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RESEARCH ARTICLE

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Advances in developing a new test method to assess spray drift potential from air blast sprayers

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Abstract

Drift is one of the most important issues to consider for realising sustainable pesticide sprays. This study proposes and tests an alternative methodology for quantifying the drift potential (DP) of air blast sprayers, trying to avoid the difficulties faced in conducting field trials according to the standard protocol (ISO 22866:2005). For this purpose, an ad hoc test bench designed for DP comparative measurements was used. The proposed methodology was evaluated in terms of robustness, repetitiveness and coherence by arranging a series of trials at two laboratories. Representative orchard and vineyard air blast sprayers in eight configurations (combination of two forward speeds, two air fan flow rates, and two nozzle types) were tested. The test bench was placed perpendicular to the spray track to collect the fraction of spray liquid remaining in the air after the spray process and potentially susceptible to drift out of the treated area. Downwind spray deposition curves were obtained and a new approach was proposed to calculate an index value of the DP estimation that could allow the differences among the tested configurations to be described. Results indicated that forward speed of 1.67 m/s allows better discrimination among configurations tested. Highest DP reduction, over 87.5%, was achieved using the TVI nozzles in combination with low air fan flow rate in both laboratories; conversely, the highest DP value was obtained with the ATR nozzles in combination with high air fan flow rate. Although the proposed method shows a promising potential to evaluate drift potential of different sprayer types and nozzles types used for bush and tree crops further research and tests are necessary to improve and validate this method.

Additional key words: spray drift test bench; sprayer settings; nozzles; fan air flow rate; vineyard and orchard sprayers.

Abbreviations used: DEAB (Department of Agrifood Engineering and Biotechnology); DiSAFA (Department of Agricultural, Forest and Food Sciences); DPV (drift potential value); SDRT (spray drift reducing technology); SEM (standard error of the mean); SSO (specific sprayer output).

Authors' contributions: Conceived and designed the experiments: MGr, EG, PB, PM and MGa. Performed the experiments, acquisition, analysis and interpretation of the data: MGr, PM and MGa. Statistical analysis: MGr and MGa. Supervising and coordinating the research project: EG and PB. Wrote the paper: MGr.

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Introduction

Spray drift remains a major problem in applying agrochemicals because the pesticides may get deposited in non-target areas outside of the treated field and pose risks to the environment and bystanders (Nuyttens *et al.*, 2007). One of the goals of the 128/2009/CE European Directive for Sustainable Use of Pesticides (EC, 2009) is spray drift reduction and improved efficiency of pesticide application. This new regulation includes the definition, establishment, and quantification of buffer zones on the basis of quantitative information about the spray drift potential of every sprayer and configuration. According to ISO 22866:2005 (ISO, 2005), spray drift is defined as 'the quantity of plant protection product that is carried out of the sprayed (treated) area by the action of air currents during the application process'. In an orchard, this includes droplets which move horizontally through the orchard canopy and beyond the orchard as well as those which are above the tree leaf canopy (via direct spraying into the air or upward diffusion from the sprayed canopy) and move vertically into the atmosphere. Most spray drift involves droplets which move above the canopy for a part of or their entire pathway (Miller *et al.*, 2003).

Several studies have evaluated and quantified the effect of the different variables that strongly influenced spray drift; these factors may be categorised as follows: equipment and application techniques, spray characteristics, operator care and skill (Arvidsson *et al.*, 2011), and environmental and meteorological conditions. Nevertheless, classifying spray techniques is challenging because these vary greatly due to the influence of environmental conditions and crop growth and leaf canopy status of different bush and tree crop types (Ozkan & Zhu, 1998; Zande *et al.*, 2000, 2010; Balsari *et al.*, 2007).

Spray drift assessments are typically mandatory in regulatory evaluations of plant protection products at the European, country, and zonal levels, and field trial results are commonly used for registration purposes (Rautmann *et al.*, 2001; Zande *et al.*, 2007). However, spray drift studies may be conducted with a range of different reference conditions (wind speed, nozzle height, temperature, humidity, etc.). Consequently, differences arise between assessments depending on the choice of standard reference conditions for tests (Huijsmans & Zande, 2011).

Recently, many studies have focused on spray drift measurements and the classification of the spray drift of field crop sprayers (Hewitt *et al.*, 2001; Landers & Gil, 2006; Nuyttens *et al.*, 2007; Baetens *et al.*, 2009; Landers, 2010; Sehsah & Herbst, 2010). Researchers have proposed easy, repeatable, and precise methods as alternatives for spray drift measurement (Southcombe *et al.*, 1997; Zande *et al.*, 2002; Balsari *et al.*, 2007; Nuyttens *et al.*, 2009) based on spray drift potential.

The difficulties faced in spray drift measurement using boom sprayers are even higher in the case of field evaluation trials in orchards and vineyard sprayers. The great heterogeneity of cultures (olive trees, vineyard, fruit orchards, citrus, etc.), important variations during the crop season with large modifications in the canopy size and density, wide options of plantation layout and relative training system, great variability in terms of spray technology, and influence of selected operational parameters during the application process (nozzle type, working pressure, forward speed, air assistance, etc.) make it much more difficult to establish an objective and widely applicable method for spray drift measurement in these situations (García-Ramos *et al.*, 2009; Cunha *et al.*, 2012; Gil *et al.*, 2013; Salyani *et al.*, 2013).

Irrespective of the large list of variables affecting spray drift during orchard spray application, it is necessary to evaluate and clarify the objectiveness, effectiveness, and repeatability of the actual ISO 22866:2005 standard (ISO, 2005). Many problems were encountered during its application (Ravier *et al.*, 2005; Llorens *et al.*, 2016), being difficult to obtain objective and reproducible results even if all the stringent requirements were followed. Therefore, this study aims at developing and testing a possible alternative methodology for quantifying the spray drift potential in air blast sprayer applications to get objective results independent of the cultivar and canopy structure variations.

Material and methods

Technical characteristics of spray drift test bench

A test bench analogue to the one described in ISO22401:2015 (ISO, 2015), consisting in a metal frame equipped with slots to place artificial collectors and with a sliding cover actuated by a pneumatic system was used. The length of test the bench was 20.0 m, it was placed transverse to the sprayer's forward direction, away from a concrete flat lane used as a tractor track (Fig. 1A). Artificial collectors with a capture area of 153.86 cm^2 (Petri dishes of 140-mm diameter) aligned in a single array transverse to the sprayer's forward direction were placed at intervals of 0.5 m (±10 mm) along the test bench slots (Fig. 1B). The first collector (the one closest to the sprayer pass) was positioned at 1.5 m distance from the sprayer's outer nozzle(s). The samplers' position was 0.25 m above the soil (±50 mm). All collectors were initially covered using the stainless steel sliding plates of the test bench. The sprayer started the application 20 m before and stopped it 20 m after the position of the collector array. The actuator of the pneumatic system for opening the collectors was activated by the sprayer pass and it was placed at a relative distance from the test bench line, so that 4 s after the sprayer passed the perpendicular line of the bench the collectors were revealed. The time of 4 s for uncovering the test bench was defined based on preliminary experiences with the test bench for boom sprayers (Balsari *et al.*, 2007; Gil *et al.*, 2014) and air-assisted sprayers (Balsari *et al.*, 2012, 2014). All tests have to be conducted in condition of calm of wind (average wind speed < 0.5 m/s). Samples were collected 60 s after the opening of the system. Each Petri dish was then covered and placed in dry and dark conditions until the spray amount collected was determined.

To evaluate the functionality of the spray drift test bench and repeatability of the results, analogue trials were conducted both in Italy (DiSAFA facilities, University of Turin-) and Spain (DEAB facilities, Polytechnic University of Catalonia-).

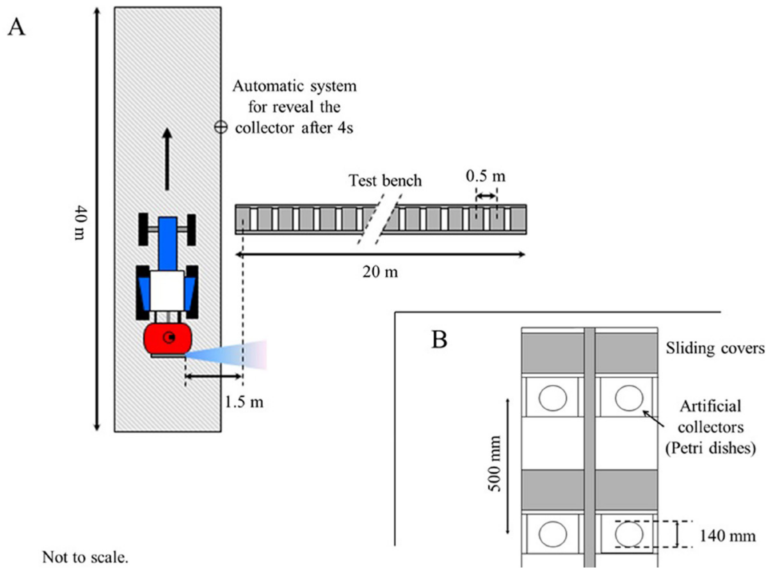

Figure 1. Drift test bench to assess spray drift potential from air blast sprayer: (A) layout scheme of test and (B) details of collectors and sliding covers.

Characteristics of air blast sprayers

Two different air blast sprayers, widespread and typically used in vineyard and orchard, were tested: (a) a mounted vineyard sprayer Dragone k2 500 (Dragone S.n.c., Castagnole Asti, AT, Italy) fitted with a 200 L polyethylene tank, a tower-shaped air conveyor (height of the top box 1300 mm) with an axial fan (diameter: 600 mm) provided with a two-speed gearbox that enables the horizontal air flow rate to be varied from 11,000 to 20,000 m^3/h and equipped with 6 nozzles on each side of the sprayer (vertical nozzles spacing 180 mm and highest positioned nozzle 1250 mm); and (b) a trailed orchard sprayer Fede Qi 90 Futur 2000 (Pulverizadores Fede S.L., Cheste, Valencia, Spain) equipped with a 2,000 L polyethylene tank, an axial fan (diameter: 900 mm) provided with a two-speed gearbox that enables the air flow rate to be varied from 29,000 to 46,000 m^3/h and equipped with 13 nozzles on each side of the sprayer, positioned in two lines (6 in the first line and 7 in the second one).

Sprayer configurations

The Dragone k2 500 sprayer was tested in four configurations resulting from combining (a) two air fan settings (air flow rate: 11,000 and 20,000 m^3/h) and (b) two nozzle types (conventional hollow cone ATR 80 orange and air induction, also called Venturi, hollow cone TVI 8002 manufactured by Albuz® CoorsTek, Evereux, France). The tests were performed at a working pressure of 1.0 MPa, and the nominal nozzle flow rates were 1.39 and 1.46 L/min, respectively. During all the tests, only six nozzles on the sprayer side facing the test bench were used; the nozzles orientation and sprayer position (0.40 m above the ground, measured from the sprayer's frame to the concrete flat lane) adopted were the same in both laboratories for all configurations and replicates tested. Furthermore, Fede Qi 90 Futur 2000 sprayer was tested by combining (a) two air fan settings (air flow rate: 29,000 and 46,000 m^3/h) and (b) two hollow cone nozzle types (conventional Albuz® ATR 80 red and air induction Albuz® TVI 80025). The tests were performed at a working pressure of 1.5 MPa, and the nominal nozzle flow rates were 2.33 L and 2.24 L/min, respectively. During the tests, only eight nozzles at the central position of the two lines (*i.e.*, four nozzles on each line) on the sprayer side facing the test bench were used; the nozzles orientation adopted was the same in both laboratories for all configurations and replicates tested.

For each thesis, five replicates of the tests were performed in each laboratory.

Influence of forward speed on spray drift potential

Although some field studies highlight that high forward speed during spray applications using boom sprayers increases both spray drift as well as the deposition (Gosh & Hunt, 1998; Dele *et al.*, 2005) others, conducted in orchard, specifies that higher forward speeds produce lower spray drift values due to the lower penetration of the air stream (bended backwards) through tree canopy (Triloff, 2015).

So, in order to investigate if forward speeds affect the generation of spray drift plume suspended in the air over the test bench, enhancing the influence of different sprayer settings on potential spray drift risk, all sprayers configurations were tested at two forward speeds: low 0.83 m/s (3 km/h) and high 1.67 m/s (6 km/h -close to the real forward speed generally adopted during spray application in vineyards and orchards-). According to the different forward speeds the Specific Sprayer Output (SSO), that is the amount of liquid sprayed during 10 mm of advancing forward, varies. In accordance to the low and high forward speed adopted in the trials using Dragone k2 500, the SSO ranged from 1,668 to 834 µL/cm (one-sided based on) employing ATR type nozzles and from 1,752 to 876 µL/cm (one-sided based on) when TVI type nozzles were tested. Assuming a hypothetical vineyard layout featuring 2.5 m distance between the rows, the application volume rates ranged from 1,334 to 667 L/ha when conventional nozzles were employed and from 1,402 to 700 L/ha using air induction nozzles. For Fede Qi 90 Futur 2000, the SSO ranged from 3,782 to 1,864 µL/cm of the sprayer advancing forward (one-sided based on) using ATR type nozzles and from 3,584 to 1,792 µL/cm (one-sided based on) when TVI type nozzles were tested. In this case, assuming a hypothetical orchard layout featuring 4.5 m distance between the rows, the application volume rates ranged from 1,657 to 828 L/ha using conventional nozzles and from 1,593 to 796 L/ha using air induction nozzles. Table 1 summarises all tests performed in both laboratories (DEAB and DiSAFA).

Characterisation of nozzle droplet size spectrum

The droplet spectrum and its variation were determined for each nozzle type used in the trials. Laboratory measurements of the droplet sizes were performed at DiSAFA using a Malvern Spraytech (Malvern Instruments Ltd., Worcestershire, UK) laser diffraction instrument. For each nozzle type, three nozzles were randomly sampled from a batch and for each single nozzle three measurements were performed to determine the values of the 10th-percentile (D[v,0.1]), 50th-percentile or volume median diameter (D[v,0.5]), 90th-percentile (D[v,0.9]), and V_{100} of each nozzle at the same pressure used in test bench trials: 1.0 MPa for ATR 80 orange and TVI 8002, and 1.5 MPa for ATR 80 red and TVI 80025.

Spray liquid and tracer concentration

Similar concentrations (5-6 g/L) of E-102 tartrazine yellow dye tracer [85% (w/w)] were added into the tanks in both laboratories. The spray deposits were quantified washing artificial collectors with a definite amount of deionized water and analysing the obtained liquid using a spectrophotometer (Thermo Scientific Genesys 20 in DEAB and Biochrom Lybra S11 in DiSAFA) set at a wavelength of 427 nm. Before each test, a blank sample procedure was arranged. Sprayed liquid were sampled directly from nozzles before and after the spraying process to determine the precise tracer concentration in the sprayed liquid in each test.

Weather conditions during trials

Wind speed and wind direction, with respect to the orientation of the spray track during the tests, were measured at 0.1 Hz frequency sampling rate. Also the air temperature and humidity were monitored during the tests. To record the weather conditions during the trials at DEAB's facilities, an automatic weather station (WatchDog weather station Model 2550, Spectrum Technologies, Inc., USA) was used. The weather conditions during the tests conducted at DiSAFA were recorded using a sonic anemometer (Gill Windsonic, Gill Instruments Ltd., Lymington, UK) combined with a Campbell CR200X data logger (Campbell Scientific, Logan, UT, USA) and Testo 625 thermo-hygrometer (Allemano Metrology, Torino, IT). In both laboratories, the weather devices were placed at 25 m distance downwind from the spray track (at the same side where the test bench was placed) at 2 m height above the ground.

The weather conditions were recorded for each replicate only during the period that the sprayer was spraying, plus 60 s after (the time required to allow all droplets suspended in the air to sediment), and then averaged. For each replicate the monitored period corresponds to 108 s or 84 s respectively if low (3 km/h) or high (6 km/h) forward speed were tested.

Assessment of spray drift potential and drift potential value (DPV)

The deposit on each artificial collector (expressed in µL/cm^2), was calculated according to the formula provided by ISO 22401:2015 (ISO, 2015).

Table 1. Variables of all configurations examined using the two sprayers.

Sprayer	Nozzle type	Fan air flow rate (m^3/h)	Forward speed (m/s)	SSO[a] (µL/cm)	Configuration Id[b]
Dragone k2 500	ATR 80 orange	20.000	0.83	1668	ATR3H
Dragone k2 500	ATR 80 orange	11.000	0.83	1668	ATR3L
Dragone k2 500	TVI 8002	20.000	0.83	1752	TVI3H
Dragone k2 500	TVI 8002	11.000	0.83	1752	TVI3L
Dragone k2 500	ATR 80 orange	20.000	1.67	834	ATR6H
Dragone k2 500	ATR 80 orange	11.000	1.67	834	ATR6L
Dragone k2 500	TVI 8002	20.000	1.67	876	TVI6H
Dragone k2 500	TVI 8002	11.000	1.67	876	TVI6L
Fede Qi 90 Futur 2000	ATR 80 red	46.000	0.83	3728	ATR3H
Fede Qi 90 Futur 2000	ATR 80 red	29.000	0.83	3728	ATR3L
Fede Qi 90 Futur 2000	TVI 80025	46.000	0.83	3584	TVI3H
Fede Qi 90 Futur 2000	TVI 80025	29.000	0.83	3584	TVI3L
Fede Qi 90 Futur 2000	ATR 80 red	46.000	1.67	1864	ATR6H
Fede Qi 90 Futur 2000	ATR 80 red	29.000	1.67	1864	ATR6L
Fede Qi 90 Futur 2000	TVI 80025	46.000	1.67	1792	TVI6H
Fede Qi 90 Futur 2000	TVI 80025	29.000	1.67	1792	TVI6L

[a] Specific Sprayer Output (SSO): amount of liquid (µL) sprayed during 10 mm of the sprayer advancing forward (one-sided). [b] The ID configuration is composed by three letters that means the nozzle type, one number that means the forward speed (expressed in km/h) and another letter that means the fan air flow rate (low and high).

Once the amount of tracer on every single collector was measured, the DPV was calculated by the following equation:

$$DPV = \sum_{i=1}^{n} D_i * Coeff$$

where *DPV* is the drift potential value in µL/cm^2 m; D_i is the spray deposit on a single deposit collector, in µL/cm^2; n is the number of collectors (40); and *Coeff* is a variable Coefficient calculated based on the cumulative deposition curve obtained from the spray deposit measured on every single collector.

The *Coeff* value calculation includes the distance reached by the spray drift, and it is calculated as follows:

$$Coeff = \sum_{n=1}^{10} Dst_{n*10}$$

where *Coeff* is the variable Coefficient in m, and Dst_n *10 corresponds to the value equal to the distance in meters from the outer sprayer nozzle where n * 10 % of the cumulative spray drift deposit calculated is achieved (*i.e.*, from 10% to 100% in intervals of 10%).

For example, Fig. 2 shows the visual pattern of two different cumulative deposition curves for two extreme and different spray applications tested and the related Coefficients used for the calculation. The higher the spray drift deposit accumulated close to the sprayer, the lower is the Coefficient applied in the calculation of the DPV.

This proposed Coefficient for calculating the DPV is aimed at weighing the deposition in relation to the distance from the sprayer achieved and penalising spray drift which reaches a longer distance rather than a shorter one.

Calculation of spray drift reduction

The spray drift reduction value was calculated based on the DPVs according to ISO 22369-1:2006 (ISO, 2006) formula, for each sprayer configuration at each laboratory.

The configuration chosen as reference spray system for calculating the spray drift reduction was the one featured by conventional nozzles combined with the high fan air flow rate for both sprayers tested. Based on the preliminary assessment, it was considered appropriate to always analyse the dataset separately for each forward speed adopted in the trials.

Statistical analysis

All the statistical analyses were performed using IBM SPSS Statistics for Windows (IBM Corp.,

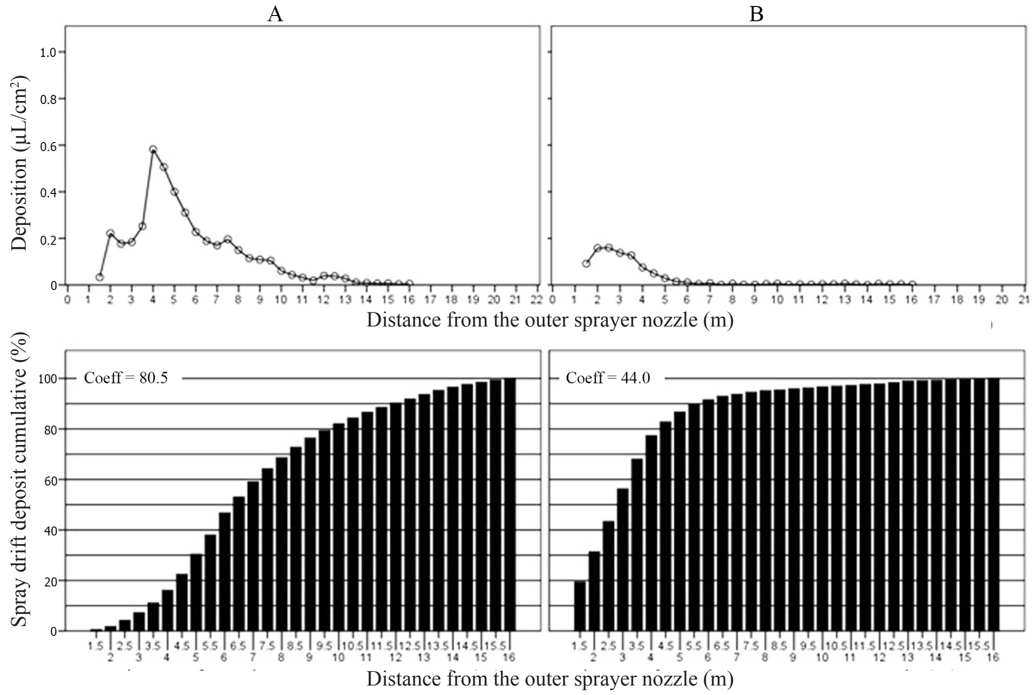

Figure 2. Example of two spray deposit profile and relative spray drift deposition cumulative curves obtained from different spray application technologies (A and B); these serve as the basis for the calculation of the coefficient (*Coeff*) used to obtain the Drift Potential Value (*DPV*) for each single replicate. A and B are the visual results of only one trial replicate, respectively for ATR6H and TVI6L configurations, using vineyard sprayer; the coefficient and then DPV calculations were performed separately for each replicate (160 replicates in total considering all the configurations tested).

2013). For each sprayer, the statistical differences among the DPVs of all tested configurations were evaluated using three-way Analysis of Variance (ANOVA) considering the laboratory, nozzle type, and fan air flow rate as a source of variation. The data were previously transformed (*ln* [DPV]) to achieve residual normality and homoscedasticity. Moreover, residuals analyses were also performed.

Results

Weather conditions during trials

For the DEAB tests, the average wind speed during all trials was 0.10 m/s, with a maximum value of 0.31 m/s. The temperature ranged from 8°C to 20°C, and the relative humidity was between 80% and 95%. For the DiSAFA trials, the average wind speed recorded during the tests was 0.51 m/s, with a maximum value of 0.88 m/s. The air temperature ranged between 18°C and 29°C, and the relative humidity was between 40% and 80%. In both laboratories the average wind direction was always between 64° and 118° relative to the travel direction of the sprayer (prevalent lateral wind respect orientation of the spray track).

Nozzles droplets spectra characteristics

Both conventional nozzles ATR (orange and red) produce very fine droplets as classified by Southcombe *et al.* (1997) to ensure excellent coverage and to be easily transported by the air of the sprayer fan towards the tree canopy. Such fine droplets are more prone to drift as the size of droplets both in terms of D[v,0.1] and D[v,0.5] presented values below than 100 µm and the D[v,0.9] value resulted less than 200 µm, meaning that all three droplet size parameters fell within the 200 µm threshold identified by Bouse *et al.* (1990) to indicate droplets more prone to drift (Table 2). Both Venturi nozzles TVI (8002 and 80025) produced coarser (C-class) droplets (Table 2): all three parameters measured resulted larger than those measured on ATR nozzles, showing D[v,0.1] values higher than 100 µm.

Vineyard sprayer

Drift Potential Value (DPV). The ANOVA results show that in the trials conducted at a forward speed of 0.83 m/s (3 km/h) (Table 3), significant effects of all the main factors, namely, the laboratory, nozzle type, and fan air flow rate on DPV (p<0.05) were

Table 2. Main characteristics of the nozzles used in the trials.

Nozzle type	Spray pressure (MPa)	D[v,0.1][a] (µm)	D[v,0.5][a] (µm)	D[v,0.9][a] (µm)	V100[b] (%)	Flow rate (L/min)	Spray angle (°)
ATR 80 orange	1.0	47	95	171	50.45	1.39	80
TVI 8002	1.0	190	606	1,271	2.42	1.46	80
ATR 80 red	1.5	32	86	173	57.64	2.33	80
TVI 80025	1.5	128	407	872	5.59	2.24	80

[a] D[v,0.1], 10% of droplets are smaller than this diameter; D[v,0.5], volume median diameter; D[v,0.9], 90% of the droplets are smaller than this diameter. [b] V_{100}: spray liquid fraction generated with small droplets (<100 µm).

detected; in contrast, there were no significant effects of the interaction among the considered factors. At a forward speed of 1.67 m/s (6 km/h) (Table 3), significant effects of the nozzle type and fan air flow rate on the DPV were detected; however, the laboratory did not show a significant effect on the DPVs. The DPV results obtained at DEAB and at DiSAFA were not significantly different. At this forward speed, the mean DPV resulted respectively 169 and 167 at DEAB and at DiSAFA laboratories. Irrespective of the fan air flow rate adopted, the mean DPV detected employing conventional nozzles -ATR80orange- (267 for DEAB and 273 for DiSAFA) was more than three-fold that using the air induction nozzles -TVI8002- (71 for DEAB and 60 for DiSAFA). This demonstrates the significant effect of using a low-drift nozzle (air induction) in reducing spray drift even in applications carried out without a target. Similarly, the use of a high fan air flow rate produced significantly higher DPVs (240 for DEAB and 204 for DiSAFA) in comparison to a low air flow rate (98 for DEAB and 130 for DiSAFA) regardless the nozzle type. In general, both laboratories obtained very similar results when the sprayer was operated at a forward speed of 6 km/h.

In general, Fig. 3 shows that the low fan air flow rate, combined with each nozzle type tested, produced mean DPVs significantly lower than those obtained adopting the high air flow rate, irrespective of the forward speed and laboratory. Keeping the same fan setting, the DPV achieved using air induction nozzles -TVI8002- was lower than that obtained with conventional nozzles -ATR80orange-. At the same time, the larger differences were measured between the DPV standard errors of mean (SEM) obtained using the conventional nozzles with respect to those found with air induction nozzles. In the tests conducted at 3 km/h (Fig. 3), the DPVs obtained in the two laboratories were

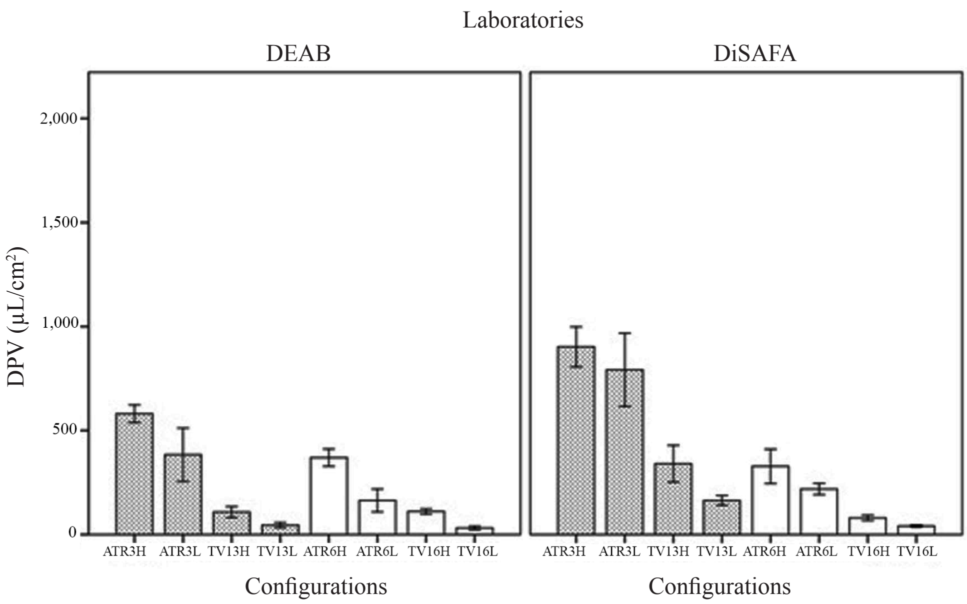

Figure 3. DPV values obtained at forward speed of 0.83 and 1.67 m/s (3 and 6 km/h) according to the configuration adopted in DEAB and DiSAFA trials using vineyard sprayer. The bars show the mean ± SE of the mean.

Table 3. Significance obtained in three-way ANOVAs for DPVs as affected by laboratory, nozzle type, and sprayer fan air flow rate using vineyard sprayer; results are categorized by forward speed (0.83 and 1.67 m/s). Data on DPV were ln-transformed before analysis.

Vineyard sprayer - Dragone k2 500				
Source	0.83 m/s		1.67 m/s	
	p (>F)	Statistical significance[a]	*p* (>F)	Statistical significance[a]
Laboratory	8.232E-06	***	0.602	NS
Nozzle type	5.498E-10	***	9.720E-08	***
Fan air flow rate	0.003	**	4.735E-04	***
Laboratory × Nozzle type	0.084	NS	0.808	NS
Laboratory × Fan air flow rate	0.423	NS	0.072	NS
Nozzle type × Fan air flow rate	0.484	NS	0.201	NS
Laboratory × Nozzle type × Fan air flow rate	0.702	NS	0.579	NS

[a] Statistical significance level: NS $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

not in agreement (*i.e.*, the DPVs obtained at DEAB for each sprayer configuration was much lower than that obtained at DiSAFA).

Spatial distribution of spray plume along the test bench. Figs. 4 and 5 respectively show the deposition curves obtained, in absence of target, for the configurations tested at the two laboratories using vineyard sprayer at 3 and 6 km/h. The greatest part of the deposition was located, in all cases, in the first few meters of the test bench; in particular, the deposition increases up to a peak positioned at a certain distance. When working at 3 km/h (), the peak position and the maximum amount of spray deposit measured along the test bench resulted different for the two laboratories. At a forward speed of 6 km/h, the deposition peak position was located within the first 5 m on the test bench regardless the sprayer configuration and the laboratory. After the peak, all the curves showed a progressive decrease of spray deposits along the test bench up to a distance of 16 m from the outer sprayer nozzle. However, the rate of decrease in the deposition as measured along the array of collectors varied depending on the sprayer configuration. In both laboratories, the rate of decrease was lower with conventional nozzles (ATR80orange) than with air induction nozzles (TVI8002). Furthermore, the use of a high air flow rate showed a slower decrease of spray deposits

Table 4. Significance obtained in three-way ANOVAs for DPVs as affected by laboratory, nozzle type, and sprayer fan air flow rate using orchard sprayer; results are categorized by forward speed (0.83 and 1.67 m/s). Data on DPV were ln transformed before analysis.

Orchard sprayer - Fede Qi 90 Futur 2000				
Source	0.83 m/s		1.67 m/s	
	p (>F)	Statistical significance[a]	*p* (>F)	Statistical significance[a]
Laboratory	0.001	***	0.817	NS
Nozzle type	0.002	**	2.523E-14	***
Fan air flow rate	0.004	**	6.508E-08	***
Laboratory × Nozzle type	0.886	NS	0.403	NS
Laboratory × Fan air flow rate	0.671	NS	0.958	NS
Nozzle type × Fan air flow rate	0.885	NS	0.981	NS
Laboratory × Nozzle type × Fan air flow rate	0.380	NS	0.281	NS

[a] Statistical significance level: NS $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

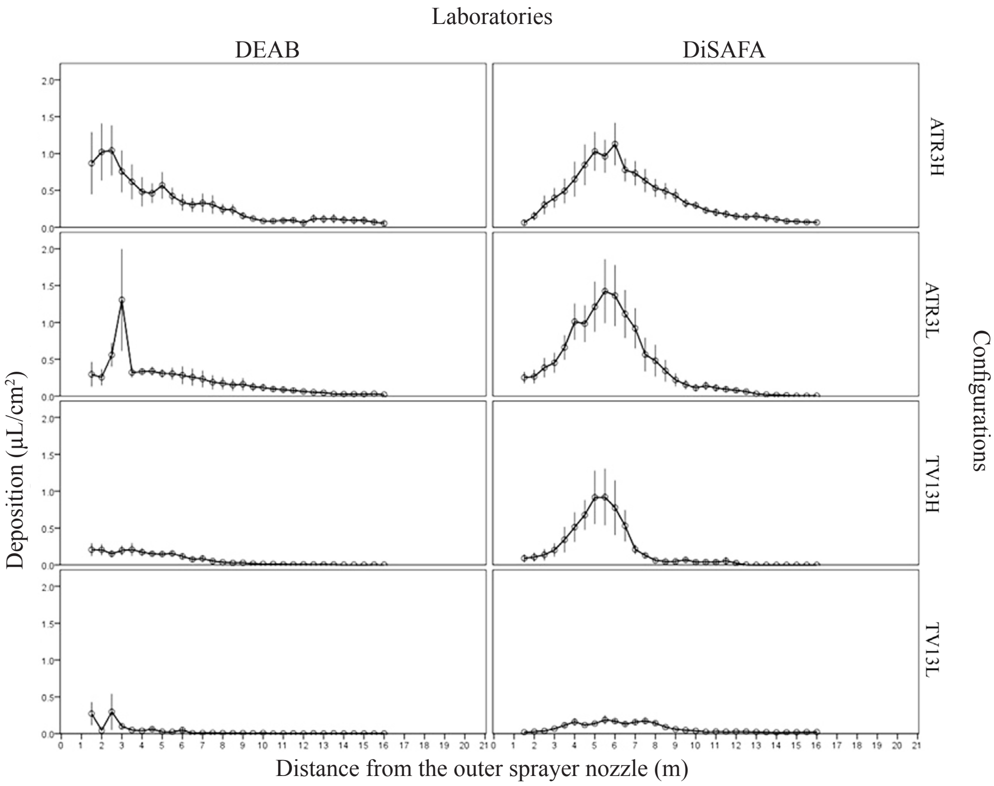

Figure 4. Spray deposit profiles obtained using vineyard sprayer at a forward speed of 0.83 m/s (3/km). The spray profile obtained from each configuration tested is shown for each laboratory (DEAB and DiSAFA). The mean ± SE of the mean (µL/cm^2) of the spray deposit on the collectors is represented at each distance from the outer sprayer nozzle.

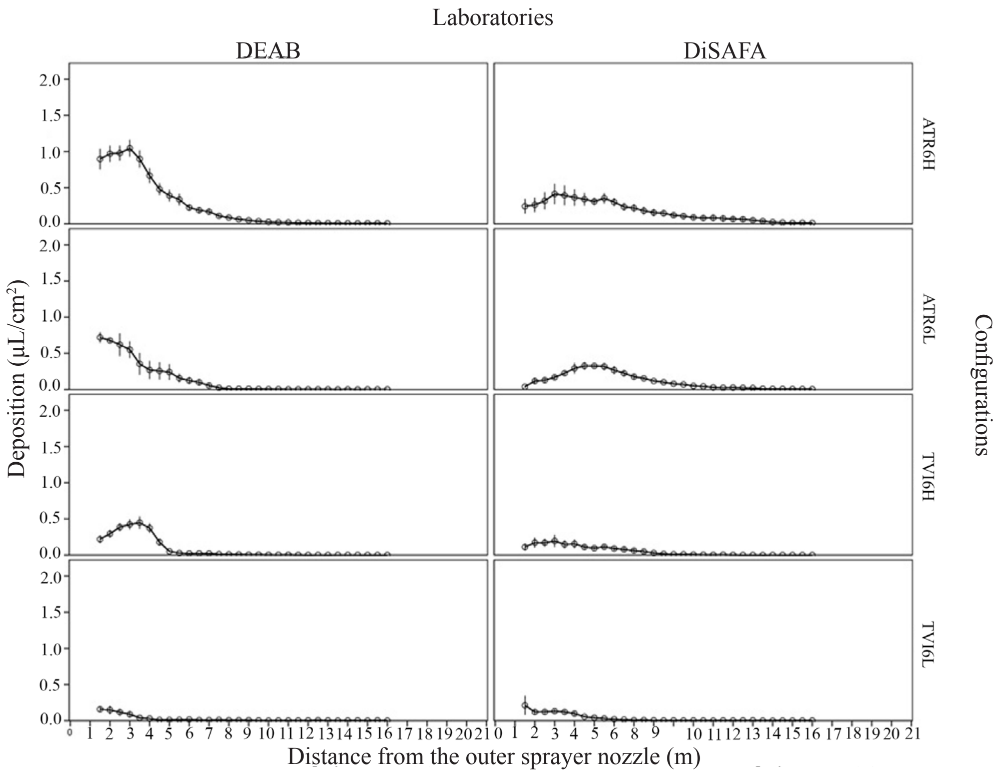

Figure 5. Spray deposit profiles obtained using vineyard sprayer at forward speed of 1.67 m/s (6 km/h). The spray profile obtained from each configuration tested is shown for each laboratory (DEAB and DiSAFA). The mean ± SE of the mean (µL/cm^2) of the spray deposit on the collectors is represented at each distance from the outer sprayer nozzle.

measured on the collectors in comparison to the tests conducted at low air flow rate. It follows that the ATR6H configuration showed the highest deposition values considering the sum of deposition measured on the entire array of collectors placed on the test bench; the total deposition decreased in the following configuration order: ATR6L, TVI6H and TVI6L.

Orchard sprayer

Drift Potential Value (DPV). As observed for the vineyard sprayer, the ANOVA results for the orchard sprayer also showed that significant differences ($p<0.05$) between laboratories were found at 3 km/h; however, no effect was found at 6 km/h (Table 4). The effects of the nozzle type and of the fan air flow rate on the DPVs were also studied. The tendency of DPVs resulted similar to that described for the vineyard sprayer. Regardless the fan air flow rate adopted, the mean of the DPV measured using conventional nozzles (422 for DEAB and 399 for DiSAFA) was more than six times greater than that observed employing air induction nozzles (62 for DEAB and 62 for DiSAFA). This confirmed the great effect of using a drift-reducing nozzle for reducing spray drift even in applications without a target. Similarly, the use of the high fan air flow rate produced significantly higher DPVs (336 for DEAB and 331 for DiSAFA) in comparison to the low air flow rate setting (148 for DEAB and 114 for DiSAFA), regardless the nozzle type, as shown by other authors (Wenneker *et al.*, 2005) showing similar results deriving from field trials (ISO22866) testing the effect of fan flow rates in combination with air induction nozzles.

In general, the tendency registered with the vineyard sprayer was confirmed testing orchard sprayer: low fan air flow rate, combined with each nozzle type tested, produced mean DPVs significantly lower than that obtained with high air flow rate, irrespective of the forward speed and laboratory (Fig. 6). The DPV measured employing the air induction nozzles (TVI80025) resulted lower than those achieved operating the conventional nozzles (ATR80red). Also in the case of the orchard sprayer when the tests were carried out at 3 km/h (Fig. 6), the DPVs obtained in the two laboratories showed some divergences (*i.e.*, DPVs obtained at DEAB for each configuration was much higher than that obtained at DiSAFA).

Spatial distribution of spray plume along the test bench. The variation in the deposits measured on the array of collectors placed transverse to the sprayer forward direction was plotted (Figs. 7 and 8) for representing the spray plume generated by all configurations tested at the two laboratories at 3 and 6 km/h. In general terms, a spray plume shape similar to that observed using the vineyard sprayer was achieved also employing the orchard sprayer: the greatest part of the spray deposition was located in the first few meters of the test bench, and the spray deposits measured on the test bench collectors increased up to a peak located at about 5 m from the outer sprayer nozzle (for tests made at a forward speed of 6 km/h). After the peak, all curves showed a progressive decrease along the distance up to 20.5 m from the outer sprayer nozzle. The tendency and rate decrease of deposits assessed along the test bench resulted similar in both laboratories, as already observed for the vineyard sprayer. Moreover, in this case, the SEM values of deposition on every single collector show better accuracy of the data at 6 km/h. Additionally, as previously mentioned in the vineyard sprayer's scatter plot analysis, at this forward speed, the SEM values of the deposition on each collector was higher for the configuration with conventional nozzles (ATR80red) than for that with air induction type nozzles (TVI80025).

Drift potential reduction

A comparison between the results obtained at DEAB and DiSAFA can be observed in, where the relative values of the spray drift reduction have been calculated based on the ATR3H (forward speed of 3 km/h) and ATR6H (forward speed of 6 km/h) configurations as a reference sprayer (value = 0). Regardless the sprayer, forward speed, and laboratory, the highest spray drift reduction percentage was always achieved using the air induction nozzles (TVI) in combination with low fan air flow rate, followed by the configuration of air induction nozzles combined with high fan air flow rate and conventional nozzles (ATR) in combination with low fan air flow rate. Furthermore, for spray drift reduction values, the greatest divergences between the laboratories were found at a forward speed of 3 km/h regardless the sprayer.

Discussion

As proved previously for boom sprayers by Gil *et al.* (2014), the proposed ad hoc test bench is also promising for the spray drift potential evaluation of air blast sprayers. The described methodology enabled to discriminate different sprayer configurations.

A study of the DPVs suggests that for the assessment of the spray drift potential in vineyard

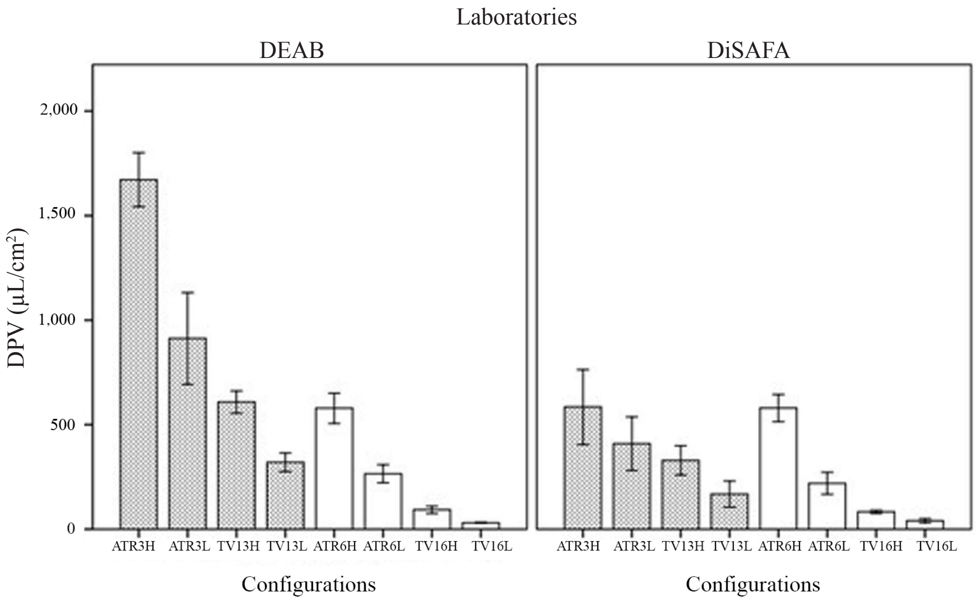

Figure 6. DPV values obtained at 0.83 and 1.67 m/s (3 km/h and 6 km/h) forward speed according to the configuration adopted in DEAB and DiSAFA trials using orchard sprayer. The bars show the mean ± SE of the mean.

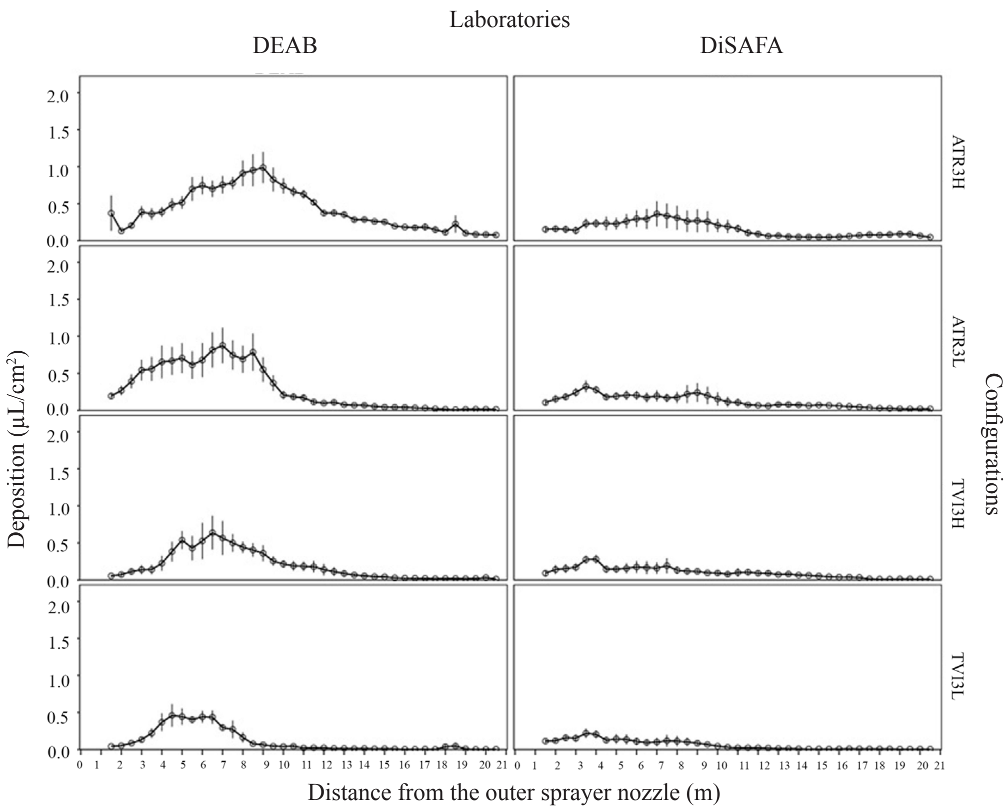

Figure 7. Spray deposit profiles obtained using orchard sprayer at forward speed of 0.83 m/s (3 km/h). The spray profile obtained from each configuration tested is shown for each laboratory (DEAB and DiSAFA). The mean ± SE of the mean (µL/cm²) of the spray deposit on the collectors

(Dragone k2 500) and orchard (Fede Qi 90 Futur 2000) sprayers using the test bench, it is better to work at forward speeds of 6 km/h because it allows the effect of the evaluated setting parameter (nozzle type and fan air flow rate) to be identified clearly irrespective of the laboratories considered. Considering the spray deposition profile (Figs. 4 and 7) obtained at 3 km/h forward speed, the differences between laboratories are due to the setting time of automatically opening the collectors: the sprayer covers half the distance compared to that covered at a speed of 6 km/h during the established test bench opening time of 4 s. Using a constant time for opening the test bench, at low forward speed, the sprayer fan is closer to the test bench when the collectors are revealed, strongly affecting the level of the spray drift deposition measured on it and in turn influencing the DPVs. On the other hand, when working at 6 km/h (Figs. 5 and 8), the relative differences observed among the profiles obtained at the two laboratories could be attributed principally to the environmental conditions during the trials. In fact, the variability of the obtained results at 6 km/h, represented by SEM values of deposition on each collector, was always lower in comparison to that obtained at 3 km/h for each sprayer configuration. The accuracy of the data obtained for each collector in the tests at 6 km/h could be an indicative parameter of the goodness of the proposed method for spray drift evaluation.

Considering the DPVs (Figs. 3 and 6) and the relative spray drift reduction (Table 5) obtained at 6 km/h, both sprayers show good similarity in the tendency of the obtained results at DEAB and DiSAFA, especially for the two configurations with the air induction nozzles (TVI: TVI6H and TVI6L). The configurations provided with conventional nozzles (ATR) showed greater divergences, variability among replicates, in both laboratories (ATR6H and ATR6L). The larger differences between SEM of the DPVs obtained using the conventional nozzles suggest that the variability of the measured data is linked to the higher fraction of small droplets, mainly prone to drift (V100 equal to 50.45% for ATR 80 orange and 57.64% for ATR 80 red, Table 2) as described by Zande *et al.* (2008; 2012) and Gil *et al.* (2014), who assumed a linear relationship between V100 and spray drift. This was also confirmed by orchard field spray drift measurements performed by Michielsen *et al.* (2009). Additionally, information about the influence of the droplet size spectrum on DPVs was obtained by analysing the gap between the DPVs obtained using ATR nozzles and those achieved using TVI nozzles: the DPVs were six-fold higher using the Fede Qi 90 Futur 2000 sprayer and three-fold higher using the Dragone k2 500 sprayer. In absence of target, the aforementioned magnitude could be in part ascribed to the influence of the axial fan diameter that produce different air flow volumes (Table 1). With the bigger axial fan mounted on the Fede Qi 90 Futur sprayer, higher spray drift potential was measured.

Table 5. Drift reduction values (%) obtained for each configuration tested at DEAB and DiSAFA laboratories using vineyard and orchard sprayers. The drift reduction values were obtained considering the ATR3H and ATR6H configurations as a reference at forward speeds of 0.83 m/s and 1.67 m/s (3 and 6 km/h), respectively.

Configuration	DEAB	DiSAFA
	Vineyard sprayer - Dragone K2 500	
ATR3H	0	0
ATR3L	33.9	12.2
TVI3H	81.3	62.3
TVI3L	92.2	81.8
ATR6H	0	0
ATR6L	55.7	33.2
TVI6H	70.1	75.7
TVI6L	91.5	87.5
	Orchard sprayer - Fede Qi 90 Futur 2000	
ATR3H	0	0
ATR3L	45.4	30.1
TVI3H	63.6	43.6
TVI3L	80.9	71.3
ATR6H	0	0
ATR6L	51.9	62.1
TVI6H	83.2	85.7
TVI6L	94.4	93.1

Furthermore, although the tests were conducted outdoor nearly in absence of environmental wind (all the parameters recorded in both laboratories were in agreement with the environmental condition requirement of ISO 22401:2015 standard), as already demonstrated in a previous study (Gil *et al.*, 2015), little changes in wind direction could strongly affect the spatial distribution of the spray deposition recovered along the entire bench and affect the DPVs themselves. As described by Ozkan & Zhu (1998), changes in wind velocity, air temperature, and relative humidity had much greater influence on the spray drift distances of fine droplets (< 100 µm diameter) than on larger droplets (> 200 µm diameter). So the difference between the laboratories in terms of the relative humidity and wind temperature could also affect the spray drift deposition

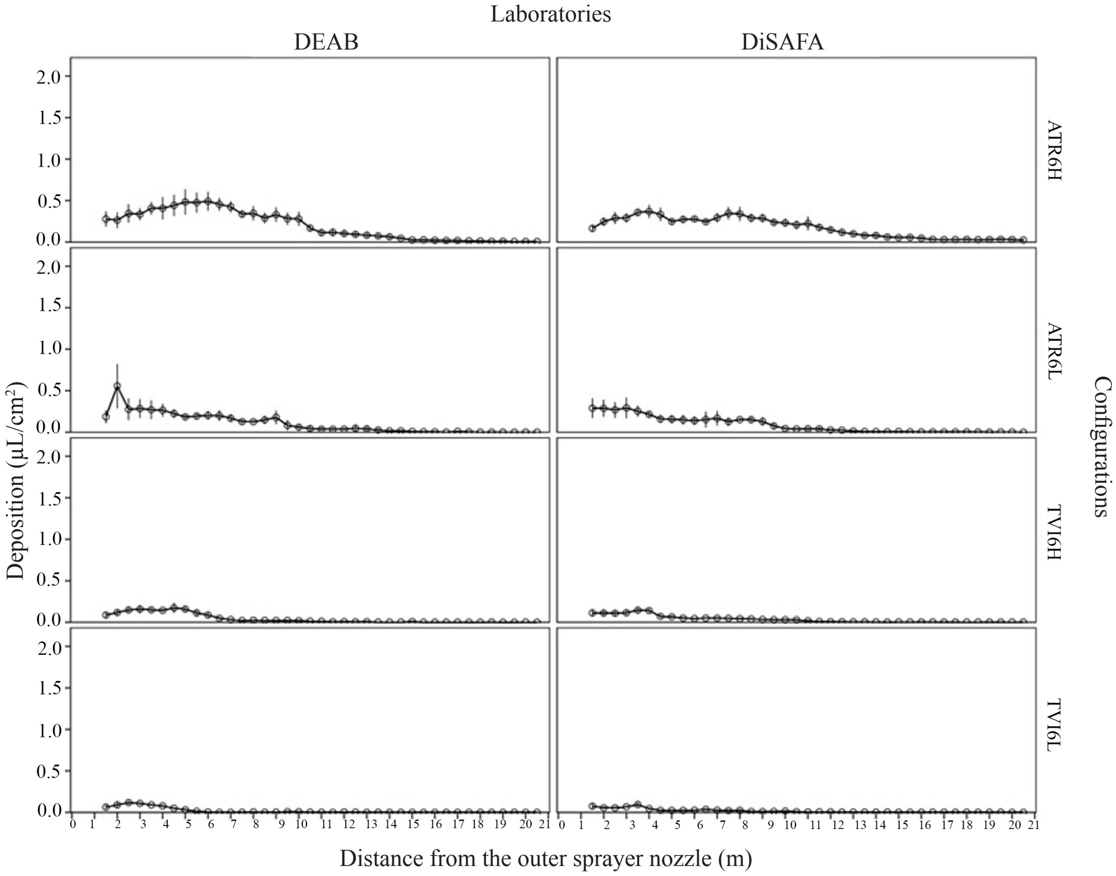

Figure 8. Spray deposit profiles obtained using orchard sprayer at forward speed of 1.67 m/s (6 km/h). The spray profile obtained from each configuration tested is shown for each laboratory (DEAB and DiSAFA). The mean ± SE of the mean (µL/cm^2) of the spray deposit on the collectors is represented at each distance from the outer sprayer nozzle.

and shape of the distribution along the test bench. These aspects become prominent when using conventional nozzles (ATR).

Simplifying, the differences obtained between laboratories could be due to the variable effect of some external technical and environmental factors during the tests; these factors interact during the trials and influence the spray drift deposition (*i.e.*, type of tractor used and weather conditions). In agreement with other authors (Hewitt *et al.*, 2001; Hofman & Solseng, 2001), the degree of influence of the external and internal (equipment and application technique) technical factors is directly linked to the liquid properties and nozzle design (droplet size distribution) with the applied pressure. In fact, the spray drift reduction values obtained using the TVI nozzles that produce very coarse droplets, irrespective of the fan air flow rate used and sprayer, differ between the two laboratories by not more than 5% (forward speed 6 km/h). On the contrary the drift reduction values obtained using ATR nozzles in combination with low fan flow rate differ between laboratories by more than 20% (ATR6H configuration used as reference). The fine droplets produced by the ATR nozzles (V_{100} equal to 50.45% and 57.64% respectively for ATR 80 orange and red), than those produced by TVI (V_{100} equal to 2.42% and 5.59% respectively for TVI 8002 and 80025), were strongly influenced by the framework condition even if in absence of environmental wind (average wind speeds less than 0.5 m/s). These combined effects, framework conditions and droplets spectra characteristics, result in a higher difference between the spray drift reduction values obtained in the two laboratories using conventional nozzles than using air induction nozzles (Table 5).

Nevertheless, it is interesting to note the similar tendency in spray drift potential reduction achieved in both laboratories depending on the configuration tested using the two types of sprayers (forward speed 6 km/h). This is in agreement with other studies that showed that the measurements of the fall-out drift can, in some cases, differ by as much as a factor of 10 for the same nozzle size and working pressure both for air blast sprayers (Zande *et al.*, 2012) and for boom sprayers (Arvidsson *et al.*, 2011). This difference could be attributed to weather conditions, spray application technology, and different measurement procedures (Nuyttens *et al.*, 2006).

Despite the influence of external and technical factors, the newly proposed DPV test methodology and calculation, based on the results obtained from experimental data, can discriminate among different sprayer configurations. In fact, the Coefficient used in DPV calculation allows configurations featured by the same total deposition but with different shapes of deposition along the distance to be discriminated. This is important because the shape of deposition along the test bench is directly linked to the configuration tested, and the DPV calculation method provided can take into account, along the whole test bench, the distance at which a specific amount of spray is deposited and how the total amount is distributed.

Considering that it is impossible to achieve standardised and identical environmental test conditions during outdoor trials, it is necessary to define a reference sprayer in terms of setting (*i.e.*, type of nozzle, operating pressure, volume of air flow rate) and type (*i.e.*, mounted, trailed, axial fan, individual air output) for each crop type (*i.e.*, orchard, vineyards, olive tree, citrus, hops, nursery tree plantation) to perform a useful evaluation of the spray drift reduction achieved by Spray Drift Reducing Technology (SDRT) tested. This has already been defined for boom sprayers according to ISO 22369-2:2010 (ISO, 2010). This is in line with the requirements of ISO 22866:2005 (ISO, 2005) and ISO 22369-1:2006 (ISO, 2006) for the comparative measurements. This means that for each country or region, it could be possible to define a different reference sprayer type and settings according to the most representative agricultural practice adopted in that region. This criteria is already adopted in the Netherlands, where the reference technique used for orchard spraying is a Munckhof cross-flow fan sprayer equipped with Albuz ATR lilac nozzles (Wenneker & Zande, 2008; Zande *et al.*, 2008; Doruchowski *et al.*, 2009; Michielsen *et al.*, 2009; Wenneker *et al.*, 2015) and, which produces a very fine spray at 7 bar operating pressure (Southcombe *et al.*, 1997), combined with the high fan gear box setting as in orchard trees full leaf situation.

The preliminary studies on developing a new test method to assess potential spray drift introduce a simple procedure for assessing the DPV and spray drift potential reduction of air blast sprayer in absence of target. The great diversity of plant species, they planting, training systems, different dimension (shape and density of the trees canopies) which are changing during the season, make it difficult to establish the objective classification and ranking of SDRTs to be tested. Therefore, on the basis of these trials, the proposed layout of a spray drift test bench, primarily developed for boom sprayers, and the new method of DPV calculation give an opportunity for the measurements of spray drift potential of air blast sprayers independent of tree canopy characteristics in an easy and quickly way. However not negligible differences were assessed between laboratories and big variability was observed among sediment drift curves, especially at lower forward velocity of the sprayer. These evidences underline the necessity of future focused studies to find the source of variability of the results and to make a more robust proposed method.

Nowadays, further studies are undergoing to properly setting the opening time of the test bench as a function of the sprayer forward speed tested, because DPV and spray drift reduction needs to be evaluated at usual application speeds (not only at 6 km/h). It will be also useful to investigate the suitability of the test bench to detect the spray drift potential risk from further types of air blast sprayers (*i.e.* pneumatic and cross flow fan sprayers). Moreover, air blast sprayers studies are underway to compare the spray drift potential risk obtained using the test bench (indirect spray drift assessment method) and the spray drift risk obtained by applying the ISO 22866:2005 (ISO, 2005) field test method (direct spray drift assessment method), as already done to check the efficacy and reliability of others indirect spray drift assessment methods used for boom sprayers (Nuyttens *et al.*, 2010, 2014).

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