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Field assessment of a newly-designed pneumatic spout to contain spray drift in vineyards: evaluation of canopy distribution and off-target losses.

(RUNNING TITLE: **Canopy spray distribution as affected by drift-reducing pneumatic nozzle.**)

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Abstract

BACKGROUND: The efficacy and environmental sustainability of pesticide application largely depend on maximizing target coverage, while minimizing off-target losses. Recently, laboratory-based measurements were used to develop new cannon-type spout to increase the droplet size spectra produced by a pneumatic vineyard sprayer. The study described below evaluated the effectiveness of the new device to reduce off-target losses (both in-field and off-field ground losses), and to distribute an adequate canopy spray. Field trials were conducted to measure canopy spray deposition, canopy coverage, and off-target losses from a multiple-row pneumatic sprayer equipped with newly-designed spout under three different positional configurations. The configurations were defined by the variation of liquid release positions from the inner to the outer part of the cannon-type spout: conventional, alternative, and extreme. Each configuration was tested in vineyard by applying a solution of water and yellow-dye tracer.

RESULTS: It was confirmed that the increased droplet size corresponding to the alternative and extreme liquid release positions has no effect on total canopy deposition or coverage. The alternative and extreme configurations produced reduced off-field losses, up to 75% and 83%, respectively, by increasing the droplet size spectra. These reduced off-field losses imply increased in-field losses of 13% and 16%, respectively.

CONCLUSIONS: The newly-designed pneumatic spout offers the first effective option for environmentally-friendly pneumatic spray pesticide application with the guarantee of canopy spray deposition and coverage levels similar to those obtained with conventional pneumatic application.

Keywords: Pesticide application; Pneumatic sprayer; Drift reducing technique; Spray quality; Tracer; Water sensitive papers; Application efficiency

Abbreviations	
AP	Alternative Position of the liquid release point in the air spout of cannon-type nozzle
CD	Canopy Deposition
CP	Conventional Position of the liquid release point in the air spout of cannon-type nozzle
D_i	Deposit measured on each artificial collectors
FGL_{in}	in-Field Ground Losses
$FGLR_{in}$	in-Field Ground Losses Reduction
FGL_{off}	off-Field Ground Losses
$FGLR_{off}$	off-Field Ground Losses Reduction
I_d	mean Impacts dimension averaged over both leaf sides
I_{d-lo}	mean Impacts dimension for lower leaf surface
I_{d-up}	mean Impacts dimension for upper leaf surface
N_i	total Number of impacts averaged over both leaf sides
N_{i-lo}	total Number of impacts for lower leaf surface
N_{i-up}	total Number of impacts for upper leaf surface
PPP	Plant Protection Product
SC	Surface Coverage averaged over both leaf sides
SC_{lo}	Surface Coverage for lower leaf surface
SC_{up}	Surface Coverage for upper leaf surface
SDRT	Spray Drift Reducing Technology
SEM	Standard Error of the Mean
$TFGL_{off}$	Total off-Field Ground Losses deposition (derived from numerical integration of sedimentation off-field losses curve)
VMD	Volume Median Diameter
WSP	Water Sensitive Paper
XP	Extreme Position of the liquid release point in the air spout of cannon-type nozzle

1 Introduction

Only a fraction of total Plant Protection Products (PPP) applied in bush/tree crops with conventional sprayers is actually deposited on the intended target.[1] Some of the applied PPP is transported outside the sprayed area by air currents as spray drift.[2] Ultimately, the spray is deposited on the ground, either directly in the path of the sprayer tractor, beneath the target tree rows, or indirectly in adjacent areas.[1,3-5] Thus, during and immediately after a spray application, non-target receptors, including water,[6] plants,[7] animals,[8-10] and humans[11,12] can be acutely exposed and may be at risk for adverse effects. Today, PPP application must simultaneously balance issues of crop profitability and human and environmental safety. As laid out by the European Directive for Sustainable Use of Pesticides 2009/128/EC,[13] the strategies for the integrated pest management and the PPP dose reduction must be favorited. Nevertheless, pesticide use and management play crucial roles in the economic sustainability of agriculture for the foreseeable future.[14] Any improvement to spray application efficacy and efficiency can potentially contribute to agricultural sustainability in three ways: i) improve PPP benefit, ii) reduce environmental and human contamination risk, and iii) raise food quality and safety standards.

In light of the need described above, pesticide application equipment design in recent years has been active. While many developments have focused on sensing module-based precision spraying[15] to maximize treatment efficacy and minimize the risks of pesticide off-target losses,[16-29] very few advances have been made in pesticide application equipment characterized by pneumatic atomization. Despite a reputation for collateral risk from drift and spray losses caused by the fine droplets generated by these sprayers, they remain widely used in the most important wine[30,31] and table grape-producing[32] vineyard areas around the world. Their suitability for low to very low volume application rates and the large working capacity make this type of spray technology an interesting option for mainly large farms.

The most common pneumatic sprayers used in vineyards are those that spray two rows simultaneously, which allows a single pass to treat two rows at once. This sprayer type is known as a "pneumatic arch sprayer." In France, where pneumatic sprayers are most widespread, they represents 70–80% of all the sprayers used in large vineyards.[30] Generally, these sprayers are equipped with two different types of pneumatic spouts:[33] (i) finger-type nozzles, with individual 'finger' spouts shooting from the main 'hand' spout to spray the row nearest the sprayer, and (ii) cannon-type nozzles, with very high air velocity wide spouts that spray the *next* row over, i.e., the row placed next to the one sprayed with the finger-type nozzles. This type of spray application has two problems. The first relates to the difference in distance between spouts and target according to nozzle type and row sprayed. Specifically, the cannons disperse spray to nearby rows with high air speeds and flight distances, which increases the time that the spray is exposed to wind and consequently, drift risk.[34] Although the droplet size spectra produced by differently-designed pneumatic spouts has been studied little, it is well known that droplets produced by cannon-type spouts are more prone to drift.[33,35] The second problem relates to the difference in droplet size spectra produced by the two spout types. Even at the same fan air speed and liquid flow rate,[33] different spray coverages could result on either side of a row, depending on the nozzle that sprayed each one.

Under actual field conditions, there are two options to increase the dimension of the droplets generated by pneumatic spouts. The first is to reduce fan air speed while increasing the liquid flow rate. However, this option was recently shown not to impact spray quality much, as only in the best cases did it alter droplet size spectra from very fine to fine.[33] The second option changes air spout size, as the larger the outlet from an air spout, the slower the air comes out.

A long history of research of hydraulic nozzle operation has indicated that the production of coarse droplets is the primary strategy for effective containment of drift phenomena during spray application.[11,36-38] Miranda-

Fuentes et al[39] have applied this concept to pneumatic nozzles with the aim of reducing drift. Based on preliminary laboratory study,[39] pneumatic cannon prototypes able to modify the droplet size spectra were developed. Varying the liquid release position from the inner to the outer side of the spout also was shown to increase substantially the droplet size spectra produced. Based on previous experimental work,[40] the droplet size spectra produced by finger-type nozzles were not modified for field trials as finger-type nozzles were proved to be less prone to drift when compared with the cannon spout at the time.

The main objective of this work was to evaluate under field conditions, using a multiple-row pneumatic sprayer able to modify the droplet size spectra produced by the newly-designed cannon-type nozzles, the capability to reduce environmental risks related to off-target losses while guaranteeing canopy depositions and coverage similar to those obtained with conventional pneumatic spray application.

2 Materials and methods

2.1 Characteristics and configurations of the tested sprayer.

A vineyard multiple-row pneumatic sprayer Cima 50 Plus equipped with a 400L polyethylene tank, steel high pressure radial fan (500 mm of diameter), and a “2 hand-2 cannon spray head (TC.2M2C.50P) (CIMA S.p.A., Pavia, Italy) was tested (Fig. 1). To spray to consecutive rows at once, two different spouts were mounted on a sprayer to deliver the liquid solution in different ways to two rows. One is a finger-type nozzle at the lower part of the spray head that delivers multiple streams of liquid to the near row and the other is throws a single stream to the far row from a cannon-type nozzle on top of the spray head (Fig. 1a,b). The result is that one side of each row is sprayed by the finger-type nozzle and the other side is sprayed by the cannon-type nozzle (Fig. 1c).

Three sprayer configurations were tested in this assessment. They were created from a combination of conventional finger-type nozzles and modifications of cannon-type nozzles by manually varying the insertion position of the liquid hose.[50] As detailed in Fig. 2, the three tested configurations differ among one another in the diameter of the spout at point of liquid release inside the cannon air spout. More specifically, a 50 mm diameter was used for the conventional position (CP) and 70 mm was used for the alternative (AP) position. For the extreme configuration (XP), the liquid hose was positioned outside the spout, at 280 mm from CP (Fig. 2). Each configurations was tested with a fixed volume (169 L ha^{-1}) applied at a forward speed of 1.67 m s^{-1} (6 km h^{-1}). To obtain the intended total sprayed volume, each nozzle had its liquid flow regulator disc (a plastic disc with calibrated holes in its perimeter) in position n° 7 to produce a liquid flow rate of 2.07 L min^{-1} from the finger nozzle and 2.67 L min^{-1} for the cannon nozzle, both at 0.1 MPa (1 bar)pressure. The total spray liquid flow rate was 9.48 L min^{-1}. The Power Take-Off (PTO) rotary speed was always set at 540 rev min^{-1}.

The droplet size spectra produced by both pneumatic nozzle types, combined with different liquid release points for the cannon-type nozzles was determined in the laboratory at DiSAFA facilities using a Malvern Spraytec laser diffraction system STP5342 (Malvern Instruments Ltd., Worcestershire, UK). The methodology was the same as the one detailed in Miranda-Fuentes et al[50]. The liquid pressure and flow rates used for droplet size measurement were identical to those used in the field trials: 1 bar and, 2.07 L min^{-1} and 2.67 L min^{-1} for finger-type and cannon-type nozzles, respectively. The droplet diameters for the 10th (D[v,0.1]), 50th –VMD- (D[v,0.5]), and 90th (D[v,0.9]) percentiles of spray liquid volume and for V_{100} values, together with airflow characteristics, determined for the different pneumatic nozzles are shown in Table 1. Three test replicates were conducted for each sprayer configuration.

2.2 Test location and crop characteristics

Tests were performed in an espalier-trained vineyard (cv: Barbera) at growth stage BBCH 89 "Berries ripe for harvest"[41] located at DiSAFA facilities in Grugliasco, Turin, Italy (45°03′60″ N 7°35′65″ E). The vine rows were 62 m long and oriented NW-SE (146° azimuth). Planting distances were 2.8 m between rows and at 0.8 m in rows with a resulting density of 4,464 vines ha^{-1}. The average vineyard height was about 2.2 m with a vegetative strip of about 1.6 m and a canopy width of about 0.5 m. To accurately characterize the vineyard crop, the Point Quadrat Technique (PQT) used for vineyard canopy characterization by others was applied.[42-44] Specifically, block PQT measurements (six blocks, four-vine canopy per block, distributed in the first two rows at three/row) were taken in the 1.6 m vegetative strip at heights between 0.60 and 2.20 m. The technique is performed by inserting a rod perpendicularly into the leaf canopy and counting the number of leaves touching the rod. For consistency, a vertical frame containing a 0.2 m × 0.2 m grid was used and the measurements were repeated for each cell of the grid. The average number of foliar contacts corresponds to the number of leaf layers measured. From these measurements, the main vegetative parameters were calculated, resulting in 2.7 leaf layers (mean), 8% gaps, and a Leaf Area Index (LAI) of 1.5, calculated according to Pergher and Petris[45].

2.3 Experimental plot layout and sampling system.

The trials were performed by spraying the two outermost downwind vineyard rows, with a total area of 347 m^2 (62 × 5.6 m) (Fig. 3). Along each of these two rows, three sampling sections (J, K, and L) were established. These sections, set at both the extremes and in the centre of the rows to account for any differences in canopy characteristics, were intended to measure the spray deposition and coverage in the canopy (§2.3.1) as well as spray in-field ground losses (§2.3.2). Adjacent to the outermost row, the sampling area for collector off-field ground losses was set (§2.3.3) (Fig. 3).

2.3.1 Canopy spray deposition and coverage measurements: experimental plot layout.

For each replicate, canopy spray deposition (CD) and leaf surface coverage (SC) measurements were performed at three locations along the sprayed rows that corresponded to the defined sampling sections (Fig. 3). Two vine canopies (one per row) within each of these sections were sampled (Fig. 4). In total, measurements were taken from six vines, distributed two per each sampling section and three per each sprayed row.

In each vine canopy, deposition and coverage parameters were assessed at nine sampling positions arranged at three heights (1, 2, and 3) and at three depths (A, B, and C) (Fig. 5a). To assess deposition, filter papers (120 mm diameter and 90 g m^{-2} extra rapid - Gruppo Cordenons S.p.A., Milano, IT) were clipped to vertical masts at each sampling position and both collector faces were oriented for spray jet exposure (Fig. 5b and c). Each collector represented a total exposed surface area of 226 cm^2. To assess coverage, two paired (one coincident with adaxial and one with abaxial leaf surfaces) 76 x 26 mm water sensitive papers (WSP) (Syngenta Crop

Protection AG, Basel, CH) attached with a staple were used at each sampling location (total exposed surface of 19.76 cm^2) (Fig. 5b and d). The selected filter paper was chosen to assess spray deposition as it had been shown to have a constant extractable fraction.[46]In the case of WSP, it has been broadly used to assess the leaf coverage during spray application field trials.[47-51e]

At the end of each spray application, samples were left to dry for ten minutes, after which the filter papers were placed into individual bags and sealed. To prevent tracer photo-degradation, the samples were collected in closed dark boxes. The WSPs were fixed to rigid supports and stored under dry controlled conditions.

2.3.2 In-field ground losses measurements: experimental plot layout.

In this case, for each replicate, in-field ground loss (FGL_{in}) measurements were also taken for each replicate at three locations along the rows sprayed in the defined sampling sections (Fig. 3). In each sampling section, the collectors were placed under the sprayed vines (two rows) and in the middle of each inter-row open space within the sprayed area (three inter-rows) (Fig. 6). Two inter-rows were used for the sprayer track (Fig. 3 and 6). At each sampling position, two paired Petri dish collectors (140 mm diameter) were affixed to wooden boards to withstand removal by the sprayer-generated air currents. Two minutes after the vineyard plot had been completely sprayed, the Petri dishes were covered and collected in closed dark boxes to prevent tracer photo-degradation.

2.3.3 Off-field ground loss measurements: experimental plot layout.

For each replicate, off-field ground losses (FGL_{off}) were measured at ten bare-soil sampling locations, placed at distances of 1, 2, 3, 4, 5, 7.5, 10, 12.5, 15, and 20 m downwind of the directly-sprayed area (Fig. 7). At each location, six discrete ground level horizontal sampler Petri dishes (140 mm diameter) were placed 1 m from each other. The first line of collectors was placed 2.4 m from the outermost row (or 1 m from the sprayed area). Two minutes after the vineyard plot had been completely sprayed, the Petri dishes were covered and collected in closed dark boxes to prevent tracer photo-degradation.

2.4 Monitoring of the environmental conditions.

A weather station was employed to monitor relevant environmental conditions during the trials. The weather station' sensors were mounted to a mast at a height of 4 m standing in the centre of the off-field loss sampling area, positioned 20 m from the sprayed area (Fig. 3 and 7). In particular, it was equipped with da sonic anemometer 232 (Campbell Scientific, Logan, UT, USA) to measure wind speed and wind direction relative to the spray track, and a thermo-hygrometer HC2S3 probe (Campbell Scientific) to measure air temperature and humidity changes. All measurements were taken at a frequency of 0.1 Hz sampling rate and all data were recorded automatically by datalogger CR800 (Campbell Scientific). The environmental conditions were monitored for the duration of each test replicate.

2.5 Spray liquid and tracer concentrations.

To measure the collector deposits, E-102 Tartrazine yellow dye tracer (85% (w/w)) (Novema S.r.l., Torino, Italy) was added to the sprayer tank at a target concentration of about 10 g L^{-1}; Tartrazine was chosen as the tracer for its high extractability level and low degradation rates.[52]

Prior to each test, two blank Petri dishes, one placed in the middle of the drift sampling area and the other placed between sprayed rows, were processed and collected 30 s before spraying started. Sprayed liquid samples were also collected directly from the spray tank (via the liquid hose at the spout release point) before and after each spraying to ascertain the precise tracer concentration at the pneumatic nozzle outlets for each test replicate.

2.6 Sample analysis and calculated parameters.

2.6.1 Deposition sample off-target losses: sediment and canopy deposition.

The artificial collectors were washed with deionized water to extract the tracer. The Tartrazine concentration was determined by measuring the absorbance of the wash solution with a spectrophotometer UV-1600PC (VWR, Radnor, PA, USA) set to 427 nm wavelength for peak absorption of the dye, and to compare the results against the calibration curve obtained in the laboratory prior to start of the analysis. To evaluate in-field ground losses (FGL_{in}), 50 ml of deionized water was added to each used Petri dish and then shaken for 10 min with an Advanced Orbital Shaker, model 5000 (VWR, Radnor, Pennsylvania, USA) for complete extraction and homogenization of the wash solution. The same procedure was performed on the Petri dishes used to collect off-field ground losses (FGL_{off}), except 10 ml of deionized water were added to each collector. To evaluate canopy deposition (CD), 100 ml of deionized water was added to the sealed bag containing the filter paper collector and was agitated for 60 min. For all cases, three absorbance measurements were taken for each sample, including blank deionized water samples, to calibrate the equipment.

The deposit on each artificial collector (Di), expressed per unit area in μL cm^{-2}, was calculated from Eq. (1) according to ISO 22401 as follows:[53]

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

where D_i is the spray deposit on a single 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 extract 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 pneumatic nozzle outlet (adim.); A_{col} is the projected area of the collector exposed to the spray in cm^2; ε is the extractability factor, equal to 0.589 according to Miranda-Fuentes et al.[46]

For each replicate, FGL_{off} deposits were measured at different distances from the sprayed area in order to draw the near-field sedimentation spray curve.[54-55] The total off-field ground losses ($TFGL_{off}$) were then calculated by numerical integration of the sedimentation curves, as proposed and successively adapted by Grella et al.[56,57] The methodology approximated the definite integral using the mid-ordinate rule.

In addition, the coefficient of variation (CV%) was calculated for the deposition values at all sample points and used as indicators of homogeneity of the deposit distribution inside the canopy.[58]

2.6.2 Canopy coverage samples

The Water Sensitive Papers (WSP) were scanned and images were produced at a resolution of 600 dpi using a CanoScan Lide25 (Canon Inc., Tokyo). A specially-programmed macro[46,59] in ImageJ (National Institutes of Health, Bethesda, MD, USA)[60] was used to determine coverage parameter values: average percentage of surface coverage (SC), total number of impacts per surface units (Ni), and mean dimension of impacts (Id). Furthermore, the adaxial (hereafter, called upper) and abaxial (hereafter, called lower) leaf sides were also calculated for each coverage parameter: percentage coverage for upper (SC_{up}) and lower (SC_{lo}) leaf side; number of impacts for the upper ($N_{i\text{-}up}$) and lower ($N_{i\text{-}lo}$) leaf side; mean dimension of impacts for upper ($I_{d\text{-}up}$) and lower ($I_{d\text{-}lo}$) leaf side.

2.7 Calculation of off-field and in-field ground loss reductions and statistical analyses.

The reduction values in off-field ground losses ($FGLR_{off}$) and in-field ground losses ($FGLR_{in}$) were derived from $TFGL_{off}$ and FGL_{in} values, respectively, according to ISO 22369-1:2006 for each configuration tested.[61] Therefore, the values of $FGLR_{off}$ and $FGLR_{in}$ were obtained through a pairwise comparison of reference spray configuration CP with candidate configurations AP and XP.

All statistical analyses were performed using IBM SPSS Statistics for Windows V25.[62] The data were tested for normality using the Shapiro-Wilk test and by visual assessment of the Q-Q plots of residuals. First, three-way Analysis of Variance (ANOVA) was used to establish the effects of the configurations tested, together with canopy depth and height. Canopy deposition CD (µl cm^{-2}) and coverage parameters were considered as dependent variables. Coverage parameters SC (%), N_i (n° cm^{-2}), and I_d (µm) were considered two ways—separately for each upper and lower leaf side and as an average of both side. In the case of N_i and I_d, the three-way ANOVA was performed on WSP images having SC values below 20%, as the reduced dataset was processed to obtain an equally-reduced dataset for all compared treatments to allow accurate effect evaluation. The 20% threshold had been defined based on preliminary study of the relationship (Fig. 8) and correlation (Table 2) between SC and N_i. This procedure was specifically adopted to avoid misinterpretation of N_i and I_d final results.[1] Indeed, as already demonstrated by other authors,[48] any spot size measurements made on WSP with coverage greater than about 20% are unreliable due to touching or overlapping. However, the SC threshold value must be defined case-by-case based on a preventive dataset analysis because it might vary with various spray application parameters (e.g., spray quality, spray application rate).

For each configuration tested, the relationship between average off-field ground loss depositions and distance from the sprayed area was evaluated using a linear regression analysis. As preparation, the data were ln-transformed to linearize the power function that related both variables, and to achieve residual normality and homoscedasticity. Afterwards, the linear fit models obtained from each configuration were compared using one-way Analysis of Covariance (ANCOVA) to evaluate the relative effectiveness of each configuration to reduce deposition while controlling for the distance from the sprayed area (covariate). Statistical differences among the in-field ground losses generated by the multiple-row pneumatic sprayer were analysed with two-way ANOVA that considered the configurations tested and sampling positions as sources of variation. In all cases, the means were compared using the FREGW post-hoc test (α = 0.05). Prior to analysis, the percentage data were $\arcsin(([\ldots]/100)^{0.5})$ transformed and the deposition data were ln[…] transformed to achieve residual normality and homoscedasticity.[63] Residual analyses were also performed.

3 Results and discussion

3.1 Environmental conditions during field trials.

The temperature, Relative Humidity (RH), and wind values recorded during the trials are compiled in Table 3. Review of the data suggest that weather conditions were relatively constant throughout CP, SP, and XP treatments. Temperatures (13.9ºC to 19.4ºC) and RH values (59.6% to 85.6%) fluctuated within relatively close ranges. Wind direction was generally from the West and ranged between 195° and 315° azimuth. The mean values for wind speed, obtained across the replicates and for each configuration tested, were broadly comparable at 0.38, 0.3, and 0.69 m s^{-1} for CP, AP, and XP configurations, respectively.

3.2 Canopy deposition

The three-way ANOVA (Table 4) indicated that the tested configurations exerted statistical influence on mean canopy deposition. In particular, AP demonstrated increased canopy depositions as compared with configurations CP and XP mean CD values of 0.234 (CP), 0.282 (AP), and 0.239 (XP) µl cm^{-2} (Table 5). Moreover, CD varied highly ($p < 0.001$) across the various depths and heights within the canopy (Table 4).
Depth result indicated that irrespective of configuration, the highest deposition was found at canopy depth Out–A, which corresponded to the row side sprayed directly by the finger-type nozzle (Fig. 9a). Similarly, among the three heights sampled along the vegetative strip, the largest deposit was found at its lowest level (Height 1), which is also the grape band (Fig. 9b). In this case, this lowest level was closest to the finger-type nozzle. In the case of canopy depth Out–C, corresponding to the row side sprayed directly by the cannon-type nozzle, the deposition amount for XP was less than half and at least three times less for CP than that found at depth Out–A. Alternatively, the AP configuration produced higher depositions at depth Out–C, as compared with either CP or XP. In all cases, depth position In–B exhibited lower deposition values relative to the two external canopy positions (Out–A and Out–B), but was not substantially different across the three tested configurations. Only AP had a slightly higher value for CP (Fig. 9a).
Among different canopy heights, the AP and XP configurations produced increased depositions at height 3 (highest canopy portion), whereas only AP was able to increase deposition at height 2 (Fig. 9b). Despite the strong deposition differences across canopy depths and heights for each configuration, deposition homogeneity (CV%) was found for all configurations: 89 (CP), 79 (AP) , and 82 % (XP) (Table 5). The CV% values obtained were comparable with those reported by other authors in more critical crops, such as olive trees traditional-trained with very expansive canopies treated by conventional axial fan air-assisted sprayers.[64]
In general, the canopy deposition results observed in this study suggest that an uneven canopy deposition, regardless of the droplet size spectra generated, results from a pneumatic sprayer that delivers a different type of spray application to different sides of the row (Fig. 1). These results align with those reported by Codis et

al,[65] who used a vineyard pneumatic arch sprayer passing every four rows, and who found that canopy deposition in the full growth stage varied significantly according to canopy depth and row side. Here, even though the two different nozzles employed in the CP configuration produced very similar droplet size spectra (Table 1),[45] the mean deposition and its homogeneity were among the lower values. This suggests that the difference in distance and position between the two nozzle types and the target (Fig. 1) have a strong effect on canopy deposition at different depths and heights, especially for the CP configuration characterized by the smallest droplet size (Table 1).

Droplets produced by the cannon spouts travel a long distance between the diffusers and the canopy, but that distance is much shorter for the hand spouts. The consequence of this is that while the fine droplets produced by the finger-type nozzles have sufficient kinetic energy to reach the canopy, droplets produced by the cannon spouts in the CP configuration have too little kinetic energy and fail to reach the target. Alternatively, the relatively coarse droplets produce by the XP configuration have an excessive kinetic energy that allows then to surpass the canopy target without deposition.[56] Hence, despite droplet energy differences in the CP and XP configuration, they produced not only similar CD reductions, but also reductions similar ones produced by intermediate droplets of the AP-configured cannon spout. Indeed, the increase of the droplet size produced by the AP liquid release position in the cannon spout resulted in a significant increase in overall canopy deposition at every depth and height (Fig. 9). It also increased the deposit homogeneity (Table 5). The effect of the non-linear relationship between droplet size and canopy deposition resulted in a lower CD amount and lower CV% performance of XP configuration, compared with AP configuration.

3.3 Spray coverage.

The three-way ANOVA of the full dataset (972 WSP) showed that increased droplet size related to modification of the cannon spout liquid release position does not significantly change ($p > 0.05$) canopy coverage (Tables 6 and 7). Despite the tendency for surface coverage values to decrease as droplet size increases, the resulting SC values (14.6 for CP, 14.4 for AP, and 13.2 % for XP) did not vary substantially by configuration (Table 7). When coverage was considered by leaf side, the mean values also fell within relatively narrow ranges: 20.5, 20.4, and 18.4 %, and 8.8, 8.3 and 8.0 % for CP, AP, and XP configurations for SC_{up} and SC_{lo}, respectively (Table 7). As demonstrated above, overall surface coverage did not vary with the configuration. On the other hand, SC, Sc_{up} and Sc_{lo} all exhibited high variation ($p < 0.001$) with changes in canopy position, depth, and height levels (Table 6).

These results are made clear in an analysis of Fig. 10, where SC, SC_{up}, and SC_{lo} are graphed separately for depth and height levels and configuration. Like the values found for deposition, coverages across the canopy were not homogenous. External canopy sections Out–A and Out–C, as well as the lowest canopy height 1, were all characterized by higher SC values (Fig. 10a and b). The inner part of the canopy was, in all cases, the least covered. The significant decrease in SC_{up} at depth level Out–C as the configuration changed from CP to AP to XP (Fig. 10c) confirmed that SC_{up} was significantly affected by configuration at different depth levels (Table 6). The Out–C depth reflects canopy coverage differences attributable to different configurations best because the WSP collectors were directly exposed to the cannon nozzle spray jet.

The same trend was also exhibited for SC_{up} at heights 2 and 3 (Fig.10d), the positions less influenced by finger-type nozzle proximity. Regardless of configuration, the fact that the pneumatic spray does not guarantee the 30% coverage threshold established by Chen et al.[66] and used by others[64] to evaluate coverage in hydraulic spray application is noteworthy. Here, only on the leaf upper side, and only at some canopy positions, was the 30% coverage threshold achieved. As for the leaf lower side (Fig. 10e and f), surface coverage was always below 15%, although higher values were achieved on the side directly sprayed by the finger-type nozzle. In rank order, the best surface coverage was at Out–A (finger-type nozzle closest to the vegetative strip), which was followed by In–B (inner canopy) and then Out–C. The wide variation in coverage at the various canopy sampling positions might relate to uneven sprayer fan airflow volumes and speeds that could lead to poor disease control.[67,68]

Surface coverage characteristics, such as the number of impacts unit and impact dimension, were analysed on the reduced dataset (756 WSP) to avoid misinterpretation (Fig. 8b). As expected, the three-way ANOVA indicated that the variation in droplet size spectra of the three configurations significantly affected ($p < 0.001$) all impact number parameters (Table 6). Specifically, N_i, $N_{i\text{-}up}$, and $N_{i\text{-}lo}$ all decreased from the highest number with CP, followed by AP , and to XP last. These results revealed how significantly different the original release liquid position in the cannon spout (CP configuration) is from the other two tested positions (Table 7). Even through cannon-type nozzle in the AP configuration has a three-fold lower VMD value (80) than that produced by the XP configuration (238), the two configurations did not differ significantly for N_i, $N_{i\text{-}up}$, and $N_{i\text{-}lo}$ (Table 7). The very fine droplets produced by the finger-type nozzles may influence this effect and partially hide the effect of the XP configuration to further reduce N_i as expected. The N_i values were 112.2 (CP), 83.5(AP), and 72.6 (XP) n° cm^{-2}. The number of impacts for separate leaf sides were 123.5 (XP), 86.7 (AP), and 81.0 (XP) n° cm^{-2} for $N_{i\text{-}up}$ and 104.4 (CP), 81.3 (AP), and 66.3 (XP) n° cm^{-2} for $N_{i\text{-}lo}$, (Table 7).

The number of impacts also differed significantly across the various depths and heights inside the canopy for N_i, $N_{i\text{-}up}$, and $N_{i\text{-}lo}$ (Table 6). In particular, the external portions of the canopy had the highest N_i values in all configurations (Fig. 11a), as well as at the lowest (1) and highest (3) heights (Fig. 11). Higher values of $N_{i\text{-}up}$ were displayed at depth level Out–C (facing the canon-type nozzle) in all configurations, as compared with those at Out–A, which was directly sprayed by and positioned close to the finger-type nozzle. Similar values were obtained for $N_{i\text{-}up}$ at heights 2 and 3 across all configurations. Contrary to $N_{i\text{-}up}$, the highest $N_{i\text{-}lo}$ values were found for each configuration at depth level Out–A and at the lowest canopy height (1). The opposing impact ratios at depths Out–A and Out–C, observed on the leaf upper and lower sides, likely relate to several factors: different directions of spray jet toward the canopy, different distances between nozzle and target, and different nozzle types. In general, the cannon-type nozzle produces more impacts on the upper side of the leaf or vegetative strip that directly faces it (Out–C) (Fig. 11c), and the finger-type nozzle guarantees more impacts on the lower side of the leaf or vegetative strip that directly faces it (Out –A-) (Fig. 11e).

Impact dimension was also investigated. Three-way ANOVA resulted as expected, and confirmed that the I_d differed significantly across the configurations ($p < 0.001$); the I_d produced by CP (492 µm) was significantly lower than those produced by AP (569) and XP (561 µm) (Tables 7 and 8). As was the case in the N_i analysis, cannon-type nozzles that produce VMD increases in the AP and XP configurations do not determine a significant enlargement in impact dimension (Fig. 12). When impact dimension was considered by leaf side (I_{d-up} and I_{d-lo}) for the various configurations, a significant difference was detected only for I_{d-lo} (Fig. 12). Generally, bigger impacts were assessed for the leaf upper side with values equal to 547, 572, and 582 µm for CP, AP , and XP configurations, respectively. On the lower leaf side, I_{d-lo} values resulted as 454 (CP), 567 (AP), and 546 (XP) µm. The analysis of impact dimension at different canopy positions (Fig. 12 a,b,c for depth; Fig. 12 b,d,f for height) reflects the heterogeneity of spray quality on the coverage; it shows significant differences for all impact dimension parameters (I_d, I_{d-up} ,and I_{d-lo}) according to height. Significant differences among the three depth levels were also found for I_{d-up}. Also worthy of note is that the VMD of cannon-type nozzles for all configurations did not match mean impact dimensions. According to other authors, overlapping stains that occur with different rate according to spray features and quality, make the I_d values obtained by WSP target image analysis unreliable for VMD droplet characterization.[51,69] Nonetheless, in the absence of matching impact dimension and expected VMD values, the experimental data allowed the quality of spray coverage to be characterized under field conditions using a pneumatic sprayer equipped with two types of spouts.

3.4 Off-field ground losses.

The off-field ground loss deposition curves for each configuration are shown in Fig. 13. The highest piles of off-field ground losses were always deposited in the first downwind meters from the sprayed area. The highest amounts were generated by CP configurations, while lower, but very similar, amounts were measured at each distance for AP and XP. Furthermore, Fig. 13 shows a statistical linear relationship between the linearized mean off-field ground loss sediment and the distance from the sprayed area for all tested configurations (CP, AP, and XP), and were found significant at $p <= 0.001$ with r^2 values of 0.988, 0.972, and 0.964, respectively. One-way ANCOVA results, used to compare configurations while controlling for distance from the sprayed area, showed that off-field loss amounts differed significantly [F(2,79)=8.852, *p*=3.40E-04]. In particular, there was significantly lower deposition of off-field losses between CP and AP (*p*=4.83E-17) and between CP and XP (*p*=3.81E-17). No differences were detected between configurations AP and XP (*p*=1.00). The interaction between deposition and distance from the sprayed area (covariate) was not statistically significant (p=0.080), indicating that the slopes of the linear models in Fig. 13 did not differ by configuration.

Once a reduction in off-field ground losses was detected, the area under the near-field sedimentation curves (Fig. 14) was calculated using the mid-ordinate rule method,[67] and the related cumulative deposition charts of off-field ground losses were also determined (Fig. 14). The total off-field ground loss values equalled 79.5 (CP), 19.3 (AP), and 13.4 (XP) µl $2000cm^{-2}$ (Fig. 14). This referred to a 2,000 cm corresponding definite amplitude of near-field sedimentation curves, that describes the trend of off-field ground losses at the different distances from the sprayed area (1 m to 20 m).

The corresponding percentage of reduction in off-field ground losses]for configurations AP and XP were calculated based on reference configuration CP (value = 0).[72] The highest value was achieved by XP configuration, corresponding to 83% of the average reduction in off-field losses as compared with CP.

Configuration AP achieved a slightly lower average reduction in off-field losses (76%). The resulting reductions were obtained at increasing mean wind speeds equal to 0.38 (CP), 0.39 (AP), and 0.69 (XP) m s^{-1}. This is important because wind speed conditions during the trials magnified the capability of XP to reduce its off-field ground losses, as higher wind speeds correspond to higher drift reductions, especially at the farthest distances (Fig. 14a). The magnitude of off-field loss reduction achieved by the low-drift pneumatic spout options (AP and XP) is comparable to values other researchers have reported using drift reducing hydraulic nozzles in vineyard field trials,[36,70,71] laboratory measurements,[38,72] or by indirect methods of assessment.[67]

3.5 In-field ground losses.

The average in-field losses measured for the tested configuration are shown in Fig. 15. A two-way ANOVA detected statistically significant differences between the configurations tested [$F(2,255)=10.303$, p=4.98E-05). Post-hoc tests (FREGW) showed that there were significant differences between CP and AP and between CP and XP (Fig. 15a); in-field losses increased 13% and 16% for the AP and XP configurations, respectively. The sampling position within vineyard rows (sprayer tracks, under-rows, and in the alley between rows) (Fig. 6) determines differences in in-field ground depositions [$F(4,255)=189.976$, p=3.15E-75). In particular, the ground deposits, measured at different locations in the vineyard, had a distinct tri-modal distribution (Fig. 15b), with its minimum at the sprayer track and its maximum under the rows. Intermediate values were found for the alley between the sprayed rows and not used as the sprayer track. An increase in spray losses in the alley between the sprayed rows was detected, especially for XP that is characterized by coarser droplets produced by the drift-reducing cannon spout. This phenomenon may result from the ballistic behaviour of coarser droplets[73] that affects droplet trajectory (higher kinetic energy) and leads to more direct ground losses in the alley between the sprayer rows. These findings agree with those reported by others,[4,5,74,75] who also found that coarser spraying results in higher ground deposits near to the sprayer. Configurations AP and XP showed lower off-field ground losses (Fig. 13a), but higher in-field ground losses (Fig. 15). Alternatively, configuration CP, characterized by the finest droplet size spectra, generated higher off-field ground losses and lower in-field ground losses. This indicated that the spray cloud generated by CP configurations, thanks to the action of wind currents, travelled farther than that produced by AP and XP, even under weak wind speeds. In a fashion similar to hydraulic atomization, the increased droplet size spectra dimensions in low-drift pneumatic cannon spouts diminishes the risk of drift generation,[76] and results in higher in-field ground losses.[12]

4 Conclusions

The spray application performance by a multi-row pneumatic sprayer used for fine spray quality application (CP configuration) was compared with that from two coarser spray quality application (AP and XP configurations). The comparison demonstrated that the variation in spray quality over the range investigated did not affect coverage (values averaged about 20% for the upper leaf side). Furthermore, coarser sprays produced greater (+20% with AP configurations) mean deposits on the canopy target. Even if the trials were not conducted per ISO22866,[2] the experimental data indicated that the drift-reducing cannon spout, mounted atop the sprayer head, has the potential to reduce drift. Indeed, it was demonstrated that under field conditions, the spout is able to significantly reduce off-field ground losses in the downwind area by amounts in the range of 76%-83%, based on the enlarged droplet size spectra produced. The most effective off-field loss-reducing configuration was that characterized by the liquid release position outside of the spout (XP), which produced reductions in off-field ground losses of up to 95% at the farther distances from the sprayed area. However, coarser sprays result in higher in-field ground losses, with values that ranged between +13% and +16%. The coarser spray applications (AP and XP configurations) are preferable configurations as they produce slightly greater mean in-field ground losses and very high reductions in off-field ground losses.

The options offered to farmers by the liquid hose release positions in the drift-reducing pneumatic cannon spout make it possible to choose droplet size spectra according to the environmental (e.g., air temperature, relative humidity, wind speed and direction) or site-specific conditions (e.g., presence in the near-field areas of sensitive non-receptor targets like water courses, sensitive crops, bystanders, and absence/presence of hedgerows) conditions, that may be more or less prone to the effects of drift generated during spray application, and without compromising coverage or deposition.

Even if the off-field ground losses data made it possible to evaluate the potential capability of the newly-designed pneumatic spout to reduce spray drift, further field trials, strictly conducted per ISO22866,[2] are required to evaluate the total amount of spray drift under the worst wind conditions, and to confirm the reductions in off-field ground losses obtained in this experiment.

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7 Tables

Table 1. Main characteristics of pneumatic nozzles used in the trials and relative droplets size spectra.

Nozzle type	Configuration ID[a]	Working pressure (MPa)	Liquid flow rate (L min^{-1})	D[v,0.1][b] (µm)	D[v,0.5][b] (µm)	D[v,0.9][b] (µm)	V_{100}[c] (%)	Air Flow Rate ($m^3 s^{-1}$)	Air speed ($m s^{-1}$)[d]
Fingers	CP, AP & XP	0.1	2.07	22	50	102	84	0.60	91
Cannon	CP	0.1	2.67	18	47	109	85	0.42	109
	AP	0.1	2.67	37	80	185	58	0.42	109
	XP	0.1	2.67	97	238	560	14	0.42	109

[a] The ID configuration is composed of initials that primarily identify the liquid release point in the cannon-type nozzles: conventional position (CP), alternative position (AP) is a liquid release point on the edge of spout, and extreme position (XP) is a liquid release point outside the spout.
[b] D[v,0.1], 10% of spray liquid volume fraction is made up of droplets smaller than this value; D[v,0.5], volume median diameter; D[v,0.9], 90% of spray liquid volume is made up of droplets smaller than this value.
[c] V_{100}: spray liquid fraction generated with droplets smaller than 100 µm.
[d] Values measured in the inner part of spouts, corresponding to the conventional liquid release position. In all cases, the Power Take Off (PTO) was settled at 540 rev min^{-1}.

Table 2: Statistical analysis of linear relationships between the number of impacts (n° cm^{-2}) and surface coverage (SC) below the 20% threshold. The correlations are shown separately for CP, AP, and XP configurations.

Configuration	**Equation**	***p* > (F)**	**Sign.**[a]	***ρ***
CP	Y=34.18+14.86*x	1.76E-80	***	0.880
AP	Y=17.72+11.84*x	1.65E-88	***	0.901
XP	Y=18.83+10.97*x	4.89E-81	***	0.871

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

Table 3: Weather conditions recorded during the trials, split by replicates.

Config. & replicates		Temperature	RH	Wind speed			Wind direction	
		Mean (°C)	Mean (%)	Min ($m\ s^{-1}$)	Max ($m\ s^{-1}$)	Mean ($m\ s^{-1}$)	Dominant	Mean (° azimuth)
CP	1	13.9	81.9	0.04	0.40	0.21	SW	227
	2	16.8	77.4	0.31	0.76	0.51	WSW	238
	3	18.9	59.6	0.04	0.78	0.43	WNW	298
AP	1	16.0	75.1	0.02	0.53	0.25	WNW	284
	2	19.4	66.8	0.32	1.40	0.83	WSW	259
	3	15.3	85.6	0.01	0.23	0.11	W	274
XP	1	18.5	62.4	0.12	1.84	0.89	NW	315
	2	15.5	83.8	0.32	0.53	0.41	SW	231
	3	16.4	71.7	0.20	0.95	0.54	SSW	195

702 Table 4: Significance obtained in three-way ANOVA for the canopy deposition (CD). The variables
703 investigated were configurations, depth level, and height level in the canopy and their interactions.
704

Sources	DF	*p* > (F)	Signif.[a]
Canopy deposition CD			
Configurations (Config)	2	0.005	**
Depth level (DL)	2	8.16E-14	***
Height level (HL)	2	2.42E-41	***
Config X DL	4	0.453	NS
Config X HL	4	0.030	*
DL X HL	4	1.94E-41	***
Config X DL X HL	8	0.857	NS

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

705

Table 5: Canopy deposition ±SE of the mean and homogeneity parameter (CV%). The significant differences among the configurations tested (CP, AP, and XP) are represented with p<0.001, post-hoc FREGW.

Variables		**Configurations**											
		CP[a]				**AP**[a]				**XP**[a]			
Mean deposit	CD (μl cm^{-2})	0.234	±	0.016	a	0.282	±	0.018	b	0.239	±	0.015	a
Deposit homogeneity	CV (%)	88.65				79.41				82.36			

[a] Mean values ± S.E.M.

Table 6: Significance obtained in three-way ANOVAs for the surface coverage, number of impacts, and impact dimension. The statistical analyses were performed separately using average values from both leaf sides (upper and lower), as affected by configurations, depth level, and height level in the canopy and their interactions.

Sources	DF	*p* > (F)	Signif.[a]	*p* > (F)	Signif.[a]	*p* > (F)	Signif.[a]
		Surface coverage					
		Averaged values (SC)		**Upper leaf side (SC_{up})**		**Lower leaf side (SC_{lo})**	
Configurations (Config)	2	0.389	NS	0.232	NS	0.725	NS
Depth level (DL)	2	1.20E-08	***	8.68E-15	***	1.65E-05	***
Height level (HL)	2	4.93E-22	***	1.25E-21	***	3.55E-13	***
Config X DL	4	0.019	*	7.35E-05	***	0.670	NS
Config X HL	4	0.182	NS	0.001	***	0.808	NS
DL X HL	4	5.17E-23	***	2.42E-56	***	0.044	*
Config X DL X HL	8	0.918	NS	0.203	NS	0.699	NS
		Number of impacts					
		Average values (N_i)		**Upper leaf side (N_{i-up})**		**Lower leaf side (N_{i-lo})**	
Configurations (Config)	2	2.66E-09	***	3.30E-05	***	3.53E-06	***
Depth level (DL)	2	3.98E-05	***	0.009	**	8.69E-08	***
Height level (HL)	2	1.96E-09	***	0.030	*	2.33E-08	***
Config X DL	4	0.891	NS	0.206	NS	0.683	NS
Config X HL	4	0.613	NS	0.027	*	0.707	NS
DL X HL	4	9.83E-06	***	0.118	NS	1.64E-09	***
Config X DL X HL	8	0.939	NS	0.002	**	0.451	NS
		Impact dimensions					
		Average values (I_d)		**Upper leaf side (I_{d-up})**		**Lower leaf side (I_{d-lo})**	
Configurations (Config)	2	1.13E-05	***	0.488	NS	2.73E-07	***
Depth level (DL)	2	0.344	NS	0.038	*	0.994	NS
Height level (HL)	2	0.003	**	0.006	**	0.001	***
Config X DL	4	0.515	NS	0.795	NS	0.676	NS
Config X HL	4	0.718	NS	0.204	NS	0.299	NS
DL X HL	4	0.003	**	0.488	NS	0.017	*
Config X DL X HL	8	0.539	NS	0.148	NS	0.542	NS

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

Table 7: Mean ±SE of the mean for surface coverage, number of impacts and impacts dimension parameters studied (averaged values over both leaf sides, upper and lower leaf sides). The significant differences among configurations tested (CP, AP, and XP) are represented with p<0.001, post hoc FREGW.

Variables		Configurations					
		CP[a]		AP[a]		XP[a]	
Mean coverage	SC (%)	14.685 ± 0.880	a	14.388 ± 0.963	a	13.193 ± 0.921	a
Upper leaf side coverage	Sc_{up} (%)	20.520 ± 1.403	a	20.446 ± 1.627	a	18.405 ± 1.490	a
Lower leaf side coverage	Sc_{lo} (%)	8.850 ± 0.847	a	8.331 ± 0.774	a	7.982 ± 0.919	a
Mean number of impacts	N_i (n° cm^{-2})	112.216 ± 5.904	b	83.514 ± 4.549	a	72.597 ± 3.718	a
Number of impacts for upper leaf side	N_{i-up} (n° cm^{-2})	123.541 ± 9.500	b	86.726 ± 6.924	a	80.987 ± 5.946	a
Number of impacts for lower leaf side	N_{i-lo} (n° cm^{-2})	104.405 ± 7.482	b	81.259 ± 6.039	a	66.263 ± 4.685	a
Mean impact dimension	I_d (μm)	491.757 ± 10.971	a	569.527 ± 13.911	b	561.353 ± 14.925	b
Impacts dimension for upper leaf side	I_{d-up} (μm)	546.992 ± 17.758	a	572.481 ± 24.676	a	581.691 ± 26.082	a
Impacts dimension for lower leaf side	I_{d-lo} (μm)	453.663 ± 12.617	a	567.452 ± 16.218	b	545.996 ± 17.242	b

[a] Mean values ± S.E.M.

8 Figures

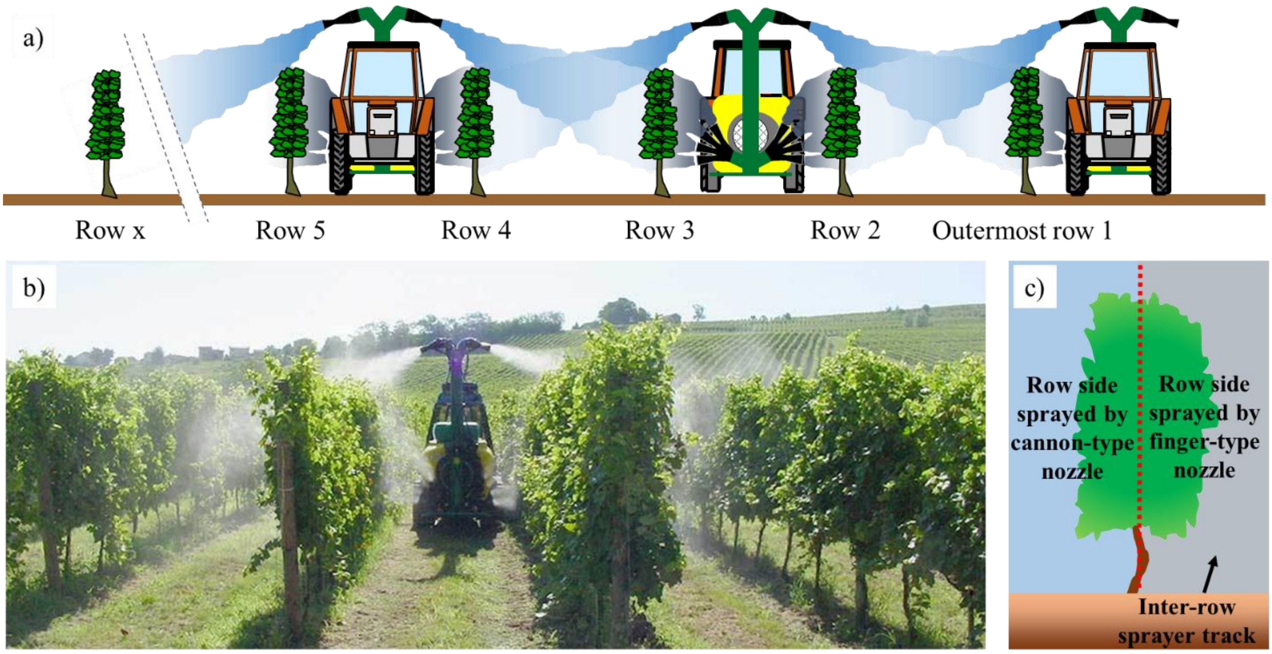

Figure 1. a-b) Spray management passages between vineyard rows with multiple-row pneumatic sprayer Cima 50 Plus 400L, equipped with two finger-type nozzles mounted at the base of the sprayer head, and two cannon-type nozzles mounted on the top, and c) application feature according to row side.

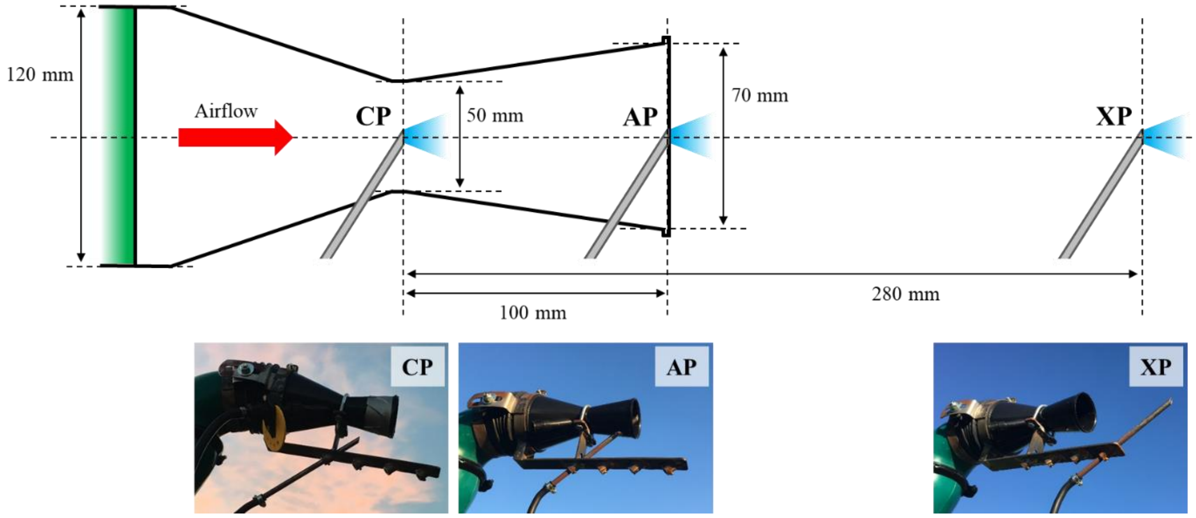

Figure 2. Conventional (CP), alternative (AP), and alternative extreme (XP) positions of insertion of the liquid hose at the release point in the air spout of a cannon-type nozzle.

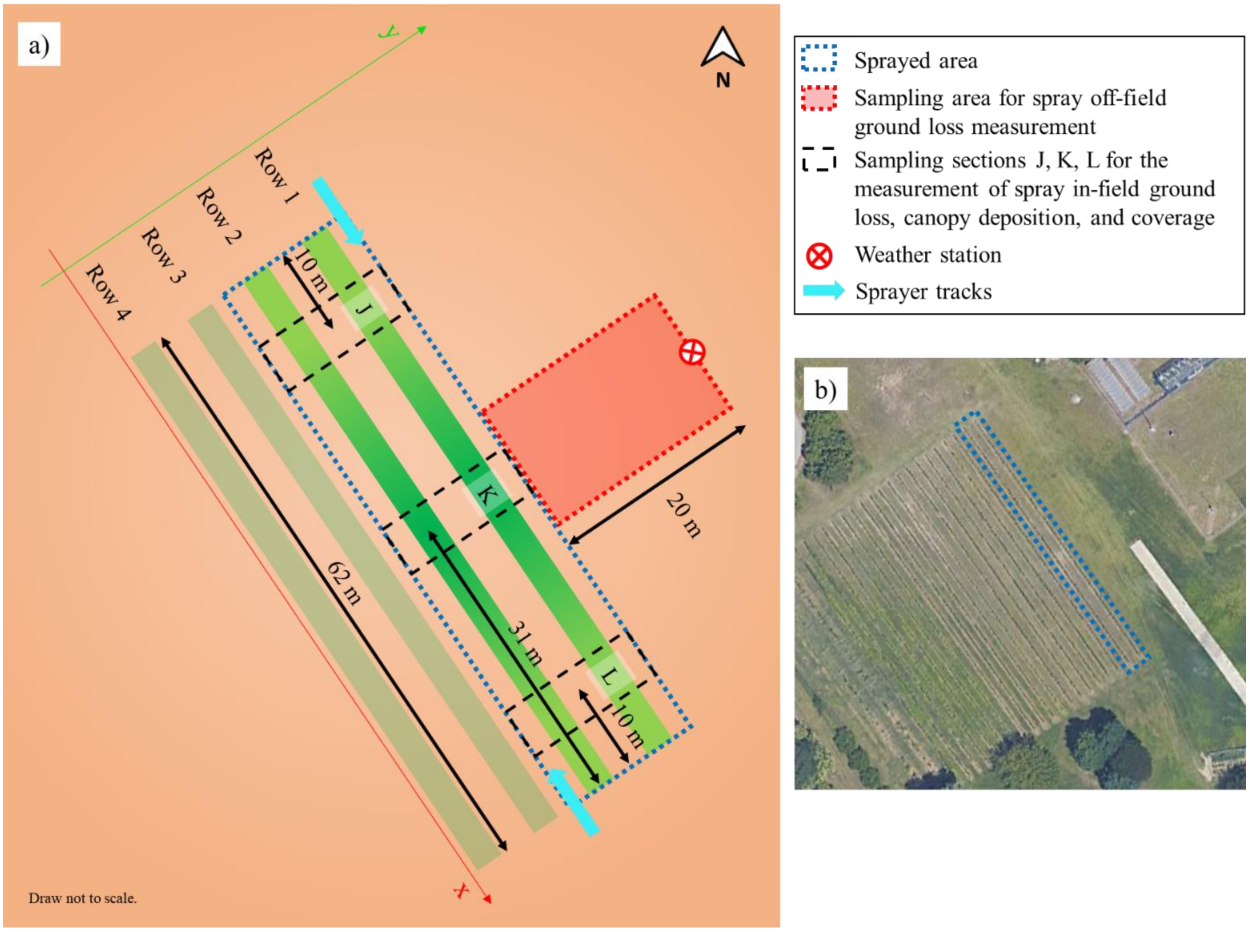

Figure 3. a) Schematic of trial layout for the measurement of canopy deposition, spray coverage, in-field ground losses, and off-field ground losses with b) an aerial view of the vineyard field trial area.

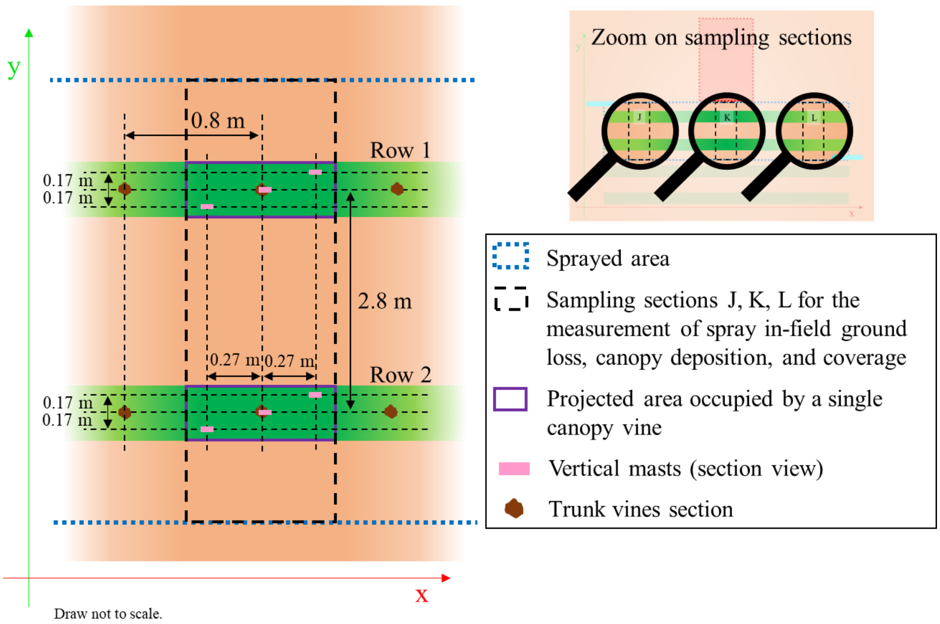

Figure 4. Test plot layout for the measurement of canopy deposition and spray coverage.

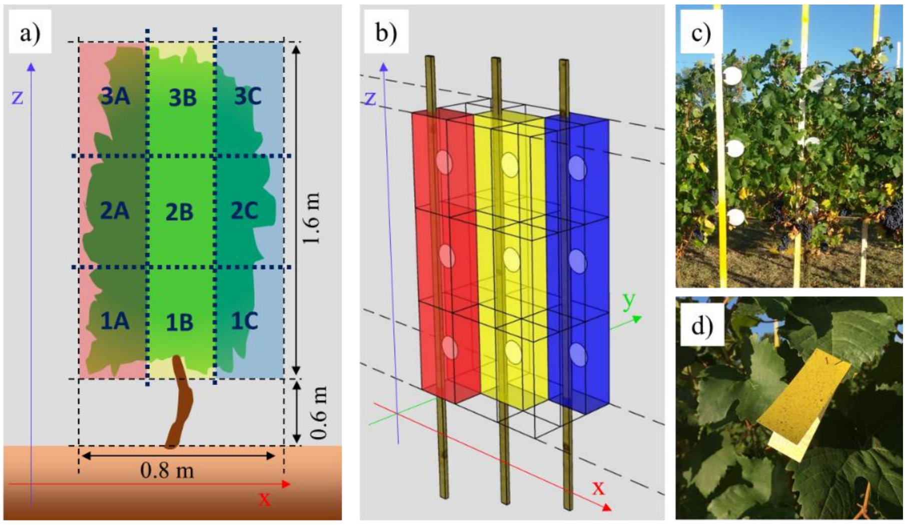

Figure 5. 2D visual schematic of the sampling strategy a) canopy depths A, B, and C, and canopy heights 1, 2, and 3. b) Schematic of 3D sampling positions. c-d) Sample placement for spray deposition and spray coverage measurement in vines and canopy.

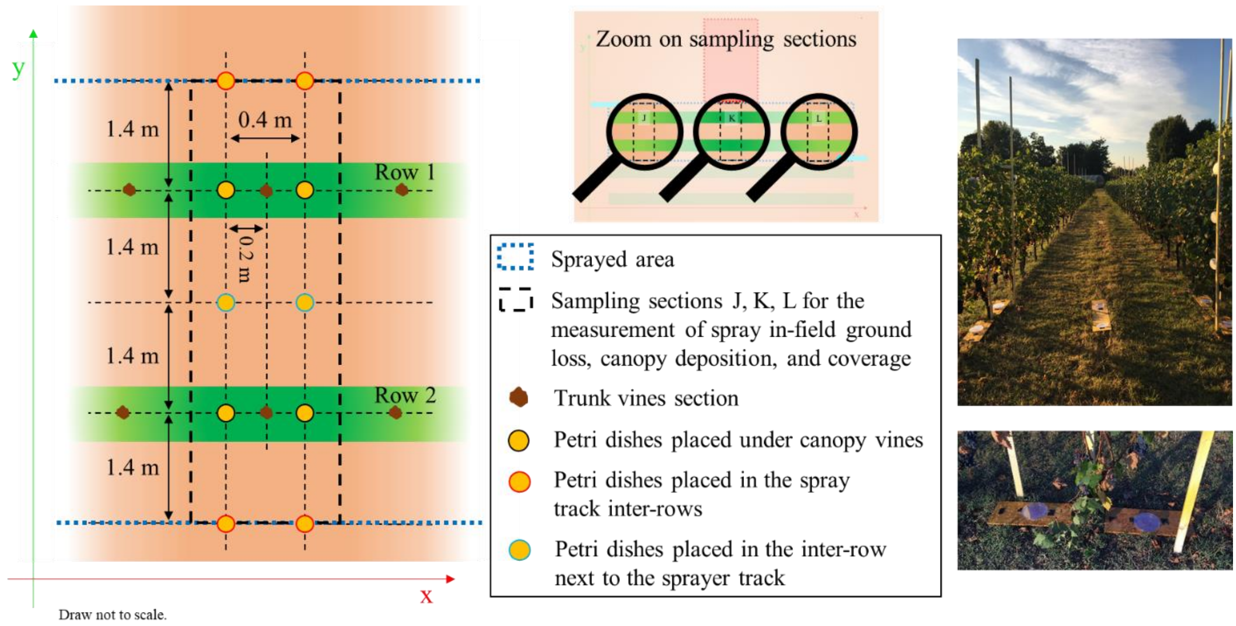

Figure 6. Test plot layout for the measurement of in-field ground losses.

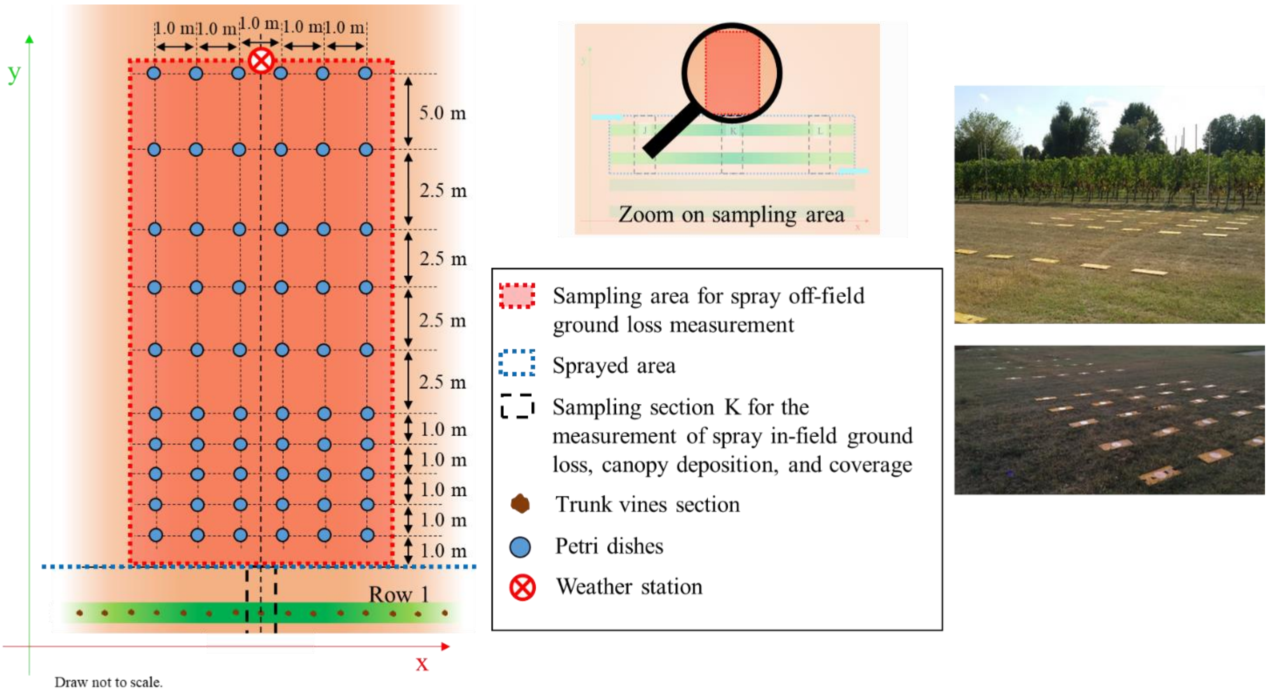

Figure 7. Test plot layout for the measurement of off-field ground losses.

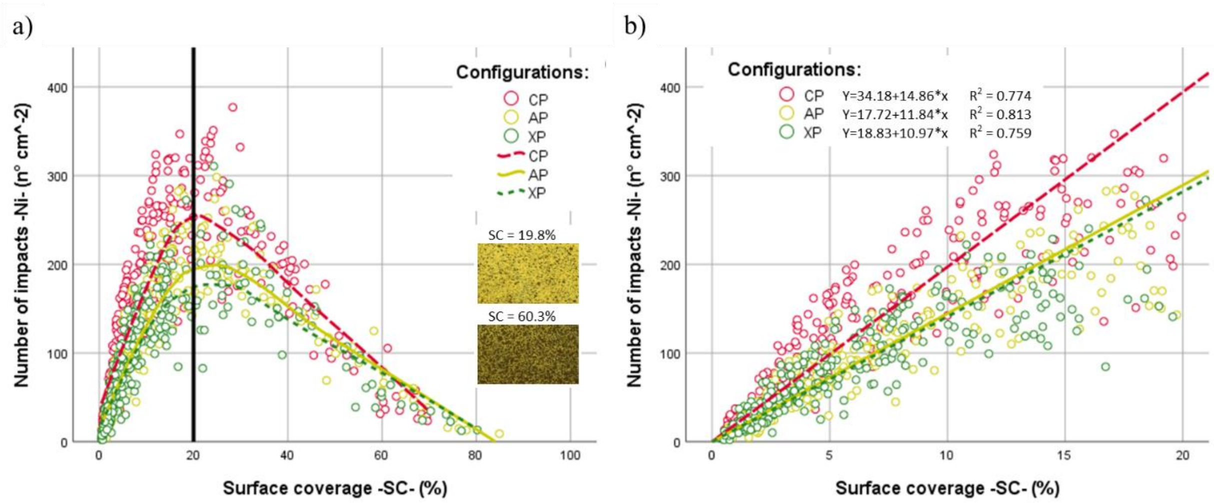

Figure 8: Relationships between the number of impacts (n° cm^{-2}) and surface coverage (SC) (%) for a) the full dataset, and b) coverage below the 20% threshold. A visual example of Water Sensitive Paper (WSP) characterized by SC below and above 20% is provided.

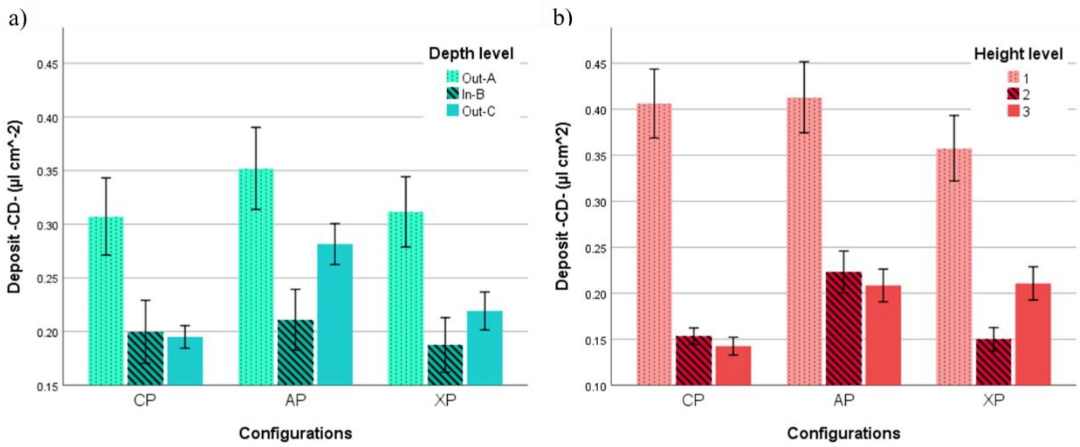

Figure 9: Canopy deposition (CD), measured in µl cm^{-2}, for each configuration tested. Graph a) depicts canopy deposition at different outer (Out–A and Out–C) and inner (In–B) depth levels, while b) depicts canopy position at different heights (1, 2, and 3), moving from bottom to top of the vegetation strip for each configuration tested. The bars on the histograms indicate the mean ± SE of the mean. Configurations: pneumatic conventional finger-type nozzle combined with cannon-type nozzle with release liquid hose in the conventional (CP), alternative (AP), and completely outside the spout (XP) positions.

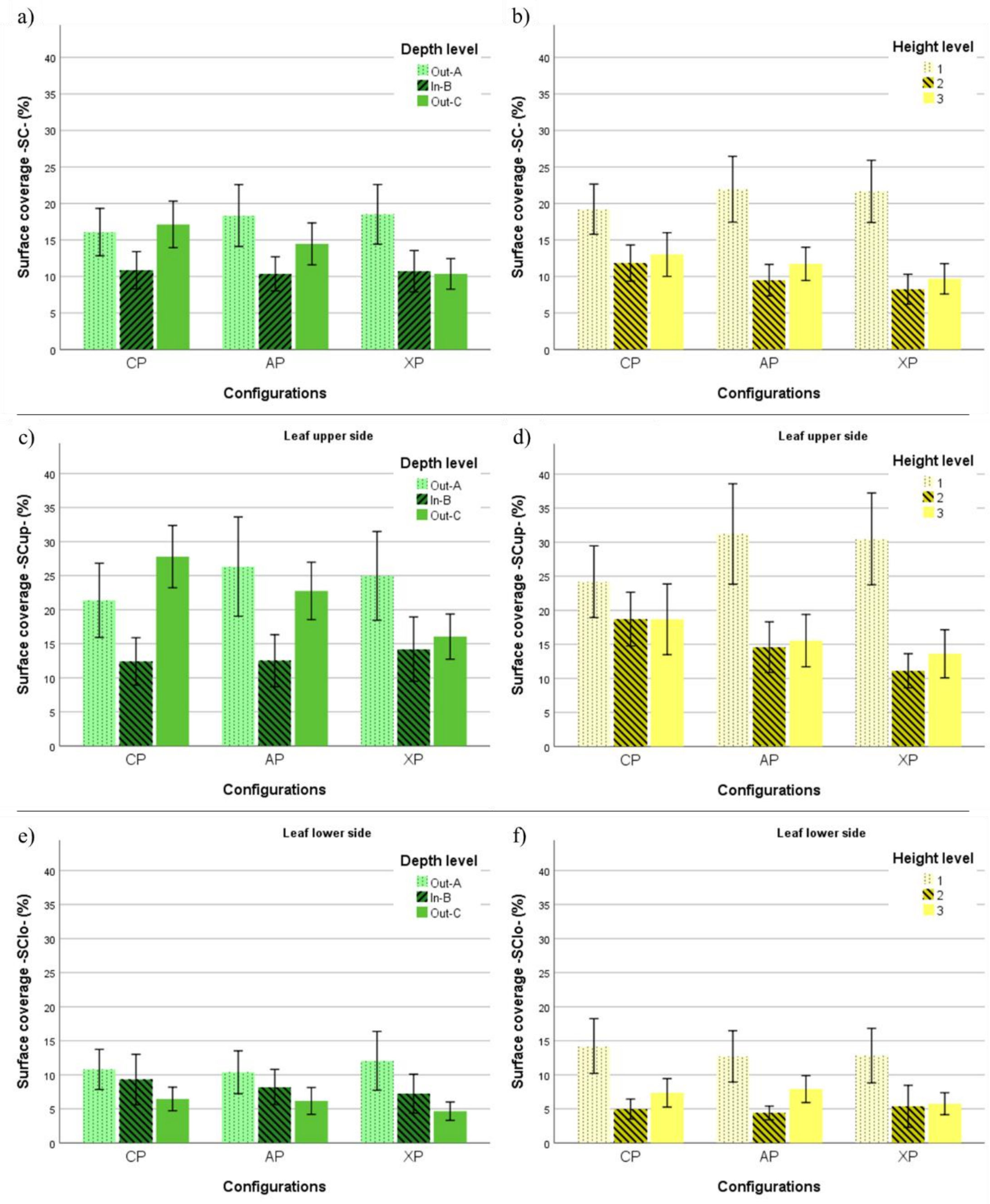

Figure 10. Surface coverage parameter graphs: a) and b) top graphs depict overall coverage derived from averaged values over leaf upper and lower sides (SC) (%); c) and d) middle graphs depict coverage for leaf upper side (SC_{up}); e) and f) bottom graphs depict coverage for leaf lower side (SC_{lo}). Data graph set a), c), and e) depicts coverage data at different outer (Out–A, Out–C) and inner (In–B) depth levels, while data graph set b), d), and f) depicts coverage data at different height levels (1, 2, and 3), moving from the bottom to top of the vegetative strip for each configuration tested. The bars on the histograms indicate the mean ± SE of the mean. Configurations: pneumatic conventional finger-type nozzle combined with cannon-type nozzle with release liquid hose in conventional (CP), alternative position (AP), and completely outside the spout (XP) positions.

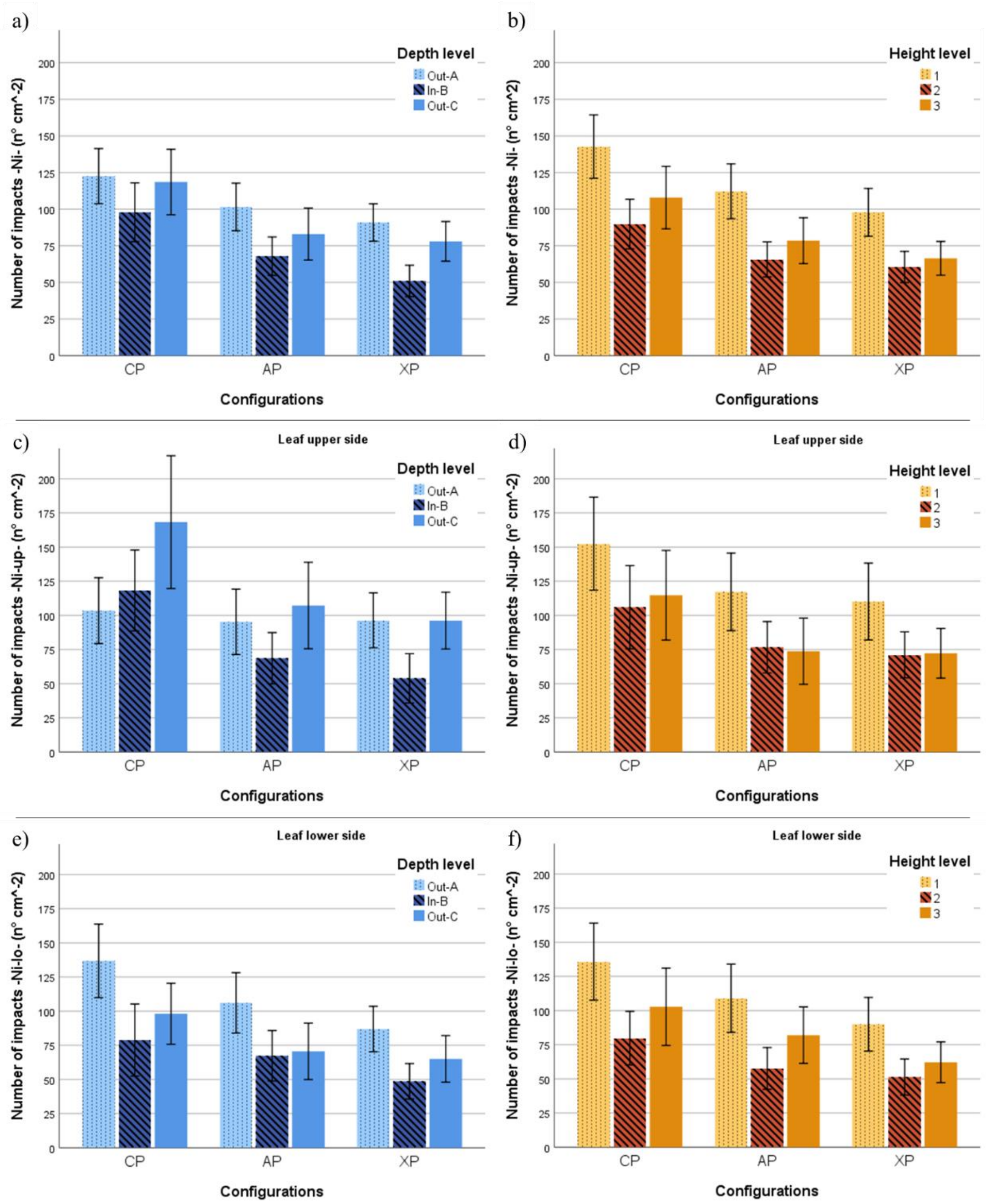

Figure 11: Impact number graphs: a) and b) depict overall impacts, derived from averaged values over leaf upper and lower sides (N_i) (n° cm^{-2}); c) and d) depict impacts on leaf upper sides (N_{i-up}); e) and f) depict impacts on leaf lower sides (N_{i-lo}-). Data graph set a), c), and e) depict impact data for different outer (Out–A and Out–C) and inner (In–B) depth levels, while data graph set b), d), and f) depict impact data for different height levels (1, 2, and 3), moving from the bottom to top of the vegetative strip for each configuration tested. The bars on each histogram show the mean ± SE of the mean. Configurations: pneumatic conventional finger-type nozzle combined with cannon-type nozzle with release liquid hose in conventional (CP), alternative (AP) and completely outside the spout (XP) positions.

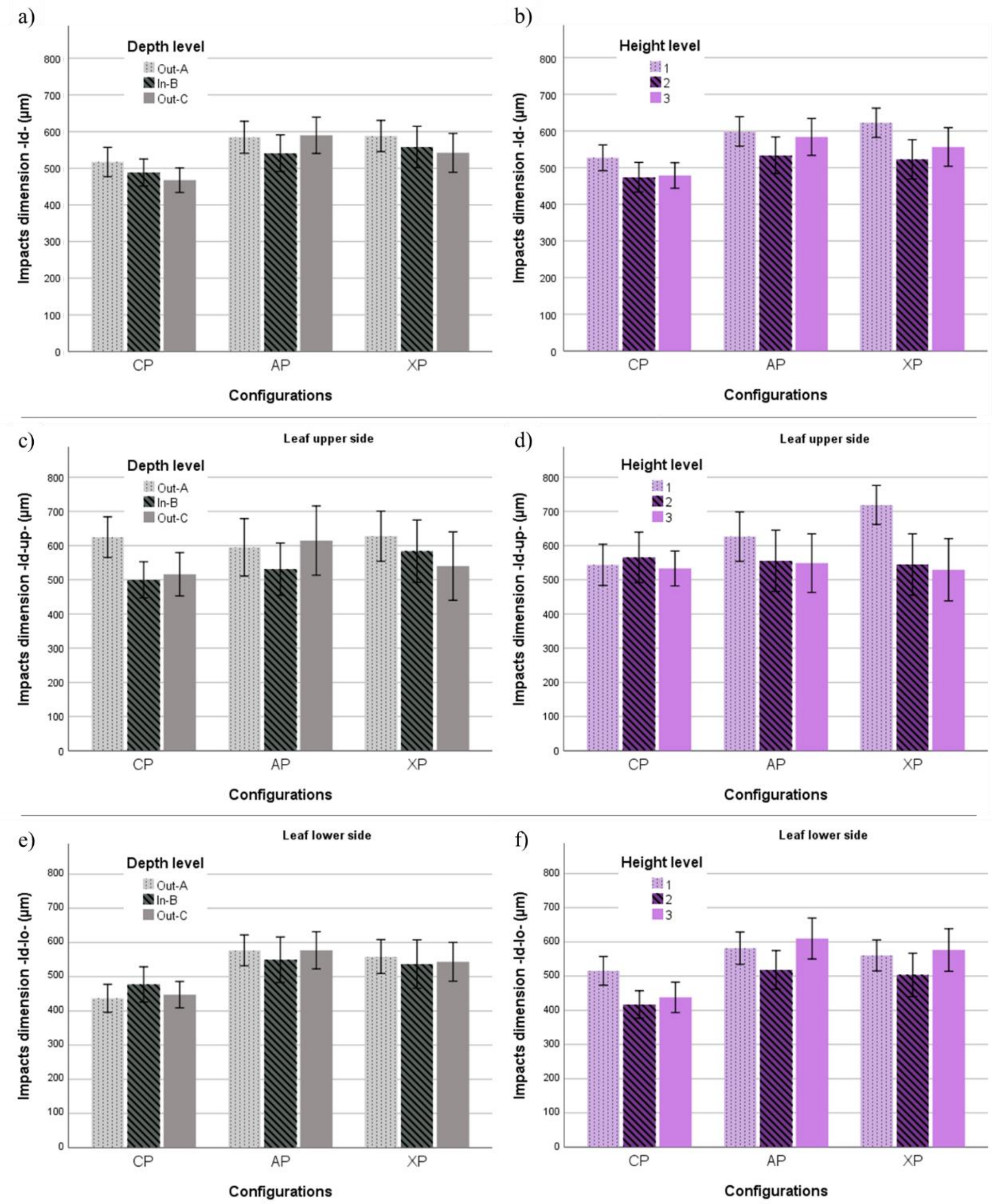

Figure 12: Impacts dimension graphs: a) and b) depict overall dimension, derived from averaged values over leaf upper and lower sides (I_d) (µm); c) and d) depict impact dimension on the leaf upper side ($I_{d\text{-}up}$); e) and f) depict dimension on the leaf lower side ($I_{d\text{-}lo}$). Data graph set a), c), and e) depict dimension data at different outer (Out–A and Out–C) and inner (In–B) depth levels, while data graph set b), d), and f) depict dimension data at different heights (1, 2, and 3), moving from the bottom to top of the vegetative strip for each configuration tested. The bars on each histogram show the mean ± SE of the mean. Configurations: pneumatic conventional fingers-type nozzle combined with cannon-type nozzle with release liquid hose in conventional (CP), alternative (AP), and completely outside the spout (XP) positions.

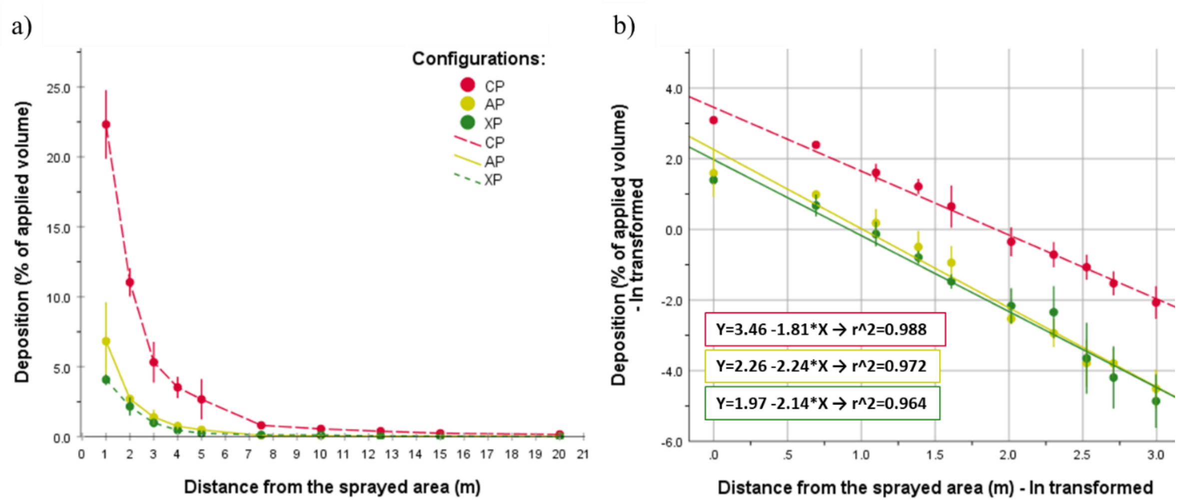

Figure 13: a) Off-field ground loss deposit profiles for each configuration tested, and b) linear relationship between deposition and distance from the sprayed area. The mean ± SE of the mean (% of applied volume) of the spray deposited on the collectors is represented at each distance from the sprayed area. Configurations: pneumatic conventional fingers-type nozzle combined with cannon-type nozzle with release liquid hose in conventional (CP), alternative position (AP), and completely outside the spout (XP) positions.

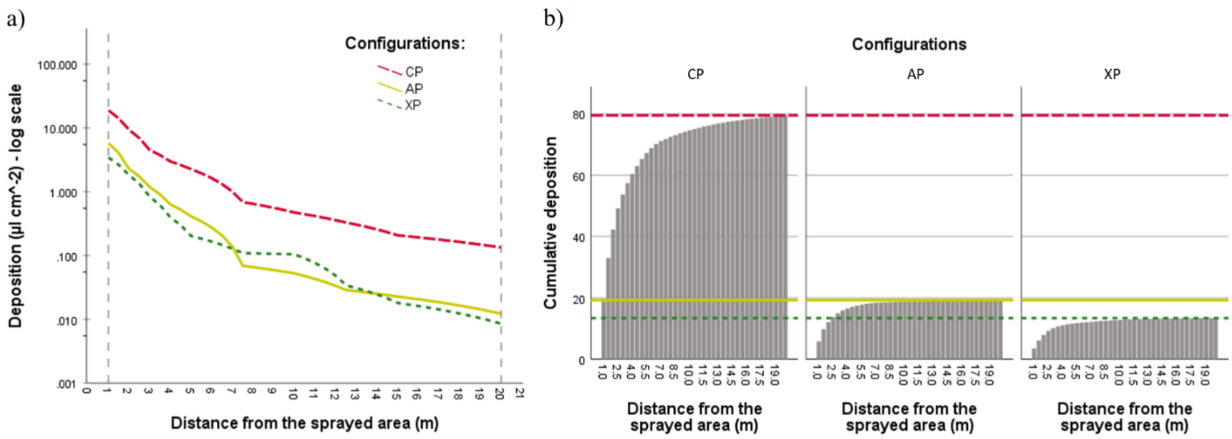

Figure 14: a) Off-field ground loss deposit profiles (log scale), and b) related deposit cumulative curves obtained from each configuration tested. Total drift thresholds are shown for the tested configurations: CP (dotted red line), AP (solid yellow line), and XP (dotted green line) These serve as the basis for the calculation of off-field ground loss reductions. Configurations: pneumatic conventional fingers-type nozzle combined with cannon-type nozzle with release liquid hose in conventional (CP), alternative (AP), and completely outside the spout (XP) positions.

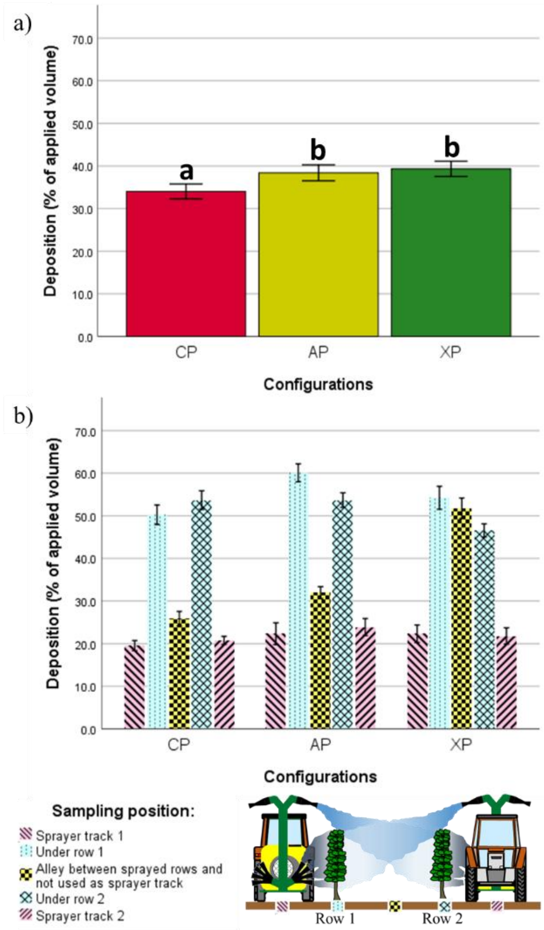

Figure 15: a) Comparison of total in-field ground loss depositions, and b) losses measured at different vineyard row positions obtained from each configuration tested. Represented are the significant differences among the average depositions measured at each position for each configurations tested, using two-way ANOVA, $p<0.001$, post hoc FREGW and the mean ± SE of the mean (% of applied volume). Configurations: pneumatic conventional fingers-type nozzle combined with cannon-type nozzle with release liquid hose in conventional position (CP), alternative position (AP), and completely outside the spout (XP) positions.