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1. Increased Emphasis on Sustainability and Standards

Brief Introduction

Crop spray applicators in North America have an increased selection of high-capacity, self-propelled boom sprayers along with an increased selection of nozzle tips geared for ever-increasing large droplets. Agricultural aviation plays an important role with timely sprays, but this article focuses on boom spray applications made with self-propelled sprayers. Developments in boom sprayers and nozzle tips used in North America, particularly the U.S., were partially due to the regulatory environment and many spray applicators using technologies to improve the sustainability of the field spray process. A brief overview of spray droplet dynamics/ atmospheric conditions, and the spray industry framework operating within regulation and collaborative efforts are highlighted – because these often drive specific sprayer and nozzle developments.

Droplets Released into Atmosphere

Use of increased droplet sizes in North America has been to reduce spray drift potential caused by air movement, lateral or vertical, in the atmosphere. To illustrate three categorical atmospheric conditions with distinct effects on spray droplets, atmospheric conditions are categorized as “good,” “marginal,” and “bad” with respect to typical spraying.

“Good” spray conditions typically occur with solar heating of the field surface and a decreasing air temperature with altitude (“lapse rate”) which creates an unstable atmosphere. The energy differential with altitude, due to temperature, tends to drive an “updraft” of air. The makeup air, to replace the air moving upward, is often with a low velocity lateral cross-flow of air near the ground. Even though droplets may not be laterally blown to deposit on a neighboring property, the “updraft” has the potential to carry the smallest droplets of the spray away from the field. Evaporation of “updraft”-carried droplets to even smaller sizes may result in long range transport of pesticide residues. In North America, long range transport was documented with fallout as far away as the Arctic regions (Gregor, 1990).

“Marginal” spray conditions are when strong lateral air currents have the potential to blow droplets out of the field that may result in drift being detected in a neighboring area. Depending on the level of lapse rate and unstable atmosphere, small droplets also have the potential to be carried by an “updraft” of air being susceptible to long range transport. Usually the stronger cross-flow of air dominates the attention towards the potential for localized spray drift.

“Bad” spray conditions occur in stable atmospheric conditions when the air temperature profile with altitude deviates from a “lapse rate,” sometimes with constant or increasing temperature levels with altitude. A temperature inversion limits upward droplet mobility such that there is increased potential for smaller droplets to move up to the inversion layer, then laterally move/float until they potentially settle back to ground level which may be out of the field. The issue is that they tend to remain in concentrated numbers with significant potential for spray drift damage.

With the propensity for potential droplet drift of small droplets, even when conditions are considered “good,” the trend has been to use ever-increasing larger droplet sizes in the U.S. and North America. Spray drift has been measured with a range of samplers, ranging from simple fallout sheets to active samples that draw in air samples that contain spray droplets (Bui et al., 1998).

U.S. Regulatory Environment for Sprays

In North America, namely the U.S., the U.S. Environmental Protection Agency (EPA) regulates pesticide product registration and pesticide use in the U.S. via the pesticide “label.” The “label” indicates the conditions under which the pesticide product may be used, including the required application details such as limited environmental conditions, nozzles, nozzle droplet size classifications (droplet sizes), no spray zones, buffer zones, and other application details. Products applied contrary to “label” language may result in serious legal troubles for violators, whether there is a detected incident of spray drift, or water/ground/personnel contamination, or not.

In a separate action, the U.S. EPA established a Drift Reduction Technology (DRT) program whereby manufacturers/companies can have their technologies tested for drift reduction based on a test protocol that may involve a wind tunnel or field studies. Technologies assigned a DRT Star rating for drift reduction category relative to a standard application, is to proactively reward drift reduction.

The U.S. EPA has a mandate to enforce the U.S. laws as determined by a well-documented political process. But, the EPA has flexibility in rule-making – and that can vary depending on the (U.S. Presidential) executive emphasis. In recent times, popular press headlines have read “EPA seems to be shifting from science to perception model on pesticides” (Laws, 2016). This is an example of strained relations between industry and regulation.

Industry Standards and Sustainability

The U.S. agricultural industry is constantly looking for ways to address environmental issues, rather than being reliant on increased regulations. Sustainability is a current emphasis of the industry. A definition of sustainability involves “not being harmful to the environment in order to support long-term ecological balance.”

Industry standards developed through a consensus process improves sustainability by helping industry sectors communicate salient information towards creating improved systems that cross technology boundaries. Creating and revising consensus standards is an on-going process involving many experts. An example ASABE (American Society of Agricultural and Biological Engineers) standard is ASABE S572 (Nozzle Classification by Droplet Spectra). Pesticide product manufacturers reference required droplet classifications on product “labels”, and nozzle manufacturers indicate nozzle tip droplet size categories for tips - so that spray applicators can pick tips (and pressures) that meet product “label.” This avoids having to indicate specific nozzle tips by brand, size, etc. on “labels.”

Sustainability often involves collaboration across companies that manufacture various products. One of the challenges of collaboration is to follow established “rules of conduct” to avoid anti-trust (anti-competition), and to have a procedure to address intellectual property and shared data. For example, a non-profit organization that helps to establish methods/protocol for data sharing is Ag Gateway – and they have a vision of a sprayer to help answer the question, “o.k. to spray?” Manufacturers of sensors, electronics, controls, and hardware collaborate to develop a smart sprayer to provide the operator with real-time data to make informed decisions about whether it is suitable to spray or not. This ultimate system would help remove the potential for sprayer operator errors. In fact, this is the direction that the North American sprayer industry is headed - based on spatial input (GPS), on-board weather sensors, proximity to areas sensitive to sprays (residential, schools, etc.), and other inputs. Controls could involve controlling the sprayer path relative to distance to sensitive areas, adjusting droplet size on-the-fly, or if faced with imminent spray drift – to shut off the spray altogether. This is similar to automotive developments to either warn the driver, or to sense an obstruction and to automatically apply the brakes without operator action to avoid a crash.

2. Technologies for Sustainability

Technologies for sprayer sustainability often build upon the technologies already employed for precision agriculture. Examples include the following: spatial location (GPS), automated vehicle steering, digital field application maps, sensors for crop health/pests/spray requirements, sprayer on-board weather monitor, variable rate application, and nozzle tips with on-the-go adjustable droplet sizes. Other technologies may also apply to sustainability. The end goal is to have technologies working together as a complete system to ensure adequate pest control with minimal impact on the environment with a favorable economic outcome for the producer.

3. Trends in Boom Spray Applications

Boom sprayers in North America are available as tractor-mounted, tractor towed, or as self-propelled units with integral engine. When considering the proportion of total sprayed field area, at least in the U.S., self-propelled sprayers account for a significant sprayed area.

Self-propelled boom sprayers have increased emphasis on sprayer productivity (cover more area in less time) and use increased droplet sizes – compared to past sprayers. Table 1 compares typical spray applications from about 1990 to 2016. **Boom sprayers are now wider, faster, smarter, and apply bigger droplets than predecessors.**

Table 1. Increased boom sprayer productivity trends – approximate values

Factor	Year ~1990	Year 2016
Boom width (m)	12 - 18	18 - 36
Sprayer speed (km h^{-1})	9 - 16	16 - 30
Theoretical Max Ha $hour^{-1}$	29	108
Spray Rates (L ha^{-1})	56 - 187	47 - 140
Estimated Droplet Volume Median Diameter (microns)	150 - 275	250 - 800
Sprayer Technologies	fixed pressure	variable pressure, nozzle, rate GPS map, self steer …to name a few

4. Trends in Nozzle Developments

Spray applicators have an ever-increasing selection of spray nozzle tips and sprayer systems integrated with tips. Many nozzle tips continue as variants of hydraulic tip technology – with increased emphasis on increased droplet sizes. Droplet sizes are typically indicated using the ASABE 572.1 nozzle classification scheme that indicates droplets as “extremely fine,” “very fine,” “fine,” “medium,” “coarse,” “very coarse,” “extremely coarse,” and “ultra coarse.” A given nozzle tip may have two or three classifications, since increased spray pressure tends to reduce droplet size. Nozzle tip manufacturers produces charts to show droplet size classes, typically organized by nozzle type, size, and pressure. This scheme allows pesticide “labels” to indicate droplet sizes in a more general format to allow various brands of nozzle manufacturers to supply tips to meet the “label” needs. This is generally how that works, although pesticide manufacturers have some leeway in proposing exact “label” language and may specify nozzle tip brands. For U.S. applications, droplet sizes on “labels” are determined through a spray drift risk assessment protocol conducted by the U.S. EPA.

Earlier recommendations in the U.S. focused on droplets 100 microns and smaller as “driftable” – but scientific evidence has shown that 200-micron droplets have a much better tendency to settle than 100 micron droplets (Zhu et. al, 1994). Hence, droplets smaller than about 150 to 200 microns in diameter are considered “driftable” under reasonable environmental conditions. Since most hydraulic nozzles create a range (spectrum) of droplet sizes, the overall emphasis in nozzle design has been to significantly reduce the fraction of spray contained in droplets smaller than 150 to 200 microns. Sometimes this means increasing the overall volume median diameter (VMD), or the value at which 50% of the spray volume is contained in droplets smaller than the VMD.

Many “drift reduction tips” with flat fan discharge are available and are probably the most popular category of nozzle tip used, at least in the U.S. These tips typically have a pre-orifice and a discharge orifice combination, or some variant. The ratio of orifice sizes also determines the coarseness of the spray. Another popular variant is to include a venturi-shaped passage between the pre-orifice and discharge orifice in which air is drawn into and mixed with the spray liquid. These venturi tips (with various trade names) may also have impinging discharge tips. Droplets sampled from venturi sprays tips often contain a small proportion of air bubbles, and there are some manufacturer claims that the “droplets explode on impact” based on an early observation. Not all claims of “explode on impact” have been substantiated for a wide range of spray applications and conditions.

A simple approach is use multiple nozzles mounted per boom nozzle body location – and the sprayer operator then manually selects the desired nozzle tip for the specific application. This is quick and typically results in a relatively constant application (spray rate and droplet size), depending on whether a pressure-based sprayer controller is used on the sprayer.

Newest sprayer capability includes variable spray rates, droplet sizes, and combinations of spray rates and droplet sizes – all from the same tip. Sprayer system technologies are typically installed immediately upstream from the nozzle tip, typically at every nozzle body, to provide flow metering and control to each spray tip. One technology uses a pulsed solenoid to control flow to the nozzle tip, often called pulse-width modulation (PWM). PWM controls flow to each nozzle proportional to the duty cycle of solenoid, and the resulting flow is duty cycle fraction times nozzle flow rating, at the selected pressure. This technology is added to existing sprayers, or sprayer manufacturers integrate these systems directly onto new sprayers.

5. Case Study: Test of Nozzles in Herbicide Resistant Palmer Amaranth

With the increased emphasis in application of large droplets, increased sprayer speed, use of advanced spray systems (PWM), and herbicide resistant weeds - a field research study measured herbicide deposits on weed leaves and on water sensitive paper.

A self-propelled sprayer equipped with a 30.5-m boom, an application speed of 24 km h^{-1}, a spray rate of 93.5 L ha^{-1}, nozzle body spacing of 508 mm, and PWM technology applied glufosinate-ammonium herbicide at an application rate of 4.5 µg cm^{-2} simultaneously through five spray nozzle tip treatments mounted in sequential groups across the boom. The application was made to large plots of natural Palmer amaranth. PWM was operated for all nozzle tip treatments except for tips equipped with a venturi (air induction), which were not recommended for PWM nozzle control.

Spray nozzle tips prioritized for this study included twin Wilger Combo-Jet tips and Spraying System Air Induction tips (Table 2). Herbicide deposits on leaves and water-sensitive paper (WSP) coverage, spot density, and droplet size characteristics at high and middle canopy locations in Palmer amaranth were used to compare nozzle tip treatments. Herbicide efficacy followed similar trends as the spray deposits, and are not reported here.

Table 2. Nozzle tip spray treatments

Nozzle Treatment		
PWM or Constant	Droplet Class[1]	Nozzle Tip (PWM duty cycle of 50%) (Boom pressure of 448 kPa)
Pre-orifice tips PWM and non-PWM		
PWM	Extremely Coarse	Combo-Jet® DR110 05[2]
Constant	Fine	Combo-Jet® SR110 015[2]
Pre-orifice tip PWM		
PWM	Extremely Coarse	Combo-Jet® DR110 08[2]
Y-Adapter Pre-orifice tips PWM		
PWM	Extremely Coarse	Combo-Jet® DR110 06[2]
PWM	Coarse	Combo-Jet® MR110 02[2]
Air Induction Extended Range tip (non-PWM)		
Constant	Very Coarse	TeeJet® AIXR11004[3]
Air Induction Deflector tip (non-PWM)		
Constant	Ultra Coarse	TeeJet® TTI11004[3]

[1] Droplet quality per ASABE S572.1 Nozzle Classification by Droplet Spectra
[2] Wilger Inc., Lexington, Tennessee
[3] Spraying Systems Co., Wheaton, Illinois

Pre-orifice tips PWM and non-PWM produced significantly greater herbicide deposits (4.4 µg cm^{-2}) than all tips except Pre-orifice tip PWM (3.4 µg cm^{-2}). Also, the latter was not significantly different from all other tips [Y-Adapter Pre-orifice tips PWM (2.7 µg cm^{-2}); Air Induction Extended Range tip (2.3 µg cm^{-2}); Air Induction Deflector tip (2.2 µg cm^{-2}). The numerically lowest deposit level, based on the overall means, was produced by Air Induction Deflector tip, though the leaf deposit was not significantly different from other tips, except the Pre-orifice tips PWM and non-PWM. Deposits of glufosinate-ammonium for high canopy locations were greater than middle canopy location deposits for a given nozzle tip treatment. Deposits expressed glufosinate-ammonium mass per unit area, calculated either as leaf area or the two-dimensional overall field area when expressing the application rate of 4.5 µg cm^{-2}. Summation of deposits across locations sometimes exceeded this rate attributed to spray cloud momentum due to the application speed of 24 km h^{-1}. The addition of more weed plants or crop plants could possibly alter spray cloud momentum or serve as interceptors of droplets at the expense of deposit levels on Palmer amaranth. Glufosinate- ammonium leaf deposits were *inversely* proportional to and significantly correlated with canopy coverage of ground that supported this hypothesis. These observations of deposit may warrant further research into the role of sprayer speed, crop canopy density, spray cloud characteristics (droplet sizes, dynamics, momentum), and methods to potentially enhance plant spray coverage.

The highest mean WSP coverage occurring at the high location for Pre-orifice tips PWM and non-PWM was significantly greater than mean WSP coverage at high locations for Air Induction Extended Range tip non-PWM and Air Induction Deflector tip non-PWM, and greater than mean WSP coverages for all tip treatment middle locations, based on p-level observations. The highest mean WSP spot deposit for the high location of Pre-orifice tips PWM and non-PWM (57.9 # cm^{-2}) was significantly greater than mean WSP spot deposits for all other tip treatments and canopy locations.

A wide range of droplet sizes resulting from the entrainment of a fine spray into an extremely coarse spray may have contributed to high values of coverage and spot deposit for Pre-orifice tips PWM and non-PWM. In conclusion, use of a Pre-orifice nozzle tips with PWM and non-PWM that produced contrasting droplet sizes for spray entrainment between the two tips provided a means to increase glufosinate-ammonium deposits on leaves and increase coverage and spot density on WSP. On the other hand, Y-adapter mounted pre-orifice tips with PWM and separate air induction nozzle tips (extended range and deflector designs) operated as non-PWM applications did not result in high levels of glufosinate-ammonium deposits on leaves and did not result in high levels of coverage and spot density on WSP.

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