# Status of Spray Penetration and Deposition in Dense Field Crop Canopies

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Published in *Journal of the ASABE* 65(5): 1107-1117 (doi: 10.13031/ja.15091). 2022 American Society of Agricultural and Biological Engineers.

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Submitted for review on 9 March 2022 as manuscript number MS 15091; approved for publication as an Invited Review Article by Community Editor Dr. Steven Thomson of the Machinery Systems Community of ASABE on 10 August 2022.

### *Highlights*

- *Crop production practices, spray drift control, and sprayer productivity affect spray penetration into dense crop canopies.*

- *Question is raised whether airflows near foliar surfaces or within the canopy can assist spray penetration under windy conditions.*
- *Current structural descriptions of canopies do not accommodate droplet trajectories to improve spray application.*
- *New nozzle tip designs, sensors, and air-assisted spraying need tuning to improve spray penetration and deposition.*

***Abstract.*** *The objective of this study was to review representative publications for improved knowledge of spraying dense field crop canopies to augment the current understanding of the interaction between target foliage characteristics, spray practices, and the environment. Emphasis was placed on measured deep-canopy spray deposits made by full-scale sprayers and studies of airflow within and around crop canopies. Airflow could act as a spray droplet carrier and/or indicator of the internal canopy structure that restricts droplet penetration. High variation in natural airflows was noted in several studies. Crop canopy descriptions for spray studies were generally limited to overall canopy/row dimensions, descriptions of individual plant structures, leaf shapes, and leaf area index. Few studies evaluated the internal canopy "openness" with characteristic shape and size of internal volumes that would accommodate spray droplet trajectories. There have been significant increases in available spray tip designs with multiple orifices, discharge configurations, and droplet sizes that offered the applicator many choices. Advanced sprayer technologies ranging from nozzle control to sensor navigation are available, provided that suitable algorithms can be developed in a timely manner that pertain to a wide variety of spray and crop conditions. The air-assist technique provides a dynamic alternative to traditional over-the-top sprays for increasing spray penetration and deposit, advocating that the specifics of air discharge, spray droplet sizes, and canopy structure can be integrated. The complexity of the spraying process needs an extensive collaborative effort of many stakeholders to develop solutions for sprays to penetrate foliage that is subject to diseases and pests.*

**Keywords.**Air-assisted sprayer, Airflow, Boom sprayer, Canopy openness, Droplet trajectory, Foliar canopy, Foliar density, Row crops, Spray blockage, Spray coverage, Spray deposit, Spray nozzles.

Much progress has been made in the development and deployment of pest control agents, various pesticide application technologies, spray research instruments, and on-board sensing, control, and navigation systems (Giles et al., 2008). Sophisticated self-propelled boom sprayers, a diverse range of spray nozzle tip designs, and electronic controls have further advanced field crop spraying in North America and elsewhere (Womac et al., 2017). Indicators of field crop sprayer developments include increased field-capacity productivity with wide booms and high sprayer vehicle speeds (Womac et al., 2001); reduced environmental impact with increased droplet sizes that drift less

(Womac, 2001); and improved sustainability of spraying with controls that continuously adjust the sprayer system operations (Al-Gaadi and Ayers, 1994; Needham et al., 2012; Pessina et al., 2011). In addition to these sprayer developments, ongoing educational efforts inform applicators of improved spray practices and of the inherent limitations due to uncontrollable weather conditions (Casady et al., 1999; Ozkan, 2016). Field crop spraying is mostly limited to over-the-top spray techniques. The fundamental problem with this type of spraying is reduced spray penetration in the foliage as foliage density increases (Gu et al., 2014; Liu et al., 2021). Crop canopy trimming and modification were examined for improved spraying to manage plant diseases (McDonald et al., 2013).

Effective crop spraying is more than a simple, over-the-top “painting process” with simple droplet settling onto a two-dimensional flat plane. Crop and weed foliage constitute complex three-dimensional architectures with foliage obstructions that intercept and block spray droplet trajectories from penetrating and reaching deep foliage surfaces in the canopy. Similarly, orchard and nursery crop canopies impeded spray and air profiles (Gu et al., 2014). For this review, a “dense field crop canopy” was viewed as having a structural trait of significant obstruction to spray penetration within the canopy. Often, field crop canopies include both crop and/or associated weeds. Reduced foliar penetration of field crop sprays contributed to problems such as Asian soybean rust (Silva et al., 2020) or herbicide resistance issues for weeds such as palmer amaranth due to recurrent sublethal doses (Cuvaca et al., 2020; Tehranchian et al., 2017). Producers were aware of foliar canopy effects and made adjustments in the canopy to improve yield production (Rowsey, 2021).

Extensive methodologies have been investigated to improve spray deposition quality inside field crop canopies. However, there are no clear integrations of these investigations to fundamentally address requirements for adequate spray penetration and targeting when complicated interactions of local microclimate and airflow inside dense canopies are encountered. It is essential to bridge the gaps between those investigated methodologies and future guidelines for establishing modern spray application practices and research directions. Thus, the objective of this study was to review representative publications for improved knowledge of spraying dense field crop canopies to augment the current understanding (ANSI/ASABE Standards, 2016) of the interaction between the target foliage characteristics, spray practices, and the environment.

# Materials and Methods

The current understanding of the interaction between the target foliage characteristics, spray practices, and the environment was best detailed with an extensive publication of boom sprayer Best Management Practices (BMPs) (ANSI/ASABE Standards, 2016), that was consensus developed by many experts. The approach taken by this review to better understand and explore the complex phenomenon of spray penetration, deposition, and coverage in dense field crop canopies was to divide and analyze this phenomenon into three distinct sections: (1) natural airflow within crop canopies; (2) droplet penetration into crop canopies; and (3) air-assist spray canopy penetration.

The rationale for the first section was to consider the potential of natural airflow within the crop canopy as a spray droplet carrier and/or indicator of the internal canopy structure for restriction of droplet penetration. Internal canopy airflow was considered as a good indicator of a healthy plant environment (Marzu, 2021). The inverse of internal canopy restriction was internal canopy "openness." Publications that include robust relations between airflow and spray penetration for field crops are sparse, but this approach has merit for expanding the knowledge base for spraying foliage. Other disciplines, such as the atmospheric sciences, regularly conduct highly-detailed airflow measurements within and around crop canopies (Baldocchi et al., 1983). Some publications examined the influence of atmospheric boundary layer stability on aerial spray drift (Tang et al., 2022), though the impact of lapse rate (air temperature versus elevation) and atmospheric stability on spray drift behavior was well known (Hoffman and Salyani, 1996; Matthews, 2014). Other applications use computational fluid dynamics to simulate airflow through standing vegetation as means to predict soil particle loss due to blowing wind (Gonzales et al., 2019).

The second section examined publications that measured spray deposits in crop canopies. This body of work often included the testing of improved nozzles or sprayers and measurements of spray penetration deposits in crop foliage. The penetration problem was challenging and often required non-conventional methods such as mechanical manipulators of crop foliage. Field spray studies also discussed the impact of environmental conditions such as wind on spray penetration.

The third section focused on publications of sprayers supplemented with air-assist technology as a forceful driver to improve spray penetration into the foliar canopy. The focus was on air-assist technology for field crops, though the potential lessons-to-be-learned from airblast orchard and vineyard spraying and the increased air velocity and turbulence in a crop canopy due to the increased wake intensity due to aerial applications were also considered.

Priority was given to studies that measured spray deposits on either natural or artificial targets in the foliage, especially from field crop sprayers typically scaled for production applications. Low priority was given to spray tests conducted with a handheld boom spraying a small plot. Priority was also given to studies that made concerted efforts to describe spray application factors, and that evaluated significant commodity crops such as soybeans, corn, and wheat produced in North America. Other field crops were considered based on difficult-to-penetrate canopies such as peanuts.

Foliage canopy details during spraying were also sought out, though very general descriptions were most common. Published descriptions of field crop canopies were often limited such that it required reader experience with the selected crop, cropping practice, region, and crop maturity to fully visualize the size, extent, geometric traits, and internal foliage overlap of the canopy. Lack of good descriptions of foliar canopies in spray publications was perhaps due to reduced guidance offered by published standards (ANSI/ASABE Standards, 2016; ANSI/ASABE Standards, 2021).

The sheer number of research publications on spraying was overwhelming. The approach was to use a representative sample of publications, which were selected based on the three general criteria: (1) perceived quality of test conditions, (2) clarity of results, and (3) conciseness of results for fitting a cumulative assessment. To collect an adequate number of publications meeting these three criteria, publication dates spanning several decades were required. Publications were primarily searched through University of Tennessee library resources for topics such as canopy airflow, spray penetration, spray deposits, pest control, and pest categories of weeds, insects, and disease.

The Results section primarily reflected publications for the three categories of natural canopy airflow, spray deposit penetration, and air assist sprayers. Individual studies were reported and integrated discussions reflected trends. Highlights of consistency or lack of consistency were noted. Potential reasons for similarities or differences were offered depending on the extent of evidence published. Based on the results, conclusions were developed to communicate the status of spraying dense field crop conditions.

# Results and Discussion

## Natural Airflow within Crop Canopies

Baldocchi et al. (1983) evaluated the very detailed characteristics of airflow above and within soybean canopies, including between rows. They determined that the wind profile had a high level of wind shear in the upper canopy and weak wind shear in the middle canopy. Wind speeds within a row and between rows converged to a common value at about 0.10 m above ground level. They noted a high degree of spatial variability in wind speed. As foliage density increased, results indicated that increased wind speed distorted canopy shape causing increased wind penetration into the canopy. Canopies were characterized with Leaf Area Index (LAI, ie. ratio of single-side leaf area to ground area) and crop height for before- and after-lodging conditions. For airflow above the canopy, roughness length and zero-plane displacement were determined from wind profiles under near neutral conditions, and canopy drag coefficients were calculated. Within-canopy airflow was measured within a row and between adjacent rows, resulting in the two different regions of airflow either having high wind shear or weak wind shear depending on heights. They attributed increased drag within the row due to increased foliage density and stiffness of foliage elements compared to between-row airflow. Additional details for attenuation and other factors were discussed.

Cionco (1983) described the coupling between airflow within the vegetation and the ambient flow of the surface boundary layer. This coupling, expressed as a coupling parameter ratio, depended on canopy density. He used a corn crop and a thinned corn crop to examine element density arrays on the degree of coupling, along with a wind tunnel experiment. The cornfield was planted at increased densities to ensure adjacent leaves intermingled and touched neighboring leaves. Masts of typical micrometeorological instrumentation measured the airflows for the two crop conditions and considered the complete energy budget of adjacent plots. Airflow coupling ratio values in corn ranged from 0.19 to 0.29 for canopy densities of 68% and 20%, respectively. However, a 100% canopy density had a coupling ratio of 0.21, indicating that canopy flow coupling in very dense canopies was less affected by canopy density.

Baldocchi et al. (1985) identified the effect of soybean leaf width on the canopy microclimate and exchanges of mass and energy in a Nebraska field. They noted a complex effect on turbulent mixing. Soybeans were planted in 0.75-m wide rows. Before crop rows overlapped, the soybean isoline with narrow leaves (0.015 to 0.03 m) resulted in increased turbulent mixing. After crop rows overlapped, the normal soybean leaf width (0.04 to 0.06 m) resulted in increased turbulent mixing that was attributed to increased canopy density and an associated increase in bluff-body effects. The narrow leaf width also resulted in an increased within-canopy vertical profile of net radiation that affected the microclimate within the canopy. This increased radiation flux affected air temperature, vapor pressure, latent heat exchange, sensible and soil heat flux, and $CO_2$ concentrations. Reduced evapotranspiration rates were noted for the narrow-leaf soybean isoline.

Meyers and Paw U (1986) developed a higher-order closure model for momentum transport in adiabatic conditions to simulate airflow above and within plant canopies including field crops of corn, soybean, bean, and wheat. They compared mean wind profiles between the model and experimental measures. Canopy characteristics (ie., vertical profiles of leaf area) were fitted with Beta distributions for a unique smooth profile of plant area density for each field crop. The model accurately predicted mean wind speeds within and above the canopy for all crops and was attributed to a constant effective drag coefficient. On the other hand, the turbulent kinetic energy predictions within the canopy needed improvement, which was attributed to the model inaccurately describing the dissipation of turbulence generated at different scales.

Wilson (1988) developed a closure model for airflow that was tested through mature corn. LAI was measured for seven plant heights, and the integrated LAI value was 2.9. Measures of velocity and other microclimate factors resulted in a discussion point of high variability of windspeed in the canopy that concluded with models that provide only a single estimate of windspeed (whether a point estimate or average) at a given height would be of no use if the application required an in-canopy windspeed estimate to an accuracy of at least 25%. In fact, Wilson (1988) stated that "one might say that if we can predict the windspeed and turbulence within ± 50%, we are doing as well as is realistic" (for within canopy variations). He used a dual frequency band turbulent energy balance which differed from earlier studies. It was concluded that the second-order closure scheme yielded good predictions for the selected test conditions, but a general validity was not claimed.

Baldocchi (1992) developed an integrated canopy micrometeorological model to simulate water vapor, $CO_2$, and sensible heat flux densities and scalar profiles over and within a soybean canopy. He noted that inside a plant canopy the mean wind velocity and associated statistics vary to a high degree as a function of height. Baldocchi stated that the "probability density functions of velocity fluctuations are skewed and kurtotic." Ultimately his model considered "biochemical, physiological and micrometeorological principles to evaluate vegetative sources and sinks" and he tested it with measurements made above and within a soybean canopy.

In another study, airflow and energy characteristics around a maturing sorghum field were determined with extensive grids of sonic anemometers, temperature/relative humidity sensors, and net radiation/ground heat flux sensors (Kochendorfer and Paw U, 2011). The leaf area index (LAI) at maturity was 4.2. Their objective was to determine factors associated with energy and mass exchange between the surface and atmosphere. They essentially determined the effects of inhomogeneity on these exchanges due to vertical and horizontal advection terms occurring near the boundaries of crop canopies. They stated, "significant mean advective horizontal and vertical flux divergence of water vapor and temperature were found even in typical daytime conditions."

Chahine et al. (2014) examined wind flow over the well-defined row structure of a vineyard under near neutral thermal stratification in contrast to horizontally uniform canopies (ie., homogeneous mature field crop). The rationale for their study was to better understand vineyard airflow to solve problems with spray drift. They summarized that turbulence over homogenous crops had high shear at the canopy top, a rapid decrease in turbulent kinetic energy and momentum flux vertically downward in the canopy, and periodic sweeps in momentum transfer. They noted that the mean flow over a vineyard was similar to uniform field crop canopies for wind directions oriented from cross-row to diagonal. LAI was estimated from earlier measurements to have a value of 1.9 for a row spacing of 1.3 m, a mean canopy height of 1.6 m, a row width of 0.6 m, and an inter-row width of 0.7 m for an aspect ratio of 0.44 (ie. 0.7/1.6). Wind was channeled between rows as the wind direction aligned with row direction. The down-row winds had intermittent turbulent structures and increased turbulent kinetic energy and momentum flux.

Sase et al. (2012) evaluated a tomato canopy for aerodynamic properties such as the drag coefficient, permeability (K), and momentum loss coefficients ($C_f$) for various leaf area densities to improve the understanding of crop presence on greenhouse ventilation and microclimate. They used a large-scale wind tunnel [3 m (high) x 4 m (wide) x 20 m (long) working section] with a tomato canopy for pressure drop and air velocity relations using a porous medium approach. LAI was 2.74 for a 1.35 m tomato crop height. A drag coefficient of 0.31 was determined. The permeability of the tomato canopy ranged from 0.006 to 0.65 for a leaf area density (L) of 4 $m^2$ $m^{-3}$. In the worst case, a mature tomato canopy had a leaf area density of L = 6 $m^2$ $m^{-3}$, a canopy permeability of K = 0.017, and a momentum loss coefficient of $C_f$ = 0.245.

An assessment of spatial and temporal variability in wind speed and direction was conducted with multiple sensors at 10 Hz for 5-h periods over a field of oats grown in Iowa (Schramm et al., 2019). Although no attempt was made to relate air velocity at a height of one meter above the ground to the air velocity within the oat foliar canopy, the study provided a perspective of the transient nature of wind close to the crop canopy. The goal was to characterize the changing wind conditions acting on a droplet released from a spray boom, and the potential impact on spray drift. They observed that a wind speed difference of 1 m $s^{-1}$ from current conditions having a mean wind speed of 3.6 m $s^{-1}$ occurred about 50% of the time. For 36 days observed for two spray seasons, the greatest variability in wind direction occurred when wind velocity was less than 2 m $s^{-1}$ (Schramm et al., 2019). Increased wind direction variability was observed during increased solar radiation in the mid-afternoon.

A brief summary of publications on natural airflow within crop canopies included many studies that measured airflow in the boundary layer and within canopies (Baldocchi et al., 1983; Meyers and Paw U, 1986; Wilson, 1988) with the micrometeorological aspects of mean air velocity and variance in velocity (Chahine et al., 2014), turbulence, energy balances (Baldocchi et al., 1985; Kochendorfer and Paw U, 2011), and/or transport mechanisms for gases and water vapor (Baldocchi, 1992; Kochendorfer and Paw U, 2011). Most data and predictions pertained to neutral atmospheric conditions (Baldocchi et al., 1983; Chahine et al., 2014). The coupling of ambient airflow above a field and the resulting airflow penetration was monitored for various crop conditions (Cionco, 1983; Chahine et al., 2014). In-canopy airflow predictions were good, though high variations in velocity and turbulence were expected within ± 50% (Wilson, 1988). A high degree of spatial and temporal variability in wind speed was reported (Baldocchi et al., 1983; Baldocchi, 1992; Wilson, 1988; Schramm et al., 2019).

Detailed micrometeorological measurements and insight into airflow interactions with field crop canopies provided a more detailed physical understanding of canopy spray penetration. However, boundary layer models alone typically do not provide enough accuracy to impact temporal- and spatial-specific applications for improved sprayer penetration into various field crop structures. This is because the physical representation of the canopy within most operational boundary-layer models is not detailed enough to accurately determine airflow within the canopy.

## Spray Droplet Penetration into Crop Canopies

For clarity, increased foliage obstruction to spray targeting within the foliage canopy constituted a “dense field crop canopy” for this review. Increased row spacing resulted in increased soybean spray coverage, though coverage was much less for deeper foliage at reduced heights above the ground (Hanna et al., 2009). Fungicide residues from narrow-row (18-cm) soybeans at a high spray rate of 187 L ha$^{-1}$ increased middle canopy leaf residues with an insignificant effect on canopy bottom residues (Derksen et al., 2008). Similarly, increased spray rates did not increase deposition in the canopy bottom (Barbosa et al., 2009). Double nozzle configurations did not improve canopy bottom coverage in soybeans for Asian Soybean Rust control (Wolf and Daggupati, 2009), though some nozzle tip designs improved dose transfer in some crops (Hall et al., 1996). Spray penetration of fungicide into wheat by double-pattern spray nozzles outperformed single-pattern nozzles on vertical targets, whereas single-pattern nozzles increased coverage on middle horizontal targets (Ozkan et al., 2012). Increased spray angle increased deposits on vertical wheat stems and vertical sprays increased deposits on horizontal targets through a dense soybean canopy (Derksen et al., 2014). Overall conclusions were difficult due to varying uncontrolled wind conditions.

Influences of spray droplet size classifications in canopy penetration varied by crop. Very coarse droplets applied in foliar bands to cotton resulted in the greatest canopy penetration and deposition in lower canopy heights during conditions of gentle wind (Womac et al., 2004). Medium or coarse sprays better penetrated a narrow-row soybean canopy (Derksen et al., 2014) compared to other droplet sizes. Droplet classifications ranging from very fine to ultra coarse yielded similar penetration of an oat canopy (Ferguson et al., 2016a). Classifications of droplet sizes hereby refer to the U.S. method (ANSI/ASABE Standards, 2020). Nozzle type impacted coverage and droplet number density on sampling cards (Ferguson et al., 2016b). Short canopies such as Japanese lawn grass (*Zoysia japonica*) experienced spray penetration issues for fungicides (Benelli et al., 2018). Deposits reaching the middle and bottom canopy levels of peanut crop foliage were inversely proportional to a plant structure indicator calculated as the square root of the product of plant height, width, leaf area index, and foliage density (Zhu et al., 2002).

Gan-Mor and Matthews (2003) reviewed the methods for the application of biopesticides as alternatives to pesticide chemicals. They noted that biopesticide application systems depended on the type of the material being sprayed, mode of action, and the "specific shape and density of the crop canopy." They noted that a high uniformity of deposition was needed to completely cover plant surfaces prone to pests, which resulted in extra wetting of foliar surfaces from very high spray volumes that tended to be dripped and lost. Many factors were highlighted, such as deposit distribution, coverage, spray rates, droplet size distributions, droplet count per unit area, foliage surface characteristics, deposit age, and formulation. A major factor for biopesticide application was the potential impact of the sprayer pressure and heat build-up on the life-form of the active ingredient (Fife et al., 2007).

University of Tennessee field studies evaluated glufosinate-ammonium deposits on leaves and water sensitive paper (WSP) at multiple heights of Palmer amaranth (*Amaranthus palmeri*) for advanced spray technologies (Womac et al. 2016, 2017). Glufosinate-ammonium efficacy was proportional to measured spray deposits. Sprayers included Pulse Width Modulation (PWM) and constant operation of single and dual nozzle configurations of pre-orifice nozzles and for Y-mounted nozzles for dual spray angles. Air-induction nozzles were operated only in constant mode since they are not compatible with PWM. Glufosinate-ammonium herbicide leaf deposits and WSP produced comparable results, especially for WSP spot deposit counts. Mean ambient wind speeds of 0.0 and 4.1 m $s^{-1}$ during two different tests resulted in mean WSP spot deposits ranging from 42.3 to 81.1 spots per $cm^2$ and from 14.0 to 47.0 spots per $cm^2$, respectively. Thus, ambient wind greatly reduced spray deposits.

Nuyttens et al. (2009) described the effects of hydraulic nozzle type, nozzle size, and operating pressure on laser-measured droplet sizes and velocities. Nozzle tips included standard elliptical orifice flat fans, pre-orifice flat fans, and (Venturi) air-induction flat fans in sizes from ISO 02 to 06 and at pressures from 2.0 to 4.0 bar. Of the varied droplet sizes, generally increased droplet size had a corresponding increase in droplet velocity at a distance of 0.5 m from the orifice discharge. Among nozzle designs for the same droplet size, droplet velocities progressively decreased from the standard elliptical orifice, pre-orifice flat fan, and were the slowest for the air-induction nozzle tip. An increase in nozzle size also increased droplet velocity. Example velocities for larger droplet sizes (>400 µm) ranged from about 4.5 to 8.5 m $s^{-1}$. Smaller droplets typically had velocities from 0.5 to 2.0 m $s^{-1}$. They cited crop penetration, spray drift, and deposit characteristics as uses of the published data.

Major technical advancements have been achieved in pesticide application technology over the last three decades, specifically the new nozzles with designs completely different from the conventional ones for reducing spray drift. New nozzles were evaluated for their effectiveness in reducing spray drift by using a wind tunnel (Derksen et al., 1999; Guler et al., 2007). Zhu et al. (1994) conducted pioneering research to track the movement of specific size droplets and their spray drift distances after the droplets were released from the nozzles on horizontal boom sprayers under different wind velocity conditions and nozzle heights. The initial work was done by using computational fluid dynamics (CFD) software (FLUENT) to model droplet movement. They also used a mono-sized droplet generator installed in a wind tunnel to determine the fate of droplets under different wind velocities (Reichard et al., 1992), resulting in research that is often cited. This work resulted in a computer program called DRIFTSIM (Zhu et al., 1995; USDA, ARS, 2021), which has been used worldwide by farmers, researchers, and sprayer and chemical manufacturers.

Realizing spray drift is a major concern, many companies have started marketing products called “drift retardant chemicals”. Wind tunnel studies evaluated drift potentials associated with off-target ground and airborne spray deposits discharged from different flat-fan and hollow cone nozzles spraying different drift retardants at various spraying pressures and wind velocities (Ozkan et al., 1993; Zhu et al., 2006a).

Although the new nozzles are able to reduce drift, very little research has been done on how these nozzles can accurately and effectively discharge droplets to achieve optimal deposition and coverage on plant canopies with completely different shapes and densities. To address this concern, Guler et al. (2012) evaluated the spray coverage and deposit density from seven types of nozzles at three different flow rates (0.76, 1.14, and 2.27 L $min^{-1}$) and two target positions (0.50 and 0.70 m below the nozzle) under controlled environmental conditions. However, the evaluation did not address the influences of a canopy, a dense canopy, or ambient wind on spray deposition quality.

Butler-Ellis et al. (2011) conducted wind tunnel spray trials in a wheat canopy to identify the factors influencing the distribution and amount of spray deposited on the lower stem. They determined that increased spray rate (volume) did not increase the amount of active ingredient reaching the lower part of the canopy.

Spray applicators intend to standardize spray settings during a season, but that does not address spray droplets targeting different canopies or zones. Several field studies were conducted in Ohio to examine deposition in soybeans (Derksen et al., 2008; Zhu et al., 2008a,b) and wheat (Derksen et al., 2012; Ozkan et al., 2012). These studies evaluated nozzle type, spray quality, volume, angle, and either air-assistance or mechanical crop openers. Results revealed that a prescriptive application (nozzle, pressure, rate of application, droplet size) improved soybean deposits, though the same prescription yielded the worst deposits in wheat. A significant finding was that results were impacted by field wind conditions. Wind affected spray droplet behavior and made it more difficult to draw consistent conclusions. Tennessee studies noted that ambient wind affected spray nozzle rankings of herbicide spray deposits on Palmer amaranth leaves and WSP within foliage (Womac et al., 2016; 2017).

De Cock et al. (2017) used a modeling technique to ascertain the optimum range of spray droplet sizes for boom sprayers applying herbicides. Outcomes included spray deposition and retention and spray drift. They determined that droplets sized from 200 µm to 250 µm offered a high degree of deposition control and low drift potential. They noted that wind fluctuations affected droplet trajectories. Impact velocities were affected by ejection velocity, release height, wind speed, and droplet size. No one “perfect” droplet size and spray condition fitted the variable ambient conditions and wind. They noted the need for further work to assess drift potential and target retention.

Liu et al. (2021) examined the influence of foliage density and foliage distribution on spray droplet deposit distribution within the foliar canopy. They proposed using an optical porosity of horizontal layers in a cotton plant canopy to use stratification porosity to quantitate the foliage. Although they used artificial plant structures to represent live cotton plants in the field, they evaluated spray deposits and a Gaussian process to model droplet size distributions in the canopy. They concluded that the complex influence of three foliage layers and the horizontal velocity component of droplet movement could not explain the droplet distribution and deposits in the lower levels.

Spray deposit distribution of over-the-top sprays were evaluated for various spray tips (Womac et al., 2001) and factors affecting spray nozzle stability such as spray boom deflections and motions (Jeon et al., 2004). Nozzles mounted on “drop legs” with upward trajectory increased spray deposit and the control of beet armyworm on leaf undersides (Womac et al., 1992). Similarly, a Lechler reduced-height nozzle mount improved canopy spray penetration and deposition on leaf undersides (Heinkel, 2018). A mechanical foliar push opener for soybeans aided deposition on middle and lower canopy targets (Zhu et al., 2008a,b). Droplets smaller than 300-µm achieved the most efficient leaf coverage on soybean leaves (Jia and Zhu, 2015).

A brief summary of publications on spray droplet penetration into crop canopies includes studies that evaluated decreased foliage density with increased row spacing (Hanna et al., 2009) to improve soybean spray penetration. An increased spray rate increased deposits in the soybean middle canopy (Derksen et al., 2008), but did not increase bottom soybean canopy residues (Derksen et al., 2008; Barbosa et al., 2009), nor did double nozzle configurations (Wolf and Daggupati, 2009). Additionally, an increased spray rate did not increase bottom wheat stem deposits (Butler-Ellis et al., 2011). However, double-pattern nozzle tips improved middle canopy deposits in wheat. Thus, the structural traits (specific shape and density) of the plants comprising the foliar canopy affected the interactions of spray and foliage (Gan-Mor and Matthews, 2003). Zhu et al. (2002) developed a spray deposit-plant structure indicator from plant height, width, leaf area index, and foliage density. Liu et al. (2021) concluded that the complex interaction of field crop foliage density and distribution affected the interaction and internal movement of spray droplets that were neither well modeled nor explained. Ambient wind significantly reduced spray penetration and spray deposits (Derksen et al., 2014; Womac et al., 2016; Womac et al., 2017). Spray nozzle droplet sizes and droplet velocities affected many application factors including canopy penetration, spray deposits, and spray drift (Nuyttens et al., 2009; Derksen et al., 1999; Guler et al., 2007; Zhu et al., 1995; Ozkan et al., 1993; Zhu et al., 2006a). Spray boom dynamic motions (Jeon et al., 2004), mechanical drop nozzles (Womac et al., 1992; Heinkel, 2018), and a foliar push opener (Zhu et al., 2008a,b) aided droplet penetration to canopy middles and bottoms.

# Air-assist Spray Canopy Penetration

Field tests of air-assisted sprays determined that discharge air velocities of 16 m $s^{-1}$ increased spray deposits in a cotton canopy by 92% and resulted in significant increases in bifenthrin insecticide (Womac et al., 1992). Orienting the air discharge 30° back tended to increase deposits on leaf undersides. In additional field trials, applying butifos and ethephon defoliants using an air-assist sprayer provided the highest mean cotton defoliation of up to 78%.

Bayat et al. (1999) evaluated air-assisted spraying deposits within plant canopies using a wind tunnel to evaluate cotton and corn crop canopies, three wind velocities (0, 2, and 4 m $s^{-1}$), and two uniform droplet sizes (130 and 300 µm). Air assistance increased deposits in the lower canopy and on leaf undersides. A Jacto air-assist sprayer with hollow-cone nozzles consistently improved the application of fungicide to the middle canopy and lower canopy leaves of soybeans compared to flat-fan nozzles producing droplets at medium spray quality (Derksen et al., 2008). Wu et al. (2021) applied air-assisted sprays to strawberries and noted the effects of airflow instability and turbulence on leaf vibrations of strawberry plants.

The penetration of a sprayer air jet into an apple tree canopy was determined for a two-fan cross-flow sprayer (Svensson et al., 2003). The collection efficiency of targets was evaluated with several targets of different sizes for effectiveness in collecting spray droplets transported by air speeds of 2, 4, and 6 m $s^{-1}$ (Zhu et al., 1996; Fox et al., 2004). Almekinders et al. (1993) evaluated droplets released in a wind tunnel with wind velocities up to 5 m $s^{-1}$. An air jet downward velocity of 11 m $s^{-1}$ greatly increased the amount of spray deposited in the target area and improved penetration into the canopy.

Zhu et al. (2006b) developed and tested a five-port air-assisted overhead sprayer to improve spray penetration in dense nursery canopies. The mean spray deposits inside taxus canopies that had an LAI of nearly 6 increased at an exponential rate as the peak air velocity increased. Taxus is a genus of coniferous shrubs. Deposits and air velocities from the new sprayer resulted in dynamic air velocities of at least 1 m $s^{-1}$ within the canopy for 1.1 s, 3.8 s, and 1.9 s at the canopy top, middle, and bottom, respectively.

Ade and Rondelli (2007) examined spray deposits from air-assisted overleaf spraying, air-assisted underleaf spraying, and conventional over-the-top sprays for a two-year study in Italy aimed to control Colorado beetle larvae in potato crop foliage. Potatoes were grown at a row spacing of 0.75 m. In the first year, the foliage of the row was 0.34 m wide and 0.30 m high. In the second year, row foliage was 0.35 m wide and averaged 0.54 m high. The mounted sprayer had individual air tubes with each tube discharging through a two-nozzle diffuser. Hollow-cone nozzles discharged 220 l $ha^{-1}$ just outside of each diffuser that discharged 30 m $s^{-1}$ of airflow. Airflow was adjusted downward at 20° below horizontal for the overleaf spraying and upward at 45° for the underleaf spraying. Results varied slightly by year. Air-assisted spraying had inner-canopy deposits that were significantly greater than conventional over-the-top sprays. In one year of the study, the underleaf air-assisted spray deposits were greater than all other spray treatments. Air-assisted treatments resulted in significantly fewer larvae on potato plants.

Fox et al. (2008) described the history of air-blast sprayer development focused on trees and vineyards. They noted how high air volumes at high velocities were able to effectively spray large fruit and nut trees rather than using the previous method with high volumes of liquid (water) carrier without airblast. Descriptions of sprayer designs included tower, directed jet, and tunnel sprayers and indicated that air-blast sprayers should reduce drift and create improvements in uniform coverage. Another observation was that growers were adapting their orchards to improve spray deposits by using dwarf plant varieties instead of large varieties. They envisioned matching the sprayer targeting to the foliage with the use of sensors and variable sprayers capable of adjusting multiple airflow outlets and nozzles. They anticipated the need for spraying natural or biological materials rather than pesticides and chemicals. These alternative spray materials may need the protection of live organisms in the spray, or the sprayer may need capabilities to handle and deliver liquids with a range of properties that well exceed current sprays. Though they were focused on orchards and vineyards, lessons learned may apply to row crops as well.

Aerial sprays from fixed-wing aircraft were also manipulated with air deflectors designed to increase the downward trajectory of airflows and entrained droplets into a crop canopy (Womac et al., 1994; Kirk et al., 1994). Chimavir Air Services, Ltd (Israel) developed boom-mounted “winglets” that were tested for effect on field spray drift, air velocity profile near the boom, and atomization characteristics of a nozzle operating behind the deflector in a high-speed airstream in a wind tunnel and field (Womac et al., 1994) and in-canopy spray deposits (Kirk et al., 1994). Womac et al. (1994) used the winglets on a turbine engine-powered aircraft at an equivalent mean ground speed of 218 km $h^{-1}$ and in a wind tunnel. Kirk et al. (1994) used the winglets on a piston engine-powered aircraft at an equivalent mean ground speed of 170 km $h^{-1}$. Spray drift at a range from 30 m to 201 m from the flight line increased with mean aircraft height but was less than applications without the Chimavir winglet. The mean angle of air deflections ranged from 18.8° to 11.9° for winglet deflector settings of maximum and minimum, respectively. Mean droplet size indicators ($D_{v0.5}$) for a various assortment of spray tips either without the deflector winglet or with the winglet averaged 182 and 235 µm, respectively (Womac et al., 1994). Kirk et al. (1994) determined that for cotton and cantaloupe crop canopies the winglet increased the aircraft wake intensity (i.e. increased air velocity and turbulence intensities in the crop canopy) through a combination of a downward deflected airstream and a reduced aircraft speed. Increased wake intensity increased spray deposits on the bottom of leaves, though deposits on leaf bottoms were very small compared to leaf top deposits in the upper canopy.

Franz et al. (1995) determined the effects of aircraft airspeed and spray height of a piston engine-powered aircraft equipped with Chimavir winglets on airflow in cotton canopies. Canopy size affected canopy airflow and turbulence life in the cotton canopy. For a reduced cotton canopy size, the mean and rms velocity were significantly greater than ambient conditions 5 s after the aircraft passed the sample line and lasted for about 5 s. In comparison, the increased cotton canopy size became significant during the first 5 s and had a similar duration as the reduced cotton canopy size.

Latheef et al. (2008) evaluated aircraft technologies of rotary atomizers, Chimavir winglets, and trumpet nozzles in addition to airspeed and aircraft height to apply insecticides to cotton foliage for control of sweet potato whitefly. They found insignificant differences between aerial spray systems based on spray deposit, coverage of active ingredient, and control of sweet potato whitefly. They concluded that further developments should be addressed in aerial delivery systems to increase the control of insects at the bottom surfaces of cotton leaves.

A brief summary of publications on air-assist spray canopy penetration included studies that evaluated various air delivery systems ranging from an air curtain at 16 m $s^{-1}$ output velocity (Womac et al., 1992) to a directed air-assist sprayer at 4 m $s^{-1}$ (Bayat et al., 1999) to spray crops ranging from cotton to corn. Air-assisted field crop spraying used air diffusers that discharged air at 30 m $s^{-1}$ to improve applications to potatoes (Ade and Rondelli, 2007). In most cases, air assistance improved droplet penetration and deposits down in the crop canopy and to the leaf undersides. Custom adjustments to the air discharge relative to the row crop canopy were critical, and typically, various angled outputs of spray and airflow increased spray penetration and foliage interception of spray droplets. Other studies evaluated tree and vineyard air-assist spraying since that was the predominant method for commercial spraying these crops, and this was noted as the improved tree and vineyard spraying method compared to previous adaptations of very high spray rate applications (Fox et al., 2008). Evaluations of aerial application systems designed for increased air velocity and turbulence intensity in the foliar canopy gave mixed results overall, depending on canopy conditions and pests (Womac et al., 1994; Kirk et al., 1994; Franz et al., 1995; Latheef et al., 2008).

# Conclusions

There is a lack of clear integration of knowledge from many spray studies, a wide variety of spray-behaviors emitted by spray application technologies, and highly variable air velocity profiles around and within crop canopies to reliably compute predictable outcomes for spraying dense field crop canopies. In other words, few know how to select and set up sprayers to solve problems involving spray penetration for increased deep-canopy deposits. This work attempts to identify and organize thought processes as a review article dealing with the status of spray penetration into dense field crops. The objective of this study was to review representative publications for improved knowledge of spraying dense field crop canopies to augment the current understanding (ANSI/ASABE Standards, 2016) of the interaction between the target foliage characteristics, spray practices, and the environment.

The following specific conclusions were derived from the comprehensive literature review presented in this article:

1. Advances in spraying have increased the basic knowledge of using increased droplet sizes to reduce spray drift, but the related impact of increased droplet sizes on canopy spray penetration and foliar coverage in crop conditions vary widely and are neither well understood nor predictable.
2. The requirements for effective spraying have changed, and they are evidently constantly changing over time. The decades-old convention of using small spray droplets to increase canopy penetration and coverage was overridden with increased attention to reducing spray drift. Or, simple factors once thought to improve spray penetration, such as increased spray rate (i.e., spray volume), failed to increase spray penetration in several studies involving various crop canopy conditions.
3. The impact of evolving crop practices on the crop canopy structure is not well understood, especially for changes to row spacing, plant population, irrigation, and/or crop varieties with different canopy heights and volumes. Improved spray penetration and spray access have been low priorities since many of the newer crop practices tend to inhibit and block spray penetration.
4. Evolving spraying practices have emphasized the increased capacity of over-the-top applications at faster speeds with wider booms and larger droplets. Knowledge of droplet interactions with the canopy has generally been a low priority. On the other hand, there have been significant increases in available spray tip designs with multiple orifices, discharge configurations, and droplet sizes that offer the applicator many choices. Advanced sprayer technologies ranging from nozzle control to sensors are available, provided that suitable algorithms can be developed in a timely manner that pertain to a wide variety of spray and crop conditions.
5. The micrometeorological environment within and around field crops has high variability in natural ambient air velocity and other related variables that can affect spray droplet movement. The status of being able to spatially- and temporally-predict natural air velocity and its variation within and around the plant canopy in the field is not developed to a precision that would be required to determine spray droplet responses due to interaction with natural airflows. The effect of simple ambient wind levels can greatly affect the magnitude of spray deposits in a field crop canopy, including spray penetration to deep

foliage levels. Canopy structure and density also play an important role in the degree to which both ambient winds and spray penetrate the canopy.

6. The internal field crop canopy structure for spray studies has been mostly limited to overall canopy/row dimensions, descriptions of individual plant structures, leaf shapes, and leaf area index. Few studies evaluated the internal canopy “openness” described with characteristic shapes and sizes of internal volumes that would accommodate spray droplet trajectories.
7. Air-assisted spraying provides a powerful alternative to traditional over-the-top spray applications. Most applications to field crops for improved canopy penetration require a customized solution regarding air and spray droplet delivery and angles of discharge for the selected crop canopy conditions being sprayed.
8. The problem is massive, and solutions are evasive. The complexity of the spraying process to achieve penetration and deposits deep in a field crop canopy will require the support and collaboration of multiple stakeholders to efficiently solve the problem with knowledge, tools, and action items needed to address future crop diseases and pests that can be harbored by foliage. A sustained collaboration is needed among manufacturers of spray nozzles; sprayer vehicles and systems; air-assisted sprayers; sensor, controller, and navigation systems; pesticides, biopesticides, and adjuvants; crop and commodity groups and crop consultants; and researchers at federal, state, university, Extension, and private institutions.

## Acknowledgments

The authors would like to acknowledge the following for the funding and support for the long-term establishment of the research capacity used in this project: The federal Hatch Act of 1887, as implemented through the USDA National Institute of Food and Agriculture (NIFA); the Tennessee Agricultural Experiment Station, and the University of Tennessee Department of Biosystems Engineering and Soil Science; The Ohio State University; The USDA-ARS Application Technology Research Unit at Wooster, Ohio; and the National Oceanic and Atmospheric Administration.

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