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Spray Drift Generated in Vineyard during Under-Row Weed Control and Suckering: Evaluation of Direct and Indirect Drift-Reducing Techniques

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Abstract: The most widespread method for weed control and suckering in vineyards is under-row band herbicide application. It could be performed for weed control only (WC) or weed control and suckering (WSC) simultaneously. During herbicide application, spray drift is one of the most important environmental issues. The objective of this experimental work was to evaluate the performance of specific Spray Drift Reducing Techniques (SDRTs) used either for WC or WSC spray applications. Furthermore, spray drift reduction achieved by buffer zone adoption was investigated. All spray drift measurements were conducted according to ISO22866:2005 protocol. Sixteen configurations deriving from four nozzle types (two conventional and two air-induction—AI) combined with or without a semi-shielded boom at two different heights (0.25 m for WC and 0.50 m for WSC) were tested. A fully-shielded boom was also tested in combination with conventional nozzles at 0.25 m height for WC. Ground spray drift profiles were obtained, from which corresponding Drift Values (DVs) were calculated. Then, the related drift reduction was calculated based on ISO22369-1:2006. It was revealed that WC spray applications generate lower spray drift than WSC applications. In all cases, using AI nozzles and semi-shielded boom significantly reduced DVs; the optimum combination of SDRTs decreased spray drift by up to 78% and 95% for WC and WSC spray application, respectively. The fully-shielded boom allowed reducing nearly 100% of spray drift generation. Finally, the adoption of a cropped buffer zone that includes the two outermost vineyard rows lowered the total spray drift up to 97%. The first 90th percentile model for the spray drift generated during herbicide application in vineyards was also obtained.

Keywords: under-row band herbicide application; weed control; grapevine suckering; drift model; spray drift reducing techniques; air-induction nozzles; shielded spray boom; buffer zone; drift mitigation; ISO22866:2005

1. Introduction

The area under vines represents one of the most important worldwide agricultural businesses covering 7.5 million hectares [1]. For total grape production, Italy (8.4 Mt) ranks second after China (13.7 Mt), followed by USA, France and Spain [1].

Similarly to other 3D crops, vineyard management requires a lot of different agricultural practices along the season; among these, weed control and suckering are essential for achieving adequate grapes' yield [2]. The uncontrolled weed growth can have significant effects on vineyard development and vigor, due to the competition for soil moisture and nutrients. This aspect is of prime importance in the new vineyard plantations, as optimum young vines' growth can be achieved in weed-free conditions during the first three years; it should be noted that uncontrolled weed growth in young vineyard plantations can reduce vines' biomass by more than 80% [3]. Therefore, the most widespread practice to manage weeds in vineyards consists of maintaining the resident vegetation in the central zone of lanes between the rows by mowing or cultivating (e.g., cover crops with green manure) to guarantee the soil conservation and tractor's accessibility, while weeds resident in the soil bands under the vines are fully controlled/removed. To date, the most widespread weed control techniques are: (i) chemical control by herbicide application; (ii) mechanical control through grass mowing; and (iii) soil harrowing [4]. Alternative weed control techniques are also available, such as (i) flame weeding [5,6], (ii) hot-foam [7] and (iii) pressurized water weed control [3], but not as widely used. Irrespective of inter-row or under-row weed control strategy, the techniques adopted are dependent on topographic area characteristics or vineyard training system [8].

The most common technique for weed control under the vines is the pre-emergence and post-emergence herbicide application, as it is relatively cheap and timely [5,9]. In addition, chemical control of weeds can be executed simultaneously with suckering operation by applying post-emergence herbicides, a practice that provides an additional advantage, due to substantial cost saving and possible environmental gains [5,10]. Indeed, suckering is another significant agricultural practice for vineyards [11,12]. Uncontrolled vine suckers' development can negatively affect canopy growth rate with related impact on the final grapes' yield [13] and quality [2]. Traditionally, suckering is conducted manually and is related to increased labor time and cost [14,15]. In order to overcome these disadvantages, mechanical methods, such as rotating scourges have been used thoroughly, but they can damage the trunk of vines [16] resulting in possible infections [17]. In addition, flaming is a feasible alternative method for the non-lignified suckers [7]. However, nowadays, spraying herbicides or synthetic growth regulators to terminate suckers has become the most popular technique by applying a band spray to the rootstock of the vine row, covering approximately one-third of the vineyard soil [13,14,18].

Since the early 1990s, a lot of studies demonstrated the adverse effect of herbicide use to both environmental and human health [19–22], especially when not applied appropriately [23]. The increased public concern has caused policy and regulatory institutions to enforce a series of actions aiming at herbicide application reduction. However, herbicide use maintains a crucial role for the economic sustainability of agriculture in the foreseeable future [22,24]. This is confirmed by the global herbicide market size that is expected to reach overall market revenue of $8 billion by 2025, by growing at a compound annual growth rate of 4.8% during the forecast period (2020–2025) (https://www.alliedmarketresearch.com/herbicides-market). The world herbicide consumption represents 48% of Plant Protection Products (PPPs) globally used [20].

In this context, various international organizations have addressed issues related to the correct use of PPPs. In March 2020, the Organization for Economic Co-operation and Development developed a report on how to manage biodiversity impacts of fertilizer and pesticide use [25]. The Food and Agriculture Organization has issued a Code of Conduct on the Distribution and Use of PPPs that promotes information exchange and best practices [26]. The World Health Organization has developed an International Program on Chemical Safety, where PPP handling is also covered [27]. At European level, in 2009, the Council of the European Union adopted Directive 2009/128/EC on Sustainable Use of Pesticides that highlighted pesticide drift risks generated during spray application [28]. This directive represents bedrock EU legislation for all improvements pertaining to spray drift reduction and efficiency of pesticide application, including an overall definition and requirement for dedicated indirect methods of drift reduction like buffer zones or no-spray zones [29,30]. Each EU Member State specifies the characteristics of these zones in its National Action Plan (NAP). Among the technical information contained in the NAP, the minimum width of buffer zones, that include both free or cropped no-spray zones, and their relationship to different spray application techniques must also be delineated (in terms of drift reduction or avoidance capacity). These requirements clearly indicate that drift measurement and the related drift reduction extent, unique to each sprayer/technology, are essential tools to achieve a more sustainable spray application [31].

According to ISO22866:2005, spray drift is "the quantity of PPP that is carried out of the sprayed (treated) area by the action of air currents during the application process" [32]. Among the pollutants from PPP use, agrochemical spray drift continues to be a major challenge because PPPs can be deposited in undesirable areas and pose risks to both the environment and bystanders [32–38]. Spray drift generated by field crop sprayers can reach 50% of the amount of PPP spray mixture applied [39], but in the case of vineyard under-row band application, this is expected to be lower due to the use of reduced boom height, length, and a low sprayer forward speed [40–42].

In order to accomplish the regulations about the spray drift reduction or avoidance, it is important to use herbicide application techniques which are able to minimize spray drift as well as increase the application efficiency simultaneously. Specific Spray Drift Reduction Techniques (SDRTs) can be used during the application of herbicides in vineyards. The SDRT of prime interest is the use of air-induction (AI) nozzles as they are broadly recognized to reduce spray drift, due to a larger droplet size spectrum than conventional flat fan nozzles [43–46]. In particular, the use of AI nozzles is of high relevance for this type of application because the most used herbicides in vineyards for both weed control and suckering are systemic (e.g., glyphosate-based herbicides) [2,47]. It is well documented that for systemic herbicides, AI flat fan nozzles guarantee the same efficacy to that obtained using conventional flat fan nozzles [48–52]. Another SDRT broadly used for herbicide application is boom shielding [53,54]. When the weed control and suckering is performed at the same time, a semi-shielded boom is commonly used consisting of a plastic cabin placed on top of the boom to protect the nozzle spray outlets. The semi-shielded boom does not interfere with the spray jet angle allowing the suckering operation. On the contrary, when the spray application is intended for weed control only, it is possible to further minimize the spray drift using a fully-shielded boom, consisting of a plastic cabin integral with a brush long enough to run on the soil. This last option is especially used for weed control in the young vine plantations, to avoid the spray contact with the green tissues, because herbicide exposure could significantly injure young vines [55]. Combination of different SDRTs could possibly provide better results in terms of drift reduction. A lot of research has been focused on spray drift generated during PPP canopy application in 3D crops using air-assisted sprayers [56–61] and PPP applications in arable field crops using boom sprayers [56,62–65]. However, to date, few experimental data are available for the spray drift generated during herbicide spray application in vineyards.

In this context, the objective of this experimental work was to compare spray drift of different under-row band herbicide spray application techniques (conventional vs. SDRTs) used for weed control only, and for weed control and suckering at the same time. Furthermore, the contribution of individual row spraying to the total ground deposition spray drift was evaluated, with the final aim to identify the spray drift reduction achievable by the adoption of cropped buffer zones. The 90th percentile model characteristics for the spray drift generated during herbicide applications in vineyards was also investigated.

2. Materials and Methods

2.1. Characteristics of Spray Application Equipment and Its Configurations Tested

A conventional boom sprayer Abbà (Abbà s.n.c., Centallo—CN, Italy) specifically designed for under-row band herbicide application in vineyards was tested. The sprayer was composed of a short boom (0.57 m width) connected to the main 200 L polyethylene tank through a long flexible hose. The tank was mounted to the tractor through the three-point linkage. It is possible to mount the sprayer boom in three different lateral positions, namely front, mid or rear of the tractor, and at different heights above the ground. In this study, the spray boom unit was rear-mounted in lateral position and equipped with two nozzle holders characterized by 0.27 m nozzle spacing (Figure 1a). Furthermore, two types of shields could be mounted: (a) a plastic cabin that provides a partial shielding called "semi-shielded boom" and (b) a long brush protecting system integral with a plastic cabin that provides a full shielding called "fully-shielded boom".

According to common farmer practices, boom height of 0.50 m was tested for simultaneous chemical weed control and suckering (Figure 1b), whilst height of 0.25 m was tested for only weed control (Figure 1c). Eight configurations for each boom height were tested, deriving from the use of conventional flat fan nozzles, XR110015 and XR11003, and AI flat fan nozzles, AI110015 and AI11003 (Teejet Technologies, IL, USA) in combination with or without the semi-shield (Table 1). The fully-shielded boom was used for weed control only (Figure 1d) combined with conventional nozzles (Table 1).

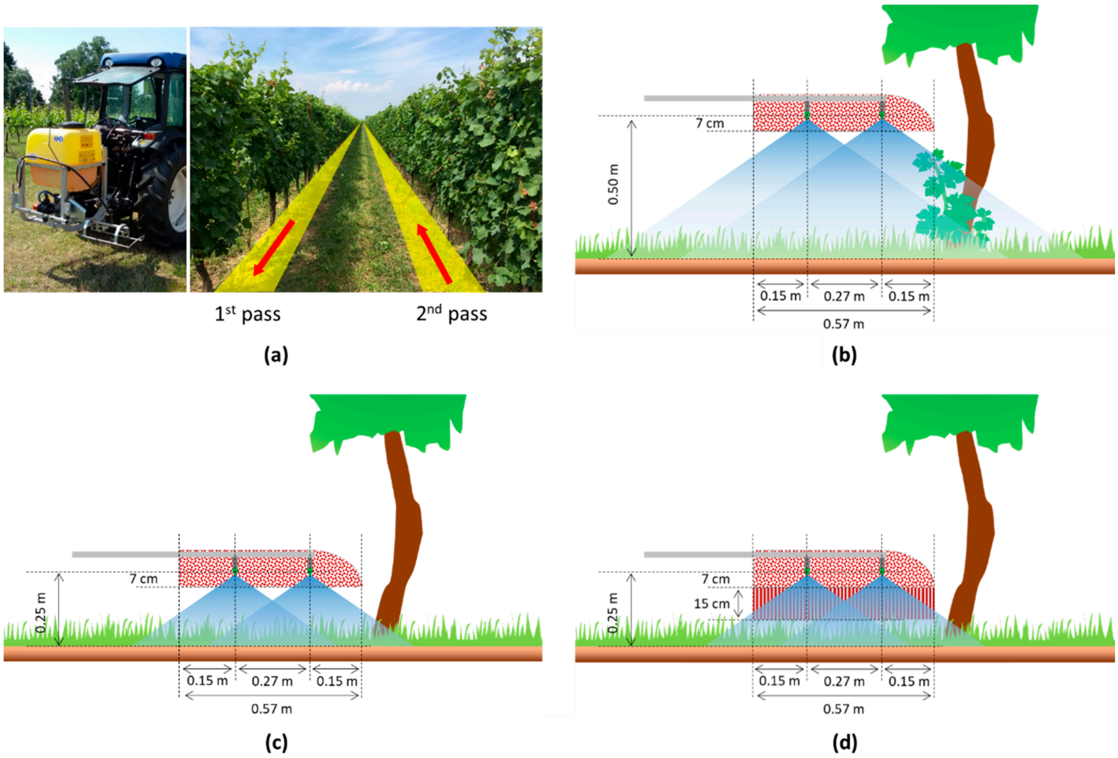

Figure 1. (**a**) Boom sprayer for the under-row band herbicide application in vineyard. The spray equipment could be used for (**b**) chemical suckering and weed control at the same time or for (**c**,**d**) weed control only; it could be employed (**b**,**c**) not-shielded, (**b**,**c**) semi-shielded and (**d**) fully-shielded.

For all tested configurations, a fixed volume of 142 L ha^{-1} was applied (Table 1). To obtain the intended total sprayed volume, the tests were performed using forward speeds equal to 1.11 m s^{-1} (4 km h^{-1}) and 2.22 m s^{-1} (8 km h^{-1}) for the 015 and 03 nozzle sizes, respectively. The same working pressure of 0.3 MPa was used, corresponding to nominal nozzle flow rates of 0.59 min^{-1} and 1.18 L min^{-1} for the 015 and 03 nozzle sizes, respectively. Applied volume rate and spray liquid pressure was selected according to the most common practices used by the farmers, derived from surveys in the ambit of TOPPS project (http://www.topps-life.org/).

Table 1. Parameter of all configurations examined using a boom sprayer for the under-row band herbicide application in vineyard (Piedmont region, Italy, spring 2018).

Configuration ID[a]	Nozzle Type	N° of Active Nozzles	Working Pressure (Mpa)	Total Liquid Flow Rate (L min^{-1})	Forward Speed (m s^{-1})	Volume Rate Applied (L ha^{-1})	Boom Height (m)	Boom Shielding
XR015_No_H	XR110015VS	2	0.3	1.18	1.11	141.6	0.50	None
XR03_No_H	XR11003VS	2	0.3	2.36	2.22	141.6	0.50	None
AI015_No_H	AI110015VS	2	0.3	1.18	1.11	141.6	0.50	None
AI03_No_H	AI11003VS	2	0.3	2.36	2.22	141.6	0.50	None
XR015_Yes_H	XR110015VS	2	0.3	1.18	1.11	141.6	0.50	Semi
XR03_Yes_H	XR11003VS	2	0.3	2.36	2.22	141.6	0.50	Semi
AI015_Yes_H	AI110015VS	2	0.3	1.18	1.11	141.6	0.50	Semi
AI03_Yes_H	AI11003VS	2	0.3	2.36	2.22	141.6	0.50	Semi
XR015_No_L	XR110015VS	2	0.3	1.18	1.11	141.6	0.25	None
XR03_No_L	XR11003VS	2	0.3	2.36	2.22	141.6	0.25	None
AI015_No_L	AI110015VS	2	0.3	1.18	1.11	141.6	0.25	None
AI03_No_L	AI11003VS	2	0.3	2.36	2.22	141.6	0.25	None
XR015_Yes_L	XR110015VS	2	0.3	1.18	1.11	141.6	0.25	Semi
XR03_Yes_L	XR11003VS	2	0.3	2.36	2.22	141.6	0.25	Semi
AI015_Yes_L	AI110015VS	2	0.3	1.18	1.11	141.6	0.25	Semi
AI03_Yes_L	AI11003VS	2	0.3	2.36	2.22	141.6	0.25	Semi
XR015_Full_L	XR110015VS	2	0.3	1.18	1.11	141.6	0.25	Fully
XR03_Full_L	XR11003VS	2	0.3	2.36	2.22	141.6	0.25	Fully

[a] ID is composed by the nozzle type (conventional: XR015 and XR03; air-induction: AI015 and AI03), the boom shielding (not-shielded: no; semi-shielded: yes) and boom height (0.50 m: H; 0.25 m: L): nozzle type_boom shielding_boom height.

2.2. Characterization of Droplet Size Spectra

The droplet size spectra produced by both conventional and AI nozzles was also determined in laboratory measurements, conducted at DiSAFA facilities (Grugliasco, Turin, Italy), using a Malvern Spraytec laser diffraction system STP5342 (Malvern Instruments Ltd., Worcestershire, UK), using the methodology detailed in Grella et al. [59]. The liquid pressure and the liquid flow rate adopted in the lab trials were the same used in the field trials (Table 1). The droplet diameter for the 10th (D[v,0.1]), 50th or Volume Median Diameter (VMD) (D[v,0.5]) and 90th (D[v,0.9]) percentiles of spray liquid volume were determined for each nozzle. Additionally, the % of spray liquid volume generated with droplet diameters smaller than 100 μm were calculated as V_{100} parameter. For each nozzle type, two nozzles were randomly sampled from a batch and for each nozzle, three measurements were performed. The two nozzles used for the laboratory droplet size measurements were then mounted on the boom sprayer for field trials.

2.3. Test Location and Experimental Plot Design

Tests were performed in an espalier-trained vineyard (cv: Barbera) located at DiSAFA facilities (45°03′60″ N 7°35′65″ E). Planting distances were 2.5 m between rows and 0.8 m within rows, resulting in density of 5000 vines ha^{-1}. The field trials were conducted at early-growth stage with BBCH-scale (Biologische Bundesanstalt, Bundessortenamt and CHemical industry) ranging between 16 and 55 [66].

Field drift measurements were carried out according to ISO22866:2005 [32]. Tests were performed by spraying a dye tracer solution in the nine outer downwind vineyard rows, covering surface area of 1395 m^2 (62 × 22.5 m) every replicate (Figure 2).

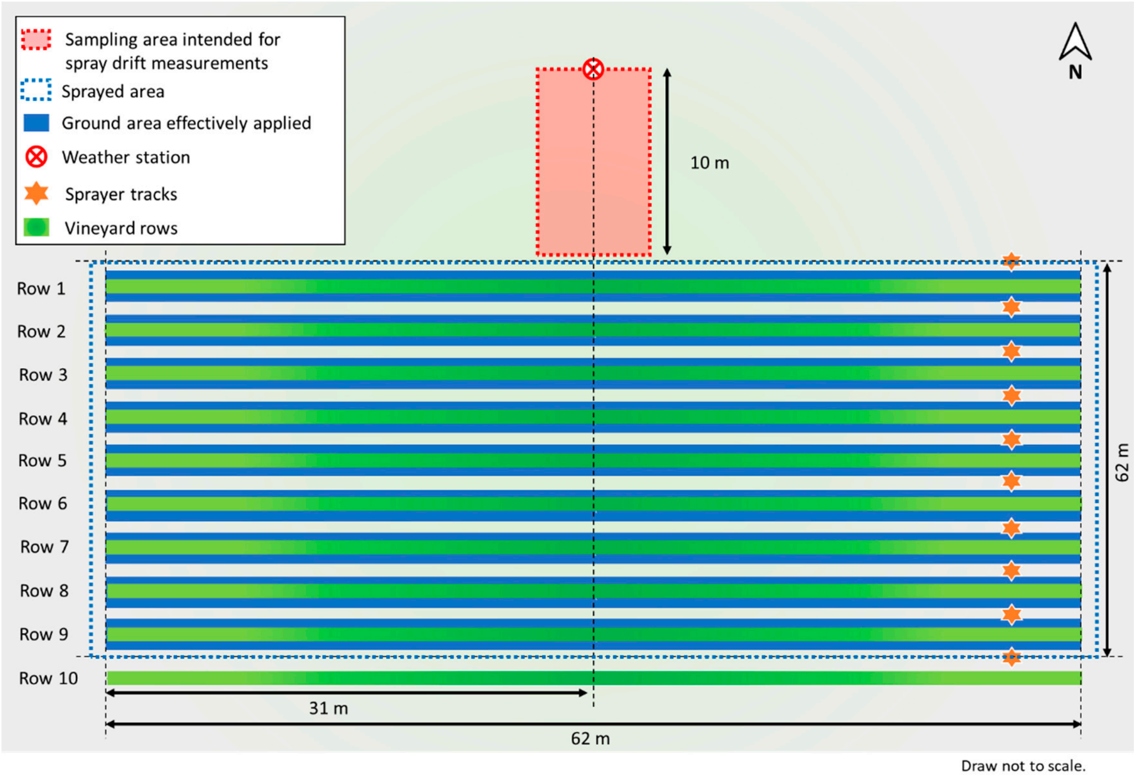

Figure 2. Overall aerial view scheme of trials' layout intended for ground spray drift measurements in vineyard (Piedmont region, Italy, spring 2018).

For each replicate, ground spray drift was measured in twelve bare-soil sampling distances, corresponding to 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9 and 10 m downwind, from the directly-sprayed area. At each location, six discrete ground level horizontal sampler Petri dishes (140 mm diameter) placed 1 m from each other were used to yield a total collection surface of 924 cm^2 at each downwind distance (Figure 3). The first line of samplers was placed at 2.25 m from the outermost row, equal to 1 m distance from the sprayed area. Based on preliminary field trials, 10 m downwind was defined as the furthest sampling distance adequate to collect more than 99% of total spray drift [67]. Two minutes after each spray application, Petri dishes were covered and collected in closed dark boxes to prevent tracer photodegradation. Three replications of measurements were conducted for each sprayer configuration in wind conditions that are as similar as is practicable, and the main parameters tested are summarized in Table 1.

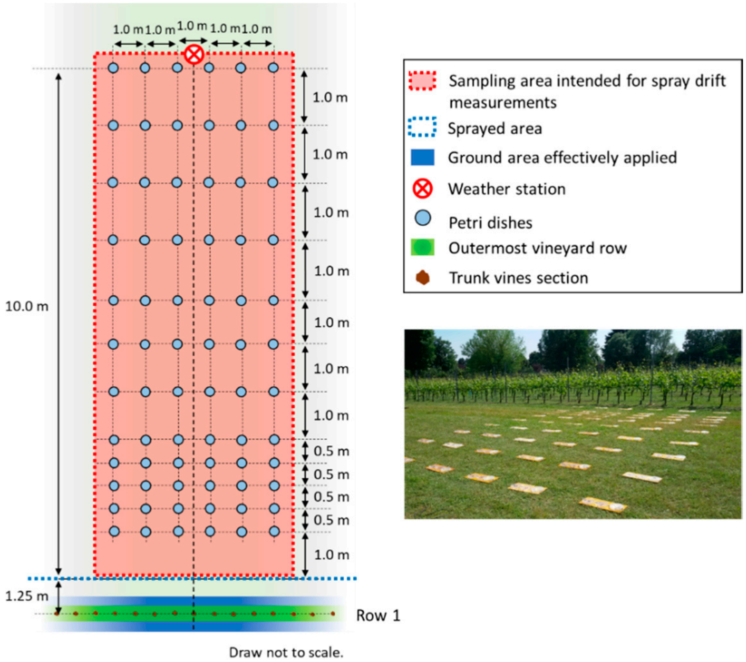

Figure 3. Test plot layout for spray drift measurements in vineyard (Piedmont region, Italy, spring 2018).

2.4. Weather Conditions—Measurements

According to ISO22866:2005 [32], a weather station was employed to monitor the environmental conditions during the trials. The station was equipped with a sonic anemometer 232 (Campbell Scientific, Logan, UT, USA) to measure wind speed and direction relative to the spray track at 4 m above the ground, and two thermo-hygrometer HC2S3 probes (Campbell Scientific, Logan, UT, USA) placed at 3 m and 4 m above the ground, respectively, to measure air temperature and humidity. All measurements were taken at a frequency of 0.1 Hz (1 per s) and all data was recorded automatically by a CR800 data-logger (Campbell Scientific, Logan, UT, USA). The weather station was positioned at the edge of the downwind area in the center of the drift sampling area (10 m away from the sprayed area) (Figures 2 and 3). The environmental conditions were monitored for the full duration of each test, in order to follow specific conditions for each test replicate to be valid for our study [32]. More specifically, (a) average wind speed should be higher than 1 m s^{-1}; (b) wind measurement counts of less than 1 m s^{-1} (outliers) should not exceed 10% of all measurements recorded; (c) mean wind direction should be 90° ± 30° to the spray track; (d) frequency of non-centered wind direction (>45°) to the spray track should not exceed 30% of data recordings; and (e) mean air temperature should remain between 5 °C and 35 °C.

2.5. Spray Liquid and Tracer Concentration

To measure deposits on collectors, the E-102 Tartrazine yellow dye tracer, 85% (w/w) (Novema S.r.l., Torino, Italy), was added to the sprayer tank at 10 g L^{-1}; Tartrazine was chosen as tracer for its high extractability and low degradation [68]. Prior to each test, a Petri dish was placed in the middle of the sprayed area and was collected 30 s before spraying started, to be used as a blank sample of reference. Three samples of the sprayed liquid were also collected from the spray tank content (sampled directly from a nozzle) before and after the spraying to ascertain the precise tracer concentration at the nozzle outlet for each test replicate.

2.6. Determination of Tracer Deposit Amount

Each Petri dish sampler was washed out using 5 mL of deionized water and the extract containing the tracer was shaken for 10 min using an Advanced Orbital Shaker, model 5000 (VWR, Radnor, Pennsylvania, USA) to completely homogenize the washing solution. Then, the Tartrazine concentration was determined by measuring the absorbance of the washing solution with a spectrophotometer UV-1600PC (VWR, Radnor, Pennsylvania, USA), set at 427 nm wavelength for peak absorption of the Tartrazine dye. The results were compared against a calibration curve obtained in laboratory using pre-set Tartrazine concentrations prior to the analysis. For each sample, three absorbance measurements were taken and blank samples of deionized water were included 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 ISO22401:2015 as follows [69]:

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

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

Once the tracer amount on each sampler was calculated, the mean values derived from the six samples placed at each downwind distance was calculated and the deposit at different distances from the sprayed area was used to draw the drift curve. The amount (μL cm^{-2}) obtained from each replicate was then transformed using a proportion to express ground sediments as percentage of application rate (%) where needed.

2.7. Drift Value (DV) and Relative Spray Drift Reduction Calculation

The surface area under the spray deposit curve, as most characteristic of near-field sedimentation [70,71], was deemed. Therefore, for each replicate, the total spray drift deposition was calculated by numerical integration of the sedimentation curves, as proposed by Grella et al. [59,72], to achieve the corresponding Drift Value (DV). The methodology allowed approximation of the definite integral using the mid-ordinate rule.

The spray drift reduction values (%) were derived from DV, averaged over replicates, according to the ISO22369-1:2006 formula for each configuration tested [73]. Therefore, drift reduction was determined through the pairwise comparison of reference spray configuration XR015_No_H with the other candidate configurations (Table 1).

2.8. Contribution of Individual Row Spraying to the Total Ground Deposition Spray Drift

Additional trials were carried out to determine the contribution of individual row spraying to the total ground deposition spray drift [74]. Under-row herbicide application was executed separately for each row, applying the ISO22866:2005 methodology (see Section 2.3 and Section 2.4) [32]. The same sampling layout (Figure 3), consisting in 6 collectors per each distance per 12 sampled distances (from 1 to 10 m from the sprayed area), were adopted. The Petri dishes were collected at the end of each sprayed row and three replications of measurements were performed per each row. In particular, based on preliminary experiments, the row contribution to the total spray drift was assessed separately as follows: row 1, row 2, row 3, row 4, rows 5 and 6 together and rows 7, 8 and 9 together (Figure 4). For this purpose, the configurations XR015_No_H and XR03_No_H were tested (Table 1).

These trials were conducted to determine the possible drift reduction achievable by the adoption of a buffer zone (e.g., evaluation of drift reduction achievable without spraying the outermost row/s). For these purposes, DVs of each drift curve, derived from single row applications, were calculated as detailed in Section 2.7. Then, the spray drift contribution (%) of each sprayed row to the total spray drift was obtained.

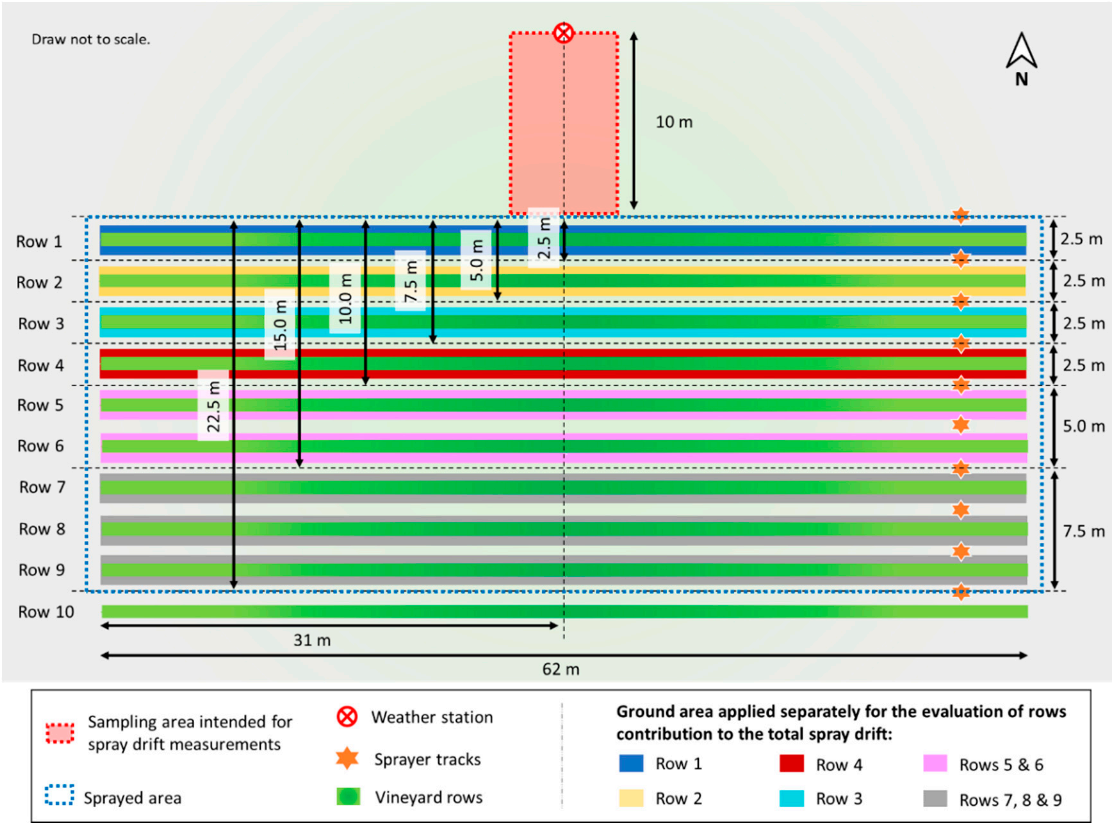

Figure 4. Overall aerial view scheme of trials' layout, "ad hoc" designed for the evaluation of the contribution of each vineyard row spray application to the total spray drift generation (Piedmont region, Italy, spring 2018).

2.9. Statistical Analyses

All statistical analyses were performed using IBM SPSS Statistics for Windows V26. The data were tested for normality using the Shapiro-Wilk test and by visual assessment of the Q-Q plots of residuals. A four-way Analysis of Variance (ANOVA) was performed to establish how the tested parameters act on the spray drift generation process with particular attention to their impact on drift reduction. The parameters investigated through four-way ANOVA were the nozzle type (conventional vs. air-induction), nozzle size (015 vs. 03), boom shield (not-shielded vs. semi-shielded) and boom height (0.50 m vs. 0.25 m above the ground); the dependent variable considered was DV. The two configurations characterized by the fully-shielded boom (XR015_Full_L and XR03_Full_L) were not included in the abovementioned statistical analyses.

Moreover, two-way ANOVA was used to evaluate the contribution of each vineyard row spray application to the total spray drift generation. Specifically, the effect of configuration (XR015_No_H vs. XR03_No_H) and rows applied individually was investigated; also in this case, the dependent variable considered was DV.

The Excel solver tool (version 2016 for Windows) was used to perform the 90th percentile experimental data fitting using the power law fit model [75]. The deviation of fitted values from measured 90th percentile deposits was determined using the Root Mean Square Error (RMSE). The RMSE is a standard way to measure the error of a model in predicting quantitative data [76]. The RMSE was then calculated from Eq. (2), accordingly to Zande et al. [65], as follows:

$$RMSE = \sqrt{\frac{\sum_{x=1}^{Nm}\left(ln(Y_{fx}) - ln(Y_{mx})\right)^2}{Nm}} \quad (2)$$

where RMSE is a measure of the average deviation in *ln(Y)*; Y_{fx} is the fitted deposit at distance *x*; Y_{mx} is the measured deposit at distance *x*; *Nm* is the number of deposits (i.e., distances—10).

3. Results and Discussion

3.1. Droplet Size Spectra Characteristics

Based on the analysis of droplet size spectra produced by both conventional and AI nozzles (Table 2), it can be seen that VMD was three time higher in AI nozzles than the conventional for the same nozzle size. It results that the flat fan conventional nozzles (XR-types) produce fine droplets while the flat fan air-induction (AI-types) produce very coarse droplets as classified by Southcombe et al. [46]. In addition, V_{100} was reduced significantly with AI nozzles, aligning this study with the widely recognized positive impact of V_{100} reduction in droplet driftability [62,77–79]. The higher the V_{100} parameter is, the higher is the potential for spray drift [80].

Table 2. Main characteristics of nozzles used in the trials and relative droplet size spectra (CPT laboratory belonging to DiSAFA, University of Turin, Italy, 2018).

Nozzle Type	Spray Angle (°)	Nozzle Size	Working Pressure (Mpa)	Flow Rate (L min^{-1})	D[v,0.1][a] (μm)	D[v,0.5][a] (μm)	D[v,0.9][a] (μm)	V_{100}[b] (%)
XR110015VS	110	015	0.3	0.59	62	132	300	37.73
XR11003VS	110	03	0.3	1.18	69	164	398	28.26
AI110015VS	110	015	0.3	0.59	161	434	819	4.80
AI11003VS	110	03	0.3	1.18	214	513	965	3.11

[a] 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 –VMD; D[v,0.9], 90% of spray liquid volume is made up of droplets smaller than this value. [b] V_{100}: Spray liquid fraction generated with diameter smaller than 100 μm.

3.2. Environmental Conditions during Field Trials

All tests were conducted with a mean wind speed above 1.0 m s^{-1} as indicated in the standard protocol. The most frequent wind directions were SSE, S, and SSW in all tests and had perpendicular direction relative to the crop rows and spray track (180° azimuth according to the Figures 2 and 5), as dictated by ISO22866:2005 [32]. Weather parameters during field trials are detailed for each replicate in Appendix A. In particular, the meteorological parameters (average wind speed and direction, mean temperature, relative humidity) measured during trials' executions and the comparison with the ISO22866 specifications are given in Table A1 (trials with 0.50 m nozzles' height above the ground—weed control and suckering), Table A2 (trials with 0.25 m nozzles' height above the ground—weed control only), and Table A3 (trials for the evaluation of individual row spraying contribution to the total spray drift generation).

In general, the wind speeds were very similar across the trials and, in most cases, resulted higher than 2 m s^{-1}; similarly to previous experimental work applying ISO22866:2005 test protocol [59]. The highest variation in wind direction was measured in trials characterized by lower average wind speed and higher outliers percentage. Furthermore, the wind direction was generally more uniform than wind speed during each trial. Bird et al. [81] underlined the difficulty of comparing different studies due to inability of isolate and correct for weather differences. Therefore, a similar wind speed and directions among the trials are of prime importance due to their high influence on spray drift deposit processes [82–84], especially for spray drift in the neighboring field [85]. However, it is well known that ISO22866:2005 field experiments using different spray systems cannot be performed under identical and perfectly repeatable conditions [30,32,57,59,60,65]. So, it is reasonable to obtain reliable information on the spray drift potential of a specific sprayer configuration for the under-row band herbicide application in vineyards, based on the analysis of weather conditions at the time of trials.

3.3. Evaluation of Spray Drift Generated by the Tested Configurations Using the Semi-Shielded and Not-Shielded Boom

Figure 5 displays the mean spray drift ground deposits (µl cm^{-2}) at different distances downwind of the sprayed area. Figure 5a illustrates spray drift deposit profiles of the conventional boom sprayer for simultaneous weed control and suckering (0.50 m nozzle height above the ground), while Figure 5b for weed control only (0.25 m nozzle height above the ground). In both cases, irrespective of configuration considered, the spray drift deposition peaked one meter away from the sprayed area. In the first three meters, spray drift showed a strong decay that was then constantly decreasing in a slight pace. Interestingly, in all cases, the farthest sampling distance where deposits were detected was 8 m, even if the samplers were placed up to 10 m distance from the sprayed area (Figure 5). Even considering the worst case (XR015_No_H—Figure 5a), the spray drift did not overtake the 8 m distance from the sprayed area. The reduced boom height (0.25 m) reduced highly the distance that spray drift could reach, especially when using AI nozzles. As expected, the configurations tested using nozzles at 0.50 m height above the ground showed an average deposition at all sampled distances higher than when 0.25 m height was used. These results confirmed the negative effect of increased spray boom height on drift generation [41,62–65]. The effect of boom height on the spray drift profiles was evident in the first sampled distance (1 m from sprayed area), where spray drift was reduced on average from 25 to 6%, from 15 to 4%, from 5 to 3% and from 6 to 2% for XR110015, XR11003, AI110015 and AI11003, respectively. At the farthest distances, the drift reduction attributable to the boom height was also consistent. Furthermore, the comparison of the two spray application techniques in Figure 5 shows that the effect of AI nozzles was enhanced when the boom height was reduced, with the spray drift deposited only in the first few meters from the spray sources in most cases. When the AI03 nozzles were used combined with the semi-shielded boom (AI03_Yes_L—Figure 5b), spray drift reached maximum 3 m distance from the sprayed area. These results confirmed that using AI nozzles is the main strategy to reduce spray drift, thanks to the increase of droplet size (Table 2).

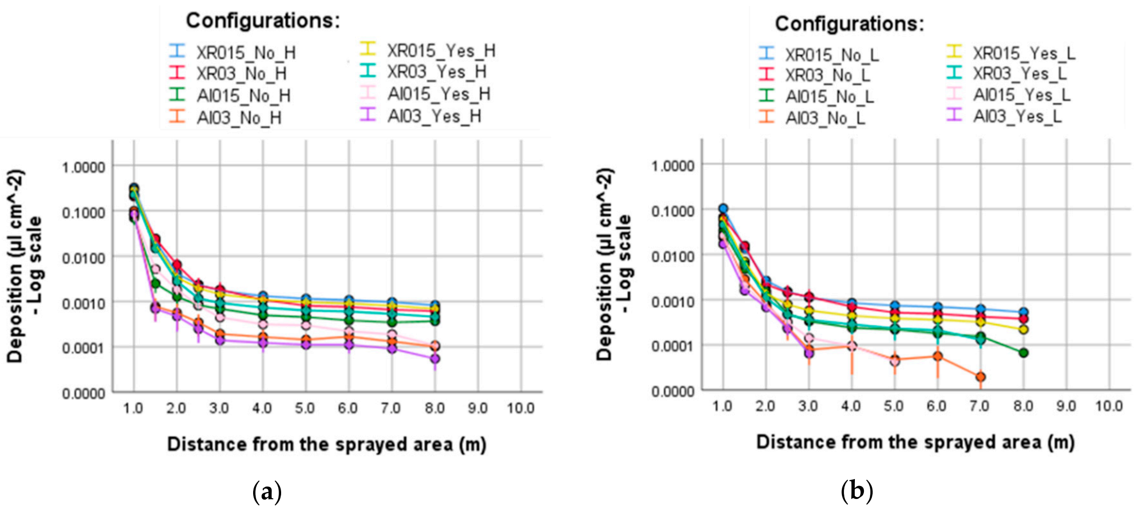

Figure 5. Spray drift deposit profiles using a conventional boom sprayer for the under-row band herbicide application (**a**) for weed control and suckering at the same time and (**b**) for weed control only. The mean ± SEM (µL cm^{-2}) of the spray deposit on the collectors is represented at downwind distances from the sprayed area. Configurations: nozzles (XR015 and XR03: conventional, AI015 and AI03: air-induction), boom shielding (No: not-shielded, Yes: semi-shielded) and boom height (H: nozzles 0.50 m, L: nozzles 0.25 m). (Field trials conducted in trellised vineyard cv. Barbera, Piedmont region, Italy, spring 2018).

It should be noted that the percentage of sprayed liquid drifted was small, as even in the worst case (XR03_No_H). The average spray drift measured at 1.5 m distance from the sprayed area was equal to 1.7% of applied volume. In general, comparing the spray drift generated during the under-row band herbicide applications with the spray generated during the canopy PPP applications in the vineyard, it is clear that the drifted herbicide spray is very limited both in terms of total amount and maximum distance reached [56]. Grella et al. [59,72] measured spray drift during vineyard canopy PPP application using a conventional axial fan sprayer and identified consistent spray drift of nearly 1% of volume applied, 30 m away from the sprayed area. Similar values, ranging between 25–30%, were measured at 1 m distance from the sprayed area [59,72].

From the spray drift profile curves (Figure 5), the DVs (μl 10,000 cm^{-2}—considering a strip of 1 cm x 10,000 cm of downwind ground area) were calculated for each tested configuration [71,72]. The results obtained from the four-way ANOVA based on the DVs (Table 3) showed that significant main effects of nozzles' type, Nt; nozzles' size, Ns; boom shielding, Bs; and boom height, Bh ($p < 0.05$) on spray drift were detected. Significant effects of the interaction among the considered factors were found for Nt, Ns and Bh. This underlines that the effect of each factor depends on the levels of the other two factors and vice versa. The averaged DVs over not-shielded and semi-shielded configurations, to display the effect of Nt*Ns*Bh, are provided in Figure 6a. In line with other studies, the results (Figure 6a and Table 3) demonstrated that AI nozzles represent the most interesting SDRT together with selection of appropriate nozzles' size [43,44,65]. Interestingly, with conventional nozzles, the reducing boom height from 0.50 to 0.25 m decreased spray drift generation in a similar extent to the use of AI nozzles at 0.50 m height (Figure 6a). This means that when the spray application was intended for weed control and suckering at the same time, the potential risk of drift generation increases substantially. Unexpectedly, the use of semi-shielded boom, Bs, was significant in reducing spray drift, but with the lowest extent among other parameters tested (Figure 6b and Table 3). As mentioned, the semi-shielded boom could be considered a SDRT of major interest, determining a more consistent drift reduction when the spray application is intended for weed control only using the boom at 25 cm height above the ground (Figure 6b).

Table 3. Significance obtained in four-way ANOVA for drift values (DVs) as affected by nozzle type (flat fan: conventional vs. air-induction), nozzle size (015 vs. 03), boom shielding (not-shielded vs. semi-shielded) and boom height (0.50 m vs. 0.25 m nozzle height above the ground). The DVs are the numerical integral of spray drift curves generated by the configurations tested for the weed control only, and weed control and suckering at the same time using a boom sprayer for under-row band herbicide application (field trials conducted in trellised vineyard cv. Barbera, Piedmont region, Italy, spring 2018).

Sources	Sum of Squares	*df*	Mean Square	*F*	*p*	Signif. [a]
Nozzles type –Nt-	511.97	1	511.97	364.77	4.666×10^{-19}	***
Nozzles size –Ns-	26.75	1	26.75	19.06	1.242×10^{-4}	***
Boom shielding –Bs-	11.55	1	11.55	8.23	0.007	**
Boom height –Bh-	534.56	1	534.56	380.86	2.466×10^{-19}	***
Nt* Ns	24.95	1	24.95	17.78	1.901×10^{-4}	***
Nt * Bs	5.61	1	5.61	4.00	0.054	NS
Nt * Bh	163.47	1	163.47	116.46	3.402×10^{-12}	***
Ns * Bs	0.72	1	0.72	0.51	0.480	NS
Ns * Bh	3.09	1	3.09	2.20	0.148	NS
Bs * Bh	2.41	1	2.41	1.72	0.199	NS
Nt * Ns * Bs	3.46	1	3.46	2.47	0.126	NS
Nt * Ns * Bh	13.41	1	13.41	9.55	0.004	**
Nt * Bs * Bh	0.59	1	0.59	0.42	0.521	NS
Ns * Bs * Bh	0.03	1	0.03	0.02	0.877	NS
Nt * Ns * Bs * Bh	1.36	1	1.36	0.97	0.333	NS

[a] Statistical significance level: NS Pr > 0.05; * Pr < 0.05; ** Pr <0.01; *** Pr < 0.001.

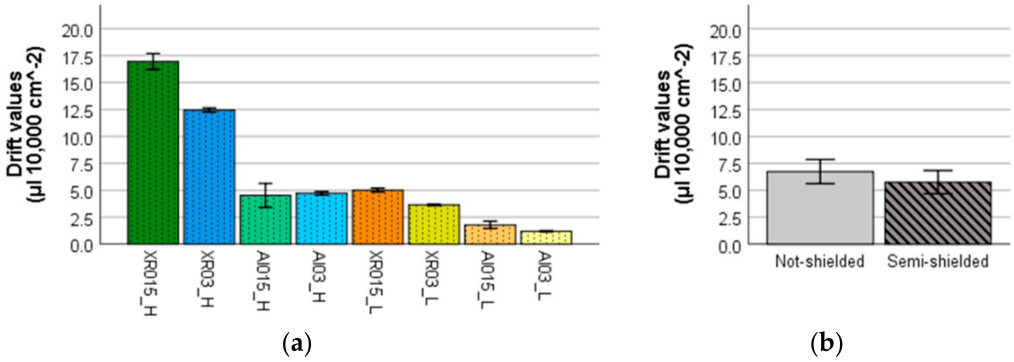

Figure 6. Drift Values (DVs) (**a**) averaged over not-shielded and semi-shielded configurations to display the effect of interaction among nozzle type*nozzle size*boom height and (**b**) averaged over nozzle type, nozzle size and boom height to display the main effect of shielding. The DVs were obtained using a conventional boom sprayer for the under-row band herbicide application intended for weed control and suckering at the same time or for weed control only according to the boom height. The mean ± SEM (μL 10,000 cm^{-2}) of the total spray drift deposition under the curve is represented. Factors tested: nozzle type (XR: conventional, AI: air-induction), nozzle sizes (015 and 03) boom shielding (not-shielded, semi-shielded) and boom height (H: nozzles 0.50 m, L: nozzles 0.25 m). (Field trials conducted in trellised vineyard cv. Barbera, Piedmont region, Italy, spring 2018).

Drift Reduction Achievable Using the Tested Spray Drift Reducing Techniques (SDRTs)

Figure 7 shows the drift reduction achieved by the tested configurations for weed control and suckering at the same time or weed control only. The spray drift reduction was calculated based on ISO22369-1:2006 using the configuration XR015_No_H as reference [73], because it achieved the highest total spray drift. SDRTs for combined weed control and suckering reduced, on average, spray drift by 53% (light-blue dotted line—Figure 7). In particular, when conventional nozzles were used the potential spray drift reduction achieved was not higher than 30%; though, large orifice nozzles (03 size) increased drift reduction. At the same time, the adoption of AI nozzles allowed to achieve drift reductions in the range of 70–80%, independent of the nozzles' size and the use of boom shield.

When SDRTs were used for weed control only, an average drift reduction of 83% was achieved (red dotted line—Figure 7). In this case, lowering boom height determined, in all cases, a drift reduction compared to the reference spray application technique XR015_No_H. Using conventional nozzles, the drift reduction achieved was in the range of 65–75% according to the nozzles' size, while the use of semi-shielded boom allowed to further decrease spray drift. Additionally, using the spray boom at 0.25 m height, the AI nozzles allowed achieving the best drift reduction reaching 95%, when the 03 nozzles combined with the semi-shielded boom were used. However, drift reduction improvement due to the use of AI nozzles was less marked than when the spray boom was used at 0.50 m height. In general, the drift reduction results confirmed that AI nozzles were the best SDRT for combined weed control and suckering, while the use of semi-shielded boom did not have clear effect. On the contrary, when the spray application was intended for weed control only, the use of semi-shielded boom showed a clear effect in reducing spray drift also in combination with conventional nozzles. Nevertheless, the combination of AI nozzles and semi-shielded boom was the best SDRT combination in all cases for both spray application techniques investigated.

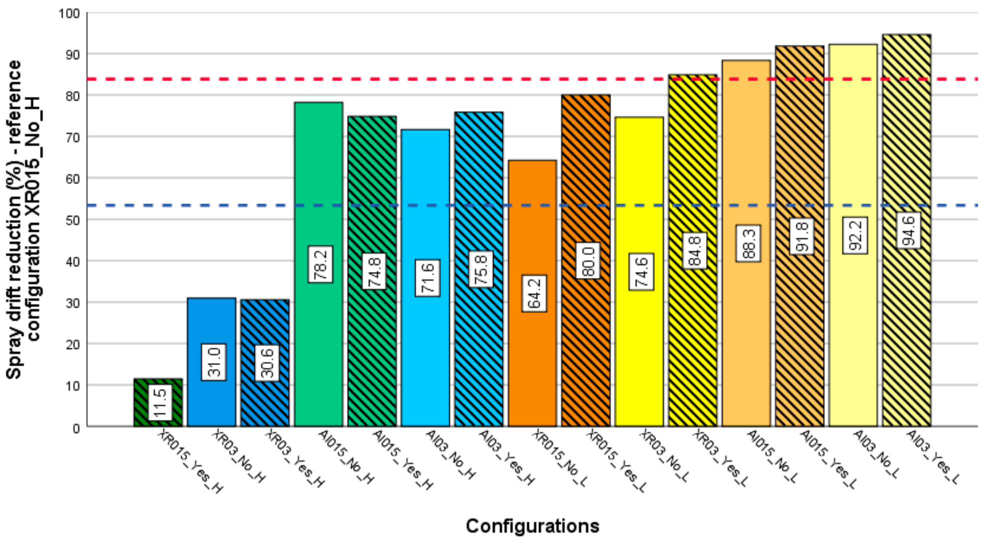

Figure 7. Drift reduction values (%) obtained for each configuration tested using a conventional boom sprayer for the under-row band herbicide application in vineyards. The drift reduction values were obtained considering the XR015_No_H configuration as a reference. The light-blue dotted line represents the average spray drift reduction for the spray application configurations intended for weed control and suckering at the same time (0.50 m boom height), while the red dotted line represents the average spray drift reduction for the spray application configurations intended for weed control only (0.25 m boom height). Configurations: nozzles (XR015 and XR03: conventional, AI015 and AI03: air-induction), boom shielding (No: not-shielded, Yes: semi-shielded) and boom height (H: 0.50 m boom height, L: 0.25 m boom height). (Field trials conducted in trellised vineyard cv. Barbera, Piedmont region, Italy, spring 2018).

3.4. Evaluation of Spray Drift Generated by the Tested Configurations Using the Fully-Shielded Boom and Their Potential Drift Reduction

According to Table 1, the spray application technique for weed control only (0.25 m height above the ground) was tested also using the fully-shielded boom. For this purpose, only two configurations (XR015_Full_L and XR03_Full_L) were tested both showcasing conventional nozzles, namely XR110015 and XR11003. The results are not displayed in Figure 5b and are not included in the four-way ANOVA analysis (Table 3), because no detectable amount of spray deposits was collected at any distance from the sprayed area. This means that the use of fully-shielded boom allowed reducing nearly 100% of spray drift generation. However, the authors cannot exclude that in more severe wind conditions, some detectable amount of spray drift could be noticed; though, the above result is strongly supported by previous work on spray drift potential in wind tunnel using the same fully-shielded boom equipped with the same conventional nozzles. Under artificial constant air flow of 5 m s^{-1}, mimicking severe wind conditions, very limited fraction of spray deposits were detected in the downwind area [54]. Therefore, when possible, the fully-shielded boom has to be chosen as the best SDRT to minimize the potential drift risk during spray application.

3.5. Contribution of Individual Row Spraying to the Total Ground Deposition Spray Drift

Figure 8 displays plots of the mean spray drift ground deposits (μl cm^{-2}) measured at different distances downwind of the sprayed area. They correlate to plumes generated while spraying vineyard row/s separately. The spray drift is split by the two tested configurations, namely XR015_No_H and XR03_No_H. The two configurations were selected as the “worst cases” from the results displayed in Figure 5 that confirm previous experimental work [54,67]. Therefore, they were used for the determination of spraying single row contribution to the total spray drift. Based on the two-way ANOVA analysis of drift value (DV) the two configurations tested were not significantly different ($F(1,24) = 3.363$, $p = 0.079$) while the contribution of each row to the total spray drift was significantly different ($F(5,24) = 30.053$, $p = 1.377 \times 10^{-9}$). The highest amount of spray drift was generated during the spray application of the first row (Figure 8). In both configurations, it achieved the farthest distance from the sprayed area. Similarly to the previous results (Figure 5), the deposits did not overtake the 8 m sampling distance. In addition, the spray application of the second row determined a considerable amount of spray drift deposit, reaching 5 m distance from the sprayed area. A severe reduction of row/s contribution was measured when spraying the farther rows due to the increasing distance between drift samplers and spray source (Figure 4). The application of row 3 achieved, as farthest distance, 3 m from the sprayed area, while the application of row 4 achieved a maximum distance of 2.5 m. Spraying rows 5 and 6 together determined a detectable amount of spray drift distance of 1 m and only using the smaller nozzles (XR110015). In both configurations, the application of rows 7, 8 and 9 did not generate spray drift deposits detectable in the downwind sampling area. In the case of simultaneous weed control and suckering, testing the worst configurations, spray application of the two outermost vineyard rows (row 1 and 2—Figure 4) determined the highest contribution to the total spray drift measured at each sampling distance. The total amount of spray drift measured in each sampled distance from the sprayed area (Figure A1) were consistent with those obtained from conventional ISO22866:2005 methodology (Figure 5).

The stacked bars chart (Figure A1), showing the piled contribution of each row to the total spray drift at each sampled distances from the sprayed area, displays the first three meters of downwind area contributing the highest amount of the total spray drift (more than 97% of total deposition for both configurations). Spray drift is influenced by many factors related to environmental conditions [59,79,84], spray techniques [42,44,65], crop type and canopy structure [56,65,86]. In 3D crops like trellised vineyards, the canopy acts as a natural windbreak, especially when the wind direction is transverse to the rows' orientation, as requested by the ISO22866:2005 test method for spray drift measurements. In this study, this led to limited contribution of farther rows to the total spray drift, but also determined the strong rate of deposition decrease in the first few meters from the sprayed area. The piled deposition in Figure A1 deposition decreased from 21 to 2% in 0.5 m width-distance (from 1 m to 1.5 m sampling distances for the configuration XR015_No_H). This suggests that even if the trials were conducted with an average wind speed higher than 2 m s^{-1} (Table A3), the real wind speed near the spray area, in most cases, was drastically reduced thanks to the action of the vine canopy, determining a limited total spray drift deposition. Similarly to the other PPP canopy spray application in vineyards, the under-row band herbicide application could also be potentially more susceptible to spray drift generation during the early growth stages than at the full-growth stages.

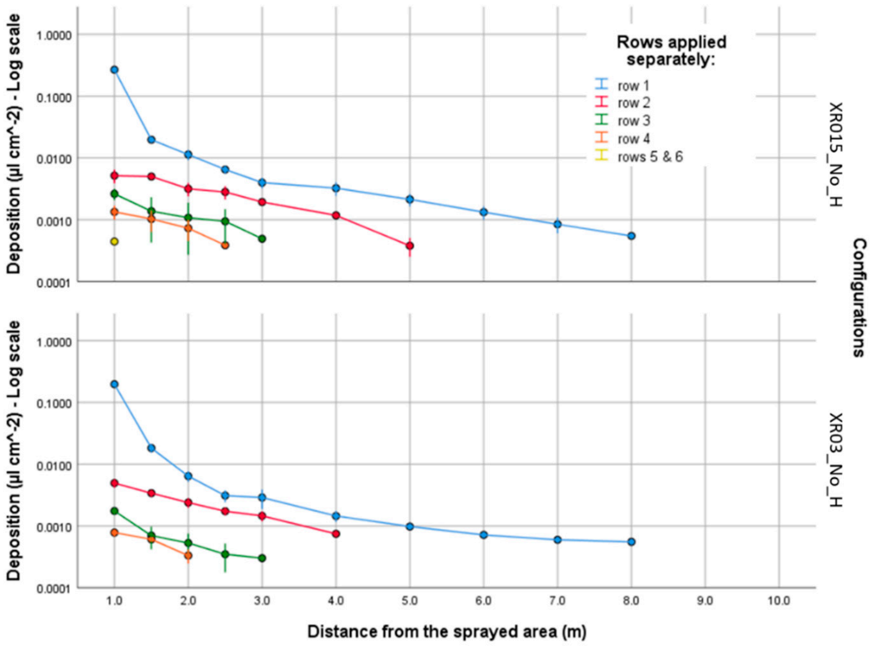

Figure 8. Spray drift deposit profiles obtained by applying separately the vineyard row/s using a conventional boom sprayer for the under-row band herbicide application intended for weed control and suckering at the same time. The mean ± SEM (μL cm^{-2}) of the spray deposit on the collectors is represented at downwind distances from the sprayed area. Row/s applied separately: row 1, row 2, row 3, row 4, rows 5 and 6 and rows 7, 8 and 9. Configurations: conventional nozzles (XR015 and XR03), boom not-shielded (No) and boom 0.50 m height above the ground (H). (Field trials conducted in trellised vineyard cv. Barbera, Piedmont region, Italy, spring 2018).

Drift Reduction Achievable through the Adoption of Cropped Buffer Zones

Figure 9 shows the total contribution of each sprayed row/s to the total spray drift generated during the under-row band herbicide application intended for weed control and suckering at the same time. The charts demonstrate that, in the worst cases, irrespective of nozzles' size (XR015 vs. XR03), the spray application of the first outermost vineyard row contributed 91% of total spray drift. The application of the second row contributed to only 6% of the total spray drift. This means that avoiding the spray application of the two outermost rows would reduce the total spray drift by more than 97%. Indeed, the application of rows 3 to 9 (Figure 4) contributed to 3% of the total spray drift. It emerges that for combined weed control and suckering, the adoption of an indirect drift reducing method like cropped buffer zones [30] including the outermost row only or the two outermost rows, allowed to minimize deeply the total spray drift deposition. Furthermore, the adoption of a cropped no-spray zone determined not only the drift reduction in terms of amount, but allowed to minimize the maximum distance reached by the spray drift. Based on the experimental results (Figure 8), the spray application of the third row determined a ground deposition up to 3 m from the sprayed area as farthest distance. Adoption of a cropped no-spray zone including the two outmost vineyard rows has achieved 97% spray drift reduction and by also using SDRTs (e.g., drift-reducing nozzles and semi-shielded boom), it is possible to further minimize the total spray drift and the distance achieved by the drift. Therefore, SDRTs open up the possibility to reduce the width of cropped no-spray zones [31]. It is interesting to point out that, irrespective of spray application techniques and adopted SDRTs for the under-row band herbicide application, a cropped no-spray zone that included the first two rows or, at least, the first one, could, in any case, guarantee a spray drift reduction of at least 95% and 90%, respectively. In a practical way, when the cropped buffer zone is required to mitigate the impact of spray drift to the sensitive areas (e.g., water courses, ditches, schools, gardens, urban areas, bystanders in general) alternative environmentally-friendly techniques for weed control and suckering (e.g., mechanical control) should be adopted only for the rows included in the cropped buffer zones.

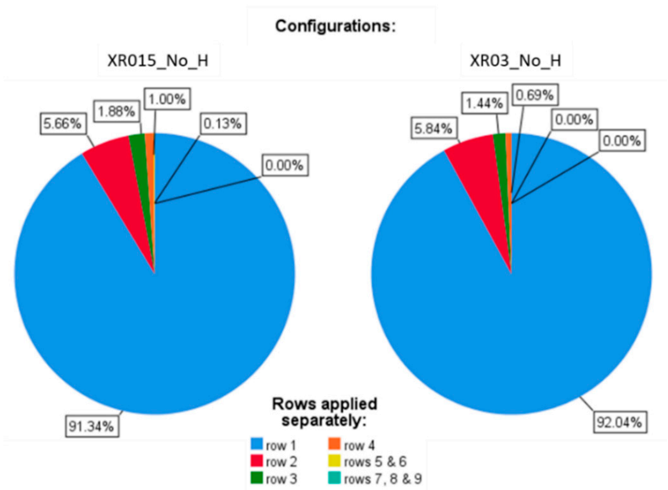

Figure 9. Contribution % of each row/s applied separately to the total spray drift represented by pie charts. Row/s applied separately: row 1, row 2, row 3, row 4, rows 5 and 6 and rows 7, 8 and 9. Configurations: conventional nozzles (XR015 and XR03), boom not-shielded (No) and boom 0.50 m height above the ground (H). (Field trials conducted in trellised vineyard cv. Barbera, Piedmont region, Italy, spring 2018).

3.6. Fit Model for the Spray Drift Generated during Under-Row Band Herbicide Application

In Figure 10, the 90th percentile spray deposition of experimental data (black dotted line) obtained from the whole dataset (data deriving from both spray applications for combined weed control and suckering, and weed control only) are displayed. The data were obtained from 48 spray applications (16 configurations × 3 replicates) conducted according to ISO22866:2005 protocol under similar environmental conditions (Tables A1 and A2). The use of the 90th percentile is in accordance with proposals made on EU-level by the FOCUS group [87]. The 90th percentile curves have been used since 1995 for the assessment of PPPs with regard to their effects on non-target organisms during the authorization procedure of PPPs [56,88,89].

Similarly, to other crops and the related spray application techniques [56,65,90], the red curve in Figure 10 shows a power law fit model, representing the spray drift reference curve peculiar for the under-row band herbicide application in vineyards. The power law model used to fit the 90th percentile spray drift experimental data is expressed according to Eq. (3) as:

$$y = A + B * x^n \tag{3}$$

where y is the spray drift deposition (%); x distance from treated area; A, B and n are the function parameters: A = 0.056, B = 18.828 and n = –6.213

The error of proposed power law in predicting quantitative spray drift deposition data was evaluated based on the calculation of RMSE. The RMSE value obtained fitting the experimental data in Figure 10 was 0.14, demonstrating that the power law model successfully fits the experimental data. The RMSE value was close to that obtained by Zande et al. [65], equal to 0.08, fitting the 90th percentile of spray drift curves obtained by spraying a bare soil surface or short crop (<20 cm) using a boom sprayer equipped with standard flat fan nozzles (XR11003/XR11004) and a boom height of 0.50 m. Figure 10 shows the very steep decline of the spray drift deposition close to the field edge for the under-row band application in the vineyard; losses lower than 1% of volume applied can be guaranteed beyond 1.65 m distance from the sprayed area. According to the 90th percentile drift curves, the same amount detected at 2.85 m distance from the sprayed area during the under-row band spray application in vineyards was detected at 30 m distance for the arable field crop application.

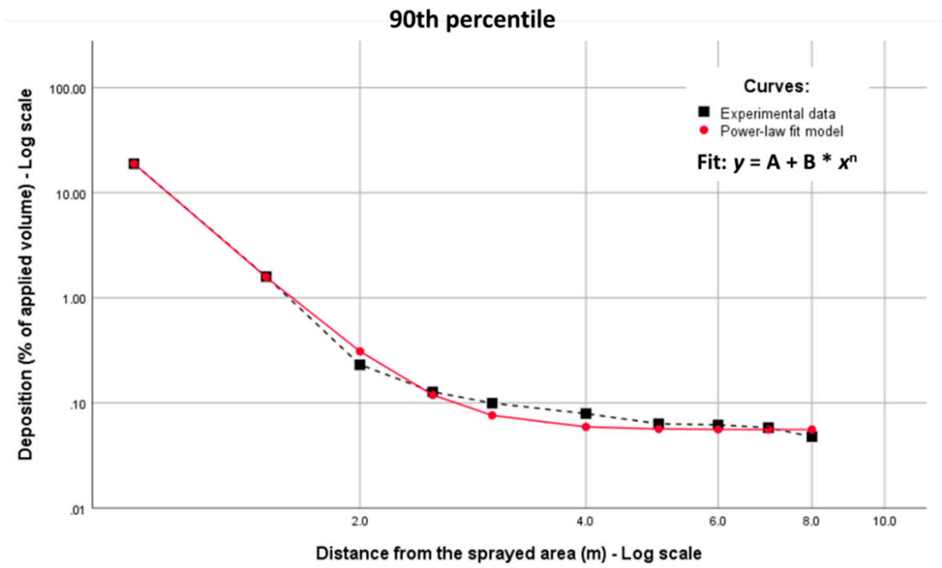

Figure 10. 90th percentile spray drift deposition, obtained using a conventional boom sprayer for the under-row band herbicide applications, is represented at downwind distances from the sprayed area. The experimental data (black dotted line) deriving from both spray application intended for weed control and suckering at the same time, and weed control only are plotted together with spray drift curves fitted as power law function (red solid line). (Field trials conducted in trellised vineyard cv. Barbera, Piedmont region, Italy, spring 2018).

4. Conclusions

The Spray Drift Reducing Techniques (SDRTs) tested for both the under-row herbicide application aimed for simultaneous weed control and suckering, and weed control only, resulted effectively in reducing substantial spray drift. In particular, when the boom sprayer was used at 0.50 m height above the ground with the purposes of weed control and suckering at the same time, the spray drift generated resulted, on average, three times higher than that generated during the spray application intended for weed control only, performed using the boom at 0.25 m height. In general, to minimize the spray drift as much as possible, the use of an AI nozzle combined with the semi-shielded boom is always recommended for both combined weed control and suckering (75% of drift reduction), and for weed control only spray applications (92% of drift reduction). When the weed control is performed with the fully-shielded boom, nearly 100% of drift reduction is achieved. Of particular interest, was the adoption of cropped buffer zones as indirect SDRTs to further minimize the potential risk of drift generation (97% of drift reduction including the two outermost rows in the buffer zone).

The right choice of direct or/and indirect measures, like buffer zones, to protect the environment, is the main strategy to minimize spray drift and maintain acceptable levels of eco-toxicological risk in the sensitive areas. Spray technology plays a key role in the environmental risk assessment for PPPs.

The 90th percentile curve, by the means of power law model, represents the first reference curve suitable in predicting quantitative data for the under-row band herbicide application in vineyards. It can be utilized during the environmental risk assessment undertaken in the ambit of studies that pave the way for the registration of herbicides [28] for this specific use. Indeed, the eco-toxicologic models accounted for ground spray drift are based on reference curves specific to both spray application techniques, crop type and growth stage.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Environmental conditions recorded during field trials simulating the spray applications for the weed control and suckering at the same time (nozzles are 0.50 m height above the ground).

Config & Replicates		Weather Parameters										
		Temperature		RH		Wind Speed				Wind Direction		
		Mean	Δ [a]	Mean	Δ [b]	Min	Max	Mean	Outliers [c]	Mean	Centered [d]	Prevalent Direction
		°C	°C	%	%	m s^{-1}	m s^{-1}	m s^{-1}	%	° az.	%	
XR015_No_H	R1	25.7	0.26	24.9	0.15	0.15	2.81	1.84	6.5	158.1	78	SSE
	R2	32.4	0.29	38.3	−0.55	1.21	2.74	2.11	0.0	199.5	83	SSW
	R3	31.8	0.14	34.0	−0.40	1.31	3.44	2.08	0.0	184.1	87	SSW
XR03_No_H	R1	25.7	0.30	24.2	−0.27	0.57	4.61	1.98	7.6	160.0	88	SSE
	R2	31.9	0.18	37.7	−0.41	1.16	3.24	1.87	0.0	198.8	90	SSW
	R3	32.2	0.12	33.2	−0.44	0.66	2.26	1.74	7.2	189.2	90	S
AI015_No_H	R1	25.5	0.29	23.6	0.11	0.52	3.78	1.96	4.3	162.4	86	SSE
	R2	31.7	0.15	35.8	−0.28	0.87	3.64	2.02	2.0	156.0	89	SSE
	R3	32.4	0.07	34.1	−0.42	1.13	3.03	1.91	0.0	181.9	86	SSW
AI03_No_H	R1	25.8	0.40	23.6	−0.48	1.30	3.84	2.36	0.0	167.2	85	S
	R2	31.8	0.11	35.7	−0.16	0.42	2.88	1.84	3.6	165.2	99	SSE
	R3	32.8	0.06	32.6	−0.08	0.43	3.43	2.07	6.8	193.3	87	S
XR015_Yes_H	R1	32.2	0.12	32.5	−0.50	1.35	2.96	2.02	0.0	200.8	95	SSW
	R2	29.1	0.07	44.1	−0.20	0.77	3.39	1.98	3.8	185.7	100	S
	R3	25.0	0.13	53.3	−0.02	0.79	3.53	2.16	1.1	179.9	95	S
XR03_Yes_H	R1	32.1	0.08	32.1	−0.28	1.17	4.11	2.37	0.0	172.9	100	S
	R2	28.7	0.00	45.1	−0.17	0.47	3.61	1.83	2.1	172.4	88	S
	R3	25.2	0.14	54.6	−0.28	0.72	4.26	2.44	2.9	165.8	90	S
AI015_Yes_H	R1	31.8	0.05	31.2	−0.14	0.79	3.69	2.11	2.7	178.1	87	S
	R2	24.3	0.17	59.6	0.01	0.95	3.73	2.01	0.5	163.0	90	SSE
	R3	25.0	0.14	57.3	0.72	0.82	4.47	2.16	3.0	200.6	85	SSW
AI03_Yes_H	R1	32.8	0.04	30.8	−0.14	1.31	3.13	1.93	0.0	187.5	96	S
	R2	24.7	0.17	57.2	−0.15	0.66	3.41	1.61	8.7	155.1	91	SSE
	R3	25.2	0.10	56.8	0.11	0.22	3.70	2.02	9.8	194.0	93	SSW

[a] Difference of temperature C° between two heights (3 m and 4 m). [b] Difference of Relative Humidity (RH %) between two heights (3 m and 4 m). [c] Percentage of records < 1 m s^{-1}. [d] Percentage of records between 180° ± 45°.

Table A2. Environmental conditions recorded during field trials simulating the spray applications for weed control only (nozzles are 0.25 m height above the ground).

Config & replicates		Weather parameters										
		Temperature		RH		Wind speed				Wind direction		
		Mean	Δ[a]	Mean	Δ[b]	Min	Max	Mean	Outliers[c]	Mean	Centered[d]	Prevalent direction
		°C	°C	%	%	m s^{-1}	m s^{-1}	m s^{-1}	%	° az.	%	
XR015_No_L	R1	24.8	0.10	42.8	−0.26	0.35	5.02	3.16	1.1	181.7	99	S
	R2	23.8	0.06	48.7	−0.16	0.83	4.11	2.71	1.1	184.8	100	S
	R3	22.1	0.01	57.6	0.06	0.93	3.94	2.14	2.2	199.9	92	SSW
XR03_No_L	R1	24.5	0.15	43.2	−0.29	1.51	4.64	3.15	0.0	177.0	100	S
	R2	23.7	0.07	50.8	−0.28	0.99	3.85	2.49	2.2	185.9	100	S
	R3	24.5	0.18	57.4	−0.75	0.98	3.68	2.09	1.1	161.1	80	SSE
AI015_No_L	R1	24.2	0.14	47.7	−0.43	0.69	3.88	2.25	3.3	181.8	100	S
	R2	23.3	0.04	51.9	−0.16	0.82	3.00	1.73	3.3	184.6	99	S
	R3	24.2	0.18	58.0	−0.68	0.79	4.50	2.38	2.2	162.0	89	SSE
AI03_No_L	R1	24.0	0.09	46.3	−0.36	1.46	3.75	2.60	0.0	176.9	100	S
	R2	22.8	0.02	55.2	−0.09	0.99	3.18	1.78	1.1	189.8	98	S
	R3	24.2	0.15	58.4	−0.64	0.43	3.43	2.07	6.5	167.8	95	SSE
XR015_Yes_L	R1	24.4	0.16	60.7	−0.80	1.48	5.10	3.19	0.0	159.7	97	SSE
	R2	23.8	0.14	59.5	−0.54	1.04	3.35	2.00	0.0	170.3	95	S
	R3	23.6	0.09	59.6	−0.46	1.15	2.97	2.08	0.0	157.3	99	SSE
XR03_Yes_L	R1	24.2	0.13	60.0	−0.66	0.89	4.09	2.55	1.1	151.6	83	SSE
	R2	23.9	0.15	58.8	−0.69	0.87	2.88	1.81	4.3	178.1	96	S
	R3	23.7	0.03	59.9	−0.39	1.18	3.93	1.97	0.0	160.3	89	SSE
AI015_Yes_L	R1	23.9	0.19	62.5	−0.86	0.67	3.21	1.97	4.3	171.3	98	SSE
	R2	23.8	0.17	59.0	−0.72	0.95	3.02	2.08	1.1	185.3	99	SSE
	R3	23.3	0.06	62.4	−0.35	1.16	4.08	2.73	0.0	153.8	100	SSE
AI03_Yes_L	R1	23.9	0.13	59.7	−0.62	0.75	3.41	2.21	1.1	200.6	98	SSW
	R2	23.8	0.11	59.0	−0.66	1.21	3.40	2.17	0.0	190.8	100	SSW
	R3	23.1	0.03	63.1	−0.29	1.10	3.42	1.92	0.0	158.9	87	SSE
AI015_Full_L	R1	25.5	0.32	29.7	0.37	1.21	3.30	2.30	0.0	189.8	100	SSW
	R2	25.9	0.42	28.3	−0.13	1.02	4.15	3.00	0.0	160.5	93	SSE
	R3	24.7	0.40	58.1	−0.48	0.79	3.14	2.07	6.5	163.1	83	SSE
AI03_Full_L	R1	25.9	0.21	29.5	−0.21	1.33	3.90	2.41	0.0	178.2	98	S
	R2	26.3	0.41	29.6	0.77	1.61	2.69	2.16	0.0	164.1	96	SSE
	R3	25.0	0.34	54.6	−0.80	1.18	3.29	2.20	0.0	183.9	95	SSW

[a] Difference of temperature C° between two heights (3 m and 4 m). [b] Difference of Relative Humidity (RH %) between two heights (3 m and 4 m). [c] Percentage of records < 1 m s^{-1}. [d] Percentage of records between 180° ± 45°.

Table A3. Environmental conditions recorded during field trials aimed to evaluate the contribution of each sprayed row to the total spray drift generation during the spray applications for the weed control and suckering at the same time (nozzles are 0.50 m height above the ground).

Config & Replicates		Row/s[e]	Weather Parameters										
			Temperature		RH		Wind Speed				Wind Direction		
			Mean	Δ [a]	Mean	Δ [b]	Min	Max	Mean	Outliers [c]	Mean	Centered [d]	Prevalent Direction
			°C	°C	%	%	m s⁻¹	m s⁻¹	m s⁻¹	%	° az.	%	
XR015_No_H	R1	1	15.4	0.33	52.5	−0.52	1.18	3.20	2.43	0.0	199.4	98	SSW
		2	15.2	0.31	54.8	−0.28	0.88	2.68	1.70	3.7	174.2	86	S
		3	15.7	0.31	53.6	−0.08	1.35	3.08	2.28	0.0	156.0	91	SSE
		4	16.2	0.21	51.1	−0.18	1.43	4.02	2.46	0.0	197.8	93	SSW
		5 & 6	16.5	0.21	50.0	0.07	1.59	3.98	2.40	0.0	195.6	95	SSW
		7, 8 & 9	16.7	0.23	48.4	−0.43	1.29	4.70	2.57	0.0	190.9	96	S
	R2	1	18.8	0.12	47.1	−0.05	1.33	4.25	2.45	0.0	176.3	92	S
		2	18.9	0.09	43.8	0.52	1.26	4.62	2.36	0.0	176.3	100	S
		3	19.5	0.10	45.0	0.28	0.89	4.01	2.45	2.9	200.0	90	SSW
		4	19.1	0.22	41.0	−0.09	0.78	5.12	2.54	2.0	177.5	88	S
		5 & 6	18.8	0.18	42.9	0.39	1.40	4.50	2.77	0.0	167.5	100	S
		7, 8 & 9	19.5	0.11	38.6	0.53	0.97	4.31	2.78	1.1	177.2	99	SSE
	R3	1	16.8	0.49	52.3	−0.70	0.98	4.94	2.92	0.6	180.5	100	S
		2	16.2	0.31	54.2	−0.07	1.00	4.04	2.39	0.0	166.6	89	S
		3	16.3	0.31	53.0	−0.65	0.96	4.51	2.65	2.4	175.0	87	S
		4	16.6	0.34	53.6	−0.29	1.78	4.88	3.44	0.0	176.1	99	S
		5 & 6	16.4	0.31	54.4	−0.49	1.27	5.40	3.19	0.0	180.9	97	S
		7, 8 & 9	16.5	0.31	53.7	−0.40	1.07	4.46	2.78	0.0	161.4	92	SSE
XR03_No_H	R1	1	17.0	0.23	47.0	−0.33	1.43	3.16	2.05	0.0	191.3	91	S
		2	17.3	0.29	52.0	−0.15	1.25	4.80	2.90	0.0	184.5	100	S
		3	17.5	0.20	50.6	−0.13	1.36	4.08	2.67	0.0	161.0	92	S
		4	17.7	0.20	49.5	−0.24	1.78	4.62	2.95	0.0	168.8	98	S
		5 & 6	18.1	0.22	48.0	−0.32	1.76	5.59	3.30	0.0	165.8	85	S
		7, 8 & 9	18.2	0.20	48.6	−0.18	1.78	4.51	2.95	0.0	171.0	93	S
	R2	1	19.7	0.12	41.9	1.07	0.78	4.27	2.38	2.3	176.2	88	SSE
		2	19.7	0.04	36.2	0.58	1.42	3.97	2.65	0.0	176.5	99	S
		3	19.9	0.01	34.0	−0.04	1.59	4.04	2.57	0.0	156.8	84	SSE
		4	20.1	0.02	38.8	1.01	0.89	3.46	2.45	3.0	169.8	83	SSE
		5 & 6	20.4	0.16	31.5	0.36	0.78	3.98	2.38	3.4	161.4	86	SSE
		7, 8 & 9	20.5	0.11	34.4	0.85	1.60	5.15	2.81	0.0	189.9	99	S
	R3	1	17.0	0.36	52.5	−0.45	1.63	4.95	2.94	0.0	173.4	87	S
		2	17.2	0.38	52.0	−0.62	0.90	3.99	2.47	0.9	162.8	90	SSE
		3	17.0	0.27	53.0	−0.36	1.39	4.79	3.00	0.0	174.6	96	S
		4	17.5	0.26	53.7	−0.22	1.92	5.10	3.17	0.0	202.6	85	SSW
		5 & 6	17.3	0.32	54.9	−0.26	0.85	5.10	3.07	1.4	198.0	97	SSW
		7, 8 & 9	17.2	0.38	56.3	−0.55	1.90	4.07	2.80	0.0	192.1	98	S

[a] Difference of temperature C° between two heights (3 m and 4 m). [b] Difference of Relative Humidity (RH %) between two heights (3 m and 4 m). [c] Percentage of records < 1 m s^{-1}. [d] Percentage of records between 180° ± 45°. [e] Row/s applied separately.

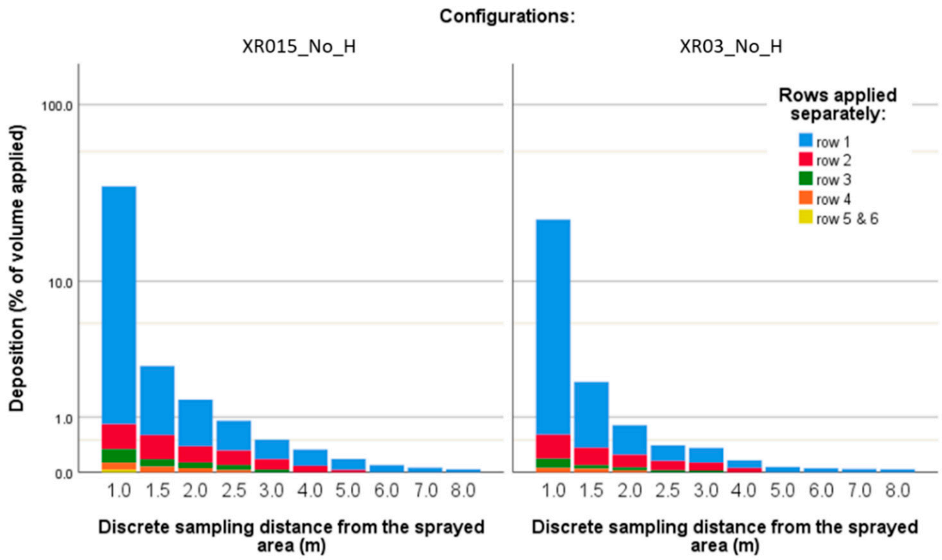

Figure A1. Contribution of each row/s applied separately to the total spray drift deposits (% of applied volume), represented by stacked bars for each sampled downwind area distance. Row/s applied separately: row 1, row 2, row 3, row 4 and rows 5 and 6. Configurations: conventional nozzles (XR015 and XR03), boom not-shielded (No) and boom 0.50 m height above the ground (H). (Field trials conducted in trellised vineyard cv. Barbera, Piedmont region, Italy, spring 2018).

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