft), and deposition at 152.40 m (500 ft).

Another potential use of the near-optimal solution is to plot any outcome metric as a function of wind speed at different release heights (application efficiency is plotted in fig. 5). For any given droplet size and wind speed, the applicator can use the graph to determine the maximum release height in order to achieve a certain level of application efficiency. For example, if an ASABE fine spray is used and 75% application efficiency is desired, then release height greater than 3 m does not work; release height of 3 m works only when the wind speed is below 1.5 m/s; for 1.9 m release height, wind speed up to 5.4 m/s is allowed. Similar graphs for other outcome metrics can also be generated to provide guidelines for applicators.

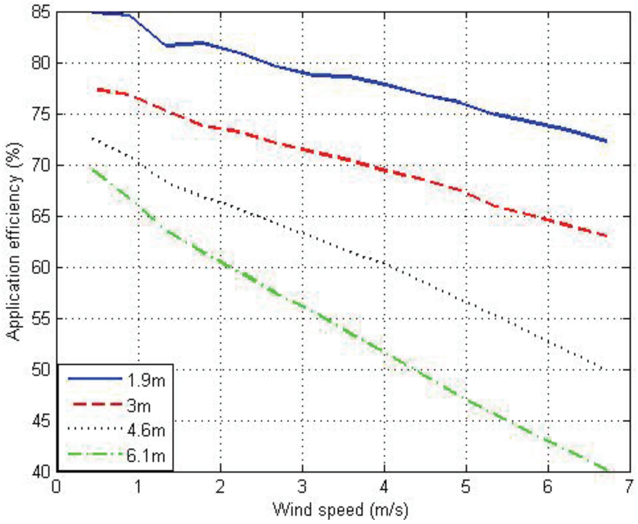

Figure 5. Application efficiencies at various release heights (ASABE fine droplet size).

SUMMARY AND DISCUSSION

Following results of previous research (Huang et al., 2010), a simulation-based optimization approach was used to develop practical guidelines for aerially applied sprays. Based on the DOE analysis results (Huang et al., 2010), the optimization effort focused on the impact of significant factors including wind speed, release height, droplet size, and swath offset. All other factors were assumed to take nominal values. This simplifying assumption made the use of a numerical search algorithm feasible in finding a near-optimal solution. Off-line simulation allows one to use higher resolution for the search algorithm. The resulting swath offset value can be easily calculated as a polynomial function of the wind speed and provides a significant improvement over the default half swath width offset.

Since the main factors are limited to wind speed, swath offset, release height, and droplet size, it is feasible to generate two factor graphs which can be used by applicators to determine whether it is possible to achieve certain levels of application efficiency or reduced downwind deposition for a given wind speed and any constraints on droplet size or release height. These graphs can be used to help the applicators in predicting and optimizing the results.

We present initial results with simplifying assumptions herein to illustrate the potential results and applicator guidance that can be achieved. While some controllable factors that have a direct impact on the downwind drift, such as application air speed, were not considered here, this approach can still be expanded to include and account for these and other factors as well. While the assumption was made that the factors included here followed uniform distributions, other probability distributions can easily be used as they are identified. In the end, this work demonstrated how designed simulations can effectively be used to determine how changes in significant operational factors influence operational outcomes and provide real-world guidance to applicators.

Future work will investigate use of more factors, a correlation study between simulation analysis and field test data, and generation of a complete set of graphs or lookup tables.

REFERENCES

ADAPCO. 2011. *WINGMAN User's Manual.* Available at: www.myadapco.com/res/pdf/manuals/Wingman_Manual.pdf.

Akesson, N. B., W. E. Yates, N. Smith, and R. E. Cowden. 1981. Rationalization of pesticide drift-loss accountancy by regression models. ABAE Paper No. 81-1006. St. Joseph, Mich.: ASAE.

Arvidsson, T. 1997. Spray drift as influenced by meteorological and technical factors. A methodological study. Swedish University of Agricultural Sciences, Acta Universitatis Agriculturae Sueciae, Agraria 71.

ASAE Standards. 2004. S561.1: Procedures for measuring drift deposits from ground, orchard, and aerial sprayers. St. Joseph, Mich.: ASABE.

ASABE Standards. 2009. S572.1: Spray nozzle classification by droplet spectra. St. Joseph, Mich.: ASABE.

Bilanin, A. J., M. E. Teske, J. W. Barry, and R. B. Ekblad. 1989. AGDISP: The aircraft spray dispersion model, code development and experimental validation. *Trans. ASAE* 32(1): 327-334.

Bird, S. L. 1995. A compilation of aerial spray drift field study data for low-flight agricultural application of pesticides. In Chelsea, Mich.: *Environmental Fate of Agrochemicals: A Modern Perspective.* M. L. Leng, E. M. K Loevey, and P. L. Zubkoff, eds. Chelsea, Mich.: Lewis Publishers.

Bird, S. L., D. M. Esterly, and S. G. Perry. 1996. Atmospheric pollutants and trace gases. *J. Environ. Qual.* 25(5): 1095-1104.

Bouse, L. F. 1994. Effect of nozzle type and operation on spray droplet size. *Trans. ASAE* 37(5): 1389-1400.

Casella, G. 2004. *Monte Carlo Statistical Methods.* New York, N.Y.: Springer.

Cooper, C. D., and F. C. Alley. 1994. *Air Pollution Control: A Design Approach.* 2nd ed. Prospect Heights, Ill.: Waveland Press, Inc.

EPA (Environmental Protection Agency). 1998. Spray drift test guidelines: Spray drift field deposition. OPPTS 840.1200, EPA 712-C-98-112. Washington D.C.: USEPA Office of Prevention, Pesticides and Toxic Substances (OPPTS).

EPA (Environmental Protection Agency). 2000. Meteorological monitoring guidance for regulatory modeling applications. EPA-454/R-99-005. Research Triangle Park, N.C.: USEPA Office of Air Quality Planning and Standards.

EPA (Environmental Protection Agency). 2001. Pesticide registration (PR) notice 2001-x draft: Spray and dust drift label statements for pesticide products. Available at: www.epa.gov/PR_Notices/prdraft-spraydrift801.htm.

Fritz, B. K. 2006. Meteorological effects on deposition and drift of aerially applied sprays. *Trans. ASABE* 49(5): 1295-1301.

Fritz, B. K., B. Bagley, W. C. Hoffmann, and Y. Lan. 2008a. Spray spectrum modifications through changes in airspeed to minimize drift. NAAA/ASABE Paper No. AA08-002. Washington, D.C.: National Agricultural Aviation Association.

Fritz, B. K., W. C. Hoffmann, Y. Lan, S. J. Thomson, and Y. Huang. 2008b. Low-level atmospheric temperature inversions: Characteristics and impacts on aerial applications. *Agric. Eng. Intl.* Vol. X. Manuscript PM 08 001.

Ganzlemeier, H., D. Rautmann, R. Spangenberg, M. Streloke, M. Herrmann, H. Wenzelburger, and H. Walte. 1995. *Studies on the Spray Drift of Plant Protection Products.* Blackwell Wissenschafts-Verlag GmbH Berlin/ Wien, Berlin.

Hewitt, A. J., D. L. Valcore, and J. E. Bryant. 1996. Spray drift task force atomization droplet size spectra measurements. *Proc. ILASS-Americas 96.* San Francisco, Calif.: The Institute for Liquid Atomization and Spray Systems – America Society.

Hewitt, A. J., D. Johnson, J. D. Fish, C. G. Hermansky, and D. L. Valcore. 2001a. The development of the spray drift task force database on pesticide movements for aerial agricultural spray applications. *Environmental Toxicology and Chemistry* 21(3): 648-658.

Hewitt, A. J., P. C. H. Miller, R. W. Dexter, and W. E. Bagley. 2001b. The influence of tank mix adjuvants on the formation, characteristics and drift potential of agricultural sprays. *Intl. Symposium on Adjuvants for Agrochemicals(ISAA).* Amsterdam. Wageningen, The Netherlands: ISAA Society.

Hewitt, A. J., D. L. Valcore, and T. Barry. 2001c. Analyses of equipment, weather and other factors affecting drift from applications of sprays by ground platforms. *Pesticide Formulations and Applications Systems 20-ASTM STP* 1400: 44-58.

Hewitt, A. J., J. Maber, and J. P. Praat. 2002. Drift management using modeling and GIS systems. In *Proc. of the World Congress of Computers in Agriculture and Natural Resources,* 290-296. Red Hook, N.Y.: Curran Associates, Inc.

Hoffmann, W. C., and M. Salyani. 1996. Spray deposition on citrus canopies under different meteorological conditions. *Trans. ASAE* 39(1): 17-22.

Hoffmann, W. C., and H. H. Tom. 2000. Effects of lowering spray boom in flight on swath width and drift. *Appl. Eng. in Agric.* 16(3): 217-220.

Huang, Y., W. Zhan, B. K. Fritz, S. J. Thomson, and A. Fang. 2010. Analysis of impact of various factors on downwind deposition using a simulation method. *J. ASTM Intl.* 7(6): 1-11.

Kaul, P., S. Gebauer, R. Neukampf, and H. Ganzelmeier. 1996. Modeling of direct drift of plant protection products: Field sprayers. *Nachrichtenbl. Deut. Pflanzenschutzd* 48(2): 21-31.

Liu, J. S. 2001. *Monte Carlo Strategies in Scientific Computing.* New York, N.Y.: Springer.

Maber, J., P. Dewar, J. P. Praat, and A. J. Hewitt. 2001. Real time spray drift prediction. *Proc. IT Symposium.* New Zealand.

Mathews, P. and P. G. Mathews. 2004. *Design of Experiments with MINITAB.* Milwaukee, Wis.: ASQ Quality Press.

Meyer, R., and D. A. Krueger. 2005. *A Minitab Guide to Statistics.* 3rd ed. Upper Saddle River, N.J.: Prentice Hall.

Miller, P. C. H., A. G. Lane, P. J. Walklate, and G. M. Richardson. 2000a. The effect of plant structure on the drift of pesticides at field boundaries. *Aspects of Applied Biology* 57: 75-82.

Miller, D. R., T. E. Stoughton, W. E. Steinke, W. E., Huddleston, E. W., and J. B. Ross. 2000b. Atmospheric stability effects on pesticide drift from and irrigated orchard. *Trans. ASAE* 43(5): 1057-1066.

Montgomery, D. C. 2008. *Design and Analysis of Experiments.* 7th ed. Hoboken, N.J.: John Wiley & Sons, Inc.

Munn, R. E. 1966. *Descriptive Meteorology: Advances in Geophysics Supplement 1.* New York, N.Y.: Academic Press.

Pasquill, F. 1961. The estimation of the dispersion of windborne material. *Meteorological Mag.* 90: 33-49.

Pasquill, F., and F. B. Smith. 1983. *Atmospheric Diffusion: A Study of the Dispersion of Windborne Material from Industrial and Other Sources.* 3rd ed. West Sussex, England: Ellis Horwood Limited, Chichester.

Potter, W. D., W. Bi., D. Twardus, H. W. Thistle, J. Ghent, M. Twery, and M. E. Teske. 2000. A genetic algorithm for aerial spray application optimization. ASAE Paper No. 001053. St. Joseph, Mich.: ASAE.

Praat, J. P., J. Maber, and D. W. L. Manktelow. 2000. The effect of canopy development and sprayer position on spray drift from a pipfruit orchard. *Proc NZ Plant Protection,* 241-247. Christchurch, New Zealand: New Zealand Plant Protection Society.

Seinfeld, J. H., and S. N. Pandis. 1998. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change.* Hoboken, N.J.: John Wiley & Sons, Inc.

Smith, D. B., L. E. Bode, and P. D. Gerard. 2000. Predicting ground boom spray drift. *Trans. ASAE* 43(3): 547-53.

SDTF (Spray Drift Task Force). 1997. A Summary of Aerial Application Studies. Available at: www.agdrift.com/PDF_FILES/Aerial.pdf.

Taguchi, G. 1987. *System of Experimental Design.* Dearborn, Mich.: Unipub/Kraus/American Supplier Institute.

Teske, M. E., and J. W. Barry. 1993. Parametric sensitivity in aerial application. *Trans. ASAE* 36(1): 27-33.

Teske, M. E., S. L. Bird, D. M. Esterly, T. M. Curbishley, S. L. Ray, and S. G. Perry. 2002. AgDRIFT®: A model for estimating near-field spray drift from aerial applications. *Environmental Toxicology and Chemistry* 21(3): 659-671.

Teske, M. E., H. W. Thistle, and G. G. Ice. 2003. Technical advances in modeling aerially applied sprays. *Trans. ASAE* 46(4): 985-996.

Thistle, H. W. 2000. The role of stability in fine pesticide droplet dispersion in the atmosphere: A review of physical concepts. *Trans. ASAE* 43(6): 1409-1413.

Turner, D. B. 1994. *Workbook of Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling.* 2nd ed. Boca Raton, Fla.: CRC Press.

Walklate, P. J. 1987. A Random-Walk model for dispersion of heavy particles in turbulent air flow. *Boundary-Layer Meteorology* 39: 175-190.

Yates, W. E., N. B. Akesson, and H. H. Coutts. 1966. Evaluation of drift residues from aerial applications. *Trans. ASAE* 9(3): 389-393.

Yates, W. E., N. B. Akesson, and H. H. Coutts. 1967. Drift hazards related to ultra-low-volume and diluted sprays applied by agricultural aircraft. *Trans. ASAE* 10(5): 628-632.

Zhan, W. 2008. Robust design of motor PWM control using modeling and simulation. In *Advances in Computational Algorithms and Data Analysis, Lecture Notes in Electrical Engineering,* 439-450. Vol. 14. Sio-Iong Ao, Burghard Rieger, Su-Shing Chen, eds. New York, N.Y.: Springer.

Zhu, H., D. L. Reichard, R. D. Fox, H. E. Ozkan, and R. D. Brazee. 1995. DRIFTSIM, A program to estimate drift distances of spray droplets. *Applied Eng. in Agric.* 11(3): 365-369.