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Advanced spraying systems to improve pesticide saving and reduce spray drift for apple orchards

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Abstract

New spraying systems embedded with different technologies have been developed for pesticide application in 3D crops. However, while applied to specific tree crops, the potential spray drift mitigation for advanced spraying systems needs to be classified due to the great variability of spray equipment and canopy structure. Here a precision spraying system was developed and compared with two typical spraying systems (conventional system, optimized system following the best management practices) for the applied volume/pesticide and spray drift in an apple orchard at two growth stages following the ISO22866-2005 protocol. Compared to the conventional system, the other two advanced systems significantly reduced the amount of ground drift (>60%) at most of the sampling distances at the growth stage BBCH 72, while the precision system demonstrated the best drift mitigation (57.3% reduction) at the stage BBCH 99. For the airborne drift, a remarkable drift reduction was also achieved with the two advanced systems. Specifically, the optimized spraying system exhibited a drift reduction by approximately 80% at the first growth stage, and the precision application demonstrated its considerable advantages in minimizing drift loss for the sparse canopy at the stage BBCH 99. Moreover, the saving of applied volume/pesticide was achieved by 12% with the optimized system and 43% with the precision system. This study revealed the necessity and prospect of the advanced spraying systems to reduce the environmental contamination and health risk from pesticide applications in fruit tree production.

Keywords Spray drift mitigation · Precision spraying · Dose adjustment · Pesticide reduction · Orchard sprayer

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Introduction

Crop protection is an essential process in the crop management, which can significantly affect crop yield and quality. Despite biological agents have been increasingly used, chemical pesticide application is still the main method to control weeds, pests, and diseases. However, in practical pesticide applications, due to growers constantly lack of knowledge and training for improving and optimizing the spray application, a large portion of the applied plant protection products (PPPs), being 30–50%, is lost to non-target sites because of run-off and spray drift loss (Balsari et al., 2002). Spray drift is defined as "the quantity of plant protection product that is carried out of the sprayed area (treated) by the action of air currents during the application process"(ISO, 2005).

The inevitable loss of pesticide during crop management, especially the spray drift, has caused several undesirable consequences: high risk of exposure and inhalation to nearby livestock and residents (Feltracco et al., 2022), environmental contamination of surface water and other living organisms (Carazo-Rojas et al., 2018; Tauchnitz et al., 2020), unintentional damage to nearby sensitive crops and plants (Marrs & Frost, 1997; Marrs et al., 1989), and excessive toxic residues in agricultural food and products (Damalas and Eleftherohorinos 2011).

As there is growing social attention and concern on the environmental contamination and health risk generated from agrochemical applications, two pesticide reduction targets have been proposed as part of the Farm to Fork Strategy in an European Green Deal: reducing the use and risk of both chemical pesticides and the more hazardous pesticides by 50% by 2030 (European Commission, 2020). These ambitious objectives have been addressed in different aspects with various strategies: developing new equipment and technologies to optimize spray application, improving the educational skills of end-users, and increasing the degree of adoption of new technologies and precision farming.

The spraying system, which generates and transports spray droplets with active ingredients to the intended vegetation, has a significant impact on the application efficiency and effectiveness. Currently, there are three main typical spraying systems used for tree crops in Europe: conventional system, optimized system following the best management practices (BMPs), and precision system. The conventional system is generally implemented with conventional airblast sprayers, performed with a high airflow/pesticide volume rate without adequate calibration and adjustments to match the target crop structure. This spraying system is commonly used by growers and delivers excessive pesticide with a high risk of runoff and drift loss (Balsari et al., 2002; Salyani et al., 2013). For the optimized spraying system following the BMPs, the sprayer is completely and fully adjusted and optimized with a comprehensive consideration of specific application technology, the target tree crop, and environmental conditions (Balsari et al., 2011). The optimization greatly mitigates the spray drift compared with the conventional system (Doruchowski et al., 2009; Balsari et al., 2002). Benefitted from the development and improvement of sensing technologies, the precision spraying system has been developed and implemented. This advanced system can adjust the spray volume and/or air flow rate precisely in real-time based on the obtained comprehensive information on the target vegetation volume, meteorological conditions, and pest and disease infections to achieve site-specific management (Balsari et al., 2008; Chen et al., 2013; Escolà et al., 2013; Gil et al., 2013; Khot et al., 2012). The precision spraying system shows a 34–88% potential savings of spray volume compared with the conventional system while still achieving similar or even better deposition quality in the target vegetation (Chen et al., 2011; Campos et al., 2019; Llorens et al., 2010; Manandhar et al., 2020).

In addition, the PPP dose expression, directly related to the total pesticide amount applied by the spraying systems, should be prioritized in practice. It is generally agreed that the dose expression for 3D crops should comply with the treated foliage area instead of the ground area commonly used in the conventional system. As the dose expression based on the ground area ignores the target vegetation volume, it is controversial to the PPP reduction pursued by the European Green Deal. Due to the complicated conditions of dose expression among European zones/countries, harmonized procedures are suggested to explore an appropriate solution aligned with specific crops, products, and equipment used for different spraying circumstances (Gil et al., 2019; Garcerá et al., 2021). Generally, for those recently defined as "specialty crops" (orchards, vineyards, olive trees, etc.) with complex and heterogeneous canopy structures, two alternative dose expression models, namely Leaf Wall Area (LWA) and Tree Row Volume (TRV), have been recommended by the European Plant Protection Organization (EPPO, 2021). Once the basic dose expression is determined, the potential dose adjustment can be implemented to determine the optimal application rate and the amount of applied pesticide according to the specific circumstances (Gil et al., 2019).

Although new advanced spraying systems integrated with different technologies are encouraged for orchard applications, their advantage and characteristics need to be demonstrated for specific tree crops that have great variability in vegetation structures. On the other hand, adequate field tests are necessary to quantify and classify the potential improvement in spray drift for the advanced spraying systems such as the precision system and optimized system as mentioned above. Thus, the goal of this research was to document the benefits of the two advanced spraying systems combined with appropriate dose adjustment technologies for apple trees through field tests. The specific objectives were: (a) to validate the effectiveness of the developed precision spraying system; (b) to evaluate spray drift potentials of three spraying systems at two growth stages following the protocol of ISO22866-2005; (c) to quantify drift reduction of the two advanced spraying system compared with the conventional system; and (d) to evaluate the potential saving of PPPs with the two advanced systems.

Materials and methods

Field test location and crop characteristics

Field tests were arranged on commercial apple tree plots (Royal Gala) of approximately 1 ha in Épila (Zaragoza, Spain) (41°33′5.1″ N, 1°13′36.6″ W). The apple plantation, trained with a fruit wall system, consisted of a layout of 4.15 m (row distance) × 1.31 m (tree distance), resulting in 1839 trees per hectare. The trials were performed at two crop stages: BBCH72 (fruit size up to 20 mm) and BBCH99 (harvested product). Prior to the experiments, 20 apple trees were selected randomly to characterize the canopy structures by manual measurements. The main canopy parameters are shown in Table 1. Little variations in the canopy geometry size were observed at two growth stages, with a TRV value of around 5000 m^3 ha^{-1}. However, the leaf area density (LAD) at BBCH 72 was 2.7 times that at BBCH 99, showing a remarkable difference.

Table 1 Canopy parameters at two selected growth stages during the trials in 2021.

Date	BBCH Code	Row distance (m)	Canopy height (m)	Canopy width (m)	TRV (m^3 ha^{-1})	LWA (m^2 ha^{-1})	LAD (m^2 m^{-3})
May 4-5th	72	4.15	2.00±0.19*	0.89±0.11	4289	9639	4.65
November 9-10th	99	4.15	2.06±0.33	1.01±0.10	5013	9927	1.73

* Mean±standard deviation

Fig. 1 Three air-assisted spraying systems used for the field trials: **a**) Hardi tower sprayer, **b**) Fede axial-fan sprayer, **c**) Fede tower sprayer.

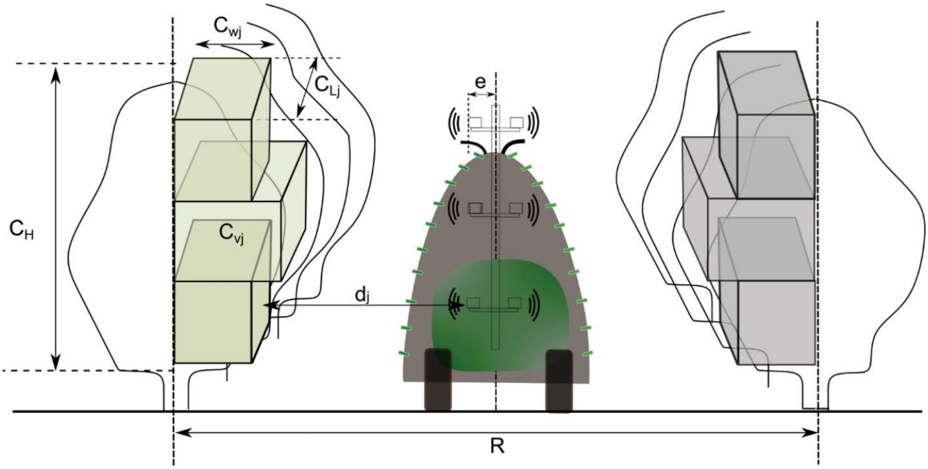

Fig. 2 Working principle of the developed precision spraying system integrated on the Fede tower sprayer. C_H is the total canopy height; C_{wj} is the canopy width for section j; C_{Lj} is the slice canopy length at section j; C_{vj} is the canopy volume to be treated per unit time at section j; d_j is the distance measured between the ultrasonic sensor and the outer surface of the vegetation; e is the distance between the sensor and the central axis of the sprayer; and R is the row space.

Sprayers used for tests

Three typical orchard air-assisted sprayers were selected for the comparative tests. The first machine was a Hardi tower sprayer (Ilemo Hardi, S.A.U., Lleida, Spain) with a 900 mm axial fan which pulled the air from the rear of the sprayer (Fig. 1a). On each side, there were 9 conventional hollow-cone nozzles (Albuz ATR Orange/Red) distributed on a vertical manifold along the air outlet. The second one was a Fede axial-fan sprayer (FUTUR, Pulverizadores Fede, S.L., Cheste, Valencia, Spain) with 10 hollow-cone nozzles (Albuz TVI Blue nozzle) positioned on an arc-shaped manifold (Fig. 1b). The third machine was a Fede tower sprayer (Inverter Qi 9.0, Pulverizadores Fede, S.L., Cheste, Valencia, Spain) equipped with an axial fan and 10 flat-fan air-injection nozzles (Lechler IDK90-015) evenly distributed on an arc shape manifold along the tower-shaped air outlet on each side (Fig. 1c). The three sprayers were all equipped with a 2000 L tank and trailed by a tractor.

Working principle of the precision spraying system

Using the Fede axial-fan sprayer (Fig. 1c) as a base, a precision spraying system implemented with the Tree Row Volume (TRV) model (Rüegg et al., 1999) was developed to adjust the spray application rate to adapt to variations in canopy volume along the tree row. The main principle of the whole system is shown in Fig. 2, based on the ideas proposed in previous research (Escolà et al., 2013; Gil et al., 2007, 2013). In order to characterize the whole tree, the wall shape canopy was equally divided into three sections across the tree height (Top, Middle, and Bottom), and the canopy volume in each section was estimated as a cube. Three ultrasonic sensors (Pepperl+Fuchs, Mannheim, Germany) were mounted at each side of the sprayer to estimate the canopy volume treated per unit time. In each section, the ultrasonic sensor measured the distance between itself and the outer surface of the vegetation in real-time. This distance was recorded and then transformed into the average canopy width, combined with other known configuration parameters, resulting in the calculation of the corresponding canopy volume to be sprayed per unit time as expressed in Eq. 1:

$$C_{vj} = \frac{[R/2 - d_j - \boldsymbol{e}] \times C_H/3 \times v \times 1000}{60} \tag{1}$$

where C_{vj} is the canopy volume treated per unit time (m^3 min^{-1}), R is the row space, C_H is the whole canopy height (m), v is the tractor forward speed (km h^{-1}), d_j is the distance between the sensor and the outer surface of the vegetation (m), and e is the distance between the sensor and the central axis of the sprayer (m).

According to the canopy characteristics, an application coefficient (i) was determined (Escolà et al., 2013; Gil et al., 2013) to calculate the application volume rate needed from nozzles for the detected canopy volume of each section with Eq. 2:

$$q_j = C_{vj} \times i \tag{2}$$

where q_j is the output volume rate (L min^{-1}) needed for matching the canopy volume at section j, C_{vj} is canopy volume treated per unit time (m^3 min^{-1}), and i is application coefficient representing the appropriate amount of spray solution needed to cover a unit canopy volume (L m^{-3}).

Three separate spray sections (top, middle, and bottom), each containing 3, 4, and 3 nozzles, respectively, were implemented on each side of the Fede tower sprayer, to discharge the spray volume with calculated nozzle flow rate to the corresponding canopy sections. The real-time adjustment of the flow rate was achieved by a proportional motor valve (Bürkert, Ingelfingen, Germany), based on the calibration curves between the input voltage to the valve and the output spray pressure/flow rate obtained from preliminary tests. When no vegetation was detected, the valve was shutoff without the spray activation. In addition, for canopy width below 40 cm, a constant spray pressure of 4 bar was maintained to guarantee a minimum spray deposit. The upper limit of spray pressure was set as 14 bar for all spray sections considering the maximum working pressure of the proportional valve. With this design, the pressure adjustment range of 4–14 bar corresponded to canopy widths of 40–65 cm and 40–85 cm, for the top and bottom spray section containing three nozzles (top and bottom) and the middle section with four nozzles, respectively. When the tree vegetation detected more than the set maximum canopy width, the spray pressure of each section was maintained at 14 bar.

For each spray section, the actual working pressure was detected and recorded by the equipped pressure sensors (Ifm, Essen, Germany) on the spray line. The operation of the whole system was under the control of a Raspberry Pi 4B module (Raspberry Pi Foundation, London, UK). Besides, all the key information related to the whole spray process was stored in real-time, which could be exported in the form of an excel file for further processing and analysis.

Working parameters of three spraying systems

The Hardi high-tower sprayer was used as a conventional spraying system. Before the tests, it was calibrated following the spray practice normally used in apple orchards. The same spray application rate of 883 L ha^{-1} was applied at the two growth stages as the reference treatment, following the practices commonly used by farmers. In contrast, the Fede axial-fan sprayer was used as the optimized spraying system and it was fully calibrated and adjusted to optimize air and liquid distribution following the best management practices (BMP) (Balsari et al., 2011). Besides, the air induction nozzles were used on the sprayer to mitigate the drift risk. For its dose adjustment, an application coefficient of 0.16 L m^{-3} was applied at both growth stages (Garcerá et al., 2020; Miranda-Fuentes et al., 2016; Silva Junior et al., 2016), resulting in a volume rate of 775 L ha^{-1} as the TRV was about 5000 m^3 ha^{-1}. For the newly developed precision spraying system, the anti-drift nozzles were used and adequate adjustment following the BMPs was also implemented. An application coefficient of 0.1 L m^{-3} was set for the detected canopy volume in the precision system (Chen et al., 2012). Based on the accumulation of volume of each spraying section at each slice time/zone during the whole spraying process, the average volume rate of the precision spraying system was calculated: 517 L ha^{-1} at BBCH 72 and 492 L ha^{-1} at BBCH 99. The detailed working parameters of each system are shown in Table 2.

Experimental design

Lay out of experimental site

The experiment plot consisted of a directly sprayed area and a downwind sampling zone at the edge of the sprayed area (Fig. 3a). According to the ISO 22866 (ISO, 2005), five outermost downwind tree rows with a row space of 4.15 m were selected to form the sprayed block, resulting in a 20.75 spraying width (Fig. 3b). The track length from one end of each

Table 2 Working parameters of conventional, optimized and precision spraying systems used for the tests at growth stages BBCH 72 and BBCH 99.

Spraying system	Parameters					
	Volume rate (L ha^{-1})	Velocity (km h^{-1})	Nozzle (quantity)	Nozzle type	Pressure (bar)	Droplet size*
Conventional system with Hardi tower sprayer	883 (BBCH72 and 99)	5.5	10+8	Albuz ATR Orange/Red	14	VF
Optimized system with Fede axial-fan sprayer	775 (BBCH72 and 99)	5.0	10	Albuz TVI Blue	15	VC
Precision system with Fede tower sprayer (PRE)	517 (BBCH72) 492(BBCH99)	5.0	20	Lechler IDK90-015	Variable (4–14)	VC

* Following the British Crop Protection Council (BCPC) droplet size classification. VF, very fine; F, fine; M, medium; C, coarse; VC, very Coarse

tree row was about 50 m (twice the largest downwind sampling distance). In total, an area of 0.1 ha block was sprayed for each test.

The drift sampling zone was a bare soil ground without obstacles and vegetation downwind the edge of the sprayed area. The spray drift zone started from the edge of the sprayed area, a half-row space from the outermost tree row. Spray drift samples were collected in two aspects: ground sediment spray drift and airborne spray drift. As shown in Fig. 3b, a sample array consisting of 9 lines in the range from 0 to 20 m, parallel to the tree row, was arranged for sampling the ground drift. Seven petri dishes with 140 mm diameter were placed in each horizontal line, resulting in a sampling surface of 1077.6 cm^2 at each distance, which satisfied the requirement of the protocol (ISO, 2005). The first five sampling rows were arranged with the interval of 1 m in the range from 1 to 5 m, and the other four rows were placed at the position of 7.5, 10, 15, and 20 m from the edge of the sprayed zone, respectively.

For sampling the airborne spray drift at locations of 5 and 10 m from the edge of the sprayed area, two vertical poles with a height of more than 6 m were placed to support the sampling collectors. 12 filter papers (8×3 cm) as samplers were placed on each pole with an interval of 0.5 m in the range from 0.5 to 6 m above the ground, respectively, to measure vertical distributions of the airborne drift.

Meteorological conditions

In order to monitor and record the meteorological information during the whole spraying process of each test, a weather station (CR800, Campbell Scientific Inc., Logan, UT, USA) was placed in the middle of the sampling area (Fig. 3b). The station was equipped with a 2D ultrasonic anemometer WindSonic 232 (Campbell Scientific Inc.) at the height of 3 m above the ground to measure wind speed (range: 0–60 m s^{-1}, resolution: 0.01 m s^{-1}) and direction (range: 0–359°, resolution: 1°) and a CS215 probe (Campbell Scientific Inc.) to measure air temperature and humidity.

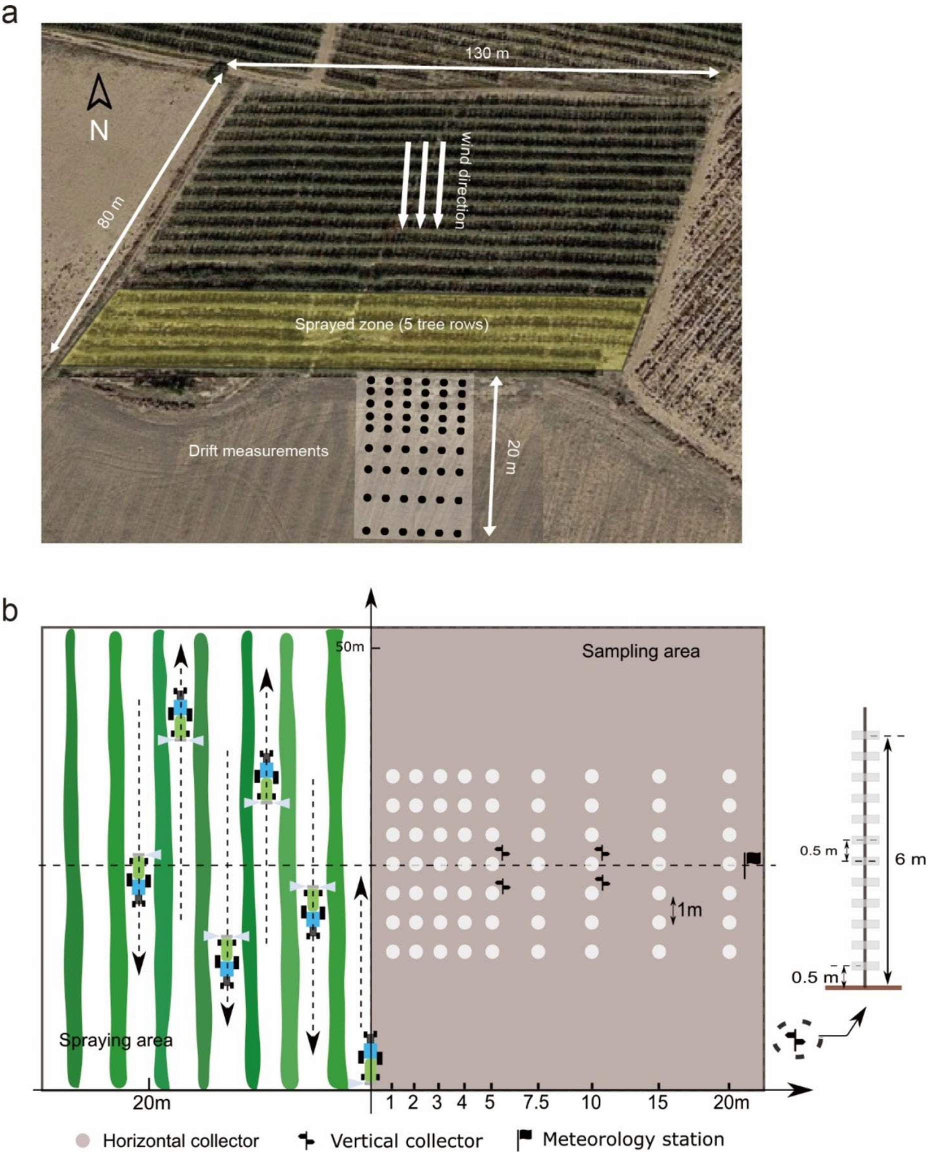

Fig. 3 **(a)** Experimental plot in an apple orchard used for drift trails. **(b)** Layout of drift trials with six spray paths according to the ISO22866 (ISO, 2005).

Implementation of the test

Following ISO 24253-2 (ISO, 2015), the E102 Tartrazine yellow dye was selected as a drift tracer because of its harmless to the environment. Prior to the field test, the applied spray solution was made at a concentration of 5 g L^{-1}, and was agitated for half an hour to ensure the uniformity and consistency of spray mixes. A team of seven trained operators implemented all the tests. First, all the sampling collectors were placed at the specified location and the tractor driver was in a state of preparation, and then an operator checked the weather station to find a favorable time window. Once the weather condition was in line with the standards ISO 22866 (ISO, 2005), the spraying application with six tracks was implemented: one side spraying for the first and last paths and double side spraying for the other four tracks (Fig. 3b). Prior to the spraying, a Petri dish as a blank sample placed in the middle of the sprayed area was collected. Besides, the start and end times of each spray track were recorded. In addition, a sample of the spray mixture from the sprayer tank was collected before and after each test, to determine the actual concentration of the spray tracer. After the spraying process was completed, Petri dishes were covered and filter papers were removed from support poles and placed in labeled ziplock bags, and all the samples were stored in a dark and dry box to maintain stability of the collected fluorescence dye for later analysis. After the canopy foliage was completely dry, the same process was repeated for next treatments, and each treatment was repeated 3 times.

Quantification of spray drift

All the drift samples were analyzed in the laboratory to quantify the drift deposition. According to the deposit amount, distilled water ranging from 20 to 200 ml was added to the sample Petri dishes, and were shaken for 5 min to fully dissolve the tracer. The sampling mixture was then extracted and discharged into a 4 mL cuvette using a pipette. The spray mixture in the cuvette was analyzed with a spectrophotometer (Synergy HTX, BioTek Instruments, Inc., Winooski, VT, USA) to obtain the corresponding absorbance value. The filter paper samples collected from the vertical poles were also analyzed following the same procedures.

According to ISO 22866 (ISO, 2005), the absolute drift deposition per unit area (μL cm^{-2}) in each artificial target was calculated following Eq. 3,

$$\beta_{dep} = \frac{(\rho_{samp} - \rho_{bla}) \times V_{dil} \times 10^6}{\rho_{tank} \times S_{col}} \tag{3}$$

where β_{dep} is amount of deposits per unit area (μL cm^{-2}), ρ_{samp} is the fluorimeter absorbance value of the sample, ρ_{bla} is the absorbance value of blank samples, V_{dil} is the volume of the dilution liquid used to dissolve the tracer (L), ρ_{tank} is the absorbance value of the tank spray sample, and S_{col} is the projected area of the collector for sampling the spray drift (cm^2).

This absolute drift deposition per unit area was then transformed into the percentage value of drift potentials corresponding to the spray application rate of each treatment using Eq. 4,

$$DP = \frac{\beta_{dep} \times 10^4}{V_S} \tag{4}$$

where DP is the spray drift potential (%), and V_s is the spray application rate (L ha^{-1}).

Drift curves were obtained after the drift deposition at each sampling point was determined. The overall drift value within the whole sampling area was defined as the surface area below the drift curve calculated by the numerical integration (Grella et al., 2017, 2019).

Furthermore, the ratio of overall drift value to sampling distance/height was defined as drift value per unit sampling distance/height.

The drift reduction potential was then calculated to quantify the drift reduction efficiency of the two advanced treatments systems compared with the conventional system. The drift reduction (%) of treatments for the ground drift at each sampling distance or for the airborne drift at each sampling height was calculated using the Eq. 5 (Nuyttens et al., 2007),

$$DRP = \frac{DP_R - DP_{LD}}{DP_R} \tag{5}$$

where DRP is the drift reduction potential (%), DP_R is the spray drift value from the conventional system, and DP_{LD} is the spray drift value from the optimized or precision system.

The overall drift reduction potential for the whole sampling area was obtained by the numerical integration of the drift reduction potential in each sample distance or height for ground drift and airborne drift, respectively (Nuyttens et al., 2007; Grella et al., 2017a; Grella et al., 2019).

Statistical analysis

IBM SPSS Statistics version 22 (IBM, Armonk, NY, USA) was used to analyze the data from the field trials. The detected extreme outliers were first removed to process the further statistical analysis. Raw data obtained from field tests were grouped with each sampling distance for ground drift, with each sampling height for airborne drift. The one-way analysis of variance (ANOVA) combined with the Student-Newman-Keules test was adopted to identify the difference in ground drift value in each sampling distance between the three treatments. Prior to the AVOVA analysis, the normality for each group was checked with Shapiro-Wilk test, and homogeneity of variance was detected with Levene's test. If the raw data was far from meeting the conditions for AVOVA analysis, the transform $\sqrt{x}$ was used to improve the data homogeneity. The same model and similar process were used to analyze the effect of different treatments on the airborne drift per unit sampling height. A p-value of below 0.05 was selected as a significant difference.

Results and discussion

Weather conditions during the trials

The weather conditions recorded for all tests are shown in Table 3. Except for one test (the third repetition of the conventional treatment applied at BBCH99), the average wind velocities (>1 ms^{-1}) satisfied the requirement of the ISO 22866 (ISO, 2005). In most cases, the average wind directions were in the range of 60 to 120° relative to the tree row direction. The ambient temperature for all the tests was in the range of 18.3 to 21.9 °C and the relative humidity was in the range of 35.8–49.6%. In addition, all the parameters related to the weather condition during the field tests generally met the requirements of ISO 22866 (ISO, 2005).

Table 3 Weather conditions during the tests.

Treatment & Replication[a]		Weather parameters									
		Temperature (°C)	RH (%)	Wind speed (m s^{-1})				Wind Direction (°)			
		Mean (5–35 °C)	Mean	Min	Max	Mean (>1 m s^{-1})	Outliers[b] (<10%)	Min	Max	Mean (90°± 30°)	Outliers[c] (<30%)
BBCH 72											
REF	1	20.52	37.60	0.22	2.96	1.26	32.1	6	358	127.77	45.6
	2	21.43	36.85	0.06	3.08	1.28	35.3	1	357	131.25	54.2
	3	21.91	36.22	0.11	3.07	1.27	38.9	36	278	157.15	64.0
BMP	1	19.16	43.08	0.57	5.71	1.91	11.8	0	353	133.95	36.9
	2	21.09	39.11	0.47	2.71	1.49	20.3	37	162	103.31	22.5
	3	21.90	35.78	0.01	2.63	1.03	48.0	0	359	154.93	83.1
VRA	1	18.34	49.62	0.42	4.46	2.08	7.6	1	359	61.64	32.3
	2	18.94	49.21	0.19	5.80	2.22	4.7	23	359	80.46	14.0
	3	19.56	46.00	0.69	5.16	1.82	6.4	42	145	93.81	4.6
BBCH 99											
REF	1	10.80	48.11	0.17	2.95	1.12	43.2	2	358	48.46	65.1
	2	8.91	52.14	0.42	1.78	1.01	50.2	85	143	121.20	4.9
	3	8.43	90.68	0.02	1.03	0.69	60.5	0	359	217.38	71.4
BMP	1	10.68	57.69	0.61	2.52	1.30	22.5	49	137	93.68	0.8
	2	11.36	56.36	0.24	3.04	1.53	14.6	5	129	66.70	16.2
	3	11.98	53.93	0.23	3.85	1.51	18.8	31	348	91.49	5.0
VRA	1	12.31	52.06	0.19	4.14	1.57	14.0	5	139	85.51	4.0
	2	13.11	49.83	0.29	2.58	1.45	22.2	0	190	50.50	41.2
	3	13.64	48.25	0.19	2.89	1.36	18.4	3	139	71.71	28.5

[a] REF – Conventional system with Hardi tower sprayer, BMP – Optimized system with Fede axial-fan sprayer, VRA – Precise system with Fede tower sprayer, [b] Percentage of records < 1 m s^{-1}, [c] Percentage of records not in the range of 90° ± 45°

Validation of the precise spraying system

The relationship between the canopy width detected and the corresponding actual spray pressure for each spray section at two growth stages is shown in Fig. 4a and b. In general, the results were in line with the intended variable rate strategy, and only a very small portion of the sampling points deviated from the intended values. It should be noted that the points with a canopy width of 20 cm in the figure included all locations with a canopy width below 20 cm. The points located on the vertical axis mainly resulted from the end of the spraying process for each tree row, where no trees presented and there was a delay to completely shut off the proportional valve, resulting in a detected pressure in the range of 4 to 6 bar. Similarly, the points close to the horizontal axis were mainly generated from the beginning of the spraying process, requiring additional response time to reach the intended spray pressure. The range of linear variation in spray pressure (4–14 bar) corresponded to canopy width ranges of 40 to 65 cm, and 40 to 80 cm, for the spray section in the top and bottom portions, and the middle portion, respectively.

Figure 4c and d show the changes of application volume rate of the three spraying systems on the left side along the row length in one test. As expected, the conventional system without considering the vegetation area gave the highest and constant application rate of

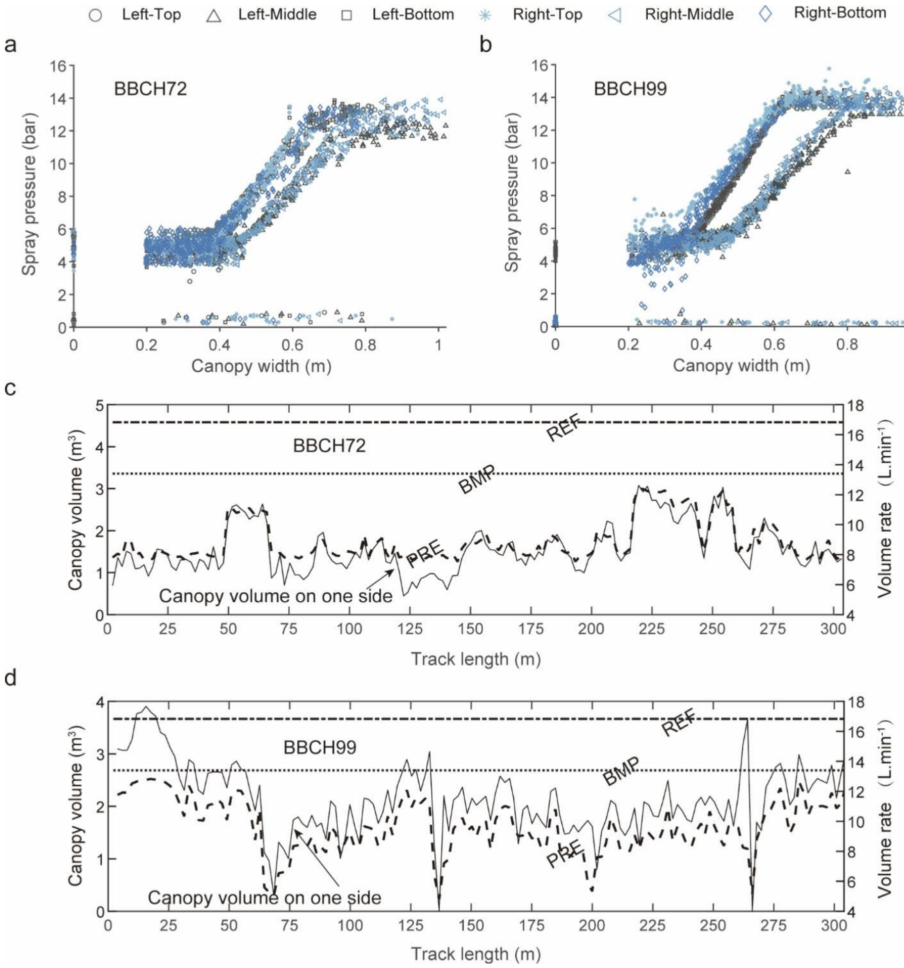

Fig. 4 Relationship between the spray pressure and detected canopy width for each spray section at BBCH72 (**a**) and BBCH99 (**b**). Canopy volume and corresponding spray output rate of the three spraying systems (REF-Conventional system, BMP-Optimized system, PRE-Precision system) on one side following the variability of the canopy volume at BBCH72 (**c**) and BBCH99 (**d**).

16.8 L min^{-1}. For the optimized spraying system following the BMPs combined with the dose adjustment according to the overall TRV of the tested apple orchard, it achieved a constant output application rate of 13.4 L min^{-1} at two growth stages, which resulted in a 12% saving of applied volume compared with the conventional system. For the precision spraying system, the output volume rate was automatically adjusted in real-time following the change of canopy volume along the crop line. Especially, when remarkable changes occurred in vegetation volume, the system exhibited a timely response with a quick adjustment of the output volume rate. The precision spraying system with variable volume rate capability enabled spray application consistency to avoid potential over/under sprays for different canopy volumes compared with constant rate applications. According to the accumulation of applied volume in both sides, the precision spraying system achieved savings of nearly 43% for each growth stage compared with the conventional system. As the same pesticide concentration was applied for the three treatments, significant pesticide savings were achieved with both advanced spraying systems.

Ground spray drift

The ground drift from the three spraying systems measured at different sampling distances at BBCH72 is shown in Fig. 5a and b. For the drift percentage (Fig. 5a), the conventional system showed a stepped decline at the first four sampling distances, with values close to 30% and 25% for the 1–2 m and 3–4 m sampling zones, respectively. This unusual change of drift deposition from the conventional system within a certain sampling area was also

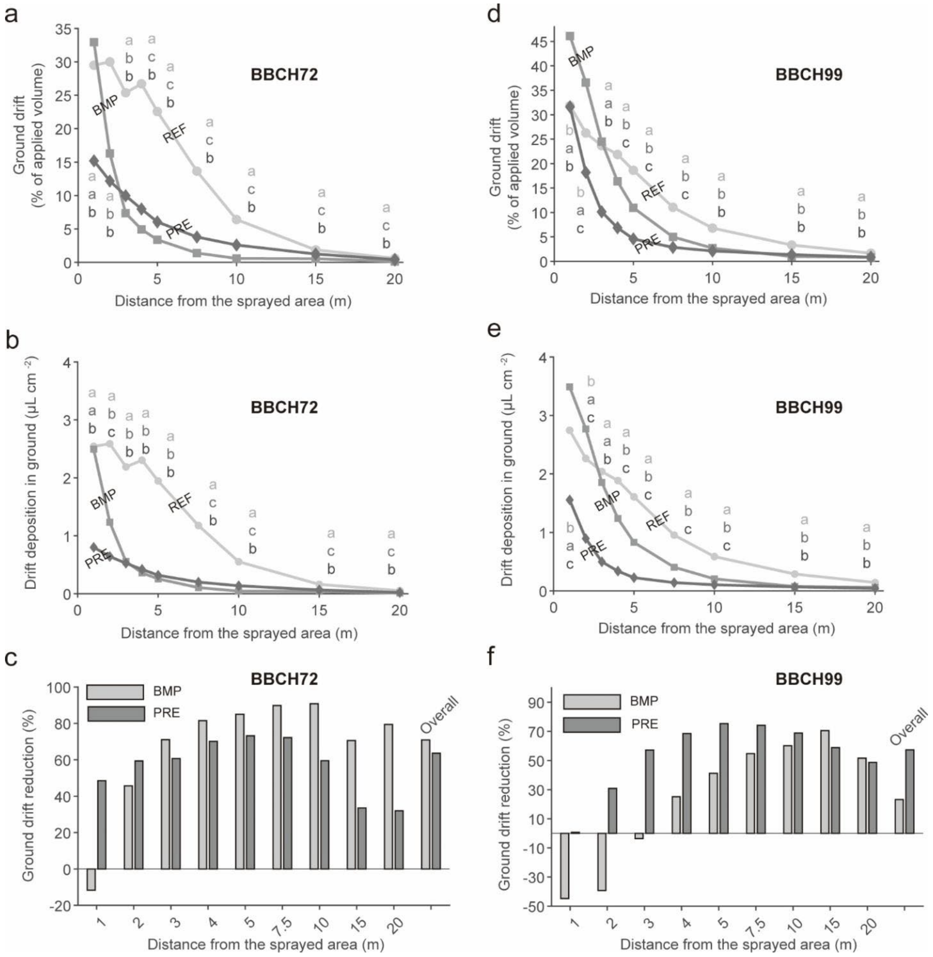

Fig. 5 Ground drift profiles from three spraying systems at BBCH72 (**a** percentage drift and **b** absolute deposition), and BBCH99 (**d** percentage drift and **e** absolute deposition). Different letters attached to the curves indicate significant differences at each sampling distance (Student–Newman–Keuls test: $p<0.05$). Potential drift reductions (%) in ground drift of optimized system (BMP) and precision system (PRE) compared with conventional system (REF) at BBCH72 (**c**) and BBCH99 (**f**).

observed in previous research (Grella et al., 2017). The drift deposition decreased sharply and almost linearly to 5% in the range of 4–10 m, and then had a moderate decrease when the distance increased to 20 m. Besides, among the three treatments, the conventional system gave the highest drift deposition at each sampling distance except for 1 m, which indicated its great potential of environmental contamination. For the optimized system, the drift deposition showed a very sharp decrease from 33.0 to 16.3% in the first 1 and 2 m and then exhibited a relatively steady and slight decay, similar to the results in previous research (Rautmann et al., 2001). Moreover, the optimized system achieved a significantly lower deposition than the other two systems when the distance was more than 3 m. On the other hand, the precision spraying system provided a steady and gradually decreasing spray drift curve along the sampling distance. Besides, it achieved a significantly lower ground drift of 15.2% at the sampling distance of 1 m, which was less than half of those from other two spraying systems. However, the trend of ground drift deposition along drift distances, quantified in absolute and percentage values, was similar for all three spraying systems (Fig. 5a and 5b). In addition, for the comparison of the ground drift from the three spraying system, the consistent results of statistical analysis were observed for the absolute and percentage value at most sampling distances.

For the drift reduction compared with conventional treatment (Fig. 5c), the two advanced spraying systems achieved similarly high total drift reduction (> 60%). The optimized system showed a high drift reduction in each sampling distance (>70%), except for the first 1 and 2 m. In contrast, the drift reduction with the precise system exhibited a trend of rising first and then falling, with a maximum value of about 70% in the range of 4–7.5 m. In general, the two advanced spraying systems that used new application technologies and appropriate dose expression demonstrated significant effects on ground drift mitigation, which agreed with previous studies (Grella et al., 2017; Wenneker et al., 2005).

For the corresponding ground drift profile at BBCH99 (Fig. 5d), a continuously decreased tendency was observed for all three systems. The conventional system produced significantly higher drift deposition than the other two advanced systems, except for the distances at the first 1–3 m. The ground drift from the optimized system showed a very sharp decrease from 46.1 to 11.0% in the range of 1–5 m, and it then gradually declined as the distance increased. In addition, the optimized system produced significantly higher deposition than the other two systems at the distances of first 1–2 m. Similarly, the drift deposition from the precise spraying exhibited a sharp decrease from 31.6 to 10.1% in the range of 1–3 m. In addition, the precision system achieved significantly lower ground drift with minimum drift potential at most sampling distances than the other two systems, especially at the first 5 m zone. Despite these differences, the trend of the ground spray drift of three spraying systems, expressed as absolute and percentage values, was similar (Fig. 5d and 5e). Besides, except for the 1 and 10 m sampling distances, the results of the statistical analysis were also consistent. The significant lower ground drift was achieved by the two advanced spraying systems at two selected growth stages, no matter quantified as the absolute drift deposition or percentage deposition of the applied volume. In addition, the ground spray drift from the two advanced spraying systems decreased sharply within the first 1–5 m range at both growth stages. Thus, the buffer zone aimed to avoid potential environmental contamination could be effectively reduced when advanced spraying systems were applied.

For the drift reduction compared with the conventional system (Fig. 5f), the precision system achieved a much higher overall reduction than the optimized system. The optimized sprayer system exhibited no anti-drift effect in the first three sampling distances. In contrast, the precision system achieved better drift reduction at every distance except for the 1 m distance. This result indicated that the precision spraying system with the variable rate application had an obvious advantage in drift reduction compared with the optimized system especially when the canopy developed to BBCH99 with low vegetation density.

Considering the ground drift reduction at two growth stages, though equipped with air induction nozzles, the optimized spraying application with the Fede axial-fan sprayer failed to achieve drift reduction at the measuring lines close to the sprayed area (1 m at BBCH72 and 1–3 m at BBCH99). This might be due to differences in the spray structure, which affected the output spray profile. The optimized system used the conventional axial-fan airblast sprayer while the other two systems used the high-tower sprayers. The radial spray plum generated from the conventional axial-fan sprayer showed poor target ability for the intended tree canopy, which resulted in a high potential of drift (Bourodimos et al., 2019).

Airborne spray drift

The airborne drift from the three spraying systems measured at 5 and 10 m from the sprayed area at BBCH72 is shown in Fig. 6a and b. The conventional system showed a higher airborne drift, also with markedly higher variation, than the other two systems at both sampling distances. In contrast, the optimized system achieved a uniform distribution with low drift. For the drift per unit sampling height of the three systems at a sampling distance of 5 m, a significant difference was observed: the highest value was detected for the conventional system (14.6%), followed by the precision system (8.5%), and then the optimized system with a significantly lower value (2.2%). At the 10 m sample distance, the airborne drift per unit sampling height of each system was only nearly half of that at 5 m, and consistent statistical analysis results were detected at two sampling distances.

The mean airborne drift of three spraying systems along different sample heights at two sampling distances at BBCH72 is shown in Fig. 6c and d. The conventional treatment exhibited the maximum drift amount at all sampling heights across the pole at 5 m, and at heights below 4.0 m for the 10 m distance. In addition, the drift curve illustrated a decreased tendency in both cases. Specially, uneven drift distributions with high deposition, more than 13.9% and 5.9% at sample distances of 5 and 10 m, respectively, were detected for the conventional system at sampling heights below 2.5 m which corresponded to the tree canopy vegetation. This result indicated that a large portion of the spray droplets generated from the conventional spraying system were not captured by the intended vegetation, resulting in high airborne drift. In contrast, the two advanced systems showed relatively low and uniform drift deposition in this area, which demonstrated the effective airborne drift reduction with the new technologies. Even distributions were observed for the optimized system: the drift deposition was no more than 4% of applied volume for each sampling height at the 5 m downwind distance and decreased to very low deposition ($<1.7\%$) at the 10 m distance. However, for the precision system at the 5 m distance, a high airborne drift of close to 10% was observed in the middle area (1.5–4.5 m), but it decreased dramatically to nearly 5% for the top and bottom areas. Considering the measuring pole at 10 m, the drift varied in the range of 2.2–5.5% and exhibited an overall decreased trend.

For the potential drift reduction (Fig. 6e and f), the optimized system exhibited a strong anti-drift effect with 84.6% and 78.9% overall reduction at the 5 and 10 m sampling dis-

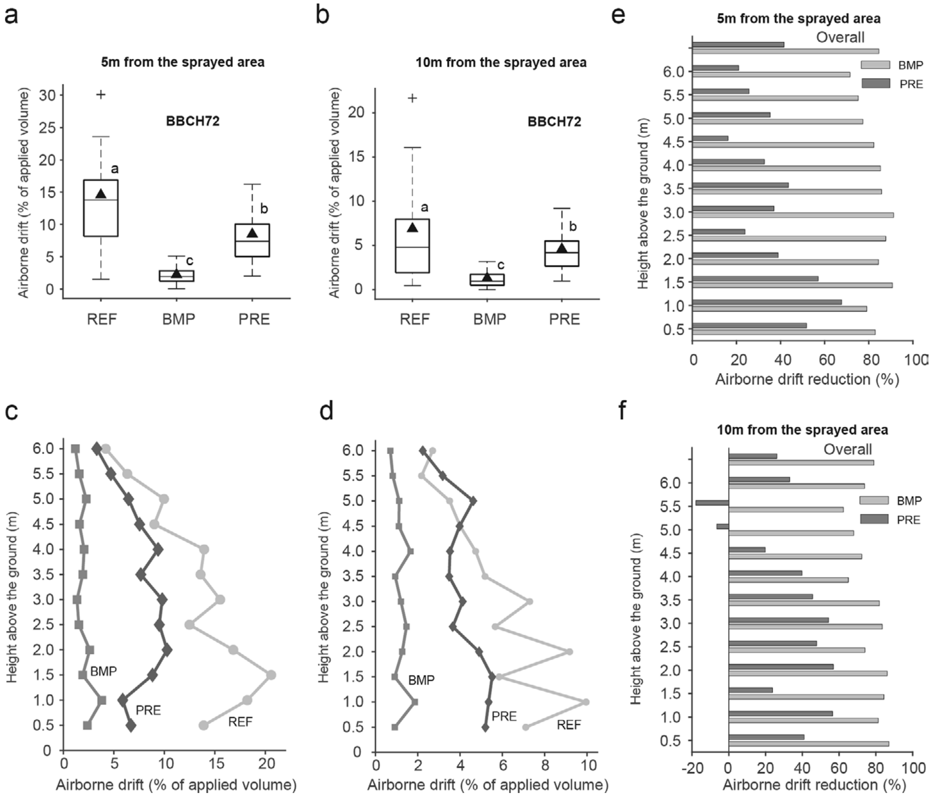

Fig. 6 Airborne drift of the three spraying systems at the sample distance of 5 m (**a**), and 10 m (**b**) at BBCH72. The black solid triangle represents the airborne drift per unit sampling height. Different letters at the top right corner of the box plot indicate significant differences (Student–Newman–Keuls test: $p<0.05$). Airborne drift distribution along the sampling height of each treatment at the sample distance of 5 m (**c**), and 10 m (**d**) at BBCH72. Potential drift reduction (%) in airborne drift of the optimized system (BMP) and precision system (PRE) compared with conventional system (REF) at the sample distance of 5 m (**e**), and 10 m (**f**) at BBCH72.

tances, respectively, and also high drift reduction at each sampling height. In contrast, the drift reduction for the precision system was not as good as the optimized application, especially at the 10 m distance, with only a drift reduction of 26.2%. This might result from the different weather conditions for these two treatments during tests. The mean wind speed for the precision system in three repetitions was higher than that for the optimized system, and the wind direction was closer to perpendicular to the tree row, which could result in a relatively more airborne drift. The significant influence of the meteorological condition on the spray drift deposition was generally observed (Arvidsson et al., 2011; Grella et al., 2017). Though the new application technologies could be used for agrochemical applications, it was essential to perform the spraying application in favorable weather conditions to achieve the spray drift mitigation.

The airborne drift of the three spraying systems measured at two sampling distances at BBCH99 is shown in Fig. 7a and b. At two sampling distances, the conventional system exhibited relatively higher drift with higher variation than other two advanced systems.

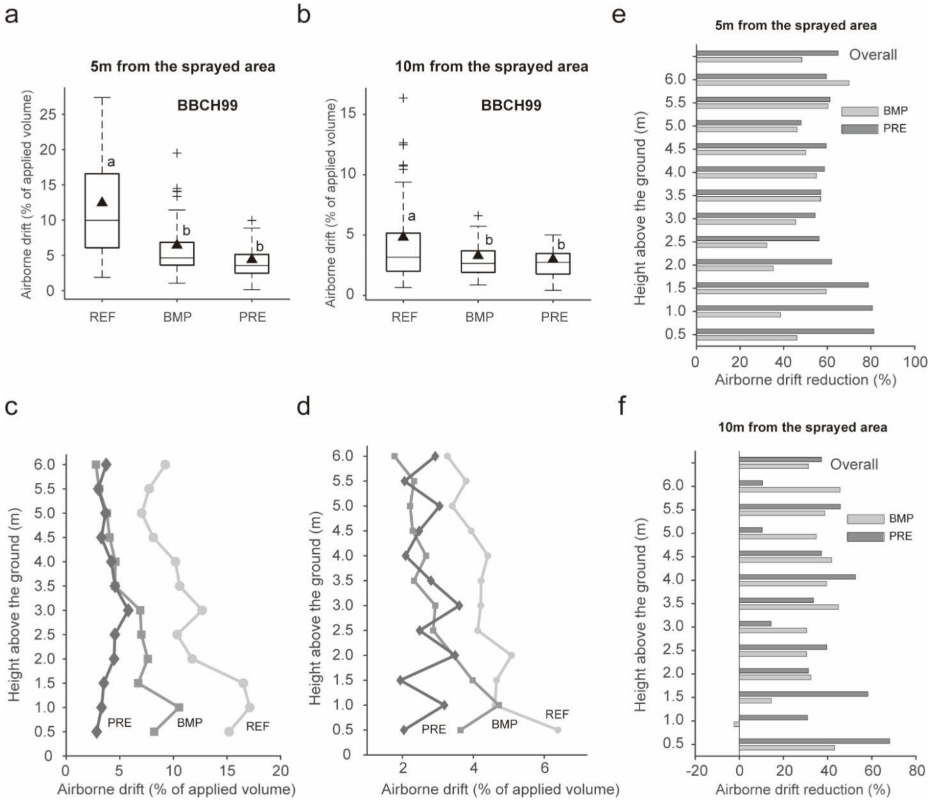

Fig. 7 Airborne drift of three spraying systems at the sample distance of 5 m (**a**), and 10 m (**b**) at BBCH99. The black solid triangle represents the airborne drift per unit sampling height. Different letters at the top right corner of the box plot indicate significant differences (Student–Newman–Keuls test: $p < 0.05$). Airborne drift distribution along the sampling height of each treatment at the sample distance of 5 m (**c**), and 10 m (**d**) at BBCH99. Potential drift reduction (%) in airborne drift of optimized system (BMP) and precision system (PRE) compared with conventional system (REF) at the sample distance of 5 m (**e**), and 10 m (**f**) at BBCH99.

Considering the drift per unit sampling height at each sampling distance, the two advanced spraying systems achieved significantly lower spray drifts than the conventional system. At both growth stages, the lower airborne drift was observed for the two advanced spraying systems, which revealed their stable drift mitigation ability, independent of the change of the canopy characteristics.

For the corresponding drift distribution along sampling heights (Fig. 7c and d), the conventional system gave the maximum deposition at almost all heights for the two sampling distances with an overall decreased trend. The same decreased tendency of airborne drift of the conventional system was observed at the two growth stages, which was consistent with the previous studies (Bourodimos et al., 2019; Grella et al., 2017). Furthermore, uneven deposition was observed at heights below 2.5 m at two sampling distances, similar to the case at BBCH72. The precision spraying system achieved a uniform distribution with a low drift of no more than 6% for the distance of 5 m. In contrast, the optimized system achieved a similar drift distribution as the precise spraying system in the height range of 3.5 to 6.0 m but a remarkably higher deposition in the bottom zone below 3.5 m. Considering the sampling distance of 10 m (Fig. 7d), low drift deposition below 4% with relatively high variations was observed at all sampling heights for the precision spraying system. The optimized system achieved a relatively uniform distribution in the range of 2.5–6 m, and the drift deposition exhibited a remarkable increase at heights below 2.5 m. In general, the airborne drift showed a remarkable decrease with the increase in measurement distances, which was consistent with the result at BBCH72. The spray droplets, not captured by the target vegetation, had limited kinetic energy. They were mainly affected by gravity, and were relatively difficult to deposit further away.

For the drift reduction of the two advanced spraying systems at BBCH99 (Fig. 7e and f), the precision spraying system achieved a better overall drift reduction than the optimized system at both sample distances, especially at 5 m. Noteworthy, the enhanced drift reduction ability of the precision system mainly resulted from better drift mitigation at sampling heights below 2.5 m corresponding to the tree vegetation zone. Generally, for the sparse vegetation with high porosity at BBCH99, spray droplets tended to penetrate and pass the whole tree canopy with high drift risk. This result indicated that the precision spraying system with variable rate could effectively increase the portion of spray droplets deposited inside the target canopy, correspondingly, minimizing the spray drift risk for the sparse vegetation. Combined with the results of ground drift, the precision spraying system demonstrated an absolute advantage to minimize the risk of spray drift for the tree vegetation with low density. This result showed that precision spraying system would have a potentially wide range of application scenarios, especially for crops at the early or late growth stages with low vegetation density, or the crop with a relatively sparse and open canopy.

Conclusions

Spray drift potentials of three spraying systems were evaluated in the apple orchard at two growth stages, following the protocol ISO 22866. The developed precision spraying system based on the TRV model achieved the precise adjustment of spray application rate in real-time according to the detected canopy volume along tree rows. In addition, the reduction of applied volume/pesticide was demonstrated for the precision and optimized spraying systems compared with the conventional system: a reduction of 12% with the optimized spraying system following the best management practices, and a higher reduction of 43% with the precise system. This result revealed the great potential of precision spraying system in pesticide reduction compared to the conventional constant rate application. Moreover, the two advanced spraying systems exhibited a significant drift reduction of 23.3–70.9% in ground drift, and 26.2–84.6% in airborne drift. For the sparse canopy with low vegetation density, the precision spraying system showed a remarkable advantage in spray drift reduction.

Therefore, the new precision spraying system, which was the integration of new application technologies, optimal practices following the best management practices, and pesticide dose adjustment according to the canopy structure, was able to minimize the environmental contamination related to spray drift risk and reduce the use of pesticide in apple orchards. This study demonstrated the prospect of using and promoting advanced spraying systems in tree crop to achieve the sustainable application of pesticides in compliance with EU regulations.

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Author Contribution Emilio Gil: Conceptualization, Resources, Field trials, Writing- Review & Editing, Supervision, Project administration. Lu Xun: Investigation, Methodology, Field trials, Visualization, Results presentation, Writing - Original draft and final document preparation. Javier Campos: Prototype development, field trials, Data management. Bernat Salas: Prototype development, Field trials, Data management. Francesc Xavier Fabregas: Field trials, Writing- Review & Editing. Heping Zhu: Data management, Review & Editing.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Arvidsson, T., Bergström, L., & Kreuger, J. (2011). Spray drift as influenced by meteorological and technical factors. *Pest Management Science*, *67*(5), 586–598. https://doi.org/10.1002/ps.2114.

Balsari, P., Marucco, P., & Oggero, G. (2002). Spray applications in Italian apple orchards: Target coverage, ground losses and drift. In *2002 ASAE Annual Meeting* (p. Paper Number: 02–1002). American Society of Agricultural and Biological Engineers.

Balsari, P., Doruchowski, G., Marucco, P., Tamagnone, M., Van de Zande, J. C., & Wenneker, M. (2008). A system for adjusting the spray application to the target characteristics. *Agricultural Engineering International: the CIGR Ejournal*, *8*(002), 11. http://cigrjournal.org/index.php/Ejounral/article/view/1237/1095%5Cnhttp://cigr-ejournal.tamu.edu/articles.html.

Balsari, P., Marucco, P., Doruchowski, G., Ophoff, H., & Roettele, M. (2011). Best management practice to reduce spray drift. *TOPPS Prowadis Projects Sponsored by European Crop Protection Association ECPA: Brusselsm Belgium*

Bourodimos, G., Koutsiaras, M., Psiroukis, V., Balafoutis, A., & Fountas, S. (2019). Development and field evaluation of a spray drift risk assessment tool for vineyard spraying application. *Agriculture (Switzerland)*, *9*(8), https://doi.org/10.3390/agriculture9080181.

Campos, J., Llop, J., Gallart, M., García-Ruiz, F., Gras, A., Salcedo, R., & Gil, E. (2019). Development of canopy vigour maps using UAV for site-specific management during vineyard spraying process. *Precision Agriculture*, *20*(6), 1136–1156. https://doi.org/10.1007/s11119-019-09643-z.

Carazo-Rojas, E., Pérez-Rojas, G., Pérez-Villanueva, M., Chinchilla-Soto, C., Chin-Pampillo, J. S., Aguilar-Mora, P., et al. (2018). Pesticide monitoring and ecotoxicological risk assessment in surface water bodies and sediments of a tropical agro-ecosystem. *Environmental Pollution*, *241*, 800–809. https://doi.org/10.1016/j.envpol.2018.06.020.

Chen, Y., Zhu, H., Ozkan, H. E., Derksen, R. C., & Krause, C. R. (2013). Spray drift and off-target loss reductions with a precision air-assisted sprayer. *Transactions of the ASABE*, *56*(6), 1273–1281. https://doi.org/10.13031/trans.56.10173.

Chen, Y., Zhu, H., & Ozkan, H. E. (2011). Development of LIDAR-guided sprayer to synchronize spray outputs with canopy structures. *American Society of Agricultural and Biological Engineers Annual International Meeting 2011 ASABE 2011*, *1*(11), 11–24. https://doi.org/10.13031/2013.37206.

Chen, Y., Zhu, H., & Ozkan, H. E. (2012). Development of a variable-rate sprayer with laser scanning sensor to synchronize spray outputs to tree structures. *Transactions of the ASABE*, *55*(3), 773–781

Damalas, C. A., & Eleftherohorinos, I. G. (2011). Pesticide exposure, safety issues, and risk assessment indicators. *International Journal of Environmental Research and Public Health*, *8*(5), 1402–1419. https://doi.org/10.3390/ijerph8051402

Doruchowski, G., Swiechowski, W., Holownicki, R., & Godyn, A. (2009). Environmentally-dependent application system (EDAS) for safer spray application in fruit growing. *The Journal of Horticultural Science and Biotechnology*, *84*(6), 107–112. https://doi.org/10.1080/14620316.2009.11512605.

EPPO. (2021). PP 1/239 (3) dose expression for plant protection products. *EPPO Bulletin*, *0*(1), 1–24. https://doi.org/10.1111/epp.12704.

Escolà, A., Rosell-Polo, J. R., Planas, S., Gil, E., Pomar, J., Camp, F., et al. (2013). Variable rate sprayer. Part 1 - Orchard prototype: Design, implementation and validation. *Computers and Electronics in Agriculture*, *95*, 122–135. https://doi.org/10.1016/j.compag.2013.02.004.

European Commission (2020). Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions – A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system, COM(2020) 381 final.

Feltracco, M., Barbaro, E., Maule, F., Bortolini, M., Gabrieli, J., De Blasi, F., et al. (2022). Airborne polar pesticides in rural and mountain sites of North-Eastern Italy: An emerging air quality issue. *Environmental Pollution*, *308*(January), 119657. https://doi.org/10.1016/j.envpol.2022.119657.

Garcerá, C., Doruchowski, G., & Chueca, P. (2021). Harmonization of plant protection products dose expression and dose adjustment for high growing 3D crops: A review. *Crop Protection*, *140* (May 2020). https://doi.org/10.1016/j.cropro.2020.105417

Gil, E., Escolà, A., Rosell, J. R., Planas, S., & Val, L. (2007). Variable rate application of plant protection products in vineyard using ultrasonic sensors. *Crop Protection*, *26*(8), 1287–1297. https://doi.org/10.1016/j.cropro.2006.11.003.

Gil, E., Llorens, J., Llop, J., Fàbregas, X., Escolà, A., & Rosell-Polo, J. R. (2013). Variable rate sprayer. Part 2 - vineyard prototype: Design, implementation, and validation. *Computers and Electronics in Agriculture*, *95*, 136–150. https://doi.org/10.1016/j.compag.2013.02.010.

Gil, E., Campos, J., Ortega, P., Llop, J., Gras, A., Armengol, E., et al. (2019). DOSAVIÑA: Tool to calculate the optimal volume rate and pesticide amount in vineyard spray applications based on a modified leaf wall area method. *Computers and Electronics in Agriculture*, *160*(March), 117–130. https://doi.org/10.1016/j.compag.2019.03.018.

Grella, M., Gallart, M., Marucco, P., Balsari, P., & Gil, E. (2017). Ground deposition and airborne spray drift assessment in vineyard and orchard: The influence of environmental variables and sprayer settings. *Sustainability (Switzerland)*, *9*(5), 728. https://doi.org/10.3390/su9050728.

Grella, M., Marucco, P., & Balsari, P. (2019). Toward a new method to classify the airblast sprayers according to their potential drift reduction: Comparison of direct and new indirect measurement methods. *Pest Management Science*, *75*(8), 2219–2235. https://doi.org/10.1002/ps.5354.

ISO (2005). ISO 22866: 2005-equipment for crop protection-methods for field measurement of spray drift.

ISO (2015). ISO 24253-2:2015 crop protection equipment — spray deposit tests of field crop sprayers — part (2 vol.). Crop deposit measurements.

Khot, L. R., Ehsani, R., Albrigo, G., Larbi, P. A., Landers, A., Campoy, J., & Wellington, C. (2012). Air-assisted sprayer adapted for precision horticulture: Spray patterns and deposition assessments in small-sized citrus canopies. *Biosystems Engineering*, *113*(1), 76–85. https://doi.org/10.1016/j.biosystemseng.2012.06.008.

Llorens, J., Gil, E., Llop, J., & Escolà, A. (2010). Variable rate dosing in precision viticulture: Use of electronic devices to improve application efficiency. *Crop Protection*, *29*(3), 239–248. https://doi.org/10.1016/j.cropro.2009.12.022.

Manandhar, A., Zhu, H., Ozkan, E., & Shah, A. (2020). Techno-economic impacts of using a laser-guided variable-rate spraying system to retrofit conventional constant-rate sprayers. *Precision Agriculture*, *21*(5), 1156–1171. https://doi.org/10.1007/s11119-020-09712-8.

Marrs, R. H., Williams, C. T., Frost, A. J., & Plant, R. A. (1989). Assessment of the effects of herbicide spray drift on a range of plant species of conservation interest. *Environmental Pollution*, *59*(1), 71–86. https://doi.org/10.1016/0269-7491(89)90022-5.

Marrs, R. H., & Frost, A. J. (1997). A microcosm approach to the detection of the effects of herbicide spray drift in plant communities. *Journal of Environmental Management*, *50*(4), 369–388. https://doi.org/10.1006/jema.1996.9984.

Fuentes, A., Llorens, J., Rodríguez-Lizana, A., Cuenca, A., Gil, E., Blanco-Roldán, G. L., & Gil-Ribes, J. A. (2016). Assessing the optimal liquid volume to be sprayed on isolated olive trees according to their canopy volumes. *Science of the Total Environment*, *568*, 296–305. https://doi.org/10.1016/j.scitotenv.2016.06.013

Nuyttens, D., De Schampheleire, M., Baetens, K., & Sonck, B. (2007). The influence of operator-controlled variables on spray drift from field crop sprayers. *Transactions of the ASABE*, *50*(4), 1129–1140. https://doi.org/10.13031/2013.23622.

Rautmann, D., Streloke, M., & Winkler, R. (2001). New basic drift values in the Authorization procedure for plant protection products. *Mitteilungen aus der Biologischen Bundesanstalt für Land- und Forstwirtschaft Berlin- Dahlem*, *383*(January 2001), 133–141.

Rüegg, J., Viret, O., & Raisigl, U. (1999). Adaptation of spray dosage in stone-fruit orchards on the basis of tree row volume. *EPPO Bulletin*, *29*(1–2), 103–110. https://doi.org/10.1111/j.1365-2338.1999.tb00803.x.

Salyani, M., Miller, D. R., Farooq, M., & Sweeb, R. D. (2013). Effects of sprayer operating parameters on airborne drift from citrus air-carrier sprayers. *Agricultural Engineering International: CIGR Journal*, *15*(1), 27–36.

Silva Junior, G. J., Scapin, M. S., Silva, F. P., Silva, A. R. P., Behlau, F., & Ramos, H. H. (2016). Spray volume and fungicide rates for citrus black spot control based on tree canopy volume. *Crop Protection*, *85*, 38–45. https://doi.org/10.1016/j.cropro.2016.03.014.

Tauchnitz, N., Kurzius, F., Rupp, H., Schmidt, G., Hauser, B., Schrödter, M., & Meissner, R. (2020). Assessment of pesticide inputs into surface waters by agricultural and urban sources - A case study in the Querne/Weida catchment, central Germany. *Environmental Pollution*, *267*. https://doi.org/10.1016/j.envpol.2020.115186

Wenneker, M., Heijne, B., & Van de Zande, J. C. (2005). Effect of air induction nozzle (coarse droplet), air assistance and one-sided spraying of the outer tree row on spray drift in orchard spraying. *Annual review of agricultural engineering*, *4*(1), 116–128.