

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

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

**This is a pre print version of the following article:**

*Original Citation:*

*Availability:*

This version is available <http://hdl.handle.net/2318/1758367> since 2022-11-19T14:59:52Z

*Published version:*

DOI:10.1002/ps.5975

*Terms of use:*

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)



# UNIVERSITÀ DEGLI STUDI DI TORINO

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21

***This is an author version of the contribution published on:***

*Pest Management Science, 2020, volume 73*

*<https://doi.org/10.1002/ps.5975>*

*M. Grella, A. Miranda Fuentes, P. Marucco, P. Balsari*

*Volume 76, Wiley, 2020, 4173-4191*

***The definitive version is available at:***

***<https://onlinelibrary.wiley.com/doi/epdf/10.1002/ps.5975>***

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

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

25 Marco Grella<sup>a,\*</sup>, Antonio Miranda-Fuentes<sup>b</sup>, Paolo Marucco<sup>a</sup> and Paolo Balsari<sup>a</sup>

26

27 <sup>a</sup>Department of Agricultural, Forest and Food Sciences (DiSAFA), University of Turin (UNITO), Largo  
28 Paolo Braccini, 2, 10095 Grugliasco (TO), Italy; marco.grella@unito.it (M.G.); paolo.marucco@unito.it  
29 (P.M.); paolo.balsari@unito.it (P.B.)

30

31 <sup>b</sup>Department of Rural Engineering, University of Córdoba, Ctra. Nacional IV, km 396, Campus de  
32 Rabanales, 14014 Córdoba, Spain; g62mifua@uco.es (A.M.F.)

33

34 \*Corresponding author: Marco Grella, DiSAFA, University of Turin (UNITO), Largo Paolo Braccini, 2,  
35 10095 Grugliasco (TO), Italy.

36 Tel.: +39.011.6708610

37 E-mail: marco.grella@unito.it

38

39 **Abstract**

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

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

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

57

58 **Keywords:** Pesticide application; Pneumatic sprayer; Drift reducing technique; Spray quality; Tracer; Water  
59 sensitive papers; Application efficiency  
60

<b>Abbreviations</b>	
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

61

## 62 **1 Introduction**

63 Only a fraction of total Plant Protection Products (PPP) applied in bush/tree crops with conventional sprayers  
64 is actually deposited on the intended target.<sup>1</sup> Some of the applied PPP is transported outside the sprayed area  
65 by air currents as spray drift.<sup>2</sup> Ultimately, the spray is deposited on the ground, either directly in the path of  
66 the sprayer tractor, beneath the target tree rows, or indirectly in adjacent areas.<sup>1,3-5</sup> Thus, during and  
67 immediately after a spray application, non-target receptors, including water,<sup>6</sup> plants,<sup>7</sup> animals,<sup>8-10</sup> and  
68 humans<sup>11,12</sup> can be acutely exposed and may be at risk for adverse effects. Today, PPP application must

69 simultaneously balance issues of crop profitability and human and environmental safety. As laid out by the  
70 European Directive for Sustainable Use of Pesticides 2009/128/EC,<sup>13</sup> the strategies for the integrated pest  
71 management and the PPP dose reduction must be favored. Nevertheless, pesticide use and management play  
72 crucial roles in the economic sustainability of agriculture for the foreseeable future.<sup>14</sup> Any improvement to  
73 spray application efficacy and efficiency can potentially contribute to agricultural sustainability in three ways:  
74 i) improve PPP benefit, ii) reduce environmental and human contamination risk, and iii) raise food quality and  
75 safety standards.

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

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

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

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

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

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

116

## 117 **2 Materials and methods**

### 118 *2.1 Characteristics and configurations of the tested sprayer.*

119 A vineyard multiple-row pneumatic sprayer Cima 50 Plus equipped with a 400L polyethylene tank, steel high  
120 pressure radial fan (500 mm of diameter), and a “2 hand-2 cannon spray head (TC.2M2C.50P) (CIMA S.p.A.,  
121 Pavia, Italy) was tested (Fig. 1). To spray to consecutive rows at once, two different spouts were mounted on  
122 a sprayer to deliver the liquid solution in different ways to two rows. One is a finger-type nozzle at the lower  
123 part of the spray head that delivers multiple streams of liquid to the near row and the other is throws a single  
124 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  
125 of each row is sprayed by the finger-type nozzle and the other side is sprayed by the cannon-type nozzle (Fig.  
126 1c).

127 Three sprayer configurations were tested in this assessment. They were created from a combination of  
128 conventional finger-type nozzles and modifications of cannon-type nozzles by manually varying the insertion  
129 position of the liquid hose.<sup>50</sup> As detailed in Fig. 2, the three tested configurations differ among one another in  
130 the diameter of the spout at point of liquid release inside the cannon air spout. More specifically, a 50 mm  
131 diameter was used for the conventional position (CP) and 70 mm was used for the alternative (AP) position.  
132 For the extreme configuration (XP), the liquid hose was positioned outside the spout, at 280 mm from CP (Fig.  
133 2). Each configurations was tested with a fixed volume (169 L ha<sup>-1</sup>) applied at a forward speed of 1.67 m s<sup>-1</sup>  
134 (6 km h<sup>-1</sup>). To obtain the intended total sprayed volume, each nozzle had its liquid flow regulator disc (a plastic  
135 disc with calibrated holes in its perimeter) in position n° 7 to produce a liquid flow rate of 2.07 L min<sup>-1</sup> from  
136 the finger nozzle and 2.67 L min<sup>-1</sup> for the cannon nozzle, both at 0.1 MPa (1 bar) pressure. The total spray  
137 liquid flow rate was 9.48 L min<sup>-1</sup>. The Power Take-Off (PTO) rotary speed was always set at 540 rev min<sup>-1</sup>.

138 The droplet size spectra produced by both pneumatic nozzle types, combined with different liquid release  
139 points for the cannon-type nozzles was determined in the laboratory at DiSAFA facilities using a Malvern  
140 Spraytec laser diffraction system STP5342 (Malvern Instruments Ltd., Worcestershire, UK). The methodology  
141 was the same as the one detailed in Miranda-Fuentes et al<sup>50</sup>. The liquid pressure and flow rates used for droplet  
142 size measurement were identical to those used in the field trials: 1 bar and, 2.07 L min<sup>-1</sup> and 2.67 L min<sup>-1</sup> for

143 finger-type and cannon-type nozzles, respectively. The droplet diameters for the 10<sup>th</sup> (D[v,0.1]), 50<sup>th</sup> –VMD-  
144 (D[v,0.5]), and 90<sup>th</sup> (D[v,0.9]) percentiles of spray liquid volume and for V<sub>100</sub> values, together with airflow  
145 characteristics, determined for the different pneumatic nozzles are shown in Table 1. Three test replicates were  
146 conducted for each sprayer configuration.

## 147 *2.2 Test location and crop characteristics*

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

## 161 *2.3 Experimental plot layout and sampling system.*

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

### 168 *2.3.1 Canopy spray deposition and coverage measurements: experimental plot layout.*

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

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

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

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

### 186 *2.3.2 In-field ground losses measurements: experimental plot layout.*

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

### 195 *2.3.3 Off-field ground loss measurements: experimental plot layout.*

196 For each replicate, off-field ground losses (FGL<sub>off</sub>) were measured at ten bare-soil sampling locations, placed  
197 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  
198 location, six discrete ground level horizontal sampler Petri dishes (140 mm diameter) were placed 1 m from  
199 each other. The first line of collectors was placed 2.4 m from the outermost row (or 1 m from the sprayed area).  
200 Two minutes after the vineyard plot had been completely sprayed, the Petri dishes were covered and collected  
201 in closed dark boxes to prevent tracer photo-degradation.

### 202 *2.4 Monitoring of the environmental conditions.*

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

### 211 *2.5 Spray liquid and tracer concentrations.*

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



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

## 220 2.6 Sample analysis and calculated parameters.

### 221 2.6.1 Deposition sample off-target losses: sediment and canopy deposition.

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

233 The deposit on each artificial collector ( $D_i$ ), expressed per unit area in  $\mu\text{L cm}^{-2}$ , was calculated from Eq. (1)  
234 according to ISO 22401 as follows:<sup>53</sup>

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

235 where  $D_i$  is the spray deposit on a single collector, expressed in  $\mu\text{L cm}^{-2}$ ;  $p_{\text{smp}}$  is the absorbance value of the  
236 sample (adim.);  $p_{\text{blk}}$  is the absorbance of the blanks (adim.);  $V_{\text{dil}}$  is the volume of the dilution liquid (deionized  
237 water) used to extract tracer deposit from the collector in  $\mu\text{L}$ ;  $p_{\text{spray}}$  is the absorbance value of the spray mix  
238 concentration applied during testing and sampled at the pneumatic nozzle outlet (adim.);  $A_{\text{col}}$  is the projected  
239 area of the collector exposed to the spray in  $\text{cm}^2$ ;  $\varepsilon$  is the extractability factor, equal to 0.589 according to  
240 Miranda-Fuentes et al.<sup>46</sup>

241  
242 For each replicate, FGL<sub>off</sub> deposits were measured at different distances from the sprayed area in order to draw  
243 the near-field sedimentation spray curve.<sup>54-55</sup> The total off-field ground losses (TFGL<sub>off</sub>) were then calculated  
244 by numerical integration of the sedimentation curves, as proposed and successively adapted by Grella et al.<sup>56,57</sup>  
245 The methodology approximated the definite integral using the mid-ordinate rule.

246 In addition, the coefficient of variation (CV%) was calculated for the deposition values at all sample points  
247 and used as indicators of homogeneity of the deposit distribution inside the canopy.<sup>58</sup>

248                    *2.6.2 Canopy coverage samples*

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

257

258                    *2.7 Calculation of off-field and in-field ground loss reductions and statistical analyses.*

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

263    All statistical analyses were performed using IBM SPSS Statistics for Windows V25.<sup>62</sup> The data were tested  
264    for normality using the Shapiro-Wilk test and by visual assessment of the Q-Q plots of residuals. First, three-  
265    way Analysis of Variance (ANOVA) was used to establish the effects of the configurations tested, together  
266    with canopy depth and height. Canopy deposition CD ( $\mu l\ cm^{-2}$ ) and coverage parameters were considered as  
267    dependent variables. Coverage parameters SC (%),  $N_i$  ( $n^\circ\ cm^{-2}$ ), and  $I_d$  ( $\mu m$ ) were considered two ways—  
268    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-  
269    way ANOVA was performed on WSP images having SC values below 20%, as the reduced dataset was  
270    processed to obtain an equally-reduced dataset for all compared treatments to allow accurate effect evaluation.  
271    The 20% threshold had been defined based on preliminary study of the relationship (Fig. 8) and correlation  
272    (Table 2) between SC and  $N_i$ . This procedure was specifically adopted to avoid misinterpretation of  $N_i$  and  $I_d$   
273    final results.<sup>1</sup> Indeed, as already demonstrated by other authors,<sup>48</sup> any spot size measurements made on WSP  
274    with coverage greater than about 20% are unreliable due to touching or overlapping. However, the SC  
275    threshold value must be defined case-by-case based on a preventive dataset analysis because it might vary with  
276    various spray application parameters (e.g., spray quality, spray application rate).

277    For each configuration tested, the relationship between average off-field ground loss depositions and distance  
278    from the sprayed area was evaluated using a linear regression analysis. As preparation, the data were ln-  
279    transformed to linearize the power function that related both variables, and to achieve residual normality and  
280    homoscedasticity. Afterwards, the linear fit models obtained from each configuration were compared using  
281    one-way Analysis of Covariance (ANCOVA) to evaluate the relative effectiveness of each configuration to  
282    reduce deposition while controlling for the distance from the sprayed area (covariate). Statistical differences  
283    among the in-field ground losses generated by the multiple-row pneumatic sprayer were analysed with two-

284 way ANOVA that considered the configurations tested and sampling positions as sources of variation. In all  
285 cases, the means were compared using the FREGW post-hoc test ( $\alpha = 0.05$ ). Prior to analysis, the percentage  
286 data were  $\arcsin([\dots]/100)^{0.5}$  transformed and the deposition data were  $\ln[\dots]$  transformed to achieve residual  
287 normality and homoscedasticity.<sup>63</sup> Residual analyses were also performed.

288

### 289 **3 Results and discussion**

#### 290 *3.1 Environmental conditions during field trials.*

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

#### 297 *3.2 Canopy deposition*

298 The three-way ANOVA (Table 4) indicated that the tested configurations exerted statistical influence on mean  
299 canopy deposition. In particular, AP demonstrated increased canopy depositions as compared with  
300 configurations CP and XP mean CD values of 0.234 (CP), 0.282 (AP), and 0.239 (XP)  $\mu\text{l cm}^{-2}$  (Table 5).  
301 Moreover, CD varied highly ( $p < 0.001$ ) across the various depths and heights within the canopy (Table 4).  
302 Depth result indicated that irrespective of configuration, the highest deposition was found at canopy depth  
303 Out–A, which corresponded to the row side sprayed directly by the finger-type nozzle (Fig. 9a). Similarly,  
304 among the three heights sampled along the vegetative strip, the largest deposit was found at its lowest level  
305 (Height 1), which is also the grape band (Fig. 9b). In this case, this lowest level was closest to the finger-type  
306 nozzle. In the case of canopy depth Out–C, corresponding to the row side sprayed directly by the cannon-type  
307 nozzle, the deposition amount for XP was less than half and at least three times less for CP than that found at  
308 depth Out–A. Alternatively, the AP configuration produced higher depositions at depth Out–C, as compared  
309 with either CP or XP. In all cases, depth position In–B exhibited lower deposition values relative to the two  
310 external canopy positions (Out–A and Out–B), but was not substantially different across the three tested  
311 configurations. Only AP had a slightly higher value for CP (Fig. 9a).

312 Among different canopy heights, the AP and XP configurations produced increased depositions at height 3  
313 (highest canopy portion), whereas only AP was able to increase deposition at height 2 (Fig. 9b). Despite the  
314 strong deposition differences across canopy depths and heights for each configuration, deposition homogeneity  
315 (CV%) was found for all configurations: 89 (CP), 79 (AP), and 82 % (XP) (Table 5). The CV% values obtained  
316 were comparable with those reported by other authors in more critical crops, such as olive trees traditional-  
317 trained with very expansive canopies treated by conventional axial fan air-assisted sprayers.<sup>64</sup>

318 In general, the canopy deposition results observed in this study suggest that an uneven canopy deposition,  
319 regardless of the droplet size spectra generated, results from a pneumatic sprayer that delivers a different type  
320 of spray application to different sides of the row (Fig. 1). These results align with those reported by Codis et

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

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

### 340 3.3 Spray coverage.

341 The three-way ANOVA of the full dataset (972 WSP) showed that increased droplet size related to  
342 modification of the cannon spout liquid release position does not significantly change ( $p > 0.05$ ) canopy  
343 coverage (Tables 6 and 7). Despite the tendency for surface coverage values to decrease as droplet size  
344 increases, the resulting SC values (14.6 for CP, 14.4 for AP, and 13.2 % for XP) did not vary substantially by  
345 configuration (Table 7). When coverage was considered by leaf side, the mean values also fell within relatively  
346 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  
347  $SC_{lo}$ , respectively (Table 7). As demonstrated above, overall surface coverage did not vary with the  
348 configuration. On the other hand, SC,  $SC_{up}$  and  $SC_{lo}$  all exhibited high variation ( $p < 0.001$ ) with changes in  
349 canopy position, depth, and height levels (Table 6).

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

358 The same trend was also exhibited for  $SC_{up}$  at heights 2 and 3 (Fig.10d), the positions less influenced by finger-  
359 type nozzle proximity. Regardless of configuration, the fact that the pneumatic spray does not guarantee the  
360 30% coverage threshold established by Chen et al.<sup>66</sup> and used by others<sup>64</sup> to evaluate coverage in hydraulic  
361 spray application is noteworthy. Here, only on the leaf upper side, and only at some canopy positions, was the  
362 30% coverage threshold achieved. As for the leaf lower side (Fig. 10e and f), surface coverage was always  
363 below 15%, although higher values were achieved on the side directly sprayed by the finger-type nozzle. In  
364 rank order, the best surface coverage was at Out-A (finger-type nozzle closest to the vegetative strip), which  
365 was followed by In-B (inner canopy) and then Out-C. The wide variation in coverage at the various canopy  
366 sampling positions might relate to uneven sprayer fan airflow volumes and speeds that could lead to poor  
367 disease control.<sup>67,68</sup>

368 Surface coverage characteristics, such as the number of impacts unit and impact dimension, were analysed on  
369 the reduced dataset (756 WSP) to avoid misinterpretation (Fig. 8b). As expected, the three-way ANOVA  
370 indicated that the variation in droplet size spectra of the three configurations significantly affected ( $p < 0.001$ )  
371 all impact number parameters (Table 6). Specifically,  $N_i$ ,  $N_{i-up}$ , and  $N_{i-lo}$  all decreased from the highest number  
372 with CP, followed by AP, and to XP last. These results revealed how significantly different the original release  
373 liquid position in the cannon spout (CP configuration) is from the other two tested positions (Table 7). Even  
374 through cannon-type nozzle in the AP configuration has a three-fold lower VMD value (80) than that produced  
375 by the XP configuration (238), the two configurations did not differ significantly for  $N_i$ ,  $N_{i-up}$ , and  $N_{i-lo}$  (Table  
376 7). The very fine droplets produced by the finger-type nozzles may influence this effect and partially hide the  
377 effect of the XP configuration to further reduce  $N_i$  as expected. The  $N_i$  values were 112.2 (CP), 83.5(AP), and  
378 72.6 (XP)  $n^\circ cm^{-2}$ . The number of impacts for separate leaf sides were 123.5 (XP), 86.7 (AP), and 81.0 (XP)  
379  $n^\circ cm^{-2}$  for  $N_{i-up}$  and 104.4 (CP), 81.3 (AP), and 66.3 (XP)  $n^\circ cm^{-2}$  for  $N_{i-lo}$ , (Table 7).

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

392 Impact dimension was also investigated. Three-way ANOVA resulted as expected, and confirmed that the  $I_d$   
393 differed significantly across the configurations ( $p < 0.001$ ); the  $I_d$  produced by CP (492  $\mu m$ ) was significantly  
394 lower than those produced by AP (569) and XP (561  $\mu m$ ) (Tables 7 and 8). As was the case in the  $N_i$  analysis,

395 cannon-type nozzles that produce VMD increases in the AP and XP configurations do not determine a  
396 significant enlargement in impact dimension (Fig. 12). When impact dimension was considered by leaf side  
397 ( $I_{d-up}$  and  $I_{d-lo}$ ) for the various configurations, a significant difference was detected only for  $I_{d-lo}$  (Fig. 12).  
398 Generally, bigger impacts were assessed for the leaf upper side with values equal to 547, 572, and 582  $\mu\text{m}$  for  
399 CP, AP, and XP configurations, respectively. On the lower leaf side,  $I_{d-lo}$  values resulted as 454 (CP), 567  
400 (AP), and 546 (XP)  $\mu\text{m}$ . The analysis of impact dimension at different canopy positions (Fig. 12 a,b,c for  
401 depth; Fig. 12 b,d,f for height) reflects the heterogeneity of spray quality on the coverage; it shows significant  
402 differences for all impact dimension parameters ( $I_d$ ,  $I_{d-up}$ , and  $I_{d-lo}$ ) according to height. Significant differences  
403 among the three depth levels were also found for  $I_{d-up}$ . Also worthy of note is that the VMD of cannon-type  
404 nozzles for all configurations did not match mean impact dimensions. According to other authors, overlapping  
405 stains that occur with different rate according to spray features and quality, make the  $I_d$  values obtained by  
406 WSP target image analysis unreliable for VMD droplet characterization.<sup>51,69</sup> Nonetheless, in the absence of  
407 matching impact dimension and expected VMD values, the experimental data allowed the quality of spray  
408 coverage to be characterized under field conditions using a pneumatic sprayer equipped with two types of  
409 spouts.

#### 410 3.4 Off-field ground losses.

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

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

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

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

### 439 *3.5 In-field ground losses.*

440 The average in-field losses measured for the tested configuration are shown in Fig. 15. A two-way ANOVA  
441 detected statistically significant differences between the configurations tested [F(2,255)=10.303,  $p=4.98E-05$ ].  
442 Post-hoc tests (FREGW) showed that there were significant differences between CP and AP and between CP  
443 and XP (Fig. 15a); in-field losses increased 13% and 16% for the AP and XP configurations, respectively. The  
444 sampling position within vineyard rows (sprayer tracks, under-rows, and in the alley between rows) (Fig. 6)  
445 determines differences in in-field ground depositions [F(4,255)=189.976,  $p=3.15E-75$ ]. In particular, the  
446 ground deposits, measured at different locations in the vineyard, had a distinct tri-modal distribution (Fig.  
447 15b), with its minimum at the sprayer track and its maximum under the rows. Intermediate values were found  
448 for the alley between the sprayed rows and not used as the sprayer track. An increase in spray losses in the  
449 alley between the sprayed rows was detected, especially for XP that is characterized by coarser droplets  
450 produced by the drift-reducing cannon spout. This phenomenon may result from the ballistic behaviour of  
451 coarser droplets<sup>73</sup> that affects droplet trajectory (higher kinetic energy) and leads to more direct ground losses  
452 in the alley between the sprayer rows. These findings agree with those reported by others,<sup>4,5,74,75</sup> who also found  
453 that coarser spraying results in higher ground deposits near to the sprayer. Configurations AP and XP showed  
454 lower off-field ground losses (Fig. 13a), but higher in-field ground losses (Fig. 15). Alternatively,  
455 configuration CP, characterized by the finest droplet size spectra, generated higher off-field ground losses and  
456 lower in-field ground losses. This indicated that the spray cloud generated by CP configurations, thanks to the  
457 action of wind currents, travelled farther than that produced by AP and XP, even under weak wind speeds. In  
458 a fashion similar to hydraulic atomization, the increased droplet size spectra dimensions in low-drift pneumatic  
459 cannon spouts diminishes the risk of drift generation,<sup>76</sup> and results in higher in-field ground losses.<sup>12</sup>

460

## 461 **4 Conclusions**

462 The spray application performance by a multi-row pneumatic sprayer used for fine spray quality application  
463 (CP configuration) was compared with that from two coarser spray quality application (AP and XP  
464 configurations). The comparison demonstrated that the variation in spray quality over the range investigated  
465 did not affect coverage (values averaged about 20% for the upper leaf side). Furthermore, coarser sprays  
466 produced greater (+20% with AP configurations) mean deposits on the canopy target. Even if the trials were  
467 not conducted per ISO22866,<sup>2</sup> the experimental data indicated that the drift-reducing cannon spout, mounted  
468 atop the sprayer head, has the potential to reduce drift. Indeed, it was demonstrated that under field conditions,

469 the spout is able to significantly reduce off-field ground losses in the downwind area by amounts in the range  
470 of 76%-83%, based on the enlarged droplet size spectra produced. The most effective off-field loss-reducing  
471 configuration was that characterized by the liquid release position outside of the spout (XP), which produced  
472 reductions in off-field ground losses of up to 95% at the farther distances from the sprayed area. However,  
473 coarser sprays result in higher in-field ground losses, with values that ranged between +13% and +16%. The  
474 coarser spray applications (AP and XP configurations) are preferable configurations as they produce slightly  
475 greater mean in-field ground losses and very high reductions in off-field ground losses.

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

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

486

## 487 **5 Acknowledgements**

488 The authors thank CIMA S.p.A., Pavia, Italy for providing the sprayer used in this experiment.

489

490 This research did not receive any specific grant funding from agencies in the public, commercial, or non-profit  
491 sectors.

492

## 493 **6 References**

- 494 1. Cross JV, Walklate PJ, Murray RA and Richardson GM., Spray deposits and losses in different sized  
495 apple trees from an axial fan orchard sprayer:2, Effects of spray quality. *Crop Prot.* **20**, 333-343 (2001).
- 496 2. International Organization for Standardization (ISO), ISO 22866:2005(E): Equipment for Crop  
497 Protection—Methods for Field Measurements of Spray Drift, ed.by International Organization for  
498 Standardization, Geneva, Switzerland, pp. 1–17 (2005).
- 499 3. Balsari P, Marucco P and Tamagnone M, A system to assess the mass balance of spray applied to tree  
500 crops. *Trans. ASAE* **48(5)**, 1689–1694 (2005).
- 501 4. Garcerá C, Moltó E and Chueca P, Spray pesticide applications in Mediterranean citrus orchards: Canopy  
502 deposition and off-target losses. *Sci. Total Environ.* **599-600**, 1344-1362 (2017).
- 503 5. Derksen RC, Zhu H, Fox RD, Brazee RD and Krause CR, Coverage and drift produced by air induction  
504 and conventional hydraulic nozzles used for orchard applications. *Trans. ASABE* **50(5)**, 1493–1501  
505 (2007).



- 506 6. Dabrowski JM and Schulz R, Predicted and measured levels of azinphosmethyl in the Lourens River,  
507 South Africa. Comparison of runoff and spray drift. *Environ. Toxicol. Chem.* **22**, 494–500 (2003).
- 508 7. Marrs RH, Frost AJ, Plant RA and Lunnis P, Determination of buffer zones to protect seedlings of non-  
509 target plants from the effects of glyphosate spray drift. *Agric. Ecosyst. Environ.* **45**, 283–293 (1993).
- 510 8. Davis BNK and Williams CT, Buffer zone widths for honeybees from ground and aerial spraying of  
511 insecticides. *Environ. Pollut.* **63**, 247–259 (1990).
- 512 9. Ernst WR, Jonah P, Doe K, Julien G and Hennigar P, Toxicity to aquatic organisms of off-target  
513 deposition of endosulfan applied by aircraft. *Environ. Toxicol. Chem.* **10**, 103–114 (1991).
- 514 10. Otto S, Lazzaro L, Finizio A and Zanin G, Estimating ecotoxicological effects of pesticide drift on  
515 nontarget arthropods in field hedgerows. *Environ. Toxicol. Chem.* **28**, 853–863 (2009).
- 516 11. Felsot AS, Unsworth JB, Linders JBHJ and Roberts G, Agrochemical spray drift; assessment and  
517 mitigation—A review. *J. Environ. Sci. Health B* **46**, 1–23 (2011).
- 518 12. Butler Ellis MC, Lane AG, O’Sullivan CM, Miller PCH and Glass CR, Bystander exposure to pesticide  
519 spray drift: New data for model development and validation. *Biosyst. Eng.* **107**, 162–168 (2010).
- 520 13. European Community (EC), Directive 2009/128/EC of the European parliament and the council of 21  
521 October 2009 establishing a framework for community action to achieve the sustainable use of pesticides.  
522 *Off. J. Eur. Union* **309**, 71–86 (2009).
- 523 14. Popp J, Petó K and Nagy J, Pesticide productivity and food security. A review. *Agron. Sustain. Dev.* **33**,  
524 243–255 (2013). <https://doi.org/10.1007/s13593-012-0105-x>
- 525 15. Berk P, Hocevar M, Stajniko D and Belsak A, Development of alternative plant protection product  
526 application techniques in orchards, based on measurement sensing systems: A review. *Comput. Electron.*  
527 *Agric.* **124**, 27–288 (2016).
- 528 16. Campos J, Llop J, Gallart M, García-Ruiz F, Gras A, Salcedo R and Gil E, Development of canopy vigour  
529 maps using UAV for site-specific management during vineyard spraying process. *Precis. Agric.* **20(6)**,  
530 1136–1156 (2019).
- 531 17. Chen Y, Zhu H and Ozkan HE, Real-time tree foliage density estimation with laser scanning sensor for  
532 variable-rate tree sprayer development. *ASABE Annual Meeting*; Paper No: 131596009 (2013).
- 533 18. Comba L, Biglia A, Ricauda Aimonino D, Tortia C, Mania E, Guidoni S and Gay P, Leaf Area Index  
534 evaluation in vineyards using 3D point clouds from UAV imagery. *Precis. Agric.* (2019) [in press]  
535 <https://doi.org/10.1007/s11119-019-09699-x>
- 536 19. Doruchowski G, Balsari P and van de Zande J, Development of a crop adapted spray application system  
537 for sustainable plant protection in fruit growing. *Acta Hort.* **824**, 251–260 (2009).
- 538 20. Garcerá C, Fonte A, Moltó E and Chueca P, Sustainable use of pesticide applications in citrus: a support  
539 tool for volume rate adjustment. *Int. J. Environ. Res. Public Health* **14**, 715 (2017).
- 540 21. Gil E, Escolà A, Rosell JR, Planas S and Val L, Variable rate application of plant protection products in  
541 vineyard using ultrasonic sensors. *Crop Prot.* **26(8)**, 1287–1297 (2007).

- 542 22. Gil E, Llorens J, Llop J, Fàbregas X and Gallart M, Use of a terrestrial LIDAR sensor for drift detection  
543 in vineyard spraying. *Sensors* **13**, 516–534 (2013).
- 544 23. Llorens J, Gil E, Llop J and Escolà A, Variable rate dosing in precision viticulture: Use of electronic  
545 devices to improve application efficiency. *Crop Prot.* **29(3)**, 239-248 (2010).
- 546 24. Li L, He X, Song J, Liu Y, Zeng A, Yang L, Liu C and Liu Z, Design and experiment of variable rate  
547 orchard sprayer based on laser scanning sensor. *Int. J. Agric. & Biol. Eng.* **11(1)**, 101-108 (2018).
- 548 25. Zaman S, Comba L, Biglia A, Ricauda Aimonino D, Barge P and Gay P, Cost-effective visual odometry  
549 system for vehicle motion control in agricultural environments. *Comput. Electron. Agric.* **162**, 82-94  
550 (2019).
- 551 26. Zidner G and Shapiro A, A novel data fusion algorithm for low-cost localisation and navigation of  
552 autonomous vineyard sprayer robots. *Biosyst. Eng.* **146**, 133-148 (2016).
- 553 27. Salcedo R, Pons P, Zaragoza T, Campos J, Ortega P, Gallart M and Gil E, Dynamic evaluation of airflow  
554 stream generated by a reverse system of an axial fan sprayer using 3D-ultrasonic anemometers. Effect of  
555 canopy structure. *Comput. Electron. Agric.* **163**, 104851 (2019).  
556 <https://doi.org/10.1016/j.compag.2019.06.006>
- 557 28. Chen Y, Zhu H and Ozkan HE, Development of a variable-rate sprayer with laser scanning sensor to  
558 synchronize spray outputs to tree structures. *Trans. ASABE* **55 (3)**, 773–781 (2012).
- 559 29. Hołownicki R, Doruchowski G, Swiechowski W, Godyn A and Konopacki PJ, Variable air assistance  
560 system for orchard sprayers; concept, design and preliminary testing. *Biosyst. Eng.* **163**, 134-149 (2017).
- 561 30. Codis S, Verges A, Auvergne C, Bonicel JF, Diouloufet G, Cavalier R, Douzals JP, Magnier J, Montegano  
562 P, Ribeyrolles X and Ruelle B, Optimization of early growth stage treatments of the vine:  
563 experimentations on the artificial vine EvaSprayViti. In proceedings of SuproFruit 2015, 13th Workshop  
564 on Spray Application Techniques in Fruit Growing, Lindau, Germany, pp. 47–48 (2015).
- 565 31. Marucco P, Balsari P, Grella M, Pugliese M, Eberle D, Gil E, Llop J, Fountas S, Mylonas N, Tsitsigiannis  
566 D, Balafoutis A, Polder G, Nuyttens D, Dias L and Douzals JP, OPTIMA EU project: main goal and first  
567 results of inventory of current spray practices in vineyards and orchards. In proceeding of 15th Workshop  
568 on Spray Application and Precision Technology in Fruit Growing – SuproFruit 2019, 16-18 July 2019,  
569 East Malling - UK, Cross, J., Wanneker, M. (Eds.), pp. 99-100 (2019). <https://doi.org/10.18174/494871>
- 570 32. Pascuzzi S and Cerruto E, Spray deposition in “tendone” vineyards when using a pneumatic electrostatic  
571 sprayer. *Crop Prot.* **68**, 1–11 (2015).
- 572 33. Balsari P, Grella M, Marucco P, Matta F and Miranda-Fuentes A, Assessing the influence of air speed  
573 and liquid flow rate on the droplet size and homogeneity in pneumatic spraying. *Pest Manag. Sci.* **75**,  
574 366-379 (2019). <https://doi.org/10.1002/ps.5120>
- 575 34. Triloff P, Results of measuring the air distribution of sprayers for 3D-Crops and parameters for evaluating  
576 and comparing fan types. In proceedings of SuproFruit 2015, 13th Workshop on Spray Application  
577 Techniques in Fruit Growing, Lindau, Germany, pp. 47-48 (2015).

- 578 35. Balsari P, Tamagnone M, Marucco P and Matta F, How air liquid parameters affect droplet size:  
579 experiences with different pneumatic nozzles. *Asp. Appl. Biol.* **132**, 265–271 (2016).
- 580 36. Grella M, Gallart M, Marucco P, Balsari P and Gil E, Ground deposition and airborne spray drift  
581 assessment in vineyard and orchard: the influence of environmental variables and sprayer settings.  
582 *Sustainability* **9(5)**, 728, (2017).
- 583 37. de Jong MW, de Snoo GR and van de Zande J, Estimated nationwide effects of pesticide spray drift on  
584 terrestrial habitats in the Netherlands. *J. Environ. Manage.* **86**, 721-730 (2008).
- 585 38. van de Zande JC, Wenneker M, Michielsen JMGP, Stallinga H, van Velde P and Joosten N, Nozzle  
586 classification for drift reduction in orchard spraying. *Asp. Appl. Biol.* **114**, 253–260 (2012).
- 587 39. Miranda-Fuentes A, Marucco P, Gonzalez-Sanchez EJ, Gil E, Grella M and Balsari P, Developing  
588 strategies to reduce spray drift in pneumatic spraying vineyards: Assessment of the parameters affecting  
589 droplet size in pneumatic spraying. *Sci. Total Environ.* **616-617**, 805-815 (2018).  
590 <https://doi.org/10.1016/j.scitotenv.2017.10.242>
- 591 40. Grella M, Marucco P and Balsari P, Evaluation of Potential Spray Drift Generated by Different Types of  
592 Airblast Sprayers Using an “ad hoc” Test Bench Device. In: Coppola A., Di Renzo G., Altieri G.,  
593 D'Antonio P. (eds) Innovative Biosystems Engineering for Sustainable Agriculture, Forestry and Food  
594 Production. MID-TERM AIIA 2019. Lecture Notes in Civil Engineering, Springer, Cham, vol 67, pp.431-  
595 440 (2020). [https://doi.org/10.1007/978-3-030-39299-4\\_48](https://doi.org/10.1007/978-3-030-39299-4_48)
- 596 41. Lorenz D, Eichorn D, Bleiholder H, Klose R, Meier U and Weber E, Phänologische Entwicklungsstadien  
597 der Weinrebe (*Vitis vinifera* L. ssp. *vinifera*). Codierung und Beschreibung nach der erweiterten BBCH-  
598 Skala. *Viticulture and Enology Sciences* **49**, 66–70 (1994). <https://doi.org/10.1111/j.1755-0238.1995.tb00085.x>
- 600 42. Brancadoro L and Campostrini F, Caratteristiche strutturali delle principali forme di allevamento ed  
601 elementi di calcolo dell'efficienza della chioma in *Forme di allevamento della vite e modalità di*  
602 *distribuzione dei fitofarmaci* ed. by Balsari P. and Scienza A., Edizioni l'Informatore Agrario S.p.a.,  
603 Verona, Italy, pp. 283-311 (2003).
- 604 43. Silvestroni O, Lanari V, Lattanzi T and Palliotti A, Delaying winter pruning, after pre-pruning, alters  
605 budburst, leaf area, photosynthesis, yield and berry composition in Sangiovese (*Vitis vinifera* L.). *Aust.*  
606 *J. Grape Wine R.* **24**, 478-486 (2018). <https://doi.org/10.1111/ajgw.12361>
- 607 44. Vitali M, Tamagnone M, La Iacona T and Lovisolo C, Measurement of grapevine canopy leaf area by  
608 using an ultrasonic-based method. *J. Int. Sci. Vigne Vin* **47**, 183-189 (2013).  
609 <https://doi.org/10.20870/oenoone.2013.47.3.1553>
- 610 45. Pergher G and Petris R, The effect of air flow rate on spray deposition in a Guyot trained vineyard.  
611 *Agricultural Engineering International: the CIGR Ejournal* **X**. ALNARP 08 010 (2008).
- 612 46. Miranda-Fuentes A, Llorens J, Rodriguez-Lizana A, Cuenca A, Gil E, Blanco-Roldan GL and Gil-Ribes  
613 JA, Assessing the optimal liquid volume to be sprayed on isolated olive trees according to their canopy  
614 volumes. *Sci. Total. Environ.* **568**, 296-305 (2016). <http://dx.doi.org/10.1016/j.scitotenv.2016.06.013>

- 615 47. Banj Đ, Tadić V, Lukinac J and Horvat, D, The use of water sensitive paper for the evaluation of spray  
616 coverage in an apple orchard. *Poljoprivreda* **16(1)**, 43-49 (2010).
- 617 48. Fox RD, Derksen RC, Cooper JA, Krause CR and Ozkan HE, Visual and image system measurement of  
618 spray deposits using water-sensitive paper. *Trans. ASAE* **19(5)**, 549-552 (2003).
- 619 49. Hołownicki R, Doruchowski G, Swiechowski W and Jaeken P, Methods of evaluation of spray deposit  
620 and coverage on artificial targets. *Electronic Journal of Polish Agricultural Universities* **5(1)** (2002).  
621 <http://www.ejpau.media.pl/articles/volume5/issue1/engineering/art-03.pdf> [Accessed 15th January 2020]
- 622 50. Rincón VJ, Grella M, Marucco P, Eloí Alcatrão L, Sanchez-Hermosilla J and Balsari P, Spray  
623 performance assessment of a remote-controlled vehicle prototype for pesticide application in greenhouse  
624 tomato crops. *Sci. Total. Environ.* **726**, 138509 (2020). <https://doi.org/10.1016/j.scitotenv.2020.138509>
- 625 51. Salyani M, Zhu H, Sweeb RD and Pai N, Assessment of spray distribution with water-sensitive paper.  
626 *Agric. Eng. Int.: CIGR Journal* **15(2)**, 101-111 (2013).
- 627 52. Pergher G, Recovery rate of tracer dyes used for spray deposit assessment. *Trans. ASAE* **44(4)**, 787-794  
628 (2001).
- 629 53. International Organization for Standardization (ISO), ISO 22401:2015(E): Equipment for crop protection  
630 - Method for measurement of potential drift from horizontal boom sprayer systems by the use of a test  
631 bench, ed.by International Organization for Standardization, Geneva, Switzerland, pp. 1–12 (2015).
- 632 54. Nuyttens D, Taylor WA, De Schampheleire M, Verboven P and Dekeyser D, Influence of nozzle type  
633 and size on drift potential by means of different wind tunnel evaluation methods. *Biosyst. Eng.* **103**, 271-  
634 280 (2009).
- 635 55. Taylor WA, Cooper SE and Miller PCH, An appraisal of nozzles and sprayers abilities to meet regulatory  
636 demands for reduced airborne drift and downwind fallout from arable crop spraying. In proceedings  
637 Brighton Conference – Weeds, pp. 447–452 (1999).
- 638 56. Grella M, Marucco P, Manzone M, Gallart M and Balsari P, Effect of sprayer settings on spray drift  
639 during pesticide application in poplar plantations (*Populus* spp.). *Sci. Total Environ.* **578**, 427-439 (2017).
- 640 57. Grella M, Marucco P, Balsari P, Toward a new method to classify the airblast sprayers according to their  
641 potential drift reduction: comparison of direct and new indirect measurement methods. *Pest Manag. Sci.*  
642 **75**, 2219-2235 (2019). <https://doi.org/10.1002/ps.5354>
- 643 58. Escolà A, Gracia F, Gil E, Val L, Spray application volume test in apple and pear orchards in Catalonia  
644 (Spain) and Variable Rate Technology for dose adjustment. ASABE Annual International Meeting.  
645 ASABE, Portland, Oregon (2006).
- 646 59. Zhu H, Salyani M and Fox RD, A portable scanning system for evaluation of spray deposit distribution.  
647 *Comput. Electron. Agric.* **76**, 38–43 (2011).
- 648 60. Rueden CT, Schindelin J, Hiner MC, De Zonia BE, Walter AE, Arena ET and Eliceiri KW, ImageJ2:  
649 ImageJ for the next generation of scientific image data. *BMC Bioinformatics* **18(529)**, 1-26 (2017).  
650 <https://doi.org/10.1186/s12859-017-1934-z>

- 651 61. International Organization for Standardization (ISO), ISO 22369-1:2006(E): Crop protection equipment  
652 - Drift classification of spraying equipment - Part 1: classes. International Organization for  
653 Standardization, ed.by International Organization for Standardization, Geneva, Switzerland, pp. 1 (2006).
- 654 62. IBM Corp, IBM SPSS Statistics for Windows, Version 25.0. IBM Corp, Armonk, NY (2017).
- 655 63. Steel R and Torrie J, Principles and procedures of statistics. McGraw-Hill Book Company, New York,  
656 Toronto, London (1980).
- 657 64. Miranda-Fuentes A, Rodríguez-Lizana A, Gil E, Agüera-Vega J and Gil-Ribes JA, Influence of liquid-  
658 volume and airflow rates on spray application quality and homogeneity in super-intensive olive tree  
659 canopies. *Sci. Total Environ.* **537**, 250–259 (2015).
- 660 65. Codis S, Carra M, Delpuech X, Montegano P, Nicot H, Ruelle B, Ribeyrolles X, Savajols B, Vergès A  
661 and Naud O, Dataset of spray deposit distribution in vine canopy for two contrasted performance sprayers  
662 during a vegetative cycle associated with crop indicators (LWA and TRV). *Data in Brief* **18**, 415-412  
663 (2018).
- 664 66. Chen Y, Ozkan HE, Zhu H, Derksen RC and Krause CR, Spray deposition inside tree canopies from a  
665 newly developed variable-rate air-assisted sprayer. *Trans. ASABE* **56**, 1263–1272 (2013).
- 666 67. Porrás Soriano A, Porrás Soriano ML, Porrás Piedra A and Soriano Martín ML, Comparison of the  
667 pesticide coverage achieved in a trellised vineyard by a prototype tunnel sprayer, a hydraulic sprayer, an  
668 air assisted sprayer and a pneumatic sprayer. *Span. J. Agric. Res.* **3(2)**, 175-181 (2005).
- 669 68. Cunningham GP and Harden J, Reducing spray volumes applied to mature citrus tree. *Crop Prot.* **17(4)**,  
670 289-292 (1998).
- 671 69. Cerruto E, Failla S, Longo D and Manetto G, Simulation of water sensitive papers for spray analysis.  
672 *Agric. Eng. Int.: CIGR Journal* **18(4)**, 22-29 (2016).
- 673 70. Jensen PK and Olesen MH, Spray mass balance in pesticide application: a review. *Crop Prot.* **61**, 23–31  
674 (2014).
- 675 71. Otto S, Loddo D, Baldoin C and Zanin G, Spray drift techniques for vineyards in fragmented landscapes.  
676 *J. Environ. Manage.* **162**, 290-298 (2015).
- 677 72. van de Zande JC, Holterman HJ and Wenneker M, Nozzle classification for drift reduction in orchard  
678 spraying: identification of drift reduction class threshold nozzles. *Agric. Eng. Int. CIGR J.* **X ALNARP**  
679 **08 0013** (2008). <http://www.cigrjournal.org/index.php/Ejournal/article/viewFile/1256/1113>
- 680 73. Heijne B, Wenneker M and van de Zande JC, Air inclusion nozzles don't reduce pollution of surface water  
681 during orchard spraying in The Netherlands. International advances in pesticide application. *Asp. Appl.*  
682 *Biol.* **66**, 193–199 (2012).
- 683 74. Sesah EME, Study of effects of forward speed and nozzle types on the spray characteristics of air  
684 assistance hydraulic sprayer. *Misr Journal of Agricultural Engineering* **24(1)**, 75–87 (2007).
- 685 75. Lešnik M, Stajniko D and Vajs S, Interactions between spray drift and sprayer travel speed in two different  
686 apple orchard training systems. *Int. J. Environ. Sci. Technol.* **12**, 3017–3028 (2015).

687 76. Nuyttens D, Baetens K, De Schampheleire M and Sonck B, Effect of nozzle type, size and pressure on  
688 spray droplet characteristics. *Biosyst. Eng.* **97(3)**, 333–345 (2007).  
689

690 **7 Tables**

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

692

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

<sup>a</sup> 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.

<sup>b</sup> 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.

<sup>c</sup> V<sub>100</sub>: spray liquid fraction generated with droplets smaller than 100 μm.

<sup>d</sup> 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<sup>-1</sup>.

693

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

697

Configuration	Equation	$p > (\mathbf{F})$	Sign. <sup>a</sup>	$\rho$
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

<sup>a</sup> Statistical significance levels: NS  $p > 0.05$ ; \* $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

698



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

700

Config. & replicates		Temperature	RH	Wind speed			Wind direction	
		Mean (°C)	Mean (%)	Min (m s <sup>-1</sup> )	Max (m s <sup>-1</sup> )	Mean (m s <sup>-1</sup> )	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

701

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. <sup>a</sup>
<b>Canopy deposition CD</b>			
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

<sup>a</sup> Statistical significance levels: NS  $p > 0.05$ ; \*  $p < 0.05$ ;  
 \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

705

706 Table 5: Canopy deposition  $\pm$ SE of the mean and homogeneity parameter (CV%). The significant differences  
 707 among the configurations tested (CP, AP, and XP) are represented with  $p < 0.001$ , post-hoc FREGW.  
 708

Variables		Configurations								
		CP <sup>a</sup>			AP <sup>a</sup>			XP <sup>a</sup>		
Mean deposit	CD ( $\mu\text{l cm}^{-2}$ )	0.234	$\pm$ 0.016	a	0.282	$\pm$ 0.018	b	0.239	$\pm$ 0.015	a
Deposit homogeneity	CV (%)	88.65			79.41			82.36		

<sup>a</sup> Mean values  $\pm$  S.E.M.

709

710 Table 6: Significance obtained in three-way ANOVAs for the surface coverage, number of impacts, and impact  
 711 dimension. The statistical analyses were performed separately using average values from both leaf sides (upper  
 712 and lower), as affected by configurations, depth level, and height level in the canopy and their interactions.  
 713

Sources	DF	$p > (F)$	Signif. <sup>a</sup>	$p > (F)$	Signif. <sup>a</sup>	$p > (F)$	Signif. <sup>a</sup>
<b>Surface coverage</b>							
		<u>Averaged values (SC)</u>		<u>Upper leaf side (SC<sub>up</sub>)</u>		<u>Lower leaf side (SC<sub>lo</sub>)</u>	
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
<b>Number of impacts</b>							
		<u>Average values (N<sub>i</sub>)</u>		<u>Upper leaf side (N<sub>i-up</sub>)</u>		<u>Lower leaf side (N<sub>i-lo</sub>)</u>	
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
<b>Impact dimensions</b>							
		<u>Average values (I<sub>d</sub>)</u>		<u>Upper leaf side (I<sub>d-up</sub>)</u>		<u>Lower leaf side (I<sub>d-lo</sub>)</u>	
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

<sup>a</sup> Statistical significance levels: NS  $p > 0.05$ ; \*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

714

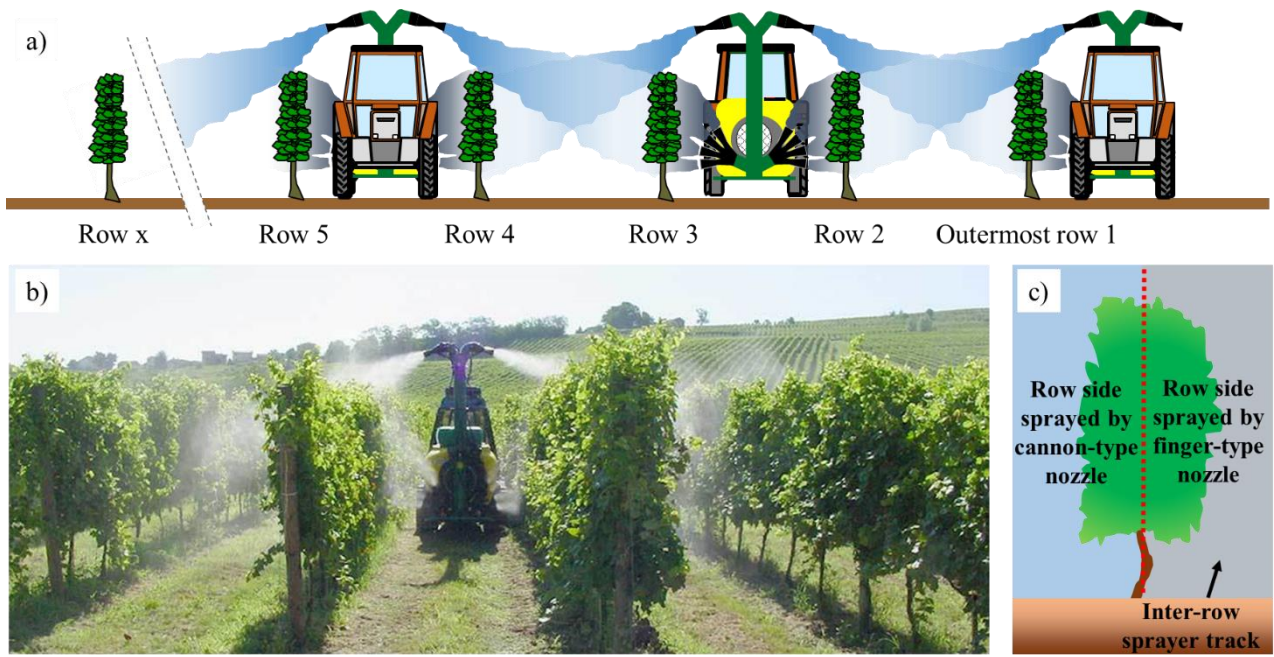
715 Table 7: Mean  $\pm$ SE of the mean for surface coverage, number of impacts and impacts dimension parameters  
 716 studied (averaged values over both leaf sides, upper and lower leaf sides). The significant differences among  
 717 configurations tested (CP, AP, and XP) are represented with  $p < 0.001$ , post hoc FREGW.  
 718

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

<sup>a</sup> Mean values  $\pm$  S.E.M.

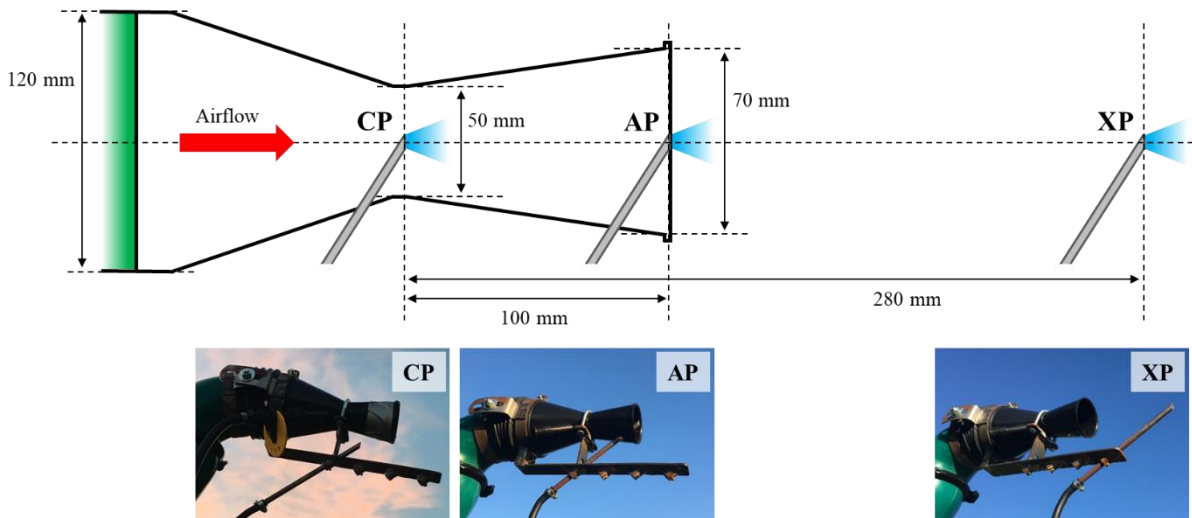
719

720 **8 Figures**



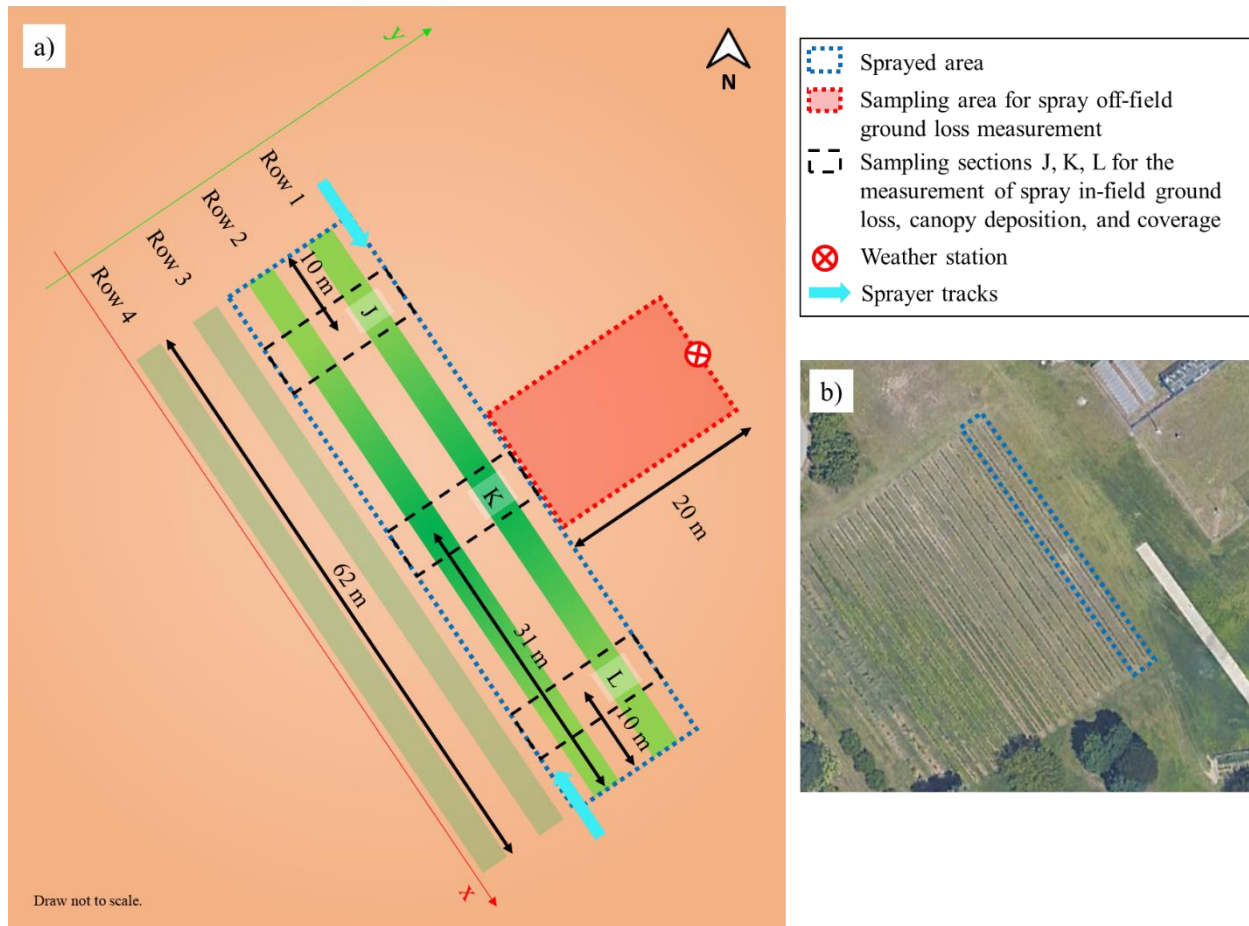
721

722 Figure 1. a-b) Spray management passages between vineyard rows with multiple-row pneumatic sprayer Cima  
723 50 Plus 400L, equipped with two finger-type nozzles mounted at the base of the sprayer head, and two cannon-  
724 type nozzles mounted on the top, and c) application feature according to row side.



725

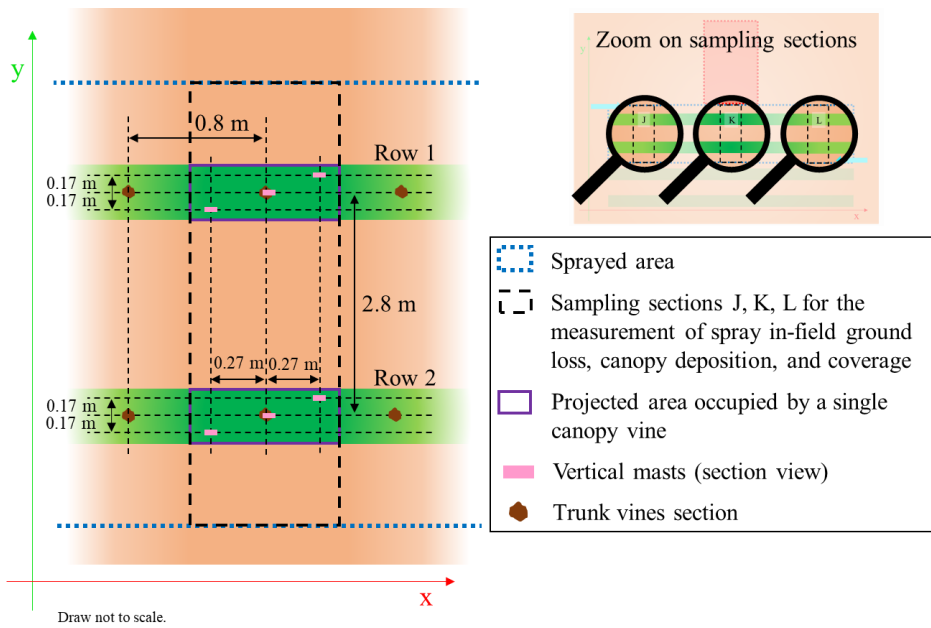
726 Figure 2. Conventional (CP), alternative (AP), and alternative extreme (XP) positions of insertion of the liquid  
 727 hose at the release point in the air spout of a cannon-type nozzle.



728

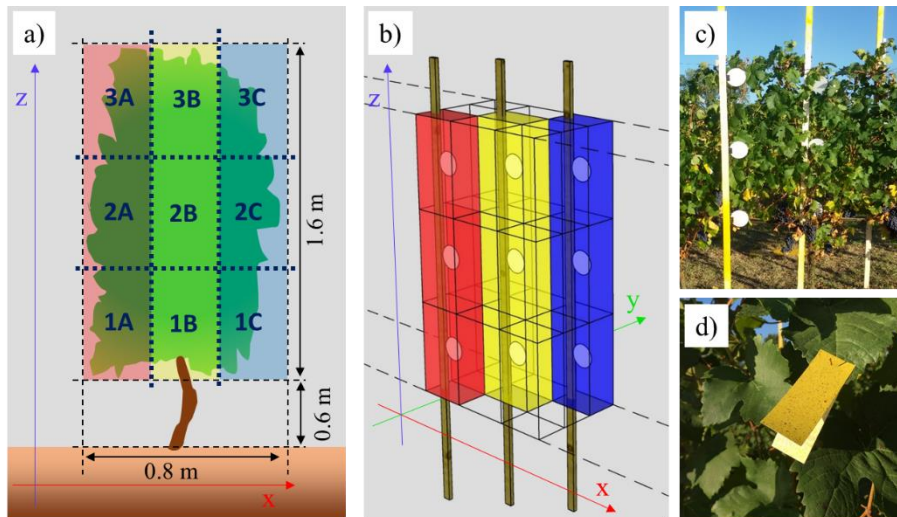
729 Figure 3. a) Schematic of trial layout for the measurement of canopy deposition, spray coverage, in-field  
 730 ground losses, and off-field ground losses with b) an aerial view of the vineyard field trial area.





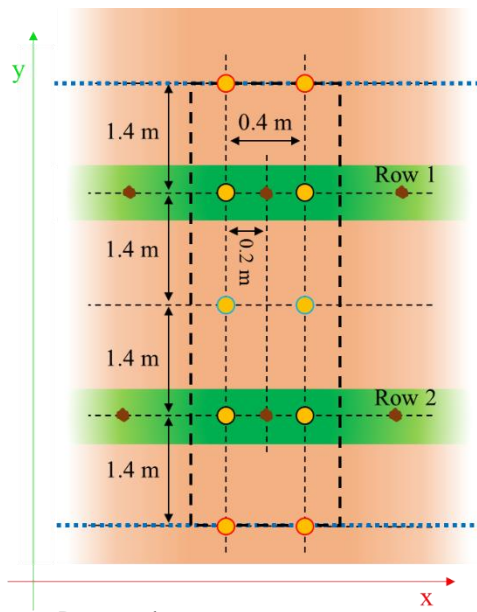
731

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

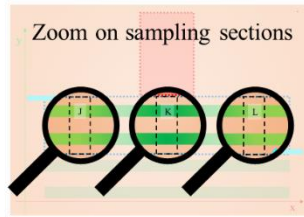








733

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



Draw not to scale.



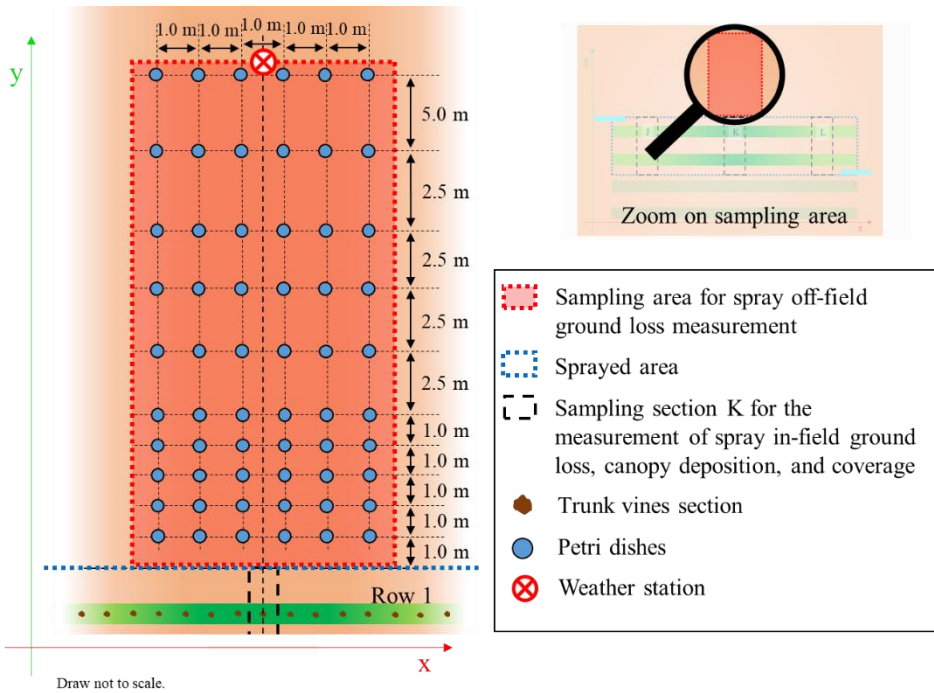
-  Sprayed area
-  Sampling sections J, K, L for the measurement of spray in-field ground loss, canopy deposition, and coverage
-  Trunk vines section
-  Petri dishes placed under canopy vines
-  Petri dishes placed in the spray track inter-rows
-  Petri dishes placed in the inter-row next to the sprayer track



737

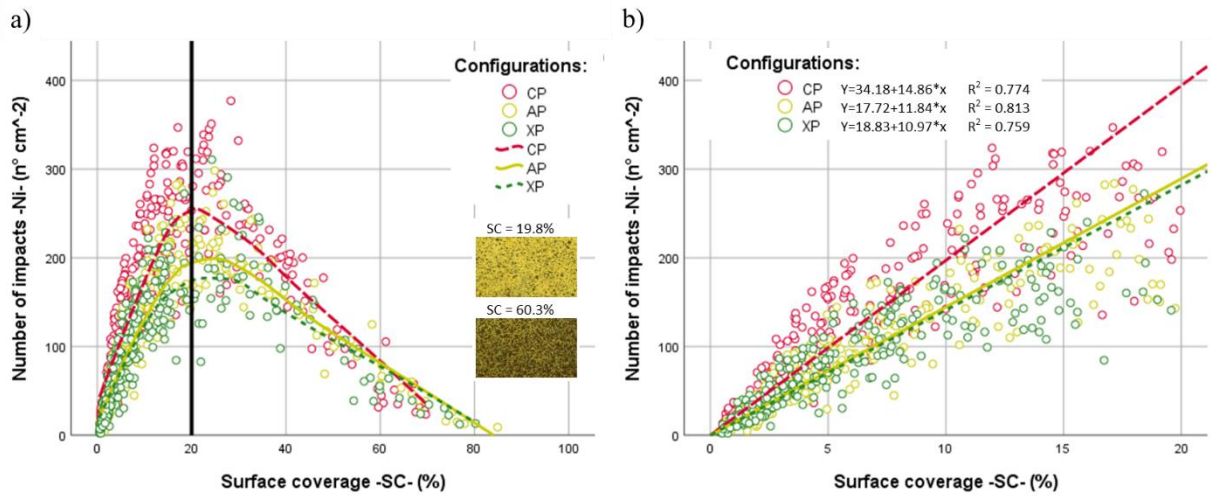
738

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



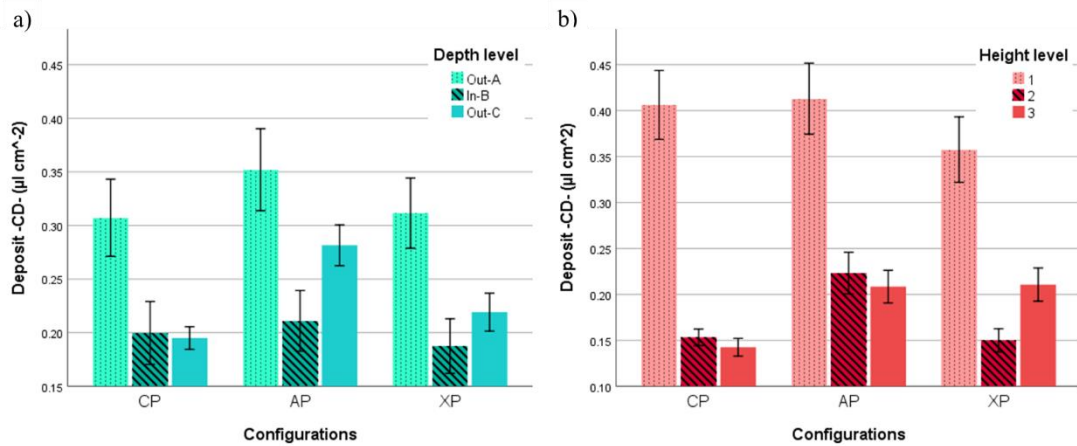
739

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



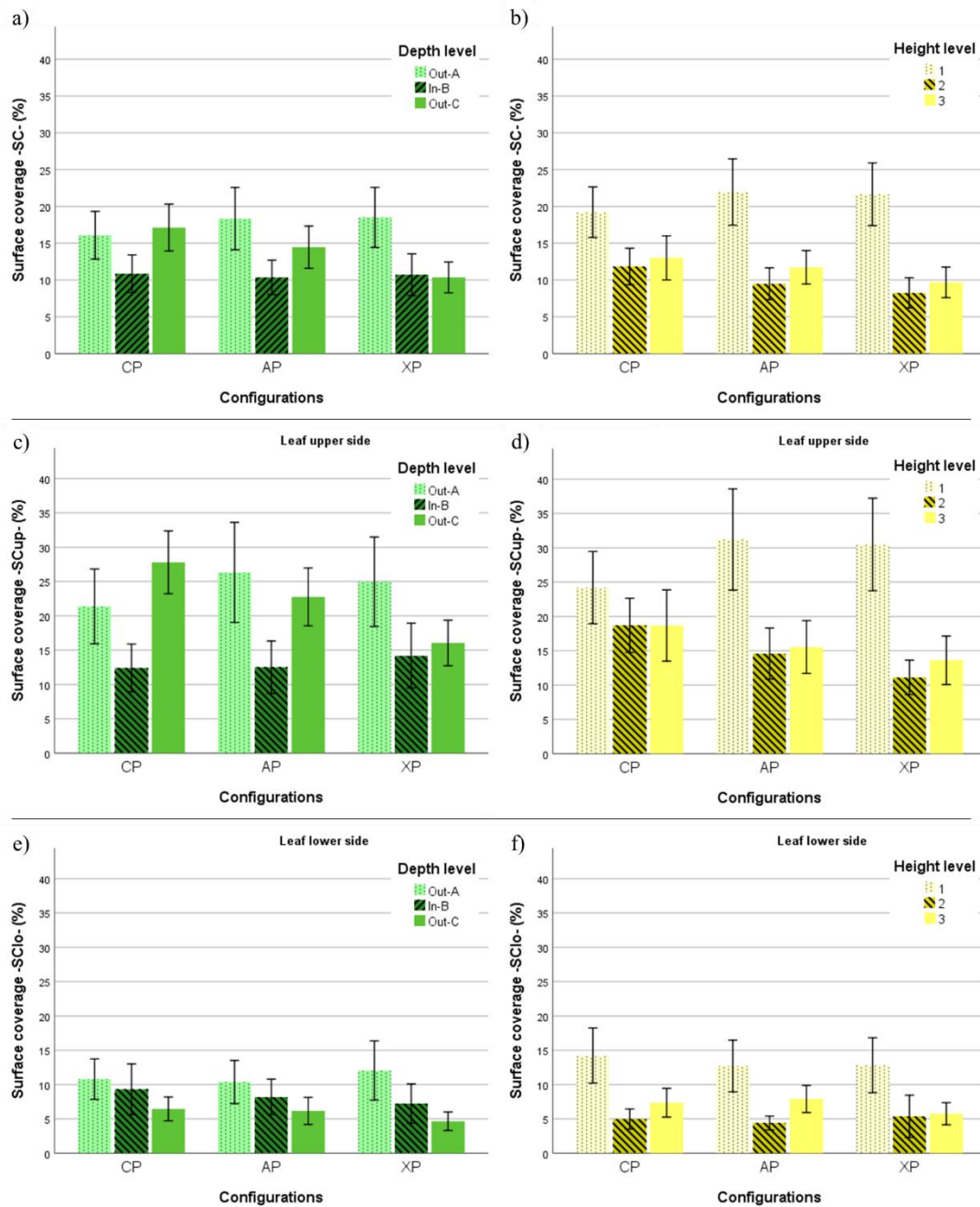
741

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



745

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



752

753

754

755

756

757

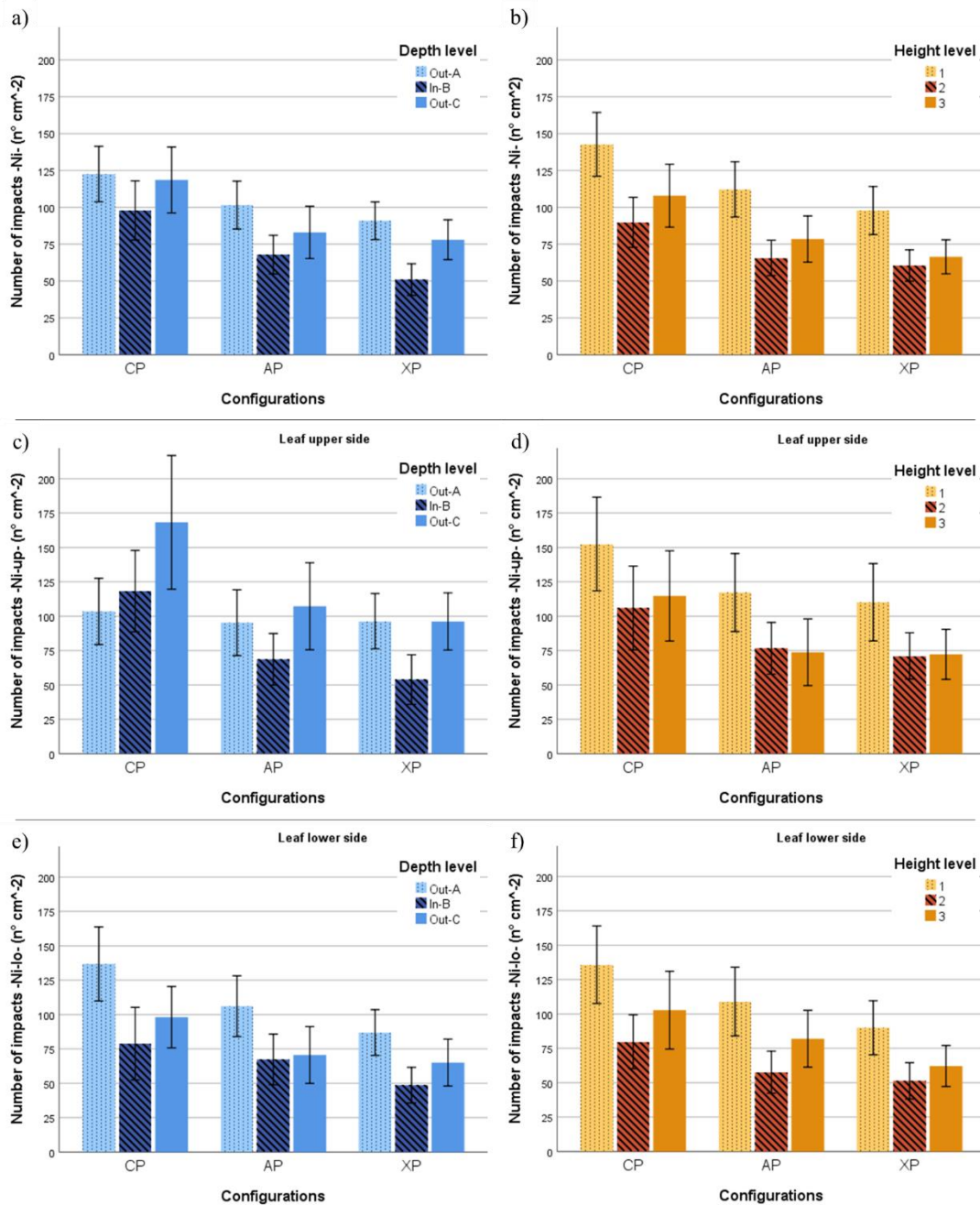
758

759

760

761

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<sub>up</sub>); e) and f) bottom graphs depict coverage for leaf lower side (SC<sub>lo</sub>). 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.



762

763

764

765

766

767

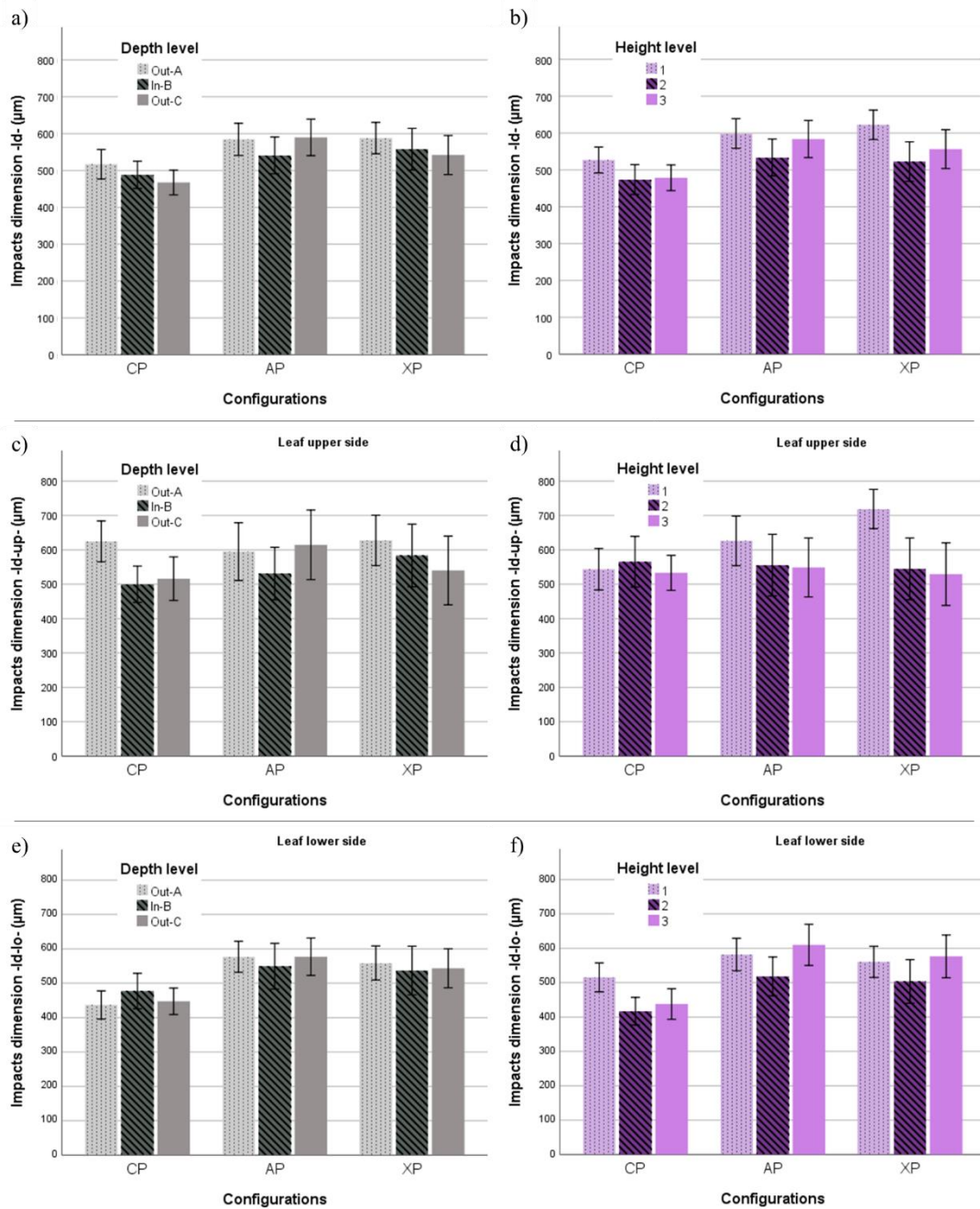
768

769

770

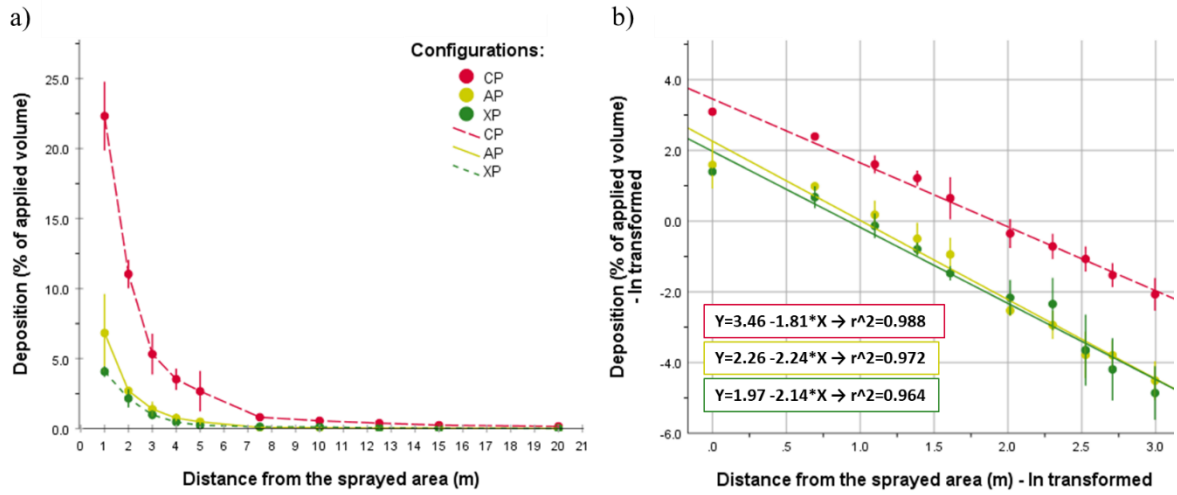
Figure 11: Impact number graphs: a) and b) depict overall impacts, derived from averaged values over leaf upper and lower sides ( $N_i$ ) ( $n^{\circ} \text{cm}^{-2}$ ); c) and d) depict impacts on leaf upper sides ( $N_{i-up}$ ); e) and f) depict impacts on leaf lower sides ( $N_{i-lo}$ ). Data graph 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  $\pm$  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.





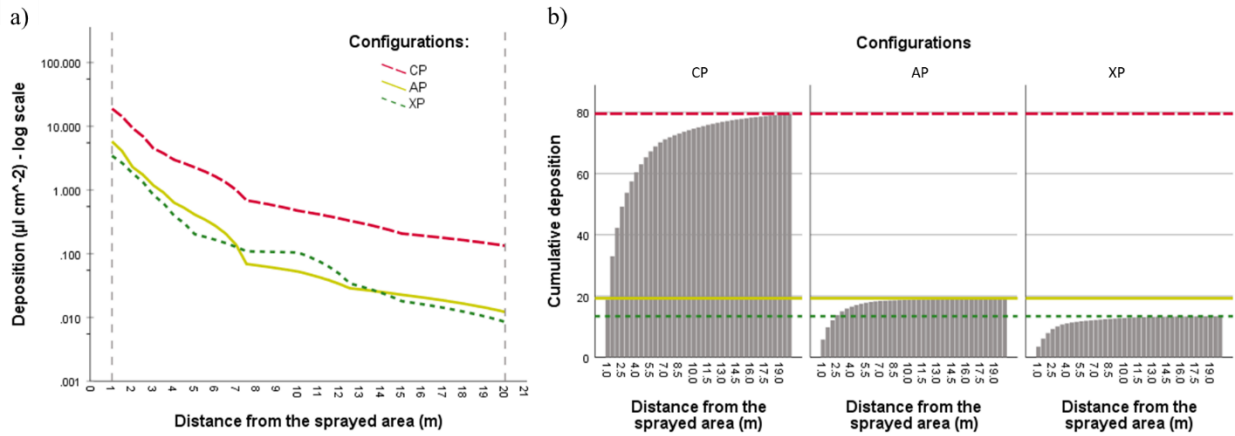
771

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



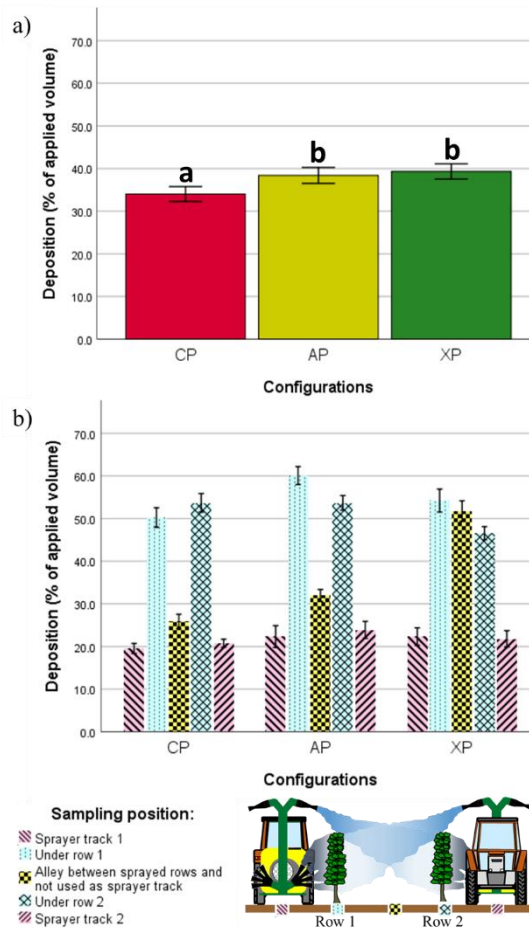
780

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



786

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



793

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