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Toward a new method to classify the airblast sprayers according to their potential drift reduction: comparison of direct and new indirect measurement methods.

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Abstract

BACKGROUND: Drift is one of the most important issues to consider for realising sustainable pesticide sprays. This study proposes an alternative indirect methodology for comparative measurements of Drift Reduction Potential (DRP) generated by airblast sprayers, aimed at overcoming practical inconveniences and drawbacks of standardized ISO22866:2005. A test bench in the absence of target crop and wind was employed to measure Drift Potential Values (DPV). A variation to the proposed method that introduced a crop between sprayer and test bench device was considered to study the canopy effect (absence/presence) and to validate the method. In parallel, direct spray drift measurements (ISO22866) were performed to obtain the Drift Value (DV). Representative vineyard airblast sprayer was tested in four configurations (combination of two fan airflow rates and two nozzle types), under the three methods (direct and indirect) and were classified according to achieved drift reduction percentages (ISO22369-1:2013) and compared.

RESULTS: Indirect methods discriminated DPV from different nozzles (conventional, air induction) and fan airflow rate (High, Low) combinations. Indirect methods also showed that despite crop influence on drift amount, target absence has a negligible effect when used specifically for DRP determination/classification. In fact, identical DRP final classifications were achieved for the two methodology tested. Alternatively, all tested configurations resulted in lower DR values following the ISO22866 field method, which caused different final classifications due to the high dependence of results on external factors.

CONCLUSIONS: The alternative test bench methodology, characterized by the absence of target crop and calm of wind, was considered feasible for comparative measurements of airblast sprayers DRP.

Keywords: test bench method; spray drift potential; Drift Reduction Potential classification; vineyard target; nozzles; fan airflow rate;

Nomenclature	
CV	Coefficient of Variation
DSD	Direct Spray Deposition based on test bench measurements in absence and presence of canopy
DSD_{AC}	Direct Spray Deposition based on test bench measurements in Absence of Canopy
DSD_{PC}	Direct Spray Deposition based on test bench measurements in Presence of Canopy
DPV	Drift Potential Value based on test bench measurements in absence and presence of canopy
DPV_{AC}	Drift Potential Value based on test bench measurements in Absence of Canopy
DPV_{PC}	Drift Potential Value based on test bench measurements in Presence of Canopy
DV	Drift Value based on ISO22866:2005 field drift measurements
DRP	Drift Reduction Potential based on test bench measurements in absence and presence of canopy
DRP_{AC}	Drift Reduction Potential based on test bench measurements in Absence of Canopy
DRP_{PC}	Drift Reduction Potential based on test bench measurements in Presence of Canopy
DR	Drift Reduction based on ISO22866:2005 field drift measurements
PPP	Plant Protection Product
SDRT	Spray Drift Reducing Technology
SEM	Standard Error of the Mean
VMD	Volume Median Diameter

1 Introduction

Increased public concern has caused policy and regulatory institutions to enforce a series of actions aimed at reducing risks from Plant Protection Product (PPP) use. In 2009 the Council of the European Union adopted Directive 2009/128/EC on Sustainable Use of Pesticides (SUD) that highlighted pesticide drift risks generated during spray applications.[1] According to ISO 22866:2005, spray drift is "the quantity of PPP that is carried out of the sprayed (treated) area by the action of air currents during the application process".[2] Among the pollutants from PPP use, agrochemical spray drift continues to be a major challenge because pesticides can be deposited in undesirable areas and pose risks to both the environment and bystander.[3,4] Spray drift is a more constant threat in bush/tree crops than in arable field crops. In an orchard, spray by means of air-assistance is directed sideways and upwards into the canopy. Therefore, drift includes not only droplets that move horizontally through the canopy and beyond, but also droplets that move above the canopy (via direct spraying into the air or upward diffusion from the sprayed canopy) and vertically into the atmosphere. Most spray drift involves droplets that move above the canopy for part or all of their pathway.[5]

Different methods to measure spray drift, both direct as spray drift field measurements and indirect as drift potential laboratory measurements, have been described. Direct drift measurements from field experiments utilize the complex and time-consuming standardized protocol ISO 22866.[2,6-10] It provides results that are highly affected by external factors like environmental conditions during testing.[11] Moreover, direct drift experiments that compare different spray systems cannot be performed under identical environmental conditions and crop structures.[2,12,13] While ISO 22866 is useful to obtain information on the driftability of a specific sprayer configuration and on the amount of drift generated within a specific crop context, the wide variation of environmental conditions and crop structures makes it unsuitable for establishing any broad ranking or classification of Spray Drift Reduction Technologies (SDRT).[14] Therefore, SDRT performances are generally determined through many test replicates made under as similar as possible conditions and pair-wise comparison. As highlighted by Llorens et al. great effort is needed to collect spray drift data for ISO standard requirements, and demonstrate that such effort does not guarantee usefulness of the results.[15]

In contrast, indirect methods allow drift measurements to be conducted under comparable and repeatable conditions. Additionally, the methods allow several measurements to be taken quickly, under controlled environmental conditions, and absent of a canopy. Until now, various studies have proposed alternative indirect drift measurement methods that target easy, repeatable, and precise procedures, with a focus having been placed on drift measurement and classification of field crop sprayers.[16-20] Researchers have proposed the following as easy, repeatable, and precise alternative indirect test methods for drift measurement based on spray drift potential: Phase Doppler Particle Analyser (PDPA) laser measurement,[21-27] wind tunnel measurement,[28-37] and test bench measurement.[38-43] Test bench measurement was recently officially-adopted by an ISO working group (ISO TC23/SC6 WG 16) as a new method for measurement of potential spray drift of horizontal boom sprayers, and the standard protocol was recently published as ISO 22401:2015.[44]

The difficulties that arise during application of the standardized test protocol (ISO 22866)[2] to field drift measurement are particularly cumbersome in field evaluation trials of arboreal crops. Highly heterogeneous cultures (olive trees, vineyard, fruit orchards, citrus, high tree plantations for wood production, and so on) exhibit some of the most varied canopy structures and dimensions during the growing season.[45-48] In some instances during their life-cycles,[49] a variety of spray technologies and operating sprayer parameters may be required (such as nozzle type, working pressure, forward speed, air assistance, air fan volume adjustment, and so forth), which hinder establishment of an objective and broadly applicable drift measurement method for three-dimensional crops,[50-52] as carefully described by Llorens et al.[15] To both simplify the test procedure and reduce trial costs, authors began to develop and test an alternative methodology for quantifying the potential spray drift generated by a bush/tree crop sprayer capable of reproducing objective results independent of cultivar and canopy structure variations.[53-56] Simultaneously, they aimed to minimize result variability due to meteorological conditions. This new methodology implied the use of a test bench device similar to that described in the ISO 22401 standard,[44] and adopted a completely different trial layout and test protocol.[55] The trials would be performed absence of a crop and nearly absent of wind. The layout was specifically designed to avoid result variability due to canopy parameters (crop type, variety, density, growth stage, pruning system, and training technique) that affect spray drift amounts,[57,58] and to minimize the strong influence of meteorological conditions on sprayed airborne droplets generally,[59] and for wind velocity and direction in particular.[14] As with the ISO 22401 principle,[44] the method assumes that longer droplet lingering times may enlarge the risk of spray drift generated in windy conditions. So, the purpose of the bench is to collect and quantify the spray fraction defined as the “potential drift fraction”. It is the fraction that remains suspended over the test bench immediately after passage of the sprayer and can potentially be carried out of the target zone by environmental air currents.

The aim of this study was to verify the suitability of the test bench and its methodology for two purposes: comparative assessment of potential spray drift generated by airblast sprayers, and classification of different sprayer configurations/SDRT according to their relative Drift Reduction Potential (DRP). The effect of spray characteristics (nozzle type) and sprayer fan airflow rate on spray drift potential was evaluated using the test bench. In addition, to validate the test bench method, the effect of the presence of the target crop on spray drift potential was assessed by comparing drift potential values obtained from test bench trials conducted absent a crop, as originally designed and proposed by Grella et al.,[55] as well as in the presence of a target. Finally, the SDRT classification obtained from test bench measurements was evaluated by comparing it with that obtained from spray drift measurements applying the ISO 22866 standard protocol.[2]

2 Materials and methods

2.1 Technical characteristics of spray drift test bench device and potential spray drift measurements.

The test bench for measuring potential drift consisted of a series of aluminium modules (2.0 m length x 0.5 m width) that were connected to reach the required total test bench length. Bench length depends on the type and configuration of the airblast sprayer to be tested. Plastic holding slots (0.5 x 0.2 m in size) were positioned every 0.5 m along the aluminium test bench where artificial collectors (Petri dishes) were placed (Figure 1). A pneumatic system of stainless steel sliding plates enabled the slots and collectors to be covered or revealed. The system was automatically activated by the sprayer passing through a trigger system that was specifically designed for this purpose.[54]

The test bench was positioned transversely to the forward direction of the sprayer (Figure 2) with the artificial collectors 0.3 m above the soil (±50 mm). Ten test bench modules were used to achieve a total 20.0 m test bench. This minimum required length was determined following the proposed protocol, which establishes that collection of more than 97% of the spray can be demonstrated by comparing deposit amounts on collectors at different positions within the array. Specifically, this means expressing the deposit on the last collector (40th) as a percentage of the total deposits collected on all other array collectors (1st – 39th). The artificial collectors were 40 Petri dishes (14.0 cm diameter) aligned in a single array transverse to the forward direction of the sprayer (Figure 1). The first collector (one closest to the sprayer pass) was positioned 1.5 m from the outer nozzle(s) of the sprayer.

All collectors were initially covered using stainless steel sliding plates on the test bench. The sprayer began its liquid application 20 m prior to the collector array and continued for 20 m after it. The actuator of the pneumatic system to open the collectors was activated by sprayer passage and was positioned away from the test bench line. Four seconds after the sprayer nozzle(s) passed the perpendicular line of the bench, the collectors were simultaneously revealed to capture the droplet fraction remaining suspended over the bench. The 4 s time delay to uncover the test bench was chosen as the most suitable to work with a constant forward speed of 1.67 m s^{-1} (equal to 6 km h^{-1}), based on preliminary tests of different forward speeds.[55]

To measure Direct Spray Deposition (DSD) at different distances from the spray source, 20 Petri dishes were aligned in a single array transverse to the forward direction of the sprayer, and collectors were placed at intervals of 1 m (±10 mm) at ground level and 2 m from the test bench (Figure 2). Also in this case, the first collector was positioned 1.5 m from the outer nozzle(s) of the sprayer. This array of artificial collectors was maintained uncovered for the duration of trial replicate.

All tests were conducted in calm of wind (average wind speed < 1.0 m s^{-1}).

Samples were collected 120 s after the opening of the system. Each Petri dish was then covered and placed under dry and dark conditions until collected spray liquid amounts were measured.

2.1.1 Experimental design to validate the methodology for potential spray drift measurements through the study of canopy effect (absence and presence).

To validate the methodology for the measurements of Drift Potential Values (DPV) from airblast sprayer, as originally proposed by Grella et al.,[55] the effect of canopy (absence and presence), on final DPVs and DRPs results, during test bench trials were evaluated. So two parallel trial methodologies were arranged and compared at DiSAFA facilities (Grugliasco, Turin, IT).

The first trials consist in applying the original methodology,[55] positioning the test bench transversely to the concrete flat lane used as the tractor track without crop target between the sprayer and the test bench (Figure 2). The second trial methodology was a variation of original one,[55] introducing the crop between sprayer and test bench device; so the bench was placed transverse to the forward direction of the sprayer, away from the outermost row of the vineyard in such a way as to maintain 1.5 m between the first collector on the test bench and the outer nozzle of the sprayer (Figure 3). The experimental vineyard (45°03’54’’N 7°35’30’’E) used for test bench trials in presence of target was espalier-trained (cv: Barbera) at growth stage BBCH 75 “Berries pea-sized, bunches hang” [60], characterized by planting distances 2.8 m between rows and 0.8 m in rows with a resulting density of 4,464 vines ha^{-1}.

The outermost row of vineyard, used as target (Figure 3) was precisely characterized applying the Point Quadrat Technique (PQT).[61,62] A vertical frame containing a 0.2 m × 0.2 m grid was used to divide the canopies wall in quadrants. In each quadrant a metal stick was introduced horizontally across the canopy, and the number of leaves met by the stick or gaps were recorded. The PQT measurements were performed along 7 m length of canopies vines placed in front of the test bench. Based on these measurements, an accurate map of leaf layers and gaps of the target canopies in front of the test bench was obtained (Figure 4). Furthermore, the canopies wall (positioned from 0.6 m to 1.80 m above the ground) was characterized by 36% of gaps, 1.4 leaf layers and 0.602 Leaf Area Index (LAI - calculated according to Pergher and Petris)[63].

The same test bench device and the same test protocol described in section 2.1 was applied in both trials.

2.2 Drift measurements following ISO 22866

2.2.1 Test location and crop characterization

Tests were performed in an espalier-trained vineyard (cv: Vermentino) at growth stage BBCH 89 "Berries ripe for harvest"[60] located in Capalbio, Grosseto, Italy (42°24′47″ N 11°22′25″ E). Planting distances were 2.5 m between rows and 0.8 m in rows to yield a density of 5,000 vines ha^{-1}.

Canopy characterization was also performed using the Point Quadrat Technique,[62] and the measurement set-up was the same as explained in section 2.1.1 . The sampling parcels in the vineyard were randomly chosen and a total of five replicates were performed. For each replicate, 90 quadrant measurements were made along three linear metres of row at canopy wall positions between 0.6 and 1.8 m above the ground. Vineyard canopies were characterized by 6% gaps, an average of 3.1 leaf layers, and 1.9 of LAI.

2.2.2 Experimental plot layout

Field drift measurements were carried out according to ISO 22866.[2] Tests were performed by spraying the eight outer downwind vineyard rows (two sides of the first eight rows starting from the edge of the upwind area) equal in surface area to 1,200 m^2 (60 × 20 m) (Figure 5).

For each replicate, ground spray drift was measured in ten bare-soil sampling locations, placed at distances of 1, 2, 3, 4, 5, 7.5, 10, 15, 20, and 30 m downwind of the directly-sprayed area. At each location, six discrete ground level horizontal sampler Petri dishes (14.0 cm diameter) placed 1 m from each other were employed (Figure 5). Exactly, the first line of collectors was placed at 2.25 m from the outermost row, equal to 1 m distance from the sprayed area.

Two minutes after the vineyard plot had been completely sprayed, Petri dishes were covered and collected in closed dark boxes to prevent light degradation of the tracer.

2.3 Monitoring of weather conditions during trials, both indirect and direct

A weather station was employed to monitor environmental conditions during the trials. It was equipped with a sonic anemometer 232 (Campbell Scientific, Logan, UT, USA) to measure wind speed and direction relative to the spray track, and two thermo-hygrometer HC2S3 probes (Campbell Scientific) placed at two different heights (1 m between sensors) to measure air temperature and humidity. All measurements were taken at a frequency of 0.1 Hz and all data were recorded automatically by datalogger CR800 (Campbell Scientific). The environmental conditions were monitored for the full duration of each test replicate.

In particular, during the test bench measurements the weather station was mounted 5 m from the test bench in line with the last collector (40^{th}) placed on the test bench (Figures 2 and 3) and the mast supporting sensors was placed at 3 m above the ground. According to trial execution times, environmental parameters were measured for 40 s plus 120 s following spray distribution. The range of atmospheric conditions required by ISO 22401 (2015),[44] and used by other authors,[64] were adopted as acceptable conditions for execution of airblast sprayer drift trials using the test bench: (a) average wind speed (< 1 m s^{-1}); (b) maximum wind speed (< 1.5 m s^{-1}); (c) mean air temperature (between 5 and 35 °C); and (d) mean relative humidity (between 40 and 95%).

Differently, during direct measurement of spray drift (ISO22866 method) the weather station was positioned at the edge of the downwind area in the centre of the drift sampling area (30 m from the sprayed area) (Figure 5) and the mast supporting its sensors was placed at least 1 m above the canopy. According to the time required for spray application of the designed field trial area, the environmental parameters were measured for 324 s, plus another 120 s after spray completion. In this case the acceptable conditions for execution of trials defined by ISO 22866 (2005)[2] were adopted: (a) average wind speeds > 1 m s^{-1}, (b) wind measurement count at < 1 m s^{-1} (outliers) not to exceed 10% of all measurements recorded; (c) mean wind direction 90° ± 30° to the spray track; (d) frequency of non-centred wind direction (> 45°) to the spray track not to exceed 30% of data recordings; and (e) mean air temperature between 5 °C and 35 °C.[2]

2.4 Characteristics of airblast sprayer and configurations tested

The mounted vineyard airblast sprayer used for all tests was the Dragone k2 500 (Dragone S.n.c., Castagnole Asti, AT, Italy), equipped with a 200 L polyethylene tank and six nozzles on each side. A tower-shaped air conveyor with an axial fan (600 mm diameter) and two-speed gearbox enabled the airflow rate to vary from 11,000 to 20,000 m^3 h^{-1}.

Table 1 summarizes all the sprayer configuration tested based on various combinations of two different air fan settings (airflow rate: 11,000 and 20,000 m^3 h^{-1}) and two nozzle types (conventional hollow cone ATR 80 orange and air injection hollow cone TVI 8002 manufactured by Albuz® CoorsTek, Evreux, France). All tests utilized a working pressure of 1.0 MPa and nominal nozzle flow rates of 1.39 and 1.46 L min^{-1}, respectively. The size spectra of nozzle droplets were characterized at the same working pressure used for spray drift measurement, as described in detail by Grella et al.[55]

During the test bench trials, only the six nozzles on the sprayer side facing the test bench were activated (Figures 2 and 3), while during the ISO 22866 method trials, nozzles on both sides of the sprayer were activated (Figure 4). It derives that, according to the vineyard layout plantation, the applied volume rates resulted in the last case of 667 L ha^{-1} and 701 L ha^{-1} using respectively conventional hollow cone and air induction nozzles.

Five replicates were conducted for each sprayer configuration tested when the test bench was used, whereas three replicates were conducted under the ISO 22866 method.

2.5 Spray liquid and tracer concentration.

In all trials, both indirect and direct, E-102 Tartrazine yellow dye tracer −85% (w/w)- (Novema S.r.l., Torino, Italy) was added to the sprayer tank at a concentration of about 10 g L^{-1},[65] which was quantified on artificial collectors with a spectrophotometer UV-1600PC (VWR, Radnor, Pennsylvania, USA) set to 427 nm wavelengths for peak absorption of the Tartrazine dye.

Prior to each test, a blank Petri dish placed in the middle of the downwind sprayed area was processed and collected 30 s before spraying started. Sprayed liquid samples were also collected from the spray tank (sampled directly from a nozzle) before and after spraying to ascertain the precise tracer concentration at the nozzle outlet for each test replicate.

2.6 Spray drift deposition assessment.

The deposit on each artificial collector (Di), expressed in µL cm^{-2}, was calculated according to ISO 22401 as follows:[44]

$$D_i = \frac{(p_{smpl} - p_{blk}) * V_{dil}}{p_{spray} * A_{col}} \quad (1)$$

where D_i is the spray deposit on a single deposit collector, expressed in µL cm^{-2}; p_{smpl} is the absorbance value of the sample (adim.); p_{blk} is the absorbance of the blanks (adim.); V_{dil} is the volume of the dilution liquid (deionized water) used to dissolve the tracer deposit from the collector in µL; p_{spray} is the absorbance value of the spray mix concentration applied during testing and sampled at the nozzle outlet (adim.); and A_{col} is the projected area of the collector detecting the spray drift (Petri dish) in cm^2.

2.7 Drift values calculation

2.7.1 Drift Potential Values –DPV-: indirect method (test bench)

Once the tracer amount on every collector was measured, the Drift Potential Value (DPV) was calculated using the methodology proposed by Grella et al. as follows:[55]

$$DPV = \sum_{i=1}^{n} D_i * Coeff \quad (2)$$

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 each collector.

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

$$Coeff = \sum_{n=1}^{10} Dst_{n*10} \quad (3)$$

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 (from 10% to 100% in 10% intervals).

2.7.2 Direct Spray Deposition: indirect methods (test bench)

For each replicate, drift (µL cm^{-2}) deposited at distances downwind of the spray source were measured from each uncovered Petri dish and used to describe the Direct Spray Deposition (DSD) curve. Following other authors,[12] we deemed the surface area under the spray deposit curve as most characteristic of near-field sedimentation. The DSD was then calculated by numerical integration of the sedimentation curves, with adaptations as proposed by Grella et al.[13] The methodology allowed approximation of the definite integral using the mid-ordinate rule.

The calculation was performed as follows:

division of the total ground deposition curve interval [*a*,*b*], into *n* equal intervals of width

$$h = \frac{b-a}{n} \quad (4)$$

where h is equal to 100 cm; a correspond to the distance (1 m) from the outer nozzle(s) of the sprayer; b corresponds to the distance (21 m) from the outer nozzle(s).

The midpoints of the intervals were determined as follows:

$$x_1 = a + \frac{h}{2}\; x_2 = a + \frac{3}{2}h\; x_3 = a + \frac{5}{2}h\; \ldots\; x_n = a + \frac{(2n-1)}{2}h \quad (5)$$

where x_1, x_2, x_3, …, x_n are the midpoints of the equal intervals h width, included in [a,b] interval.

The calculation of the sum of the areas of the rectangles followed:

$$S_n = h * [f(x_1) + f(x_2) + f(x_3) + \ldots f(x_n)] \quad (6)$$

where S_n is the sum of the rectangles; h are the rectangle bases (1 m); and $f(x_1)$ $f(x_2)$ $f(x_3)$ … $f(x_n)$ are the rectangle heights.

2.7.3 Drift Values –DV-: direct method (ISO22866)

After the tracer amount on each collector was measured, the mean of values was calculated from the six Petri dishes situated at each downwind position. To derive comparable spray drift curves for each tested configuration, the amount (µL cm^{-2}) obtained from each replicate was normalized to express ground sedimentation at a reference spray volume of 600 L ha^{-1}. For each replicate, we also calculated the numerical integral of the spray drift curves to achieve its corresponding Drift Value (DV).[12] The DVs for ground spray drift curves were calculated by the same way as for ground drift curves Grella et al.[13] As described in section 2.6.1 (equations 4-6), an approximate definite integration using the mid-ordinate rule was performed.

2.8 Calculation of spray drift reduction and classes achieved

The DRP_{AC}, DRP_{PC}, and DR values were derived from DPV_{AC}, DPV_{PC}, and DV values, respectively, according to the ISO 22369-1:2006 formula[66] for each indirect and direct test method used and each configuration tested. Classification is determined from comparison of the spray drift reductions achieved using the reference spray equipment (conventional nozzle ATR80 orange in combination with a high fan airflow rate) and a chosen candidate sprayer configuration. The ISO22369-1 defines reduction classes A to F as follows: A ≥ 99 %, B 95 % ≤ 99 %, C 90 % ≤ 95 %, D 75 % ≤ 90 %, E 50 % ≤ 75 % and F 25 % ≤ 50 %.

2.9 Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows.[67] The data were tested for normality using the Shapiro-Wilk test and by visual assessment of the Q-Q plots of residuals for DSD, DSD_{AC}, DSD_{PC}, DPV, DPV_{AC}, DPV_{PC}, and DV. Natural logarithm transformation (ln […]) was used to achieve residual normality and homoscedasticity of all data. Residuals analyses were also performed.

First, to determine whether absence or presence of canopy was associated with the total deposition assessed on the permanently uncovered collector array, a one-way Analysis of Variance (ANOVA) was performed on the DSD values with absence or presence of canopy as the fixed factor. To discern if spray application technique (tested configurations) was associated with direct spray deposition, two one-way ANOVA were performed on DSD_{AC} and DSD_{PC} values, respectively, with tested configurations as the fixed factors.

Second, a three-way ANOVA with presence or absence of the canopy, nozzle type, fan airflow rate, and their interactions as fixed factors was performed of DPV to investigate the effect of assessment method (test bench trials in absence or presence of canopy), nozzle type, and fan air flow rate. To study the effect of application technique (combination of different nozzle type and fan airflow rate), two one-way ANOVA tests were performed of DPV_{AC} and DPV_{PC} values, respectively, with the tested configuration as the fixed factor. The Ryan-Einot-Gabriel-Welsch procedure based on an F test (FREGW) was performed on DPV_{AC} and DPV_{PC} values to determine differences among the configurations tested.

Third, a two-way ANOVA with nozzle type and fan airflow rate, and their interactions as the fixed factor was performed on DV to investigate the effect of spray application technique. Finally, a one-way ANOVA was performed on DV with configurations tested as the fixed factor to study the effect of application technique (combination of different nozzle type and fan airflow rate). In this case, a FREGW post-hoc test was performed on DV values to determine the differences among the configurations tested.

Statistical significance in all cases was when $p < 0.05$.

3. Results

3.1 Weather conditions

During test bench replicate trials in either target absence or presence, the acceptable conditions for test bench measurements were met (Tables 2 and 3). The test bench trials performed absence of target canopies experienced maximum and minimum wind speeds of 0.78 and 0.01 m s^{-1}, respectively; across test replicates, the highest average wind speed was 0.43 m s^{-1} (Table 2). The mean prevalent wind direction ranged between 58° and 321° relative to the spray track (driving direction from Nord-East to Nord-West – Figure 2), while temperature and relative humidity ranged from 12.1 to 15.0 °C and from 57.4 to 79.0 %, respectively. The wind speeds monitored during the canopy present test bench trials were, in general, slightly higher than those monitored in the absence of a canopy; maximum and minimum wind speeds were 1.50 and 0.01 m s^{-1}, respectively, and test replicates averaged top wind speeds of 0.71 m s^{-1} (Table 3). Although the prevalent wind direction during the trials was lateral to the spray track, the mean wind directions measured during the canopy present trials ranged between 78° and 254° relative to the travel direction of the sprayer (driving direction from East-Nord-East to West-South-West – Figure 3). Temperature and relative humidity values ranged between 12.1 and 16.8 °C and between 48.1 and 84.6 %, respectively. Furthermore, the same tests were replicated under very similar air temperatures and relative humidity readings (replicate differences never exceeded the extreme of 4.4 °C and 18.2%, respectively).[44,64]

Also the "acceptable conditions for field measurement of spray drift" per ISO 22866 were accomplished, conducting trials at consistent (outliers across all replicates varied less than 9.7 % from the range) mean wind speeds above 1 m s^{-1} (range from 1.27 m s^{-1} to 3.08 m s^{-1}) (Table 4). Finally, all other parameters conformed to ISO 22866 requirements: wind direction measured between 60.2° and 102.2° relative to the spray track (90 ± 30° mandatory); proportion of non-centred winds (wind direction > 45° to the spray track) comprised less than 25.6 % of the total; mean temperatures ranged between 22.2°C and 24.6°C.

3.2 Direct Spray Deposition (DSD) and spray plume spatial distribution along the test bench

Figures 6 and 7 compare the deposition curves generated from the collector array left uncovered throughout trial duration to measure Direct Spray Deposition (DSD) at different distances from the spray source, as well as the curves from collectors aligned inside the test bench slots that were initially covered and then revealed 4s after sprayer passage (per test bench protocol). Figure 6 displays the deposition curves absent a canopy, while Figure 7 depicts the curves from trials with the canopy present (espalier-trained vineyard BBCH 75).

In all cases, the largest DSD was found in the first few meters of the spray source. As expected, within 1 and 6 to 8 m—depending on sprayer configuration tested—the amount of DSD measured on the permanently uncovered collectors (black dots) was higher than that measured on the collectors revealed 4s after sprayer passage (red dots). On the other hand, irrespective of configuration tested (Figures 6 and 7), the deposition amounts shown (red and black lines) are very similar at 8 m from the spray source. A possible interpretation of this results is that deposits far from the spray source is mainly composed of the finest droplets; finest droplets remained suspended in the air for a longer time after the sprayer pass and were more susceptible to air currents transport far away from the spray source,[68] regardless of target presence or absence. On visualization, the principal difference between the target absent DSD_{AC} (Figure 6) profile and the DSD_{PC} target present (Figure 7) profile is curve shape. In particular, without regard for configuration, the black lines in Figure 6 increase to a peak positioned at a distance unrelated to the position of a collector, while the black lines in Figure 7 peak at the first collector position (1.5 m) because the airflow of the sprayer fan was mitigated by the target vineyard canopies. The influence of vineyard canopies was further confirmed by ANOVA (Table 5). It showed a significant effect from the presence or absence of a target on DSD ($p<0.01$), with mean DSD_{PT} less than DSD_{AC} at 444 and 674, respectively.

Separate ANOVA analyses of DSD derived from the two test bench trial layouts (target presence or absence) (Table 6) revealed no significant effect from the tested configurations for either DSD_{AC} or DSD_{PC} ($p>0.05$). While the configurations tested using both test bench trial layouts generated differently-shaped DSD curves (black curves) (Figures 6 and 7) and different DSD values (Table 5), no useful information about sprayer configuration-specific spray drift performance was gleaned from the DSD results (Table 6).

Various considerations were deduced from visual examination of the spray plume spatial distributions along the test bench. Figures 8(a) and 9(a) display the deposition curves obtained for configurations tested in the absence and presence of a canopy, respectively. In general, both test bench trial layouts produced very similar results overall, despite differences in deposition amounts along the test bench collector array as a function of test bench layout. As Figures 8(a) and 9(a) demonstrate, the rate of deposition decrease varied with sprayer configuration, while the proportional decrease among all tested configurations was similar for both test bench trials. The rate of decrease in both trials layouts was lower with conventional nozzles (ATR80 orange) than it was with air induction nozzles (TVI8002), and when the high fan sprayer airflow rate was used as compared to the fan sprayer set at the lower airflow rate. From this follows that the ATR6H configuration resulted in the highest depositions when the sum of spray deposits along the entire collector array on the test bench was considered. Total deposition decreases in both bench trial layouts resulted in the following large to small ranking of the configurations: ATR6H, ATR6L, TVI6H, and TVI6L.

3.3 Drift Potential Value –DPV-

The results obtained from ANOVA analysis of DPV, calculated from test bench deposition curves, detected a significant effect ($p<0.01$) from all considered factors: target absence or presence, nozzle type, and fan airflow rate (Table 7). In contrast, there were no significant effects from the interaction among the considered factors. The DPV results obtained from test bench measurements in target absence (DPV_{AC}) and in target presence (DPV_{PC}) differed significantly. Mean DPV was 177 for DPV_{AC} and 146 for DPV_{PC}. Regardless of fan airflow rate, the mean DPV using conventional ATR80 orange nozzles was more than four-fold (287 for DPV_{AC} and 241 for DPV_{PC}) those DPVs using air induction TVI8002 nozzles (67 for DPV_{AC} and 50 for DPV_{PC}). This demonstrates the significant effect of using a drift-reducing nozzle (air induction) to reduce spray drift in the presence or absence of a target, which confirmed the findings of other authors.[69,70] Similarly, regardless of nozzle type, high fan airflow rates produced significantly higher DPVs (221 for DPV_{AC} and 176 for DPV_{PC}) *versus* low airflow rates (133 for DPV_{AC} and 115 for DPV_{PC}).

The previous results seem to confirm the known effects of nozzle type and fan airflow rate on DPV reduction.[39,40,55,56] In addition, the ANOVA analyses presented in Figures 8(b) and 9(b) demonstrate the significant effects ($p<0.001$) of sprayer configuration (combination of different nozzle types and fan airflow rates) on both DPV_{AC} (Figure 8(b)) and DPV_{PC} (Figure 9(b)). Furthermore, the post-hoc analysis on DPV_{AC} and DPV_{PC} showed that each configuration differs significantly from the others; the test bench allowed sprayer apparatuses to be compared under conditions similar to field operations, and not limited to a single sprayer parameter. Similar to the deposition results obtained from the test bench (Figures 8(a) and 9(a),) DPV_{AC} and DPV_{PC} configuration decreases rank as follows from large to small: ATR6H, ATR6L, TVI6H, and TVI6L (Figure 8(b) and 9(b)).

3.4 Drift Value (DV)

Figure 10(a) displays plots of the mean spray drift ground deposits measured at different distances downwind of the sprayed area. They correlate to plumes generated while spraying a vineyard crop with a Dragone k2 500 sprayer. As with spray drift measurements using indirect test methods, drift curves derived from field trials following the ISO 22866 methodology[2] resulted in lower rates of ground deposition decrease with conventional nozzles (ATR80 orange) than with air induction nozzles (TVI8002). Furthermore, high airflow rates showed that collected spray deposit decreases, as compared to tests conducted at low airflows. This tendency was confirmed by ANOVA (Table 8) that made evident the significant effects from the main factors tested: nozzle type and fan airflow rate ($p<0.01$). In contrast, no significant effects were found among the considered factor interactions. Even though the ANOVA results (Figure 10(b)) indicated that configurations significantly affected DV (p<0.001), the post-hoc analysis showed only configurations ATR6H and TVI6L differed significantly. In fact, configuration ATR6L was not significantly different from configurations ATR6H and TVI6H; at the same time, configuration TVI6H did not differ significantly from configurations ATR6L and TVI6L. Nonetheless, and like the results obtained for DPV_{AC} (Figure 8(b)) and DPV_{PC} (Figure 9(b)), the DV decreases resulted in the following configuration ranking (large to small): ATR6H, ATR6L, TVI6H and TVI6L (Figure 10(b).

3.5 Comparison of drift assessment methods: Drift Reduction Potential and classifications obtained.

A comparison of drift potential measurements (DPV_{AC} and DPV_{PC}) obtained from indirect test methods with those obtained from direct methods (DV) can be observed in Table 9. The Coefficient of Variations (CVs) measured between 30.7% and 10.7%, which demonstrated generally higher values for conventional *versus* air induction nozzles. This behaviour is not necessarily attributable to result dependence on external factors, as is especially true in direct measurement of spray drift. In this case, the CV percentages aligned, and in some cases were much lower, with those obtained by other authors performing indoor trials using a test bench for boom sprayers who found CV values between 9.7% and 71.0%.[64]

For each test method and configuration tested, the relative percentages of spray drift reduction (DRP_{AC}, DRP_{PC} and DR) have been calculated based on reference sprayer ATR6H (value = 0). Regardless of test methodology, the highest spray drift reduction was always achieved when air induction nozzles (TVI8002) were used in combination with a low fan airflow rate (TVI6L candidate configuration), followed by air induction nozzles combined with a high fan airflow rate (TVI6H candidate configuration), and ending with conventional nozzles (ATR80 orange) combined with a low fan airflow rate (ATR6L candidate configuration). Results did not differ when DRP_{AC} and DRP_{PC} values were compared within the configuration tested. Achieved drift reductions potential were as follows: 87.1% DRP_{AC} and 86.6% DRP_{PC} for TVI6L, 75.1% DRP_{AC} and 78.7% DRP_{PC} for TVI6H, and 37.3% DRP_{AC} and 33.9% DRP_{PC} for ATR6L. Both indirect methods yielded the same final classification:[66] classes F for ATR6L, and D for TVI6H and TVI6L configurations.

Nevertheless, some considerable differences were detected in the results from the indirect *versus* direct assessment methods. The test bench method in both layouts (absence and presence of target) resulted in a more pronounced effect from nozzle type on DRP than did the field experiments (direct test method). The drift reductions achieved for direct spray drift measurements were as follows: 59.9% DR for TVI6L, 45.6% DR for TVI6H, and 27.2% for ATR6L. This effect led to different final classifications[66] for configurations tested under ISO 22866:[2] class F for ATR6L, F for TVI6H, and E for TVI6L.

4. Discussion

Test bench measurements using airblast sprayers confirm that finer droplets (conventional nozzles) resulted in higher potential drift values, in agreement with other authors' results (Figure 8 and 9). [40,64,70] Indeed, spray drift differences increased with higher airflow rates (Table 9) because it propelled droplets farther.[71] In particular, the results obtained when the test bench method was applied in the presence of a canopy (Figure 9) confirmed the field trial finding of other authors that high fan volumes increase drift losses.[13,63,72-74] At the same time the comparison of the originally-designed test bench trials (absent a target) (Figures 6 and 8) to a modified test bench trials, that foresee the presence of real vineyard target, (Figures 7 and 9) verified that the target exerted a significant influence both on the amount of direct spray deposition (DSD) on the permanently uncovered collector array (Table 5) and on the DPVs (Table 7) measured on the collector array placed inside the test bench and revealed 4s after sprayer passage. These findings underscored the capability of canopies to entrap spray particles,[75-77] and to reduce both DSD_{PC} (Table 6) and DPV_{PC} (Table 9). Of interest is that no airblast sprayer configuration tested produced statistical differences for either DSD_{AC} or DSD_{PC} (Table 6). This suggested that no potential drift risk information can be obtained from specific sprayer configurations or SDRTs tested when the testing conditions include a single pass in front of an array of permanently uncovered collectors and in calm of wind. In particular, the absence of different DSD_{PC} values for the various configurations tested might be attributable to the small amount of liquid sprayed (single alley sprayed using just one side of sprayer) during calm wind conditions that have counteracted the proven spray drift differences usually associated with nozzle type.[22] Normally, increased wind speed enhances the drift reductions of air induction nozzles because large particle size impacts off-target drift more in windy conditions and therefore, plays a strong role during spray drift generation.[13,78,79] On the other hand, DPV_{AC} (Figure 8) and DPV_{PC} (Figure 9) values differed significantly when configurations were varied, confirming the usefulness of test bench in determine potential spray drift. Sure enough, irrespective of the applied indirect test protocol (canopy absence or presence), the test bench device could detect potential drift risk related to different configurations.

So, the comparison of drift potential reduction (DPR) generated by different airblast sprayer configurations was performed per ISO 22369-1,[66] using ATR6H configuration as the reference; candidate and reference spray system comparison yielded identical rankings of the tested configurations irrespective of indirect test method used –target absence or presence- (Table 9); in both cases, configurations are ranked as follows from larger to smaller reduction based on DRP_{AC} and DRP_{PC} values: ATR6L, TVI6H, and TVI6L. Furthermore, pair-wise comparison of DRP_{AC} and DRP_{PC} values from the tested configurations differed less than 3.6 %. These very low DRP percentage differences produced identical final classifications for both the proposed test bench protocols (target absence and presence): class F for ATR6L; class D for both TVI6H and TVI6L configurations (ISO22369-1 classes)[66]. Overall, the results derived from the two different indirect methods confirmed that assessment outcomes vary greatly due to measurement differences in the protocols,[80] but when relative measurements of drift reduction potential are required, dedicated reference values based on the adopted layout result in the same final classification (Table 9). Furthermore the results proved that, when the objective is the evaluation of technical factors that affect pesticide air emissions during bush/tree crop application,[4,81] the trials conducted in absence of target allow to avoid variability in spray drift results stemming from many sources: target crop/canopy type,[13,82,83] complex architecture and cultivation geometry,[84-86] training systems,[58] and growth stage,[57,87] validating the method as originally proposed by Grella et al.[55]

Finally, the direct measurements of spray drift conducted per ISO22866 method underline that although the combination of nozzle type and fan airflow rate determines DV differences exclusive of their interaction (Table 8), Figure 10b puts forth that result variability from field trials did not determine statistical differences among the configurations tested. In fact, only the most different/more drift-prone (ATR6H) and least different/less drift-prone (TVI6L) configurations demonstrated statistical significance. Even though no statistical difference was found in the field trials for any configuration tested, the ISO2239-1 was applied to determine DR values for each candidate configuration[66] using, also in this case, ATR6H as reference. So, the drift classifications obtained, based on drift measurements conducted per either the ISO 22866 or the test bench methodologies, were compared. Direct and indirect measurement methods produced identically ranked DR and DRP reductions, whereas air induction nozzles (TVI8002), irrespective of fan airflow rate (High or Low), yielded smaller reductions (by at least 25%) than did the indirect test bench methods (Table 9). These differences translated to different final classifications in the field trials: class F both for ATR6L and TVI6H and class D for TVI6L (ISO 22369-1 classes)[66] (Table 9). Nuyttens et al.[64] also noticed deep discrepancies during comparison of indirect test bench DRP values for boom sprayers and direct field drift measurements[2] for the same configuration, which were attributed to meteorological condition differences, especially humidity.

The DV discrepancies between direct spray drift assessment results obtained in this research and that obtained in the previous study, conducted by Grella et al.[13] using the same airblast sprayer, configurations and adjustments (Table 4) (Table 3 in Grella et al.[13]), are consequences of the variability related to the field uncontrollable variables (e.g. weather conditions, tree canopies characteristics), found even when field measurements are performed under the stringent requirements of the standardized methodology.[2] These results confirmed that fall-out drift can, in some cases differ by as much as a factor of ten for the same nozzle size and working pressure,[80] a difference that might relate to weather conditions,[13] phenological stage,[57] and/or canopy structure.[58] Although ISO 22866 requires trials to be performed under specific and consistent weather conditions, it is nearly impossible to conduct field trials under perfectly repeatable crop structure and environmental conditions. Therefore, while drift information for a specific sprayer configuration obtained using the ISO 22866 test protocol is helpful, the wide variation of the results makes them difficult for ranking or classifying drift reductions attributable a specific sprayer configuration or SDRT tested. This is proved comparing results of this research with that obtained in the previously work; the rank order of configurations tested (Table 9) is at odds with the rank order produced from the same configurations tested in ISO 22866 field trials in a Spanish vineyard where DVs decreased from ATR6H to ATR6L to TVI6L to TVI6H.[13] Finally, indication about the usefulness of data obtained from both methodology direct and indirect can be drawn. When airblast sprayer drift loss quantification data are required for environmental risk assessments, such as for PPP registration,[26] the unique spray drift sampling strategy requires many test replicates to be tested under similar conditions and pair-wise comparison using the ISO 22866 standard; indeed, the test bench methodology as originally designed occurred in the absence of wind and target (Figure 2), which made it difficult to estimate drift amounts at different distances from the sprayed area, or spray source, and to compare them with those obtained under the ISO 22866 methodology (Figure 5). Drift values under real conditions can only be obtained through field experiments.[12,38] On the contrary, the methodology for quantifying the potential spray drift generated by bush/tree crop sprayer is capable of reproducing objective results independent canopy structure variations [53-56] and minimizing at the same time results variability due to the meteorological conditions, making indirect method the most suitable for establishing any broad ranking or classification of SDRT.

5. Conclusions

Based on the comparison of experimental results obtained from the application of indirect (test bench in absence and presence of canopies target) and direct (ISO 22866) methodologies for spray drift measurements, the following conclusions can be drawn:

- The test bench method makes it possible to discriminate potential drift generated by different airblast sprayer configurations and confirms previous results that employed the method as originally designed.[55]
- The comparison of the indirect test methods indicated that the absence or presence of a canopy affected Drift Potential Values (DPV) obtained from the various configurations tested, yet calculated Drift Reduction Potentials (DRP) resulted in identical final classifications[66] regardless of indirect methodology tested.
- The test bench methodology as originally proposed by Grella et al.[55] in absence of a target was validated, proving that the target absence had a negligible effect when test bench is used for comparative measurements aimed to determine the DRP of a given airblast sprayer configuration or SDRT.
- On the contrary, when spray drift is evaluated for its environmental effects, then drift values are obtainable only through field drift experiments that rely on ISO 22866.[2] While direct spray drift measurements are useful to obtain information on the driftability of a specific sprayer configuration and on the amount of drift generated within a specific crop context, the wide variation of environmental conditions and crop structures makes it unsuitable for establishing any broad ranking or classification of SDRT.
- Furthermore, ISO 22866 application is complex and due to the high dependence of results on external factors, even if stringent requirements are met, it is very difficult to obtain consistent results among replicates.

As general conclusions, the indirect test bench methodology proposed facilitates comparison among sprayer apparatuses in a manner that approximates field conditions because it considers multiple sprayer components and adjustments (e.g. combination of nozzles types and flow rates, together with sprayer type). Furthermore, compared with application of ISO 22866 test method, the original test bench measurements method is easier to apply and results are highly reproducible suggesting that objective DPR results can be obtainable in different laboratories for the same sprayer, once the reference system has been defined. Moreover, the test bench method as proposed performs well on three fronts: reduces trial costs, obtains objective information independent of target type and seasonal variations, and minimizes the influence of environmental conditions, especially wind speed. The drift test bench method is, therefore, a feasible alternative for measuring airblast sprayer potential drift and for classifying sprayer generated drift.

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8. Tables

Table 1. Configuration variables examined during testing of vineyard sprayer Dragone k2 500.

Nozzle Type	**Fan Airflow Rate (m^3 h^{-1})**	**Forward Speed (m s^{-1})**	**Configuration ID [a]**
ATR 80 orange	20,000	1.67	ATR6H
ATR 80 orange	11,000	1.67	ATR6L
TVI 8002	20,000	1.67	TVI6H
TVI 8002	11,000	1.67	TVI6L

[a]: the ID configuration is composed by three letters that means the nozzle type, one number that means the forward speed (expressed in km h^{-1}) and another letter that means the fan airflow rate (Low and High).

Table 2. Weather conditions recorded during test bench trials in the absence of a canopy, by replicate.

Config & Replicates		Weather parameters									
		Temperature		**Relative Humidity**		**Wind speed**				**Wind direction**	
		Mean[a] (°C)	**Mean[b] (°C)**	**Mean[a] (%)**	**Mean[b] (%)**	**Min ($m s^{-1}$)**	**Max ($m s^{-1}$)**	**Mean ($m s^{-1}$)**	**records > 1 m/s (%)**	**Mean (° azimuth)**	**Prevalent direction**
ATR6H	1	14.7	15.0	57.8	57.4	0.01	0.30	0.09	0.0	55	NE
ATR6H	2	13.1	13.5	64.1	64.0	0.08	0.78	0.38	0.0	356	N
ATR6H	3	12.6	12.9	70.9	71.4	0.06	0.61	0.23	0.0	329	NNW
ATR6H	4	12.6	12.1	76.6	75.6	0.03	0.78	0.35	0.0	3	N
ATR6H	5	12.3	12.7	76.5	75.5	0.00	0.42	0.12	0.0	51	NE
ATR6L	1	13.0	13.3	76.8	74.1	0.04	0.36	0.22	0.0	5	N
ATR6L	2	12.9	13.2	77.6	74.9	0.03	0.22	0.13	0.0	6	N
ATR6L	3	12.8	13.1	77.4	75.0	0.07	0.83	0.43	0.0	7	N
ATR6L	4	12.7	13.3	77.1	73.9	0.01	0.59	0.22	0.0	33	NNE
ATR6L	5	12.7	13.2	77.7	74.1	0.07	0.62	0.33	0.0	9	N
TVI6H	1	12.6	13.3	78.9	73.8	0.06	0.66	0.33	0.0	3	N
TVI6H	2	12.7	13.4	79.0	73.4	0.15	0.49	0.31	0.0	321	NW
TVI6H	3	12.8	13.5	76.8	72.5	0.01	0.60	0.20	0.0	8	N
TVI6H	4	12.7	13.5	76.4	72.2	0.01	0.34	0.11	0.0	47	NE
TVI6H	5	12.8	13.4	78.3	73.5	0.09	0.72	0.36	0.0	2	N
TVI6L	1	13.9	14.4	70.8	68.6	0.02	0.70	0.31	0.0	29	NNE
TVI6L	2	13.6	14.0	72.6	70.4	0.11	0.64	0.29	0.0	4	N
TVI6L	3	13.4	13.8	73.4	71.0	0.00	0.26	0.09	0.0	58	ENE
TVI6L	4	13.2	13.6	75.1	72.7	0.01	0.39	0.12	0.0	41	NE
TVI6L	5	13.0	13.4	75.7	73.7	0.02	0.39	0.25	0.0	33	NNE

[a] 1st height above the ground

[b] 2nd height above the ground

Table 3. Weather conditions recorded during test bench trials in the presence of a canopy, by replicate.

Config & Replicates		Weather parameters									
		Temperature		Relative Humidity		Wind speed				Wind direction	
		Mean[a] (°C)	Mean[b] (°C)	Mean[a] (%)	Mean[b] (%)	Min (m s^{-1})	Max (m s^{-1})	Mean (m s^{-1})	records > 1 m/s (%)	Mean (° azimuth)	Prevalent direction
ATR6H	1	12.1	12.4	67.2	63.7	0.20	0.91	0.51	0.0	254	WSW
ATR6H	2	12.4	13.0	70.5	65.5	0.28	1.05	0.71	0.7	78	ENE
ATR6H	3	13.2	13.5	65.8	62.4	0.21	1.17	0.62	14.3	335	NNW
ATR6H	4	16.4	16.3	51.5	50.7	0.01	0.84	0.36	0.0	27	NNE
ATR6H	5	17.0	16.8	50.4	49.8	0.04	1.50	0.66	5.0	354	N
ATR6L	1	15.0	15.3	79.6	78.4	0.06	0.90	0.31	0.0	6	N
ATR6L	2	14.3	14.6	83.7	81.6	0.12	0.59	0.40	0.0	8	N
ATR6L	3	14.3	14.7	83.7	81.1	0.48	0.82	0.64	0.0	356	N
ATR6L	4	14.6	14.9	82.1	80.1	0.17	0.97	0.45	0.0	17	NNE
ATR6L	5	14.4	14.7	84.3	82.0	0.11	0.42	0.24	0.0	20	NNE
TVI6H	1	14.6	14.7	58.5	56.8	0.03	1.35	0.53	13.2	282	WNW
TVI6H	2	15.5	15.5	54.9	53.4	0.02	0.73	0.43	0.0	77	ENE
TVI6H	3	15.7	15.6	53.8	52.9	0.03	0.59	0.30	0.0	353	N
TVI6H	4	17.0	16.5	48.1	48.4	0.10	1.24	0.70	11.9	295	WNW
TVI6H	5	17.1	16.7	51.5	51.4	0.04	0.61	0.36	0.0	39	NE
TVI6L	1	14.4	14.8	84.6	81.6	0.51	0.93	0.70	0.0	357	N
TVI6L	2	15.0	15.1	81.3	79.9	0.31	0.94	0.59	0.0	358	N
TVI6L	3	15.2	15.3	80.2	79.1	0.17	0.66	0.37	0.0	357	N
TVI6L	4	15.6	15.6	79.6	78.4	0.13	0.89	0.53	0.0	9	N
TVI6L	5	15.9	15.9	79.4	78.0	0.10	0.93	0.41	0.0	33	NNE

[a] 1st height above the ground

[b] 2nd height above the ground

Table 4. Weather conditions recorded during ISO 22866 field trial,[2] by replicate.

Config & replicates		Weather parameters										
		Temperature		Relative Humidity		Wind speed				Wind direction		
		Mean[a] (°C)	Mean[b] (°C)	Mean[a] (%)	Mean[b] (%)	Min (m s^{-1})	Max (m s^{-1})	Mean (m s^{-1})	Outliers[c] (%)	Mean (° azimuth)	Centered[d] (%)	Prevalent direction
ATR6H	1	24.6	24.5	43.3	43.6	0.95	5.31	3.08	0.1	177.6	97.7	S
	2	24.2	24.1	47.4	47.7	0.86	5.04	2.82	0.4	182.9	99.7	S
	3	24.0	23.9	48.3	48.5	0.66	4.76	2.70	0.3	181.0	99.6	S
ATR6L	1	23.7	23.7	45.9	46.2	0.63	4.01	2.37	1.4	150.2	77.1	SSE
	2	23.6	23.5	46.5	46.6	0.81	3.64	2.08	2.2	150.7	87.6	SSE
	3	23.0	23.0	48.9	48.8	0.48	3.79	1.72	6.6	154.9	94.6	SSE
TVI6H	1	23.6	23.5	60.0	60.4	0.35	3.35	1.40	8.1	155.9	81.2	SSE
	2	23.3	23.2	62.2	62.5	0.38	2.34	1.56	9.4	153.8	88.9	SSE
	3	22.2	22.2	52.0	51.6	0.68	2.13	1.27	9.7	165.8	99.0	SSE
TVI6L	1	23.1	23.1	52.4	52.5	0.60	4.28	2.17	3.4	186.7	98.9	S
	2	22.3	22.3	56.9	56.8	0.66	4.02	1.89	2.9	192.2	98.2	SSW
	3	23.9	23.7	58.5	59.0	0.52	3.85	2.30	2.1	151.4	74.4	SSE

[a] 1st height above the ground

[b] 2nd height above the ground

[c] Percentage of records < 1 m s^{-1}

[d] Percentage of records between 180° ± 45°

Table 5. Significance obtained in one-way ANOVA for Direct Spray Deposition based on test bench measurements in the absence and presence of a canopy (DSD), as affected by absence or presence of canopy in test bench trial layouts. Data on DSD were ln-transformed before analysis.

	DSD[a]	
Source	***p* >F**	**Sign.[b]**
Absence or presence of the canopy	0.002	**

[a] Direct Spray Deposition based on test bench measurements in absence or presence of canopy -DSD-

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

Table 6. Significance obtained in one-way ANOVA for Direct Spray Deposition based on test bench measurements in the Absence of Canopy (DSD_{AC}) and Direct Spray Deposition based on test bench measurements in the Presence of Canopy (DSD_{PC}), as affected by configurations tested in test bench trials. Data on DSD_{AC} and DSD_{PC} were ln-transformed before analysis. The mean values of DSD_{AC} and DSD_{PC}, and the relative ± SE of the mean obtained for each configuration tested are also reported. Configuration parameters: nozzle (ATR: conventional, TVI: air induction), forward speed (6 km h^{-1}), and airflow rate (L: low, H: high).

	DSD_{AC}[a]		**DSD_{PC}[b]**	
Source	***p* >F**	**Sign.[c]**	***p* >F**	**Sign.[c]**
Configurations	0.153	NS	0.201	NS
	Mean	**± SE of the mean**	**Mean**	**± SE of the mean**
ATR6H	533.4	39.1	384.9	83.1
ATR6L	621.7	54.0	373.7	29.8
TVI6H	632.6	23.4	522.6	28.6
TVI6L	509.6	45.5	493.2	12.9

[a] Direct Spray Deposition based on test bench measurements in Absence of Canopy -DSD_{AC}-

[b] Direct Spray Deposition based on test bench measurements in Presence of Canopy -DSD_{PC}-

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

Table 7. Significance obtained in three-way ANOVA for Drift Potential Value based on test bench measurements in the absence and presence of canopy (DPV), as affected by absence or presence of canopy, nozzle type, and fan airflow rate. Data on DPV were ln-transformed before analysis.

	DPV[a]	
Source	***p* >F**	**Sign.[b]**
Absence or presence of the canopy	0.001	**
Nozzle type	3.454E-22	***
Fan airflow rate	5.528E-09	***
Absence or presence of the canopy x Nozzle type	0.477	NS
Absence or presence of the canopy x Fan airflow rate	0.360	NS
Nozzle type x Fan airflow rate	0.237	NS
Absence or presence of the canopy x Nozzle type x Fan airflow rate	0.549	NS

[a] Drift Potential Values based on test bench measurements in absence and presence of canopy -DPV-

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

Table 8. Significance obtained in two-way ANOVA for Drift Values based on ISO22866 field drift measurements (DV) as affected by nozzle type and fan airflow rate. DV data were ln-transformed before analysis.

	DV[a]	
Source	***p* >F**	**Sign.[b]**
Nozzle type	2.177E-04	***
Fan airflow rate	0.014	**
Nozzle type x Fan airflow rate	0.903	NS

[a] Drift Value based on ISO22866:2005 field drift measurements -DV-

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

Table 9. Spray drift values and relative spray drift reduction (%) based on indirect test bench trials in the absence or presence of canopy and direct (ISO 22866)[2] field drift trial methods of measurements for the configurations tested. Classification of the different configurations tested according to their drift risk (ISO 2369-1),[66] were evaluated using test bench and ISO methodologies is also provided. Drift reduction values were obtained considering the ATR6H configuration as a reference and the ATR6L, TVI6H, and TVI6L configurations as candidates. Configuration parameters: nozzle (ATR: conventional, TVI: air induction), forward speed (6 km h^{-1}), and airflow rate (L: low, H: high).

Test method	Configurations		DPV_{AC}[b]		DRP_{AC}[e] (%)	Class[a]
			Mean	CV %		
Indirect	Reference	ATR6H	353.3	30.7	0	-
	Candidate	ATR6L	221.4	10.7	37.3	F
	Candidate	TVI6H	87.9	10.7	75.1	D
	Candidate	TVI6L	45.6	16.4	87.1	D
			DPV_{PC}[c]		DRP_{PC}[f] (%)	Class[a]
			Mean	CV %		
Indirect	Reference	ATR6H	290.1	30.2	0	-
	Candidate	ATR6L	191.7	16.9	33.9	F
	Candidate	TVI6H	61.9	17.3	78.7	D
	Candidate	TVI6L	38.8	20.0	86.6	D
			DV[d]		DR[g] (%)	Class[a]
			Mean	CV %		
Direct	Reference	ATR6H	909.7	6.0	0	-
	Candidate	ATR6L	662.2	24.3	27.2	F
	Candidate	TVI6H	494.5	16.1	45.6	F
	Candidate	TVI6L	365.1	19.9	59.9	E

[a] Classes provided by ISO22369-1:2006: A ≥ 99 %, B 95 % ≤ 99 %, C 90 % ≤ 95 %, D 75 % ≤ 90 %, E 50 % ≤ 75 % and F 25 % ≤ 50 %.

[b] Drift Potential Values based on test bench measurements in absence of canopy -DPV_{AC}-

[c] Drift Potential Values based on test bench measurements in presence of canopy -DPV_{PC}-

[d] Drift Value based on ISO22866:2005 field drift measurements -DV-

[e] Drift Reduction Potential based on test bench measurements in absence of canopy -DRP_{AC}-

[f] Drift Reduction Potential based on test bench measurements in presence of canopy -DRP_{PC}-

[g] Drift Reduction based on ISO22866:2005 field drift measurements -DR-

8. Figures

Figure 1. Drift test bench to assess potential spray drift from airblast sprayer with collector and sliding cover detail.

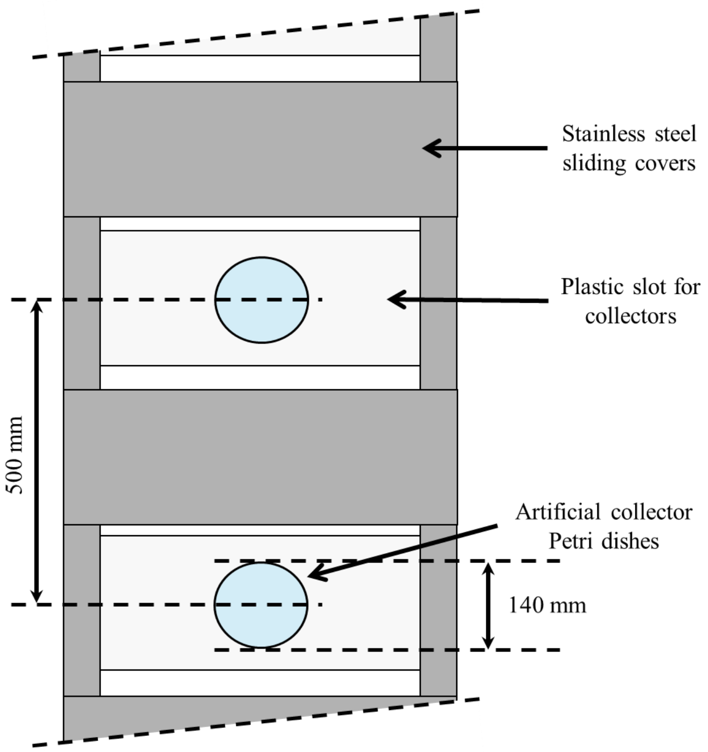

Figure 2. Drift test bench to assess potential spray drift from airblast sprayer with the layout of field test as originally designed by Grella et al.[55]

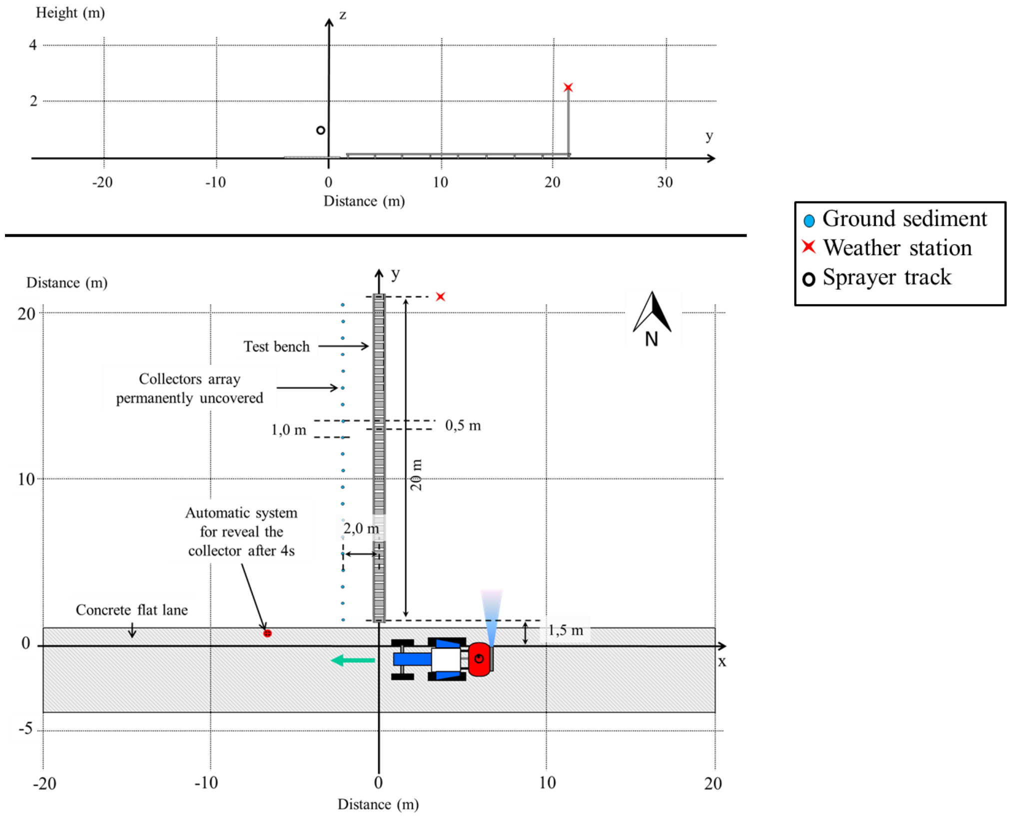

Figure 3. Drift test bench to assess potential spray drift from airblast sprayer, and layout of field test to assess the influence of canopy.

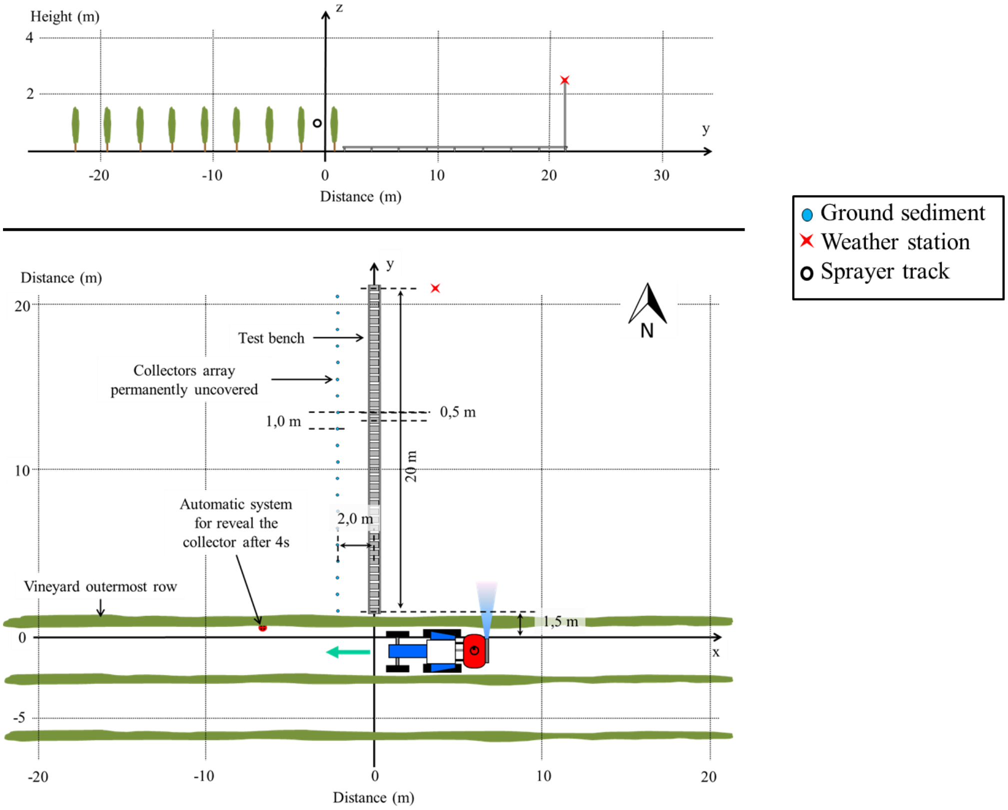

Figure 4. Target characterization: map of the number of leaf layers of the outermost vineyard row canopies positioned in front of the test bench.

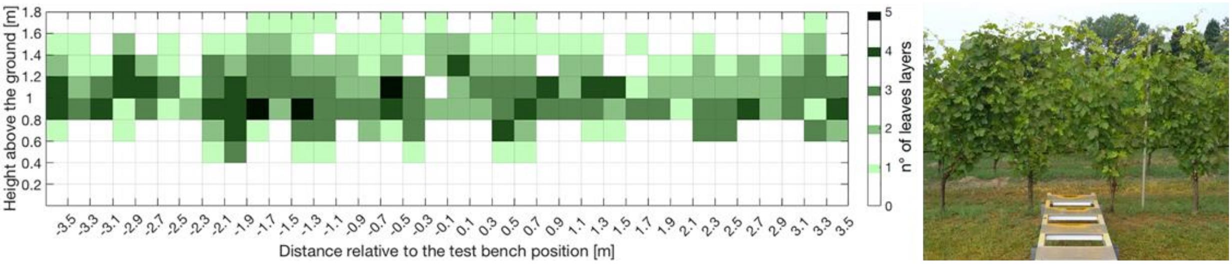

Figure 5. Trial layout according to the ISO 22866.[2]

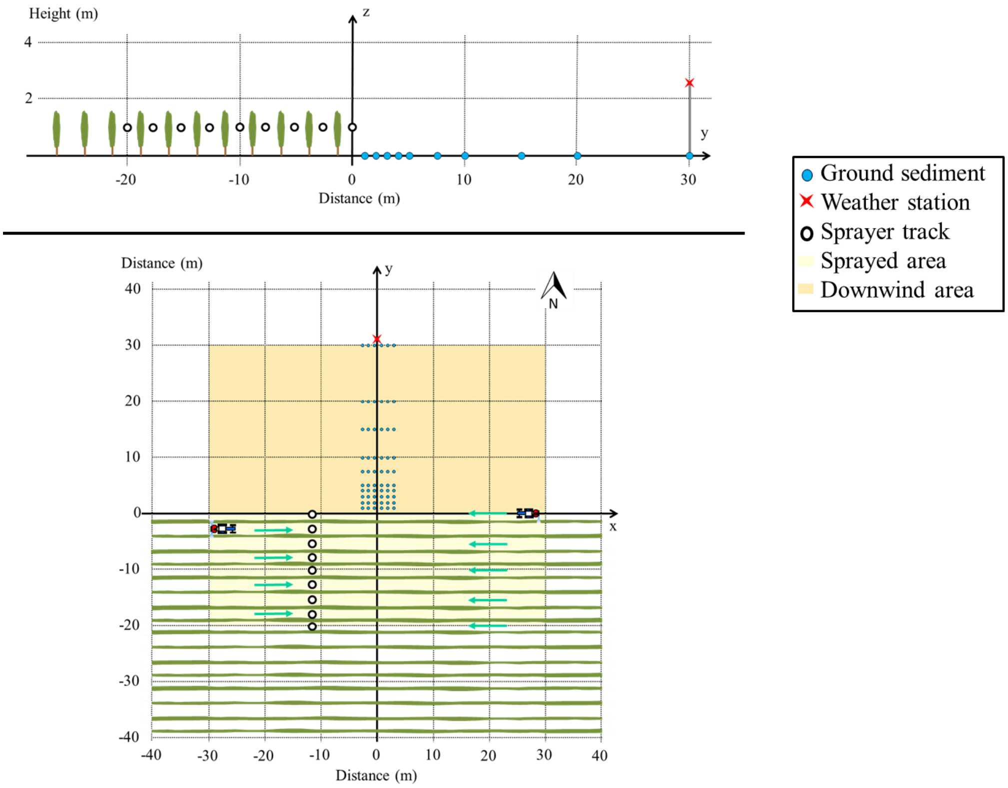

Figure 6. Spray deposit profiles obtained from each sprayer configuration of nozzle type (ATR80 orange and TVI8002) and fan airflow rate (high and low) tested absent a canopy. The mean ± SE of the mean (μL cm^{-2}) spray deposit on the collectors initially covered and then revealed 4s after the sprayer passed in front of the test bench (red dots) and on the collectors permanently uncovered (black dots) are represented for each distance from the outer sprayer nozzle.

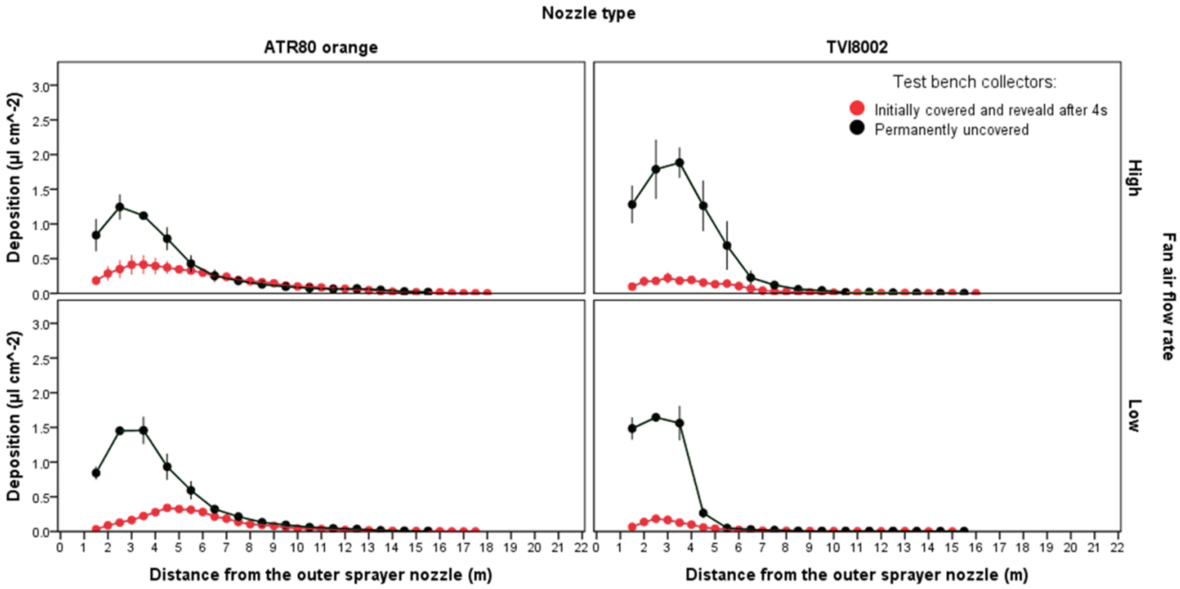

Figure 7. Spray deposit profiles obtained from each sprayer configuration of nozzle type (ATR80 orange and TVI8002) and fan airflow rate (high and low) tested in the presence of a canopy (espalier-trained vineyard BBCH 75). The mean ± SE of the mean (µL cm^{-2}) of the spray deposit on the collectors initially covered and then revealed 4s after the sprayer passed in front of the test bench (red dots) and on the collectors permanently uncovered (black dots) are represented for each distance from the outer sprayer nozzle.

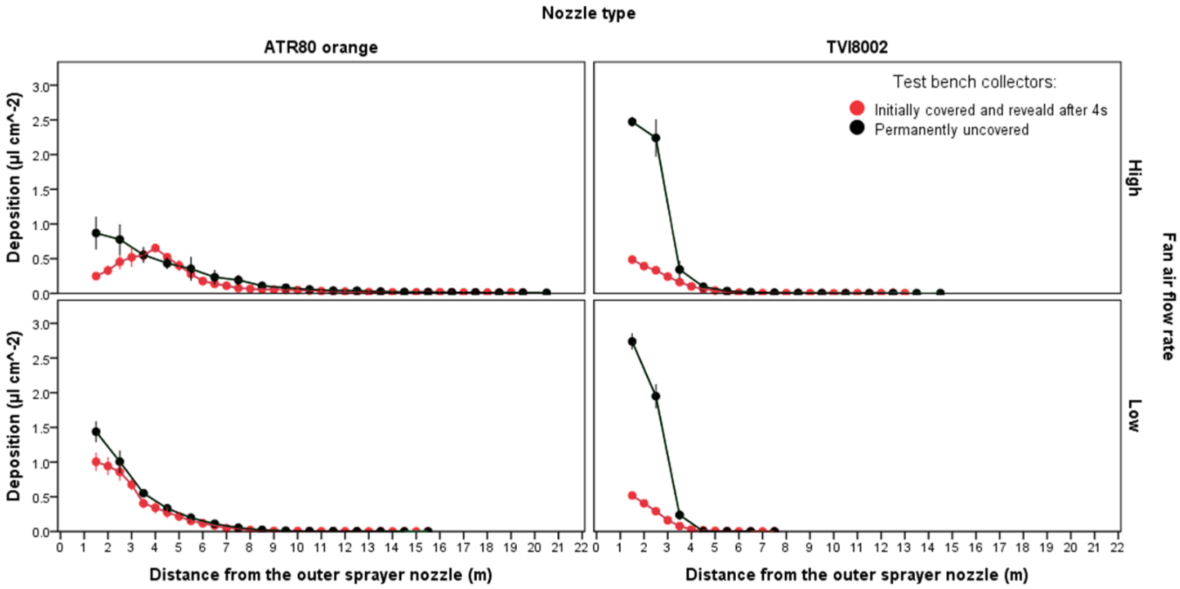

Figure 8. Comparison of test bench spray deposit profiles obtained from each configuration tested (a), and relative Drift Potential Values based on test bench measurements in Absence of Canopy (DPV_{AC}) (b); significant differences in DPV_{AC} of configurations tested are represented. One-way ANOVA, ***$p < 0.001$, post hoc FREGW. Mean ± SE of the mean (µL cm^{-2}) is represented both for spray deposit on the collectors at each distance from the outer sprayer nozzle (a) and for DPV_{AC} of each configuration tested. Configuration parameters: nozzle (ATR: conventional, TVI: air induction), forward speed (6 km h^{-1}), and airflow rate (L: low, H: high).

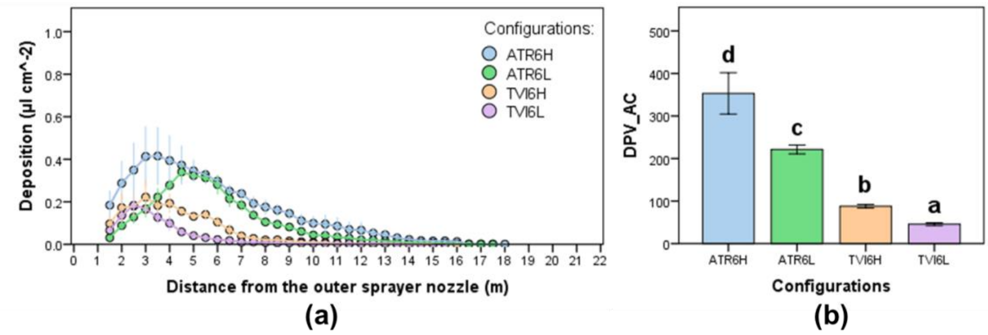

Figure 9. Comparison of test bench spray deposit profiles obtained from each configuration tested (a), and relative Drift Potential Values based on test bench measurements in Presence of Canopy (DPV_{PC}) (b); significant differences in DPV_{PC} of configurations tested are represented. One-way ANOVA, ***$p < 0.001$, post hoc FREGW. Mean ± SE of the mean (μL cm^{-2}) is represented both for spray deposit on the collectors at each distance from the outer sprayer nozzle (a) and for DPV_{PC} of each configuration tested. Configuration parameters: nozzle (ATR: conventional, TVI: air induction), forward speed (6 km h^{-1}) ,and airflow rate (L: low, H: high).

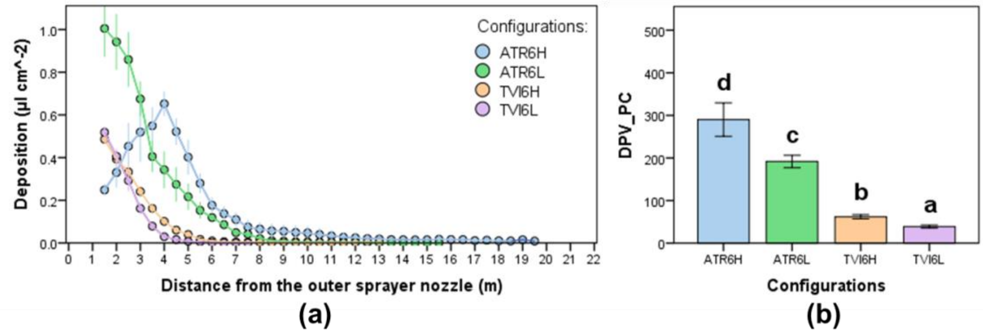

Figure 10. Comparison of spray drift deposit profiles obtained from each configuration tested (a), and relative Drift Values based on ISO22866:2005 field drift measurements (DV) (b); significant differences among the DVs of configurations tested are represented. One-way ANOVA, ***$p < 0.001$, post hoc FREGW. The mean ± SE of the mean (µL cm^{-2}) is represented both for spray deposit on the collectors at each distance from the sprayed area (a), and for the DV of each configuration tested. Configuration parameters: nozzle (ATR: conventional, TVI: air induction), forward speed (6 km h^{-1}), and airflow rate (L: low, H: high).