American Society of
Agricultural and Biological Engineers

An ASABE Section Meeting Presentation

Increasing Spray Efficacy – An Integrated Approach

Ian M. McLeod, P.Eng, MSc.E

Forest Protection Limited, 2502 Route 102 Highway, Lincoln, New Brunswick, Canada.

Written for presentation at the
2011 ASABE/NAAA Technical Session
Sponsored by ASABE Technical Committee PM-23/6/2
45th Annual Convention & Exposition
Las Vegas Convention Center, Las Vegas, NV
December 5, 2011

Abstract. *Since its incorporation in 1952, Forest Protection Limited (FPL) has participated in research to increase the efficacy of sprays and improve application methods. Financial contributions from the Atlantic Canada Opportunities Agency – Atlantic Innovation Fund in 2006-2011 provided the means to develop new technologies while creating new products for use in the aerial application industry. Development of the three Accuair components was a multifaceted, multidisciplinary project that involved collaboration between FPL and its partners in the public and private sectors.*

The wind tunnel component included modification of an existing wind tunnel facility for advanced aerial spray research. It was used to measure and calibrate spray systems for FPL and other aerial applicators. In 2010, the wind tunnel facility was used for background research instrumental in the creation of an aerial spray measurement test method.

The Forest Protection Optimization System (ForPRO) component was developed as a plug-in tool for forest management software. It overlays insect defoliator risk data on forest stand information, giving forest managers the ability to simulate economic outcomes of outbreak and protection scenarios. The system also includes powerful optimization tools to assist in creating spray programs that minimize use of product and reduce costs associated with operating spray aircraft.

Much of the integration occurs within an Aerial Management System (AMS) component. It is an aircraft-based guidance, navigation and control system that enhances on-target delivery of sprays. The system makes use of real-time meteorology, radar altimetry and wind tunnel spray

drop size data to optimize and offset aircraft flight lines to compensate for wind borne drift. Optimized block layouts from the ForPRO System can be uploaded to a navigation console.

As much as it has been the creation of commercial products, the research and development that went into the Accuair system represents thousands of person-hours of work and a notable advancement in aerial spray drift reduction technology. An experimental program in 2006 in Florida was designed to test an AMS and to evaluate its effectiveness against standard spray configurations in adverse spray conditions and ideal spray conditions. Results of this experimental program show that an AMS using optimized spraying, and information obtained from wind tunnel spray tests delivers more on-target deposit in most spray scenarios than a standard non-optimized configuration.

The presentation will recap recent history of aerial spray research and development in New Brunswick, Canada and show results of an early validation experiment designed to test an AMS and demonstrate its ability to reduce off-target spray drift.

Keywords. Wind Tunnels, Planning, Optimization, Aerial Spraying, Drift Reduction

Introduction

Since its incorporation in 1952 Forest Protection Limited (FPL) has actively participated in research to improve the way forestry sprays are applied. This included work to increase efficacy of sprays through the use of effective drop sizes, careful calibration of atomization equipment and adoption of strategies that enhance targeting and uniformity of deposition. In 2006, FPL and its partners obtained funding from the Atlantic Canada Opportunities Agency – Atlantic Innovation Fund (ACOA-AIF) to develop the core technologies of the Accuair system over a 5-year period. As much as it has been the creation of commercial products, the three Accuair components represent an extensive body of research, millions of dollars of investment and thousands of person-hours of work on special experimental programs. Development of an Aerial Management System (AMS) has led to many innovations and industry firsts.

There are three streams that feed the AMS development:

- The use of wind tunnels in measuring spray drop sizes and in calibration of spray equipment.
- ForPRO planning software that integrates forest stand composition and insect defoliation data in calculating areas most at risk of economic damage by forest pests. It includes algorithms to help program managers optimize insecticide applications that minimize aircraft costs and overall program costs.
- Integration of wind tunnel and planning data in an onboard navigation and guidance system capable of optimizing flight line offsets based on real-time altitude and meteorological data.

At present, the wind tunnel produces standardized drop size information for use in drift prediction software. ForPRO is a software package ready for deployment on large scale infestation for a variety of forest defoliators. The AMS is installed on two Air Tractor AT-802F and one Cessna C188 aircraft. Operational optimized spraying was carried out in 2007 following successful experimental trials in 2006. An AMS has since been used on operational programs in the provinces of Ontario (2007, 2008), Quebec (2010, 2011) and New Brunswick (2011).

History of Development

Work on an AMS began in the 1990s with trials of the individual technologies such as GPS navigation, radar altimeters, data logging systems, onboard meteorology probes and automatic flow control systems. These evaluations were carried out on aircraft as funding allowed [Mickle & Robison, 1991, Davies, 1994, Mickle, 1998, Mickle, 1999]. At the same time FPL was evaluating changes in application strategies to improve coverage within spray blocks, including modified flight paths and multiple passes on upwind edges of blocks. Models were developed to examine the effects of spray drop sizes on drift in and out of target spray blocks [Riley, 1995, Picot, 1994, Mickle 1998, Mickle, 1999].

Integration of these systems commenced in 2000 when automatic flow control was used on an aircraft to adjust product flow rate as speed changed relative to the ground. This was shown through a series of trials to significantly reduce application rate variability [Mickle, 2000]. Information from a protection and planning software was added to try and improve the way that forest stands are prioritized for protection in terms of economic return [Mickle, 2003]. Though it was able to increase the value of treatments, it prioritized the forest in small disconnected polygons. This new requirement created a need for more advanced control and guidance system capable of effectively treating smaller areas.

A report by Mickle (2005) describes comparisons of the wind speed profile measured by an onboard meteorological probe to SODAR (SOnic Detection and Ranging measurements). This validated the onboard meteorology probe as a good method of velocity measurement at typical spray release heights. Following this evaluation, work began on a system that made use of real-time altitude data, GPS position and drift estimates based on the USDA's pesticide spray dispersion model AGDISP to calculate flight line offsets. Offsetting in this way compensates for spray drift in crosswinds and ensures maximum deposit in the block. A system was used experimentally in 2006 [Cormier, 2006, Mickle et. al, 2007] to spray 8 ha triangular blocks. It was shown that the offset flying method improved deposition within the block over standard flying methods. Approval of ACOA-AIF funding in 2006 allowed for accelerated development of a system which was evaluated in operational programs over the following years. Its use in 2007 for a Province of Ontario jack pine budworm application marked the first time that such a system was used in an operational agricultural or forestry application. A re-design of some system components was effected in 2009, The Accuair AMS was completed in 2010. This system was used on large-scale operations throughout the spring and summers of 2009, 2010 and 2011.

In parallel with AMS development, researchers at the University of New Brunswick (UNB) were studying sprays in a high-speed wind tunnel. The tunnel was developed to provide a critical piece of information in the integrated approach – the drop size distribution. This parameter describes the size of drops in the spray cloud and the relative amounts of each size. Through the 1990s [Goguen, 1994], hydraulic sprays were studied using an optical array probe in a tunnel having a short test section. Instrumentation later included a laser diffraction system (1991). AIF funding included the purchase of a new laser diffraction system (2007). A concurrent National Sciences and Engineering Research Council (NSERC) collaborative research and development agreement with UNB saw the purchase of a Phase Doppler system (2008). The tunnel's test section was also lengthened in 2007-2008 to 5 m and an aerodynamic re-design enabled speeds up to 300 km/h. Today the tunnel is used to study a wide range of aerial sprays from those generated by rotary atomizers to hydraulic nozzles. In 2010-2011, work at the wind tunnel was instrumental in gathering scientific data that laid the groundwork for a proposed American Society for Testing and Materials (ASTM) aerial spray characterization standard.

The Accuair Components

Wind Tunnel

The Accuair Wind Tunnel is owned and operated by FPL (Figure 1) and is located at the Acadia Research Forest outside Fredericton, New Brunswick, Canada. It is one of a few wind tunnels in the world capable of testing real liquid spray products at full scale and full aircraft speed. The tunnel is specifically designed to satisfy the need for accurate spray drop measurement for spray equipment calibration. In order to simulate aerial application conditions, the Accuair Wind Tunnel is designed to produce a highly uniform, low-turbulence airstream up to 300 km/h in its 1m diameter, 5m long test section. Spray testing is done in wind tunnels to achieve tight control over wind speed, environmental conditions and to facilitate the use of vibration-sensitive laser drop sizing equipment that cannot easily be mounted on an actual aircraft. The wind tunnel enables researchers to understand how fluids act under real atomization conditions, which is essential to accurate predictions by spray drift simulations and to efficacious sprays using modern aerial management systems. In addition, spray drift simulations are used to guide regulatory decisions and to formulate the content of pesticide labels, which is of direct interest to operators and manufacturers alike.

The wind tunnel employs two instruments to characterize sprays. The Laser Diffraction (LD) system provides rapid measurements across the spray plume within the line of sight of a laser beam. The beam can be traversed across the spray plume. The LD system provides an estimate of size and is insensitive to fluid inhomogeneity, inclusions or opaque drops, making it a good choice for characterizations of real spray products. The Phase Doppler system (PD) provides point measurements of spray drop size and velocity, but is usable only on transparent fluids. The point measurement must also be traversed in two dimensions across the spray cross section, requiring much more time to obtain an average of the plume. The PD system is used primarily as a reference instrument and to check the accuracy of LD estimates and to help develop good spray measurement practices.

Figure 1. Accuair (HJ Irving – JJC Picot) Wind Tunnel

Forest Protection Optimization System

The Accuair Forest Protection Optimization System (ForPRO) is a plug-in for Forest utility software (FORUS Research, Fredericton, New Brunswick, Canada). It is designed to integrate with existing decision-support tools and software, providing an overlay of insect pest damage risk and an evaluation of the marginal benefit of insecticide applications. ForPRO gives forest managers the ability to simulate a variety of outcomes and make cost-effective decisions regarding insecticide application. This functionality was implemented in an analysis of timber supply impacts of a spruce budworm outbreak on the Crown forests of New Brunswick in 2009. It was also used to predict timber supply impacts of balsam fir sawfly and hemlock looper outbreaks in Newfoundland. In 2011, it was used to help prioritize applications for a small balsam fir sawfly outbreak in New Brunswick.

An important function included in ForPRO is the Blocking Assistant. It is an ArcGIS extension that calculates optimal block layouts for aerial application. In addition to forest stand risk data, the blocking assistant considers distances that aircraft must travel to treat the prescribed areas and the costs associated with the flight plan. Because ForPRO integrates seamlessly with existing planning and GIS software, the optimal blocking information it provides can be uploaded to most modern navigation equipment.

Aerial Management System

There are many factors affecting the transport of aerial spray drops in the environment from release to deposit. An AMS accounts for as many factors as possible to control and guide the pilot through the most efficacious application.

- *Release height above the target* has a direct bearing on how far a spray will drift. Higher release generally equals greater drift. Release height is measured using a radar altimeter or laser altimeter.
- *Aircraft position and orientation* is determined through use of GPS receivers. A wing-tip dual-receiver system enables very accurate estimates of aircraft pitch, roll and yaw angle relative to the direction of flight.
- *Wind speed at altitude and at spray location* is fundamental in the correct estimation of drift. In general, wind speed increases with height. At release heights typically used in forestry applications, the difference between ground-based and aircraft-based velocity measurements are often significant. Location of the measurement is an important consideration. In forestry applications, wind speed and heading from nearby met towers often vary significantly from the wind speed measured at the aircraft's position. Wind speed and heading are measured using a probe, fixed to an aircraft's wing, that compensates for aircraft motion and orientation in calculating wind speed and heading relative to the ground.
- *Orientation of spray lines and aircraft heading relative to the wind* play a role in the direction that a spray drifts after release. This information is input by program operators. An AMS references the information and compares to real-time inputs from both the onboard meteorology probe and the GPS. For example, flying directly into a headwind, it is necessary to delay boom on and off to compensate for drift opposite the direction of flight. Flying in a perpendicular crosswind necessitates movement of the flight line upwind. Boom valve delays and offsets are both required for non-orthogonal wind headings.

- *Aircraft speed relative to ground* is obtained from the GPS and is used to adjust auto-flow control equipment and in the meteorology probe's calculation of wind speed and heading from raw probe data.
- *Drop size distribution* has a bearing on drift potential and is therefore considered in the offset calculation. Small drops drift farther than larger drops. Accurate knowledge of the drop size distribution (DSD) is obtained primarily from wind tunnel testing of full-scale nozzles and atomizers. Correct estimates of DSD are central to accurate drift estimates by the spray drift model.
- *Relative humidity and temperature* factor into spray drift because they affect the rate of evaporation. This factor can be significant, especially with fine sprays or highly volatile sprays. Evaporation has the effect of shrinking drop sizes over time and increasing drift.
- *Aircraft Wake* varies according to the geometry, speed and weight of the spray aircraft. Generally, heavier aircraft with large wings create larger disturbances that persist even after the aircraft leaves the immediate area. The large vortices in the wake entrain small drops and wash downward toward the target, hastening drop transport toward target foliage. Information on aircraft wake and persistence is included in the drop transport model used by the AMS computer.

It is important to convey information to pilots in a clear and concise manner. The AMS displays in two locations. A navigation screen in the cockpit shows the aircraft's position and relevant map features such as water, block boundaries and landing strip locations. On the nose of the aircraft there is a light bar which shows critical application parameters such as speed, altitude and heading to aid the pilot during boom-on times. The in-cockpit interface gives the ability to modify some parameters and provides an interface for program operators to output data logs and input new instructions to the system.

In addition to guidance, an AMS controls the system during a mission. The pilot flies the aircraft to the intended offset spray line. The booms automatically turn on and off, adjusting flow rate to obtain the desired application rate without the need for pilot interaction

An AMS achieves greater efficacy through optimized spraying. This means

- Making use of the best planning and drop size measurement tools available.
- Real-time measurement of critical parameters on the aircraft at the time of spraying.
- Clear, accurate guidance and user interface to help pilots during application.
- Assuming control of spray systems in flight to remove human error and reduce incidences of misapplication.
- Data logging for post-spray analysis and recommendations for improvement.

Spray Standard Development

Configuration of the wind tunnel spray sample from which the DSD is determined is central to its interpretation. For results to be meaningful, the sampling must represent the flux (flow rate) of drops through the measurement location since flux is analogous to deposition in the near wake of the atomizer. This means that the DSD must describe both the size of drops and must represent the rate at which drops of each size pass through the measurement area, Instruments like the PD system are capable of estimating flux directly using drop velocity information. The LD system is incapable of velocity detection and its measurements are only comparable to flux-based estimates when is assumed that all drops are traveling at a uniform speed. This requirement poses a significant problem for certain spray configurations in wind tunnels.

In 2009 through 2010, experimental parameters were studied in the Accuair wind tunnel using the LD and PD instruments to determine their effect on the measured result. The work focused

primarily on “difficult” sprays with complex cross sections like those produced by rotary atomizers. These atomizers produce a strong aerodynamic wake and the high-rpm spinning action tends to separate spray drops by size within the spray plume. While this has little impact on final deposit, within the wind tunnel the effect on instrument results is notable, with LD measurements near the edges of the spray having volume median diameter (VMD) values 3 times the VMD of measurements near the centre of the spray. Compounding the difficulties are the effects of non-uniform drop velocity due to the aerodynamic wake of the atomizer and secondary drop shatter because of the high relative velocities between the drops and the air flow.

The Accuair Wind Tunnel facility played a central role in resolving these difficulties and helped to develop a set of guidelines to address issues with LD spray measurement. The guidelines were at first compiled to address difficult sprays but are equally applicable to other wind tunnel aerial spray measurement scenarios. The information was compiled in a standard testing methodology, submitted to ASTM in 2011. It is hoped that adoption of a standard will increase the accuracy of drift models.

Aerial Management System – A Validation Trial

One early AMS validation trial occured in January of 2006 (Florida) quantified the improvement in spray deposition using optimized methods (Mickle, 2007). An AT-802F aircraft was equipped with GPS navigation and guidance, auto-boom systems, a radar altimeter, onboard meteorology and ten rotary atomizers. These were integrated with a central control system that made use of AGDISP drift simulations to calculate appropriate upwind offsets. Atomizers were calibrated for a 50 μm VMD Btk insecticide spray in the wind tunnel and the DSD for that spray was used in the drift predictions. The study examined differences in drop deposit density as measured by Kromekote cards for multiple sets of 8 ha blocks and one 64 ha block in non-forested areas. Blocks were sprayed using optimized and standard methods alternately. The smaller 8 ha blocks were triangular in shape and were rotated relative to wind direction to obtain best and worst-case application scenarios.

The primary target of concern in eastern Canadian forests is the spruce budworm. Drop densities were compared to efficacy threshold determined through past trials using Btk insecticide on potted spruce trees. In these trials it was determined that 20 drops/cm^2 is efficacious in controlling spruce budworm populations. Drop densities on Kromekote cards greater than 20 drops/cm^2 were therefore considered “efficacious”. Drop densities less than 20% and greater than 5% were considered “acceptable deposit” and drop densities lower than 5 drops/cm^2 were considered as “low deposit”. To simulate the typical application over eastern Canadian forests, application rate was 1.5 L/ha of dyed Foray 76B insecticide. Nominal aircraft ground-speed was 240 km/h, target altitude was 23 m and track spacing was 100 m.

For the 8 ha small-block trials, square sampling grids were established for both the standard and optimized spray scenarios, each having 289 Kromekote cards distributed at regular intervals across the surface area. A triangular spray block boundary was drawn within the grid with an apex of the triangle pointing either into the wind or with the wind direction. There were four spray lines established on each block, measuring 50 m, 150 m, 250 m and 350 m in length (Figure 2). The orientation where the triangle’s apex pointed into the wind was considered “worst case” since the longest line with the greatest drift potential was on the downwind side of the block. Six trials were completed by spraying alternately with optimization and in standard configuration on similar triangular spray blocks at two locations. Between each pair of spray runs, Kromekote cards were collected and analyzed.

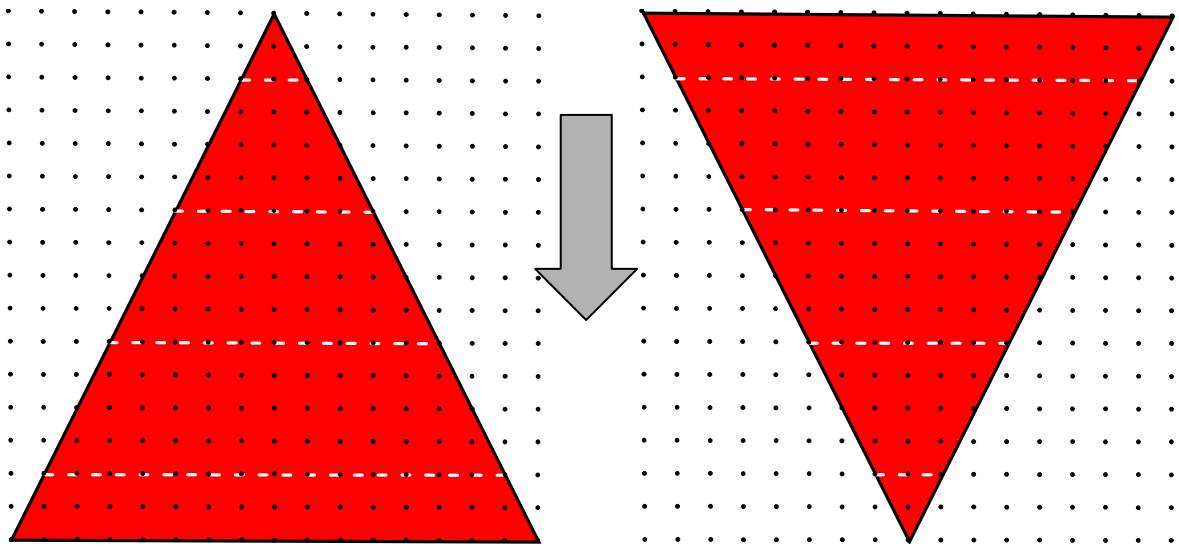

Figure 2. Worst case (left) and best case (right) 8 ha block orientations. Grey arrow denotes wind direction. Dots represent sample locations and dashed lines represent spray lines.

In the 8 ha tests, block orientation had negligible effect on the amount of low-deposit area. In both orientations, low-deposit area was 3 times greater for standard spray configuration than it was for the optimized case. Block area receiving efficacious deposit (>20 drops/cm^2), was shown to be dependent on block orientation. Efficacious deposit area was 5 times greater for the best case orientation using optimized configuration and 2.5 times greater for the standard configuration. Results of the small block deposit trials are summarized in Table 1.

Table 1. Deposit summary for 8 ha triangular block experiments. Percentages represent the fraction of the total cards having low deposit and efficacious deposit.

	Optimized Configuration		**Standard Configuration**	
Orientation	**Low Deposit**	**Efficacious Deposit**	**Low Deposit**	**Efficacious Deposit**
Best Case	21.9%	33.6%	65.7%	11.0%
Worst Case	25.0%	6.7%	63.2%	4.4%

Figure 3 (page 11) shows the relationship between low-deposit area and block orientation relative to the wind. In the worst case block orientation (Wind direction relative to apex close to 0°), results show a reduction in low-deposit area when using optimized spraying. This effect is more pronounced when the blocks are in the best case orientation (wind direction relative to apex close to 180°. Figure 4 shows results of efficacious deposit as it relates to wind speed. Regardless of orientation, optimized configurations give more efficacious deposit area than the standard spray configuration. In the highest wind conditions, the optimized spray was able to deliver some on-target spray while standard configuration was not.

In the 64 ha block trials, 325 Kromekote cards were used to sample deposit in the area. The trial was repeated 5 times - 3 optimized trials and 2 standard configuration trials. Spraying the larger 64 ha blocks gave better overall efficacious deposit area than the 8 ha block trials (Figure 4, Page 12) because drifting spray from upwind lines is more likely to land within the large block than it is on smaller blocks. In one case, standard configuration outperformed optimized spraying but wind speeds (and by extension drift) were minimal. At higher wind speeds, optimized spray configuration gives more efficacious deposit. A summary of deposit data for the 64 ha block is shown in Table 2.

Table 2. Deposit summary for 64 ha block experiments. Percentages represent the fraction of total cards having acceptable deposit and efficacious deposit.

Optimized Configuration			**Standard Configuration**		
Wind Speed (knots)	**Acceptable Deposit**	**Efficacious Deposit**	**Wind Speed (knots)**	**Acceptable Deposit**	**Efficacious Deposit**
			4.7	13.1%	79.4%
			10.8	49.1%	30.6%
5.8	22.8%	62.8%			
7.6	18.8%	60.6%			
9.7	12.8%	75.3%			

Conclusion

The three Accuair components are the product of many years of research, experimental and operational evaluation. The wind tunnel, the aerial management system and the forest protection optimization system were developed into useful tools that, when used together, can significantly increase a spray program's efficacy while minimizing costs.

The wind tunnel has been involved research program that saw physical modifications and improvements to measurement techniques. It was closely involved in the creation of a wind tunnel standard, authored by an international group of researchers and submitted to ASTM in 2011

An experimental program in 2006 in Florida was designed to test an AMS and to evaluate its effectiveness against standard spray configurations in adverse spray conditions and ideal spray conditions. Results of this experimental program show that an AMS using optimized spraying delivers more on-target deposit in most spray scenarios than a standard non-optimized configuration.

The experiments identified two areas of improvement in the system: the need for faster boom actuation and updates to the meteorological probe's firmware.

Redesign of several system components, including modifications to boom valve hardware and updates to meteorological probe firmware were effected. The current AMS version has been in operational use since 2009 and is a valuable tool for increasing efficacy, decreasing product wastage and protecting the environment.

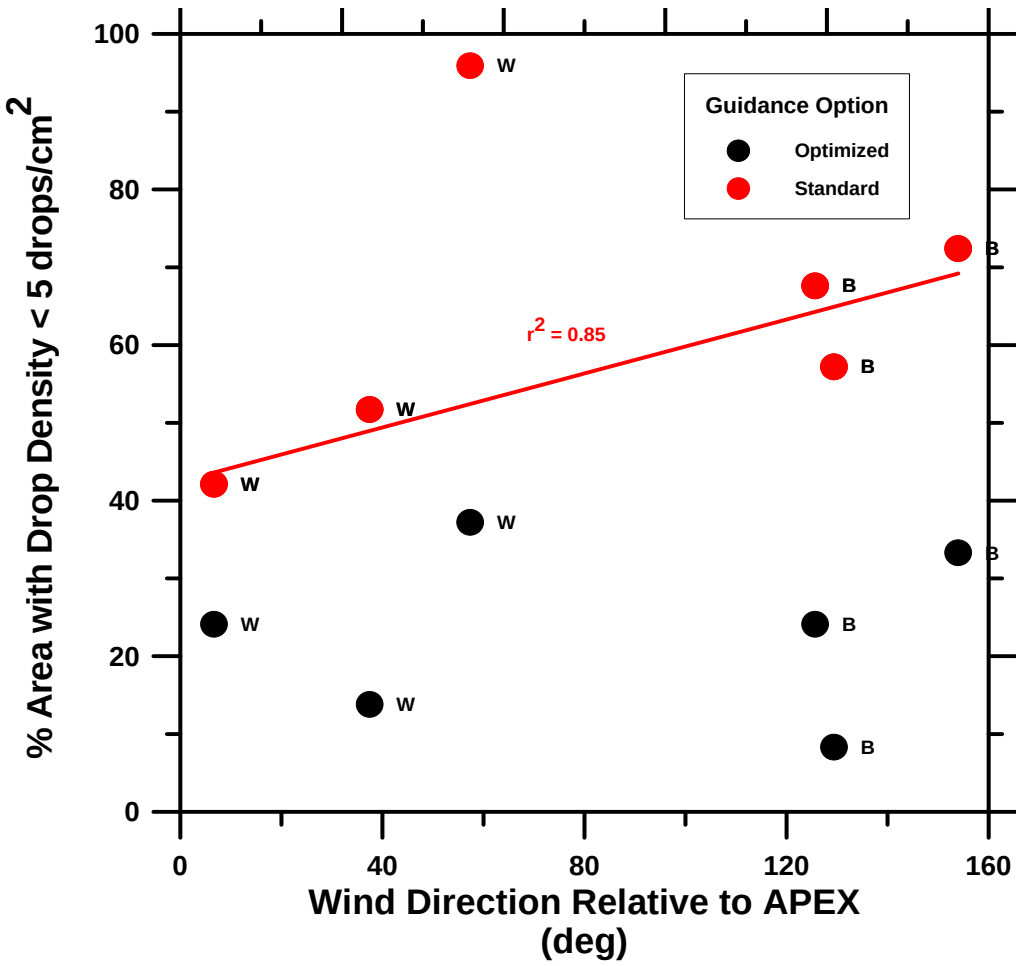

Figure 3. Impact of block orientation relative to wind direction on low deposit. Best (B) and worst (W) case trials are labeled.

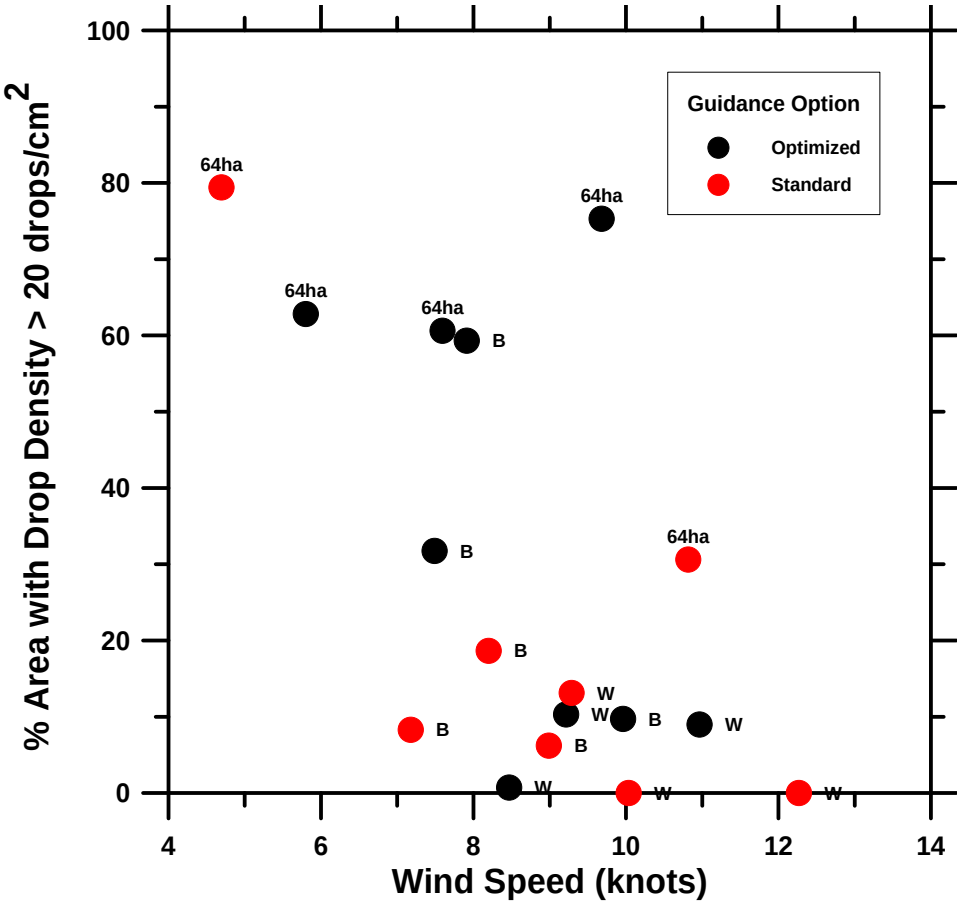

Figure 4. Area receiving adequate deposit summarized for block size, wind speed and guidance option.

References

Mickle, R., Robinson, A.G., 1991. An Evaluation of a Radar Altimeter for Forestry Spraying. FPL Library, Fredericton, NB, 6 p.

Davies, D., 1994. Some Operational Parameters for Consideration in Aerial Pesticide Applications and Their Potential for Future Development. Capco Technical Session, pp. 53-55.

Riley, C. 1994. Factors Affecting the Deposition and Drift of Pesticide Sprays. Capco Technical Session, pp. 13-24.

Mickle, R. 1998. Developing Effective Strategies for Managing Current and New Epidemics of Spruce Budworm. FPL Library, Fredericton, NB, 100p.

Mickle, R. 1999. Optimization Trials for Insecticide Spraying Into Small Blocks, Murdochville Results. FPL Library, Fredericton, NB, 36p.

Picot, J. 1994. Deposit and Drift in Aerial Spraying. Capco Technical Session, pp. 33-52.

Mickle, R. 2000. An Evaluation of the Auto Cal Flow Controller. FPL Library, Fredericton, NB, 15p.

Mickle, R. 2003. Optimizing Treatment Programs Using PROPS Polygons. FPL Library, Fredericton, NB, 24p.

Mickle, R. 2005. Evaluation of the AIMMS-20 Airborne Meteorological package. FPL Library, Fredericton, NB, 19p.

Cormier, G. 2006. Aerial Application to PROPS Polygons. SERG-I Workshop Proceedings, pp.206-207

Mickle, R., Rousseau, G., Cormier, G. 2007. Optimized Aerial Application to PROPS Forest Polygons. SERG-I Workshop Proceedings, pp.206-207

Goguen, R., 1994. Atomizer Characteristics With the Malvern 2600C Particle Size Analyzer. MScE Thesis, University of New Brunswick Department of Chemical Engineering.