Pesticide dose based on canopy characteristics in apple trees: reducing environmental risk by reducing the amount of pesticide while maintaining pest and disease control efficacy

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Abstract

Although many different designed air-assisted sprayers can be used for pesticide application in apple orchards, the lack of adequate adjustments according to specific crop characteristics leads to application inefficiencies and failures. To evaluate the spray coverage and biological efficacy of different application techniques combined with an alternative dosage adjustment based on tree row volume (TRV), field tests with five different techniques were carried out at three crop stages on a commercial apple orchard. The results showed that conventional mist-blower with a high application volume (800 L ha^{-1}) exhibited an excessive coverage with a high risk of contamination at the early crop stage (BBCH19), whereas other treatments using different application techniques, with a reduced volume rate and pesticide dose of 75%, were equivalent with good uniformity, revealing the great importance of suitable adjustment for the sprayers. For the middle and late stages (BBCH64 and 75), the orchard sprayer equipped with vertical booms provided the maximum coverage, and the pneumatic sprayer achieved significantly higher impacts density, which revealed their advantages and high efficiency for dense apple trees. The newly developed multi-fan sprayer and pneumatic sprayer achieved consistent coverage during the entire crop stage, independent of the changes in canopy structure (TRV). This indicates that a suitable setting and adjustment of the sprayer can contribute to a consistent spray quality. In general, benefiting from these new spraying technologies, an average reduction of 60.7% in pesticide dose and volume rate were achieved within the entire season, maintaining the same threshold of pest and disease control as that of the higher reference dose normally applied. These results demonstrate the importance of an alternative dose adjustment method to meet the requirements of the Farm to Fork strategy.

Keywords: Coverage, TRV, Apple orchard, Dosage adjustment, Orchard sprayer, Farm to Fork strategy.

1. Introduction

Pesticide application is a necessary and crucial activity for crop protection during the whole season that can directly affect the quality and yield of crops. Moreover, the inevitable off-target losses and drift resulting from the application of plant protection products (PPPs) can lead to several undesirable consequences, such as environmental contamination, especially in water bodies, excessive pesticide residues in agricultural food, and health risks to related animals and operators (Nuyttens et al., 2007). Therefore, a successful pesticide application will have a balance among economic, environmental, and social effects, with a focus on sustainable development.

Recently defined specialty crops include a wide list of cultures of particular circumstances and additional difficulties during the pesticide application process (Tona et al., 2018). Miranda-Fuentes et al. (2015) demonstrated the possibility of obtaining good application quality without using excessive application volumes or high airflow rates, thus avoiding the negative impacts of pesticide usage efficiency, spray drift, fuel consumption, and noise emission. Ozkan (2009) suggested that sustainable agriculture, good water quality, profitability, and increasing health, safety, and socio-ecological concerns require a more prudent use of pesticides.

For this purpose, actions based on the implementation of best management practices (BMPs), development of new technologies (Campos et al., 2021; Gil et al., 2020b), and expansion of the educational skills for end-users (Gil et al., 2020a) will be combined to achieve a more sustainable food production process.

However, because of the great variability in 3D crop characteristics generated from crop varieties, training systems, growth stages, pruning practices, and other factors, only when the sprayer is well calibrated and adjusted under field conditions can a high-quality spray application be achieved in practice, despite the type of sprayer used (Balsari et al., 2002).

Pesticide dose adjustment is a key aspect of optimization, as it directly affects and determines the spray efficiency and biological efficacy. Dose expression of PPPs applied via foliar spray in orchards, vineyards, and other high-growing crops has generated extensive and controversial discussions (Garcerá et al., 2021; Gil et al., 2021; Triloff, 2005; Walklate and Cross, 2012). The practical information available in many PPP labels, especially in southern Europe, has traditionally referred to a standard spray volume of 1000 L ha^{-1}, without particular consideration of the canopy structure, leading to an excessive recommended dose rate per unit area, in a clear controversy with the European legal framework aimed at reducing the usage and risks of pesticides. Additionally, special legal circumstances in some EU countries, such as Italy, establish a minimum dose of PPP per hectare, independent of canopy characteristics. These legal aspects are contrary to the results of recent studies (Ferguson et al., 2016; Hanafi et al., 2016; Shen et al., 2017), where it has been demonstrated that an accurate spray adjustment based on canopy characteristics (Gil et al., 2021) allows reducing pesticide quantities while maintaining the efficacy of pest and disease control with a low environmental impact.

Determining the optimal volume rate to avoid over/under dosing is a difficult task for each specific spraying operation, and it needs a global consideration of the target characteristics and spray technique. Benefitting from previous studies in this matter, two main dosage adjustment models based on the leaf wall area (LWA) and tree row volume (TRV), involving different canopy parameters to characterize the target, have been proposed (EPPO, 2021), validated, and implemented for spraying applications (Rüegg et al., 1999; Solanelles et al., 2006; Siegfried et al., 2007; Walklate et al., 2003; Walklate et al., 2011; Walklate and Cross, 2012).

With respect to pesticide application in apple orchards with different spraying techniques, great efforts have been made to improve and optimize the application efficiency. Previous researchers have found that a directed air-assisted sprayer with air spouts set at 20° upwards achieved better spray quality than conventional and cross-flow sprayers in modern orchards (Holownicki et al., 2000). Cross et al. carried out a series of field tests to optimize the key operational parameters of conventional axial fan sprayers in apple trees of different sizes (Cross et al., 2001a; 2001b; 2003). They concluded that variations in the applied volume rate greatly affected spray coverage but showed only a small effect on normalized spray deposits in the trees and off-target losses. A strong correlation was observed between the canopy deposition profile and outlet air flow pattern of different sprayers, and while selecting the sprayer type, the characteristics of the canopy should be prioritized in pome fruit trees (Duga et al., 2015).

These results are only part of a large body of literature on spray application technologies that clearly demonstrate the direct influence of how PPPs are applied and the quality and safety of this process. Considering the recently published European Farm to Fork strategy (European Commission, 2020), it is clear that some of the main factors to consider in achieving the great challenge of 50% pesticide use reduction in Europe by 2030 are related to the selected spray technology and the definition of the best management practices (Balsari et al., 2011).

Although many measures have been applied to optimize the conventional pesticide application in apple orchards, the potential savings which can be achieved in practice still need to be studied and verified by further field tests, using a comprehensive evaluation in terms of the spray distribution within the canopy and final pest and disease control. For this reason, the main objectives of this study were to improve the spray application process on a commercial orchard plantation and achieve a reduction in PPP dose, to align with the European requirements, thereby reducing the negative environmental effects while maintaining the efficacy of pest and disease control. The specific objectives were to: a) evaluate the spray qualities of five typical representative and newly developed sprayers at three growth stages in terms of spray coverage; b) evaluate the potential savings of pesticides and quantify the biological efficacy of pest and disease control while reducing the amount of PPP used; and c) compare the effectiveness of traditional spray application in apple tree plantations with the latest developments in spray technologies.

2. Materials and methods

2.1. Spray application equipment

A wide range of sprayers consisting of three air-assisted sprayers and one pneumatic sprayer (Fig. 1) was selected to conduct the field experiments. The main technical characteristics of each selected sprayer are as follows:

a. Conventional orchard low-tower sprayer Teyme Eolo® 2000 (Teyme, Lleida, Spain): a 2000 L trailed sprayer equipped with a 900 mm axial fan and 54 nozzles. The air outlet of the fan was composed of two parts: an arc-shaped outlet at the bottom and a tower-shaped outlet at the top. At the bottom, three nozzle groups were arranged in a staggered-parallel alignment, and each contained six nozzles distributed along the radial direction. At the top, there was a manifold on the upper and lower sides of the air outlet, provided with three and six nozzles, respectively.

b. Multi-fan sprayer (Teyme, Lleida, Spain): a trailed orchard sprayer (36 nozzles) provided with a 3000 L tank and 36 nozzles and featured with six individual hydraulically driven axials, three per side, covering the whole canopy structure. The fan speed could be adjusted individually and electronically from the tractor cab according to the canopy structure.

c. Vertical boom air-assisted sprayer (Pulverizadores Fede, S.L., Cheste, Valencia, Spain): A trailed sprayer with a 2000 L tank and 32 nozzles and fitted with a centrifugal turbine that directed the airflow to six vertical rigid ducts, three per side, which were fixed to two vertical booms. The duct located in the top had two air outlets, and the other two in the middle and bottom each contained three outlets. In addition, each outlet was divided into four air spouts by three internal deflectors.

d. Pneumatic sprayer (Martignani, Ravenna, Italy): a trailed pneumatic orchard sprayer provided with a 1500 L tank and four specially designed diffusers with six liquid outlets for each, two per side, located at the top and bottom, arranged in front and back, to cover the entire canopy height.

Fig. 1. The sprayers used for the field trials: a) Teyme EOLO 2000 conventional axial-fan sprayer b) Teyme prototype sprayer equipped with six independent electric axial fans; c) Fede orchard sprayer equipped with vertical booms (VERTICAL); d) Martignani pneumatic sprayer.

2.2. Arrangement of the field tests

Field tests were carried out on a commercial apple plantation of approximately 4.3 ha (41°36’46″ N, 0°51’43″ E) in the village of Mollerussa (Lleida, Spain). Royal Gala was the main apple variety in the orchard, and two rows of the Granny Smith variety were periodically planted every six rows of the main variety for pollination purposes. The apple orchard was trained with sole axe and featured by a 3.9 × 0.9 m layout, resulting in 2849 trees per hectare.

Three representative crop stages (Uwe Meier, 2001) over the whole season were selected to carry out the experimental work: BBCH19 (first leaves fully expanded), BBCH64 (about 40% of flowers open), and BBCH75 (fruit about half that of the final size). Prior to the field tests, a complete canopy characterization including the measurement of row distance, canopy height, canopy width was conducted, and the Tree Row Volume (TRV) and Leaf Wall Area (LWA) was obtained accordingly (Table 1). A dedicated weather station (CR800, Campbell Scientific Inc., Logan, UT, USA) placed in the orchard was used to monitor and record the weather condition during the trials. The station was equipped with a 2D ultrasonic anemometer WindSonic 232 (Campbell Scientific Inc.) to measure wind speed and direction and a CS215 probe (Campbell Scientific Inc.) to measure air temperature and humidity.

Table 1 Canopy characteristic parameters in three growth stages.

Date	BBCH Code	Row distance (m)	Canopy height (m)	canopy width (m)	TRV (m^3 ha^{-1})	LWA (m^2 ha^{-1})
10/03/2020	19	3.90	3.17 ± 0.11*	1.46 ± 0.13	11867	16256
28/05/2020	64	3.90	4.00 ± 0.02	1.40 ± 0.12	14359	20513
02/07/2020	75	3.90	4.00 ± 0.03	1.27 ± 0.11	13026	20513

* Mean ± standard deviation.

2.3. Sprayer's adjustment and determination of operational parameters

Five spray treatments were arranged for each selected canopy stage. As a reference sprayer (REF), the conventional Teyme EOLO 2000 L was calibrated according to the normal procedure on the farm (800 L ha^{-1} for BBCH19 and 1000 L ha^{-1} for BBCH64 and BBCH75) and compared to the other four alternatives. The first one, identified as REF-BMP, was generated using the same conventional sprayer but following a calibration process complying with the recommended best management practices (BMPs), including the calculation of the applied volume rate based on the canopy characteristics (Deveau, 2016; Doruchowski et al., 1995; Gil et al., 2013). The same principle was applied to determine the applied volume rate for the rest of the sprayers in each previously defined crop canopy stage. Furthermore, the other three treatments were performed with the corresponding sprayers: a multi-fan sprayer (MULTIFAN), a sprayer with vertical booms (VERTICAL), and a pneumatic sprayer (PNEUMATIC). Accordingly, the application coefficient i (L m^{-3}) was established at 0.0153 for BBCH19 and increased to 0.03 for BBCH64 and BBCH75 (Doruchowski et al., 2012; Escolà et al., 2013; Garcerá et al., 2021). These volume adjustments resulted in 200 L ha^{-1} for BBCH19 and 450 L ha^{-1} for the middle and late canopy stages, representing reductions to the applied volume rate of 75% and 55%, respectively.

Considering that in all the cases the concentration of PPP (g or cc/100 L) was maintained at the same values as selected by farmers (REF), the proposed reduction of the applied volume rates derived in equivalent reductions of the amount of pesticide applied per hectare. Table 2 shows the main operational parameters selected for the sprayer’s adjustment.

Preliminary air flow measurements for the four evaluated sprayers indicated the average value of airflow (m^3 h^{-1}) was 66000 for the conventional sprayer, 32000 for Multifan sprayer, 18000 for the pneumatic sprayer, and 5500 for the vertical boom sprayers.

Table 2 Operational parameters for each treatment at three crop stages.

Parameters	Treatment				
	REF	REF-BMP	MULTIFAN	VERTICAL	PNEUMATIC
	BBCH 19 – 10/03/2020				
Vol. (L ha^{-1})	800	200	200	200	200
Vel. (km h^{-1})	8.0	8.0	8.0	8.0	8.0
Nozzle (No.)	18 + 35	18	18	24	4 (outlets)
Nozzle (type)	Albuz ATR Yellow/ Brown	Albuz AXI 80° 015	Albuz AXI 80° 015	Teejet XR 80° 01	Diffusers
Pressure (bar)	10.0	3.0	3.0	4.0	1.5
Droplet size*	VF	F	F	F	VF
Flow rate (L min^{-1})	42.7	10.7	10.7	10.7	10.7
	BBCH 64 – 28/05/2020 and BBCH 75 – 02/07/2020				
Vol. (L ha^{-1})	1000	450	450	450	450
Vel. (km h^{-1})	8.0	8.0	8.0	8.0	8.0
Nozzle (No.)	36 + 18	36	36	32	4 (outlets)
Nozzle (type)	Albuz ATR Yellow/ Brown	Albuz AXI 80° 015	Albuz AXI 80° 015	Albuz AXI 80° 015	Diffusers
Pressure (bar)	7.5	3.5	3.5	4.0	1.5
Droplet size	VF	F	F	F	VF
Flow rate (L min^{-1})	53.3	24.0	24.0	24.0	24.0

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

2.4. Experimental setup

The plantation pattern of the six rows of Royal Gala (main variety) and two rows of Granny Smith acting as pollinators was considered when defining the experimental blocks. The 4.3 ha parcel was divided into a total of seven blocks (Fig. 2a), in such a way that the two rows of pollinator trees acted as a boundary between adjacent experimental blocks. The two blocks at both ends of the parcel, marked as number 0, were used as the control area without any treatment during the season to evaluate biological efficacy. The sampling protocol for the spray quality evaluation agreed with the ISO 22522:2007(E) standard (ISO, 2007). Three apple trees in the central row of each experimental block were chosen for sampling, considering each tree as one of the three repetitions of each experiment. On every single tree, rectangular strips of water-sensitive papers (WSP) were placed on the side of the selected leaves facing the spray direction (adaxial or abaxial side) located in the different zones within the canopy to cover the whole tree structure. (Fig. 2b and 2c). The whole canopy was divided into four height levels, and at each height level, four WSPs were placed symmetrically in the canopy on both sides: two inside the canopy structure (Int_L and Int_R) and two placed on the exterior layers canopy (Ext_L and Ext_R). During the spray process, the selected sample row was sprayed from both sides, as well as the two adjacent rows on the left and right sides, following the normal spraying procedure adopted by the farmer. After the completion of each spraying process, the total WSP samplings were properly collected, placed onto a dedicated template, and placed in a dark and dry container for further analysis.

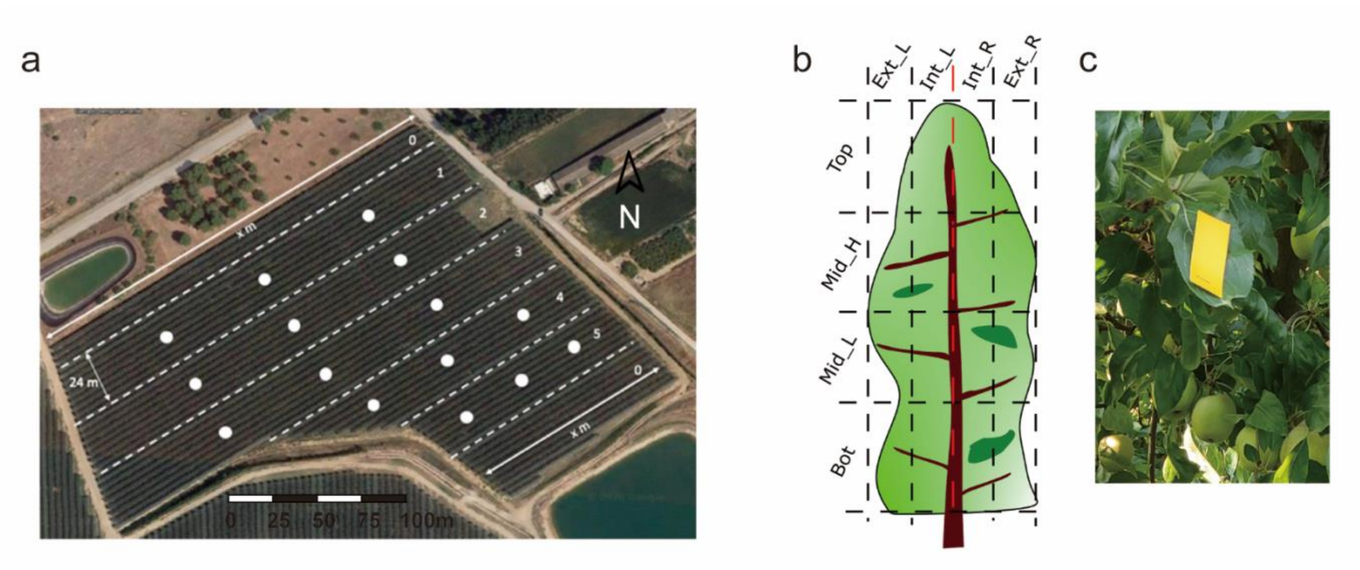

Fig. 2. (a) Plot's distribution in the parcel: 0. Control plots (without treatments) for biological efficacy tests; 1. MULTIFAN; 2. VERTICAL; 3. PNEUMATIC; 4. REF-BMP; 5. REF. The white dots indicate the sampling points for the evaluation of the spray quality distribution. (b) Scheme of sample's location on the tree, following ISO 22522 (ISO, 2007). Bot (bottom), Mid_L (middle low), Mid_H (middle high), Top (top), Ext_L (exterior left), Int_L (interior left), Int_R (interior right), Ext_R (exterior right). (c) Detail of water-sensitive paper's placement on leaves.

In addition to the spray coverage evaluation of different application techniques at the three specific canopy stages, all the blocks were sprayed throughout the season, following the technical recommendations addressed by the advisor. In all cases, the working parameters and recommended volume rate were maintained, allowing for the corresponding reduction in the amount of PPP.

2.5. Data processing and statistical analysis

Each WSP was scanned at a high resolution of 600 ppi in the laboratory, and then the ImageJ free software (LOCI, University of Wisconsin, USA) was used to analyze the coverage (%) and the number of impacts per unit area N_i (N cm^{-2}) of each sample.

As the applied volume of the conventional treatment (REF) was much higher than those for the other four treatments at each growth stage, it was not reasonable to directly compare each treatment. The normalized coverage (Nor_Cov) and impacts density (Nor_N_i), defined as the potential achieved coverage and impacts per 100 L application volume (Cross et al., 2001a; Gil et al., 2011), were introduced to enable comparisons between all the sprayers.

IBM SPSS Statistics version 22 (IBM, Armonk, NY, USA) was used to perform the statistical analysis of the data obtained during the field trials. Data from the three growth stages were analyzed separately, dependent on the crop stage. Statistical analyses were performed in terms of the raw absolute data and the normalized data.

As for the raw absolute data, the statistical differences between treatments were assessed based on two aspects: mean coverage and mean impacts. In addition, the five treatments were divided into two groups: one group contained the REF and REF-BMP, for which a t-test was applied to assess the potential improvement for the adequate adjustment following best management practices (BMPs); additionally, a second group consisted of the four treatments using the same application volume (REF-BMP, MULTIFAN, VERTICAL, and PNEUMATIC), for which one-way analysis of variance (ANOVA) combined with the Student-Newman-Keuls test was used to evaluate the influence of each application technique. For each treatment, the same statistical analysis model was used to assess the influence of the canopy position (canopy height and width) on the spray quality (coverage and impacts density) for each treatment.

As for the normalized coverage and impacts density, the one-way ANOVA combined with the Student-Newman-Keuls test was used to evaluate the statistical differences between the five treatments. For all tests, a p-value <0.05 was considered statistically significant.

Prior to the statistical test, the Shapiro-Wilk test was used to check the normality of the data. If the obtained data showed poor normality, the generally used transform formulas (the $\arcsin\left((x/100^{0.5})\right)$ or $\ln(x+1)$ transforms for the spray percentage data and the $\ln(x)$ or $\sqrt{x}$ transforms for the impacts data) were used to improve the normality with consideration of the specific situation (McDonald, 2014). Levene's test was also conducted to confirm the homogeneity of the test variance.

2.6. Evaluation of pest/disease control efficacy

The pest/disease control efficacy of the five treatments was evaluated in terms of the four most common apple pests and diseases: rosy apple aphid (*Dysaphis plantaginea*), codling moth (*Cydia pomonella*), powdery mildew (*Podosphaera leucotricha*), and apple scab (*Venturia inaequalis*). Regular field controls following the European and Mediterranean Plant Protection Organization (EPPO) guidelines (OEPP/EPPO, 1988) were carried out in all the defined experimental blocks during the entire season.

3. Results and discussion

3.1. Weather conditions during each treatment

The detailed weather condition during each test is shown in Table 3. The small changes were observed for the temperature and relative humidity during each test date, with the maximum variation of 7° and 24%, respectively. The wind speed was small in all treatments with a maximum value of 1.12 m s^{-1} and the mean wind direction ranged from 164° to 253°. In general, no big difference was observed for the meteorological conditions between each treatment at different growth stages, which confirmed that the results of each treatment were comparable.

Table 3 Weather conditions during the treatments at each growth stage

Date of trials	Treatment	Temperature (°C)	Relative humidity (%)	Wind speed (m s^{-1})	Wind direction (°)
10/03/2020	REF	13.4	56	0.65	183
	REF-BMP	15.0	52	0.32	212
	MULTIFAN	10.0	71	0.27	253
	VERTICAL	8.3	76	0.60	196
	PNEUMATIC	12.2	62	0.25	203
28/05/2020	REF	27.2	38	1.07	201
	REF-BMP	28.0	37	0.43	178
	MULTIFAN	24.2	44	0.62	198
	VERTICAL	21.4	56	0.81	164
	PNEUMATIC	26.4	38	0.94	234
02/07/2020	REF	29.6	50	1.12	178
	REF-BMP	30.8	46	0.40	192
	MULTIFAN	26	59	0.78	189
	VERTICAL	24.8	63	0.52	205

PNEUMATIC	28.6	52	1.05	232

3.2. Spray distribution over the canopy

3.2.1. Absolute values of recovery and impacts density

The overall spray quality of each sprayer during the three growth stages is shown in Fig. 3. For the overall coverage at BBCH19 (Fig. 3a), as expected, the reference sprayer (REF) with a high-volume rate obtained the highest percent coverage (53.3%), more than three times the coverage obtained with the same sprayer adjusted following the best management practices (REF-BMP), but with much higher variability. This demonstrates the necessity of dose adjustments in apple trees at the early stage, and the benefits of such adjustments, including greatly improved spray quality and, more importantly, greatly reduced water and pesticide usage. The four treatments with the same reduced volume showed no significant difference and achieved a similar and acceptable coverage ranging from 15.5% to 17.3%, also exhibiting good uniformity. For the corresponding impacts (Fig. 3b), the reference conventional sprayer used at the highest volume rate provided the lowest value with high variability in the samples. On the contrary, the REF-BMP achieved a significantly higher mean with a reduced dispersion, indicating better uniformity. As for the treatments with the same volume, the MULTIFAN achieved a significantly lower N_i (132.2 impacts cm^{-2}) and the best uniformity, while the other three sprayers showed similar results ranging from 144.2 to 169.4 impacts cm^{-2}, and the VERTICAL showed a much higher variability between samples. Notably, the reference conventional sprayer generated the maximum coverage but the lowest impacts density at BBCH19. This is mainly due to the difficulties and limits of the analysis software used to distinguish a large number of overlapped droplets deposited on the WSP, while spray coverage was above 20% (Grella et al., 2020a; Zhu et al., 2011).

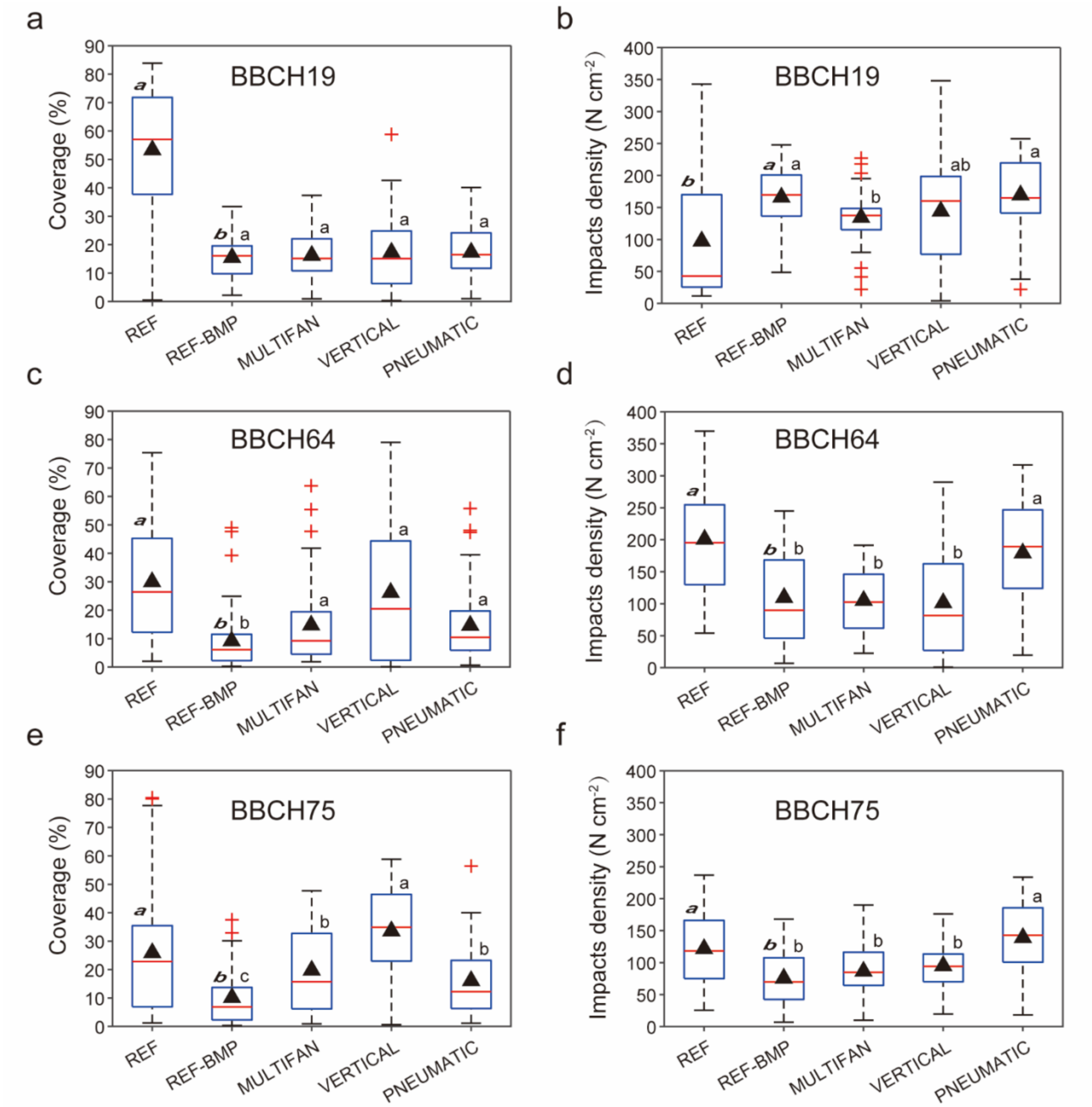

Fig. 3. Overall coverages and impacts densities for the whole tree canopy of the five sprayers at three crop stages. The black solid triangle represents the mean value. Different italic bold letters in the top left corner of the box plot indicate significant differences (T-test: $p < 0.05$). Different letters in the top right corner of the box plot indicate significant differences (Student–Newman–Keuls test: $p < 0.05$).

Considering the latter two stages BBCH64 and 75 (Fig. 3c-3f), as for the two treatments with the conventional sprayer, the conventional application with a high-volume rate (1000 L ha$^{-1)}$ achieved a better spray quality with significantly higher coverage and impacts density than the treatment following the best management practices. This result indicates the difficulties in achieving a comparable absolute spray quality thru conventional application for the apple trees with dense vegetation, even though the necessary and enough calibration and adjustment is applied in practice. As for the group with the same low volume rate (450 L ha^{-1}), in terms of the spray coverage, the REF-BMP always showed a significantly lower coverage, indicating the poor target ability of the conventional technique compared with that of other new techniques， and the other treatments showed no statistical difference at BBCH64 and the sprayer with vertical boom achieved the maximum value at BBCH75. Considering the corresponding impacts, the maximum value was always observed for the pneumatic sprayer.

3.1.2. Normalized values of recovery and impacts density

Figure 4 shows the statistical analysis results of the normalized values of coverage (%) and impacts density (N cm^{-2}). The five treatments showed no significant differences in their normalized coverage at the early crop stage (Fig. 4a). However, for the normalized impacts (Fig. 4b), the reference sprayer obtained a minimum value that was significantly lower than that of the other treatments.

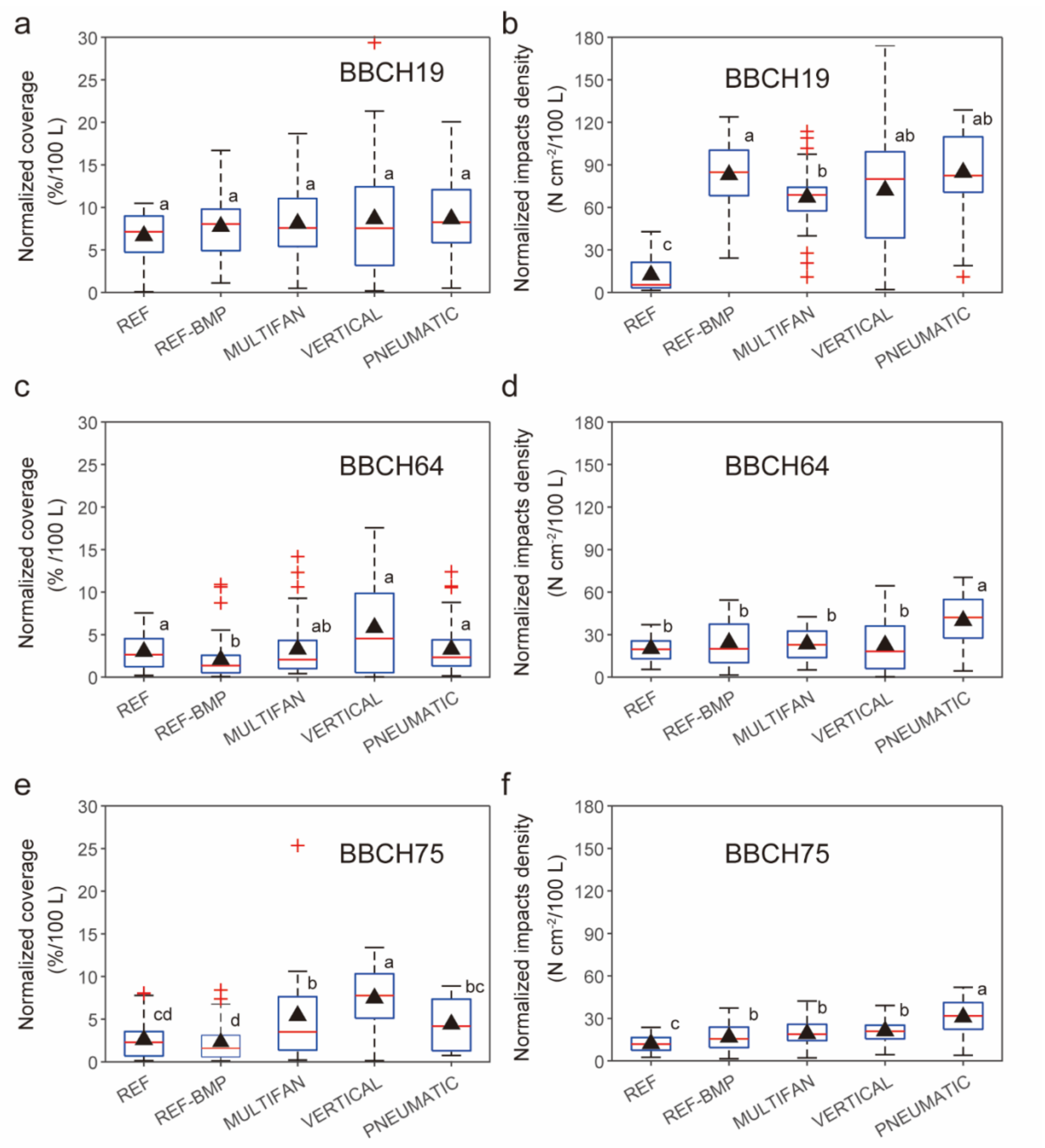

Fig. 4. Overall normalized coverage and impacts density at the whole tree canopy of the five sprayers at three crop stages. The black solid triangle represents the mean value. Different letters in the top right corner of the box plot indicate significant differences (Student–Newman–Keuls test: $p < 0.05$).

In the middle stage BBCH 64 (Fig. 4c and 4d), the REF-BMP exhibited a significantly lower normalized spray coverage than the other four treatments, except for the multi-fan sprayer. In addition, the maximum normalized coverage was observed for the VERTICAL. The PNEUMATIC obtained a significantly higher normalized impacts density than the other treatments.

In the late-stage BBCH75 (Fig. 4e and 4f), the performance of each treatment varied greatly in the normalized spray coverage. The VERTICAL obtained the maximum normalized coverage, significantly higher than that of all other treatments, which indicates its strong ability in increasing on-target spray coverage among different techniques. This advantage of the sprayer characterized by a directed air jet has also been stated in previous studies (Duga et al., 2015; Holownicki et al., 2000). As for the normalized impacts density, the pneumatic sprayer achieved a maximum value.

Focusing on the two treatments with the conventional axial fan sprayer, although no significant difference was detected for the normalized coverage in the early stage, the application efficiency significantly increased after the adjustment on the axial fan sprayer, according to the analysis of the absolute spray coverage before this adjustment. According to two commonly used evaluation methods, the high-volume treatment with a conventional axial-fan sprayer at the early crop stage led to excessive absolute spray coverage and significantly decreased normalized deposition due to the saturation effect (Balsari et al., 2002; Cross et al., 2001a; Świechowski et al., 2014). Additionally, the REF-BMP treatment did not achieve a better normalized coverage than the REF did at the latter two stages, which is in agreement with the results of previous studies (Balsari et al., 2002; Cross et al., 2001a; Świechowski et al., 2014). As the tree canopy expands with a stronger ability to capture spray droplets, the applied adjustment on the conventional sprayer cannot always achieve significantly higher efficiency than that of conventional high-volume-rate applications. In general, for the relatively dense canopy (BBCH64 and 75), the pneumatic sprayer achieved a significantly higher impacts density, similar to the results found by Miranda-Fuentes et al. (2018). This indicates that the pneumatic sprayer has an advantage in enhancing the impacts density for apple trees. In addition, the treatments of MULTIFAN and PNEUMATIC showed consistency in their normalized coverage.

3.2.3. Overall spray quality distribution

Based on the spray quality data at 16 sample zones within the tree canopy, the spatial distribution of the spray quality for each sprayer at the three growth stages (Fig. 5 and Fig. 6) was obtained using Matlab version 9.7 (MathWorks Inc.) with linear interpolation. In the case of BBCH19 (Fig. 5a), almost the whole canopy received excessive coverage (>30%) for the case of conventional sprayer at maximum volume rate (REF). The coverage distribution within the canopy of the REF-BMP was uniform but with lower values (<20%). The MULTIFAN and PNEUMATIC sprayers obtained a good uniformity distribution with coverage ranging from 10% to 30%, and an area of relatively high deposition was detected at the lower right part of the canopy. In contrast, the vertical boom sprayer treatment resulted in poor uniformity, and a low coverage below 10% was observed within the internal parts of the canopy, showing its reduced penetration ability.

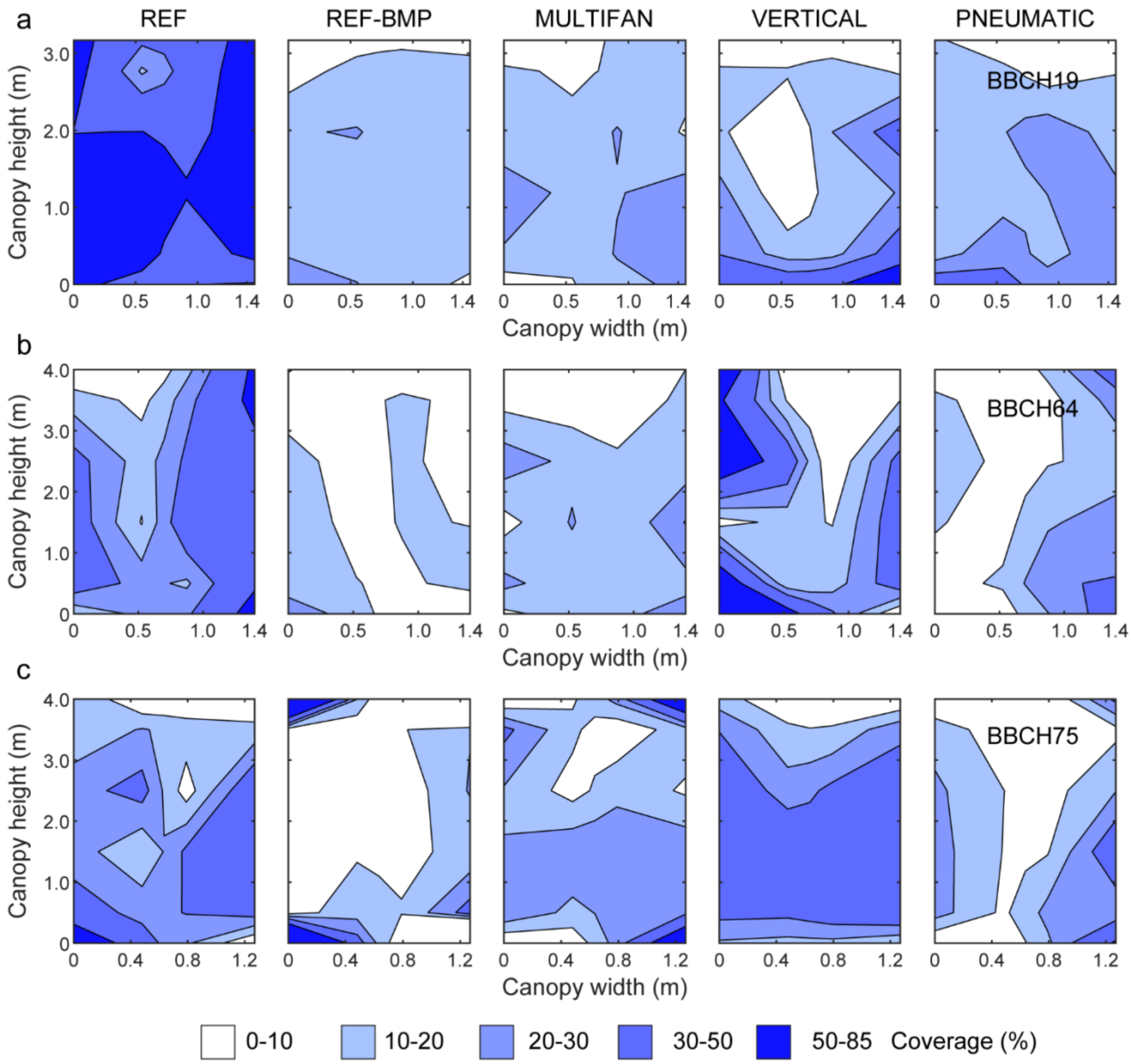

Fig. 5. Spatial distribution of spray coverage (%) for the five treatments within the whole tree canopy at three crop stages.

For BBCH64 (Fig. 5b), the REF sprayer obtained the highest coverage compared with that of the other four sprayers, and the coverage at the right side of the canopy was notably higher in the range of 30%–50%. Although the distributions of REF-BMP and PNEUMATIC showed relatively good uniformity, a large area inside the canopy with coverage below 10% was observed, showing the weakness of the sprayers in canopy penetration. The MULTIFAN showed good homogeneity, whereas the coverage at the upper canopy was low (below 10%). The VERTICAL showed relatively high coverage, with the largest variation. In addition, the coverage inside the canopy was low, indicating the difficulty in penetrating the tree canopy.

Considering stage BBCH75 (Fig. 5c), the REF achieved a high coverage for the whole canopy but had poor uniformity. In contrast, the REF-BMP had the lowest coverage of less than 10% for most of the canopy. The VERTICAL showed high coverage with good uniformity throughout the canopy. Additionally, the MULTIFAN provided a much more uniform distribution with higher coverage at the bottom part of the canopy than at the top. The coverage at the internal canopy was below 10% for PNEUMATIC, indicating its poor ability to force the droplet target into the inner canopy.

The corresponding impacts density distribution is shown in Fig. 6. In the case of BBCH19 (Fig. 6a), REF showed the lowest impacts density values, of less than 150 impacts cm^{-2} for most of the canopy areas, as well as poor uniformity. The REF-BMP and MULTIFAN demonstrated a good and uniform distribution with N_i ranging from 150 to 200 impacts cm^{-2} and 100 to 150 impacts cm^{-2}, respectively, in most of the canopy areas. A very uneven distribution with low N_i in the interior canopy was observed for the VERTICAL. The treatment of PNEUMATIC resulted in low variability within the canopy, but the impacts density inside the canopy had a marked decrease.

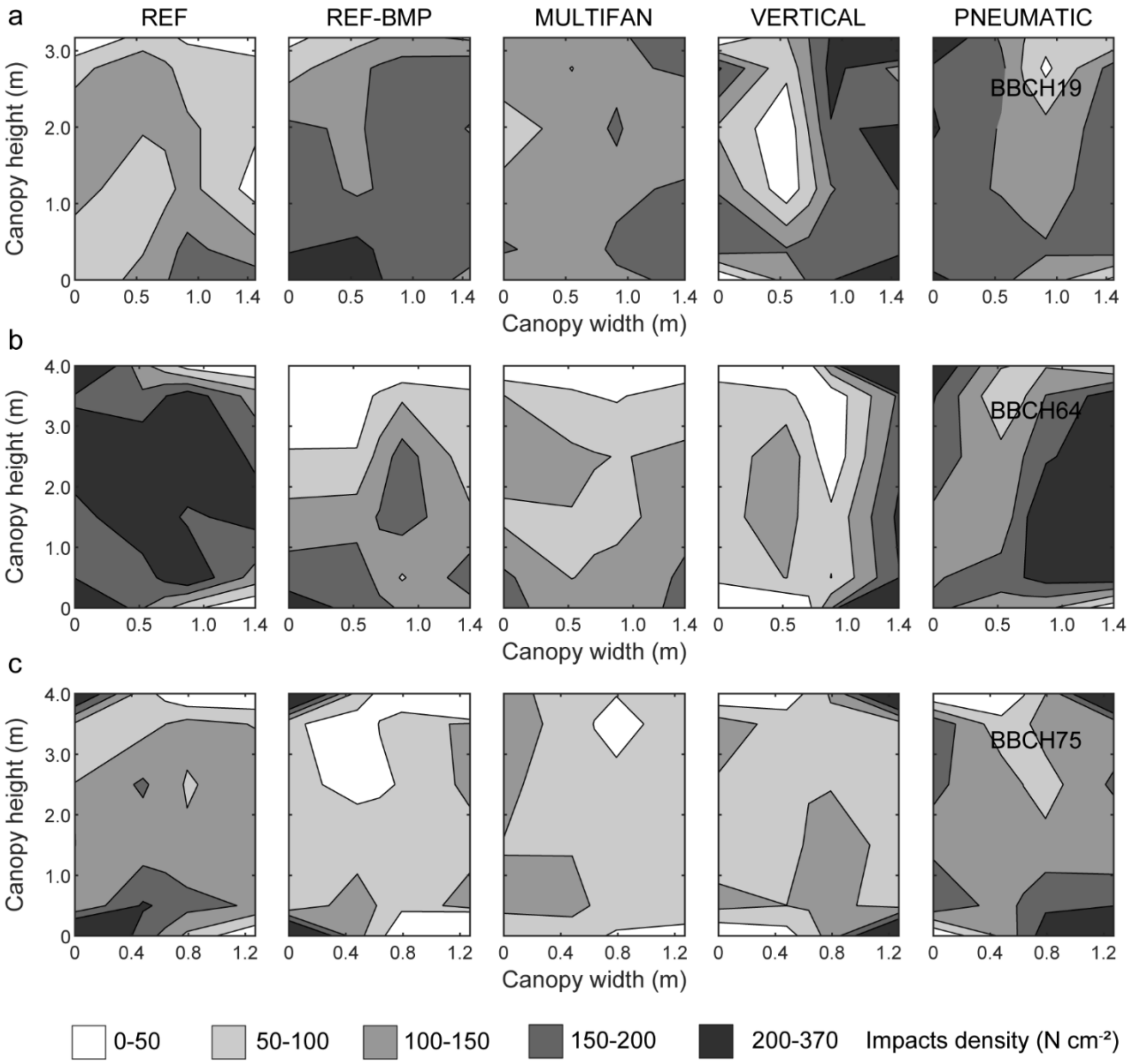

Fig. 6. Spatial distribution of impacts density for the five treatments within the whole tree canopy at three crop stages.

As for the middle stage BBCH64 (Fig. 6b), the distribution for the REF showed good uniformity with a very high impacts density in the range of 200–370 impacts cm^{-2} for most of the canopy area. The REF-BMP and MULTIFAN showed the same decreasing trend with an increase in canopy height. A very uneven distribution was observed on the right side of the canopy for the VERTICAL. The N_i distribution on the left and right sides of the canopy showed good uniformity for the pneumatic sprayer, but the right part had a remarkably higher impacts density.

In the case of stage BBCH75 (Fig. 6c), the REF and PNEUMATIC showed similar distributions with high impacts density ranging from 100 to 150 impacts cm^{-2} for most of the canopy area. The canopy area with N_i below 50 impacts cm^{-2} was the largest for the REF-BMP. The MULTIFAN and VERTICAL obtained a relatively uniform distribution with impacts density below 150 impacts cm^{-2}.

3.3. Spray quality distribution within the canopy

3.3.1 Spray quality distribution within the canopy height

The coverage and impacts density distributions along the canopy height at the three crop stages are shown in Fig. 7 and 8, respectively. At stage BBCH19 (Fig. 7a), a significant difference in spray coverage at different canopy height levels was only detected for the multi-fan sprayer. The coverage within canopy height showed much higher variability for the REF, and in contrast, the REF-BMP achieved a uniform distribution, showing the benefits of properly calibrating the machine according to the needs of the vegetation. In general, the coverage of the five sprayers, except for the REF-BMP, decreased with an increase in canopy height. Although the canopy height did not show a significant effect on the corresponding impacts density for each treatment (Fig. 8a), the REF-BMP and MULTIFAN achieved consistent spray quality across the canopy width with low variability. Additionally, the N_i at each canopy height was the lowest for the REF.

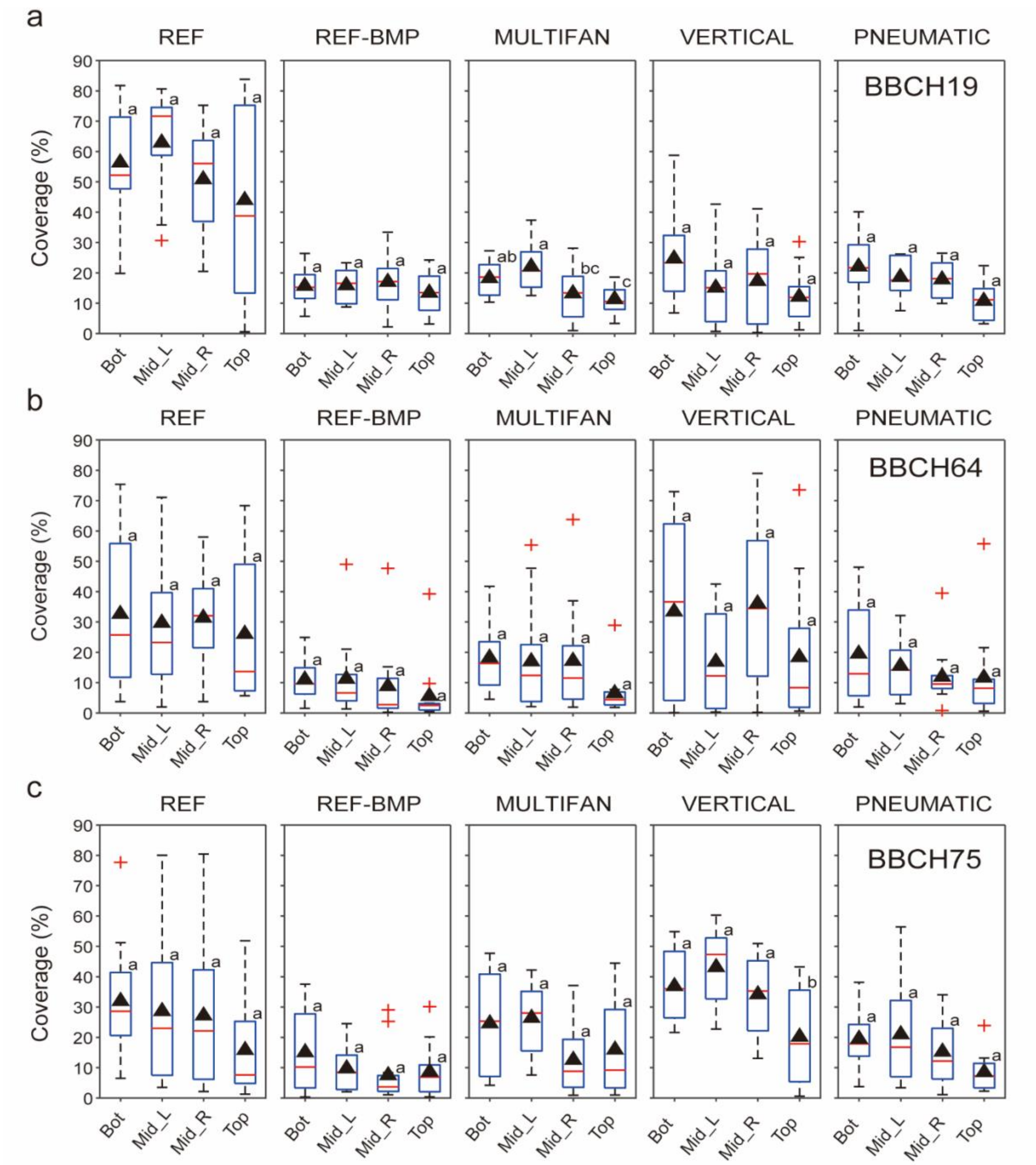

Fig. 7. Coverage distributions within the canopy height for the five sprayers at three crop stages. Bot (bottom), Mid-L (middle low), Mid-H (middle high), Top (top). The black solid triangle represents the mean value. Different letters in the top right corner of the box plot indicate significant differences (Student–Newman–Keuls test: $p < 0.05$).

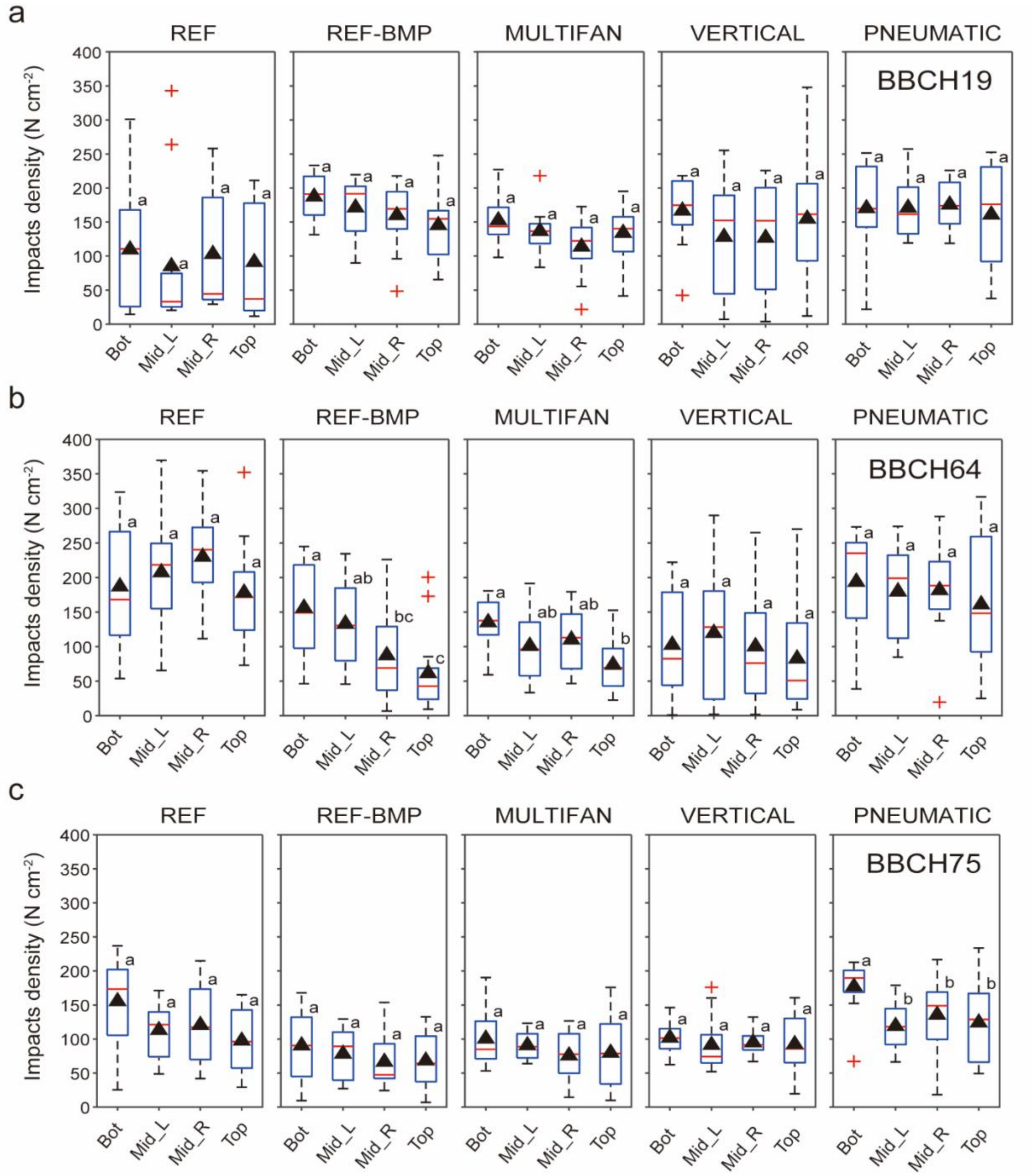

Fig. 8. Impacts density distributions within the canopy height for the five sprayers at three crop stages. Bot (bottom), Mid-L (middle low), Mid-H (middle high), Top (top). The black solid triangle represents the mean value. Different letters in the top right corner of the box plot indicate significant differences (Student–Newman–Keuls test: $p < 0.05$).

Considering stage BBCH64 (Fig. 7b), no statistical difference was detected for the coverage at different canopy heights, but the REF and VERTICAL achieved higher coverage with the greatest variability at each height. Similar to the case at the early stage, the coverage followed the same decreasing trend with an increase in canopy height. Moreover, a similar coverage pattern within the canopy height was detected for the REF-BMP and MULTIFAN, but the MULTIFAN provided a higher value at each canopy height. The corresponding impacts density among different canopy heights differed significantly only for the REF-BMP and MULTIFAN, with significantly lower values at the top of the canopy (Fig. 8b), and consistent with the coverage distribution, the same decreasing trend of N_i could be seen. Additionally, the REF and PNEUMATIC showed a very similar distribution with a higher impact's density at each height.

At BBCH75 (Fig. 7c), when canopy height was considered, a significant difference was only detected for the VERTICAL with a significantly lower value at the top canopy. A similar mean coverage at each canopy height was detected for the REF and VERTICAL, which was much higher than that for other treatments, but the REF showed the greatest variability. Additionally, coverage tended to decrease as canopy height increased. No statistical difference was observed for the corresponding impacts density within canopy height, except for the PNUEMATIC, which had a significantly higher value at the bottom of the canopy (Fig. 8c). The impacts density distributions within canopy height for the REF and PNEUMATIC were similar with higher values than those of the other three treatments, which gave similar and uniform distributions with a mean N_i of approximately 100 impacts cm^{-2} at each height.

Considering the effect of the canopy height on the spray coverage for different sprayers during the entire stage, a clear decreasing trend was detected in most cases, and the lowest coverage was always obtained at the top part of the canopy (Mid-H or Top). This suggests that it is a common difficulty to improve the spray quality of the top part of the tree canopy for different application techniques, which has also been presented in previous research (Duga et al., 2015; Cross et al., 2001a). Although the high-volume-rate treatment (REF) achieved a higher coverage at each canopy height than the other treatments, it showed the greatest variability, which implied that the conventional application without suitable adjustments led to inconsistent spray distribution within the target canopy. The sprayer with vertical booms achieved a much higher coverage at the exterior canopy for the dense apple tree at the latter two stages, resulting in a significantly higher overall mean coverage than that of other application techniques. For the number of impacts within the canopy height, each sprayer exhibited a much higher variability at BBCH64, but achieved a relatively uniform distribution at BBCH75. As the selected working parameters were the same for each treatment in the latter two stages, this difference reflected the high influence of the canopy structure on the spray quality. Moreover, similar to the case of the coverage, a decreasing trend for the impact density as the height increased was also observed, especially at BBCH64. Consistent with the distribution of the overall impact's density, the REF and PNEUMATIC showed higher N_i at each height for BBCH64 and 75.

3.3.2. Spray quality distribution within the canopy width

The coverage and impacts distributions of each sprayer within the canopy width at the three crop stages are shown in Fig. 9 and 10. At BBCH19 (Fig. 9a), the coverage varied significantly across the various canopy depths for the vertical boom sprayer, with a lower coverage at the internal part of the canopy (Int_L). The largest variability for coverage within the canopy depth was shown by the reference sprayer. In contrast, the REF-BMP, MULTIFAN, and PNEUMATIC obtained a uniform and similar coverage pattern regarding to the canopy width, indicating a good capability for droplet distribution inside the tree canopy. Consistent with the coverage distribution, a significant difference in the corresponding impacts density within the canopy width was only detected for the vertical boom sprayer with significantly lower N_i in the interior canopy (Int-L) (Fig. 10a). The REF exhibited the worst uniformity for N_i at each canopy width zone, but good uniformities were observed for the REF-BMP and MULTIFAN. Additionally, the N_i in the exterior canopy was higher than that inside the canopy for the PNEUMATIC.

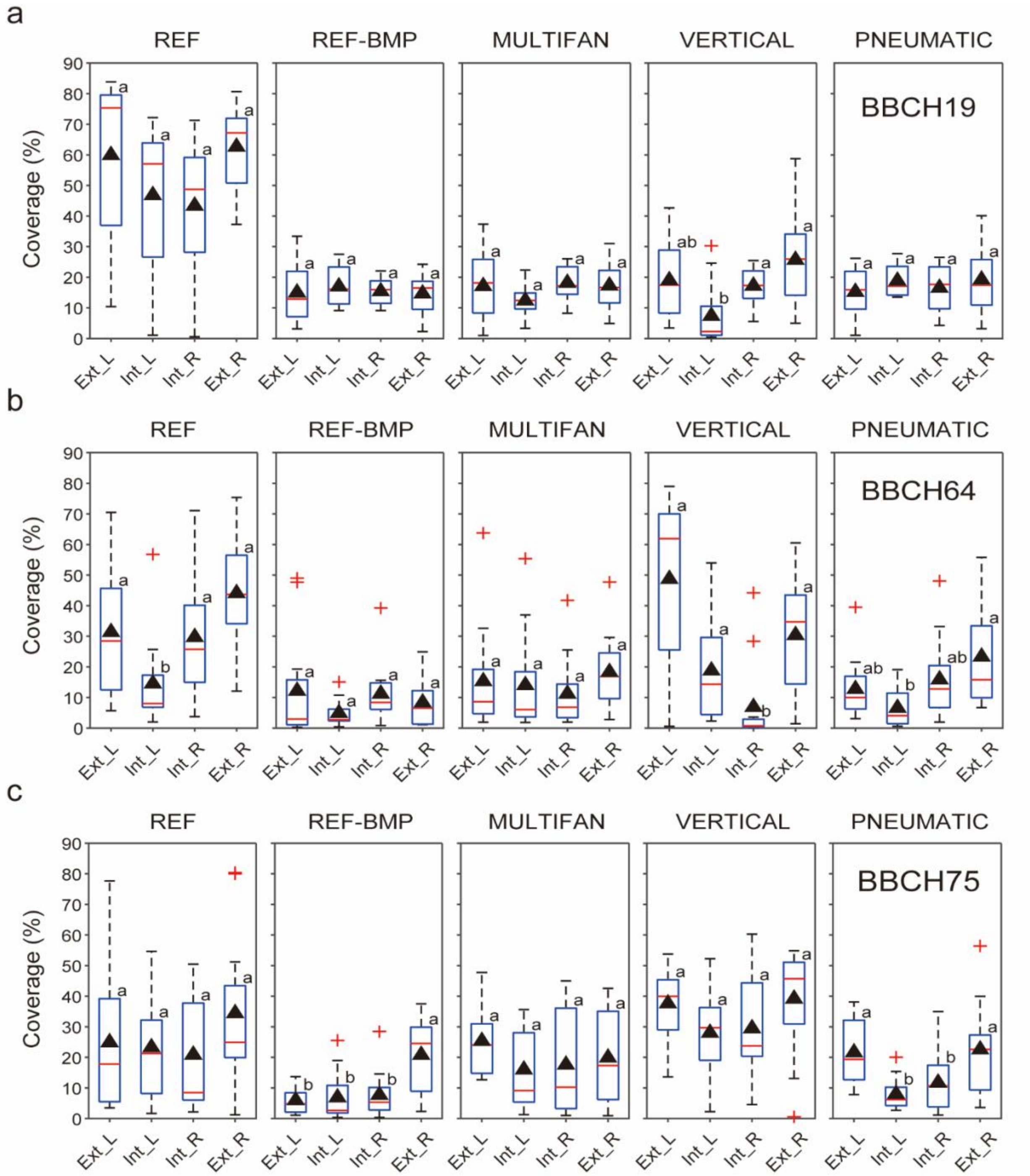

Fig. 9. Coverage distributions within the canopy width for the five sprayers at three crop stages. Ext-L (exterior left), Int-L (interior left), Int-R (interior right), Ext-R (exterior right). The black solid triangle represents the mean value. Different letters in the top right corner of the box plot indicate significant differences (Student–Newman–Keuls test: $p < 0.05$).

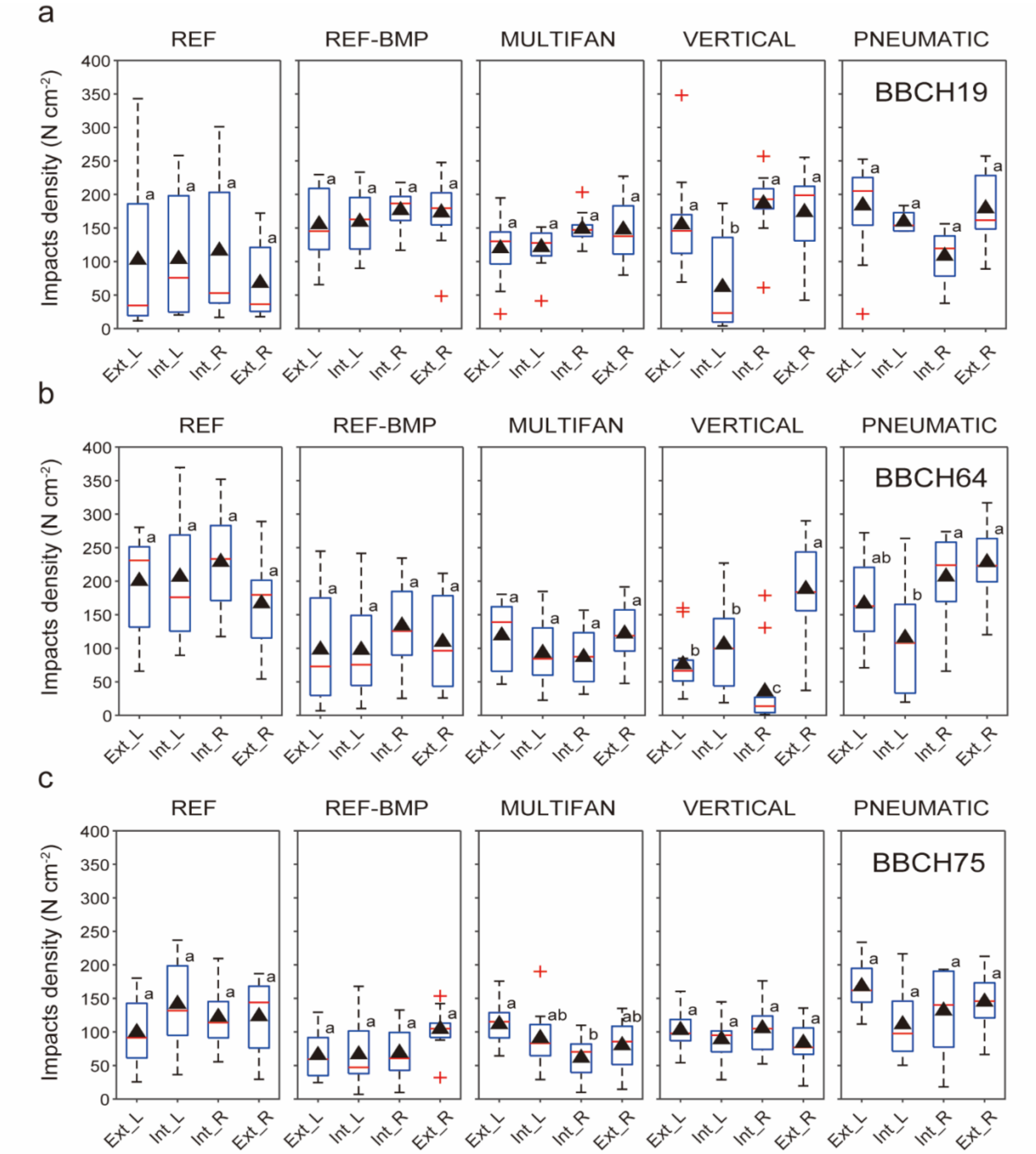

Fig. 10. Impacts density distributions within the canopy width for the five sprayers at three crop stages. Ext-L (exterior left), Int-L (interior left), Int-R (interior right), Ext-R (exterior right). The black solid triangle represents the mean value. Different letters in the top right corner of the box plot indicate significant differences (Student–Newman–Keuls test: $p < 0.05$).

For BBCH64 (Fig. 9b), the REF-BMP and MULTIFAN showed consistency again with small variations in the spray coverage at each canopy width, and no significant differences were observed. For the other treatments, the coverage inside the canopy was significantly lower than that of the exterior canopy. The variation in canopy width did not significantly affect the impacts density for the REF, REF-BMP, and MULTIFAN with relatively uniform distributions (Fig. 10b). The N_i in the canopy width zone varied significantly for the VERTICAL, and the N_i inside the tree canopy (Int_L) was significantly lower for the PNEUMATIC. Additionally, the REF and PNEUMATIC had considerably increased values in each canopy width zone.

With respect to BBCH75 (Fig. 9c), no statistical difference in the surface coverage was detected among the different tree canopy depths for the REF, MULTIFAN, and VERTICAL. The REF-BMP showed significantly higher coverage at the external canopy zone (Ext-R), more than double those of other widths. The coverage value inside the canopy was significantly lower than that of the exterior canopy for the PNEUMATIC. In general, much higher coverage was observed for each canopy width for the REF and VERTICAL. The corresponding impacts density within canopy width showed no significant difference for each treatment except for the MULTIFAN, with significantly lower N_i at the internal part of the canopy (Int-L) (Fig. 10c). The REF and PNEUMATIC exhibited much higher N_i values at each canopy width with greater variability, while the VERTICAL showed better uniformity. Consistent with the coverage distribution, the REF-BMP obtained a much higher N_i in the exterior canopy (Ext-R), while the impacts density distributions of the other three widths were very similar.

In general, the MULTIFAN provided the best uniformity of spray quality distribution within the canopy width throughout the stage. Consistent with the overall impacts, the REF and PNEUMATIC gave much higher N_i values at each canopy width for the latter two stages.

3.4. Efficacy on pest and disease control and potential pesticide reduction

Table 4 Complete pesticide application program; pesticide doses following the label's recommendation and pesticide dose reduction based on the adjusted volume rate.

Date	Product	Dose (cc, g/100 L)	Volume rate (L)		cc, g/ha		Dose reduction
			Conv.	Low vol.	Conv.	Low vol.	
6-Feb.	Copper Oxide 75% [WG] P/P	200	800	200	1.60	0.40	75%
20-Feb.	Sulphur 80% p/p WG	1000	800	200	8.00	2.00	75%
12-Mar.	Copper Oxide 75% [WG] P/P	200	800	200	1.60	0.40	75%
	Pyriproxyfen 10% p/v, (EC)	50	800	200	0.40	0.10	75%
	Sulphur 80% p/p WG	1000	800	200	8.00	2.00	75%
	Tebuconazole 25% [EW] P/V	60	800	200	0.48	0.12	75%
	Flonicamid 50% [WG] P/P	25	800	200	0.20	0.05	75%
26-Mar.	Bupirimate 25% [EC] P/V	50	800	200	0.40	0.10	75%
	Tau-fluvalinate 24% p/v. EW	20	800	200	0.16	0.04	75%
14-Apr.	Sulphur 80% p/p WG	1000	800	200	8.00	2.00	75%
	Acetamiprid 20% p/p	5	800	200	0.04	0.01	75%
	Fluopyram 20% + Tebuconazole 20% [SC] P/V	5	800	200	0.04	0.01	75%
23- Apr.	Sulphur 80% p/p WG	1000	1000	450	10.00	4.50	55%
	Fluxapyroxad 30% [SC] P/V	3	1000	450	0.03	0.01	55%
	Mancozeb 80% p/p (WP)	200	1000	450	2.00	0.90	55%
	Betaciflutrin 2,5% [SC] P/V	8	1000	450	0.08	0.04	55%
29- Apr.	Abamectin 1,8% + Chlorantraniliprole 4,5% [SC] P/V	75	1000	450	0.75	0.34	55%
	Sulphur 80% p/p WG	1000	1000	450	10.00	4.50	55%
	Mancozeb 75% [WG] P/P	200	1000	450	2.00	0.90	55%
	Trifloxistrobin 50%	15	1000	450	0.15	0.07	55%
9-May.	Chlorantraniliprole 20% [SC] P/V	20	1000	450	0.20	0.09	55%
	Mancozeb 75% [WG] P/P	150	1000	450	1.50	0.68	55%
	Myclobutanil 12,5% [EC] P/V	50	1000	450	0.50	0.23	55%
	Difenoconazol 25% p/v (EC)	25	1000	450	0.25	0.11	55%
18-May.	Trifloxistrobin 50%	15	1000	450	0.15	0.07	55%
	Mancozeb 75% [WG] P/P	200	1000	450	2.00	0.90	55%
	Chlorantraniliprole 20% [SC] P/V	20	1000	450	0.20	0.09	55%
	Sulfoxaflor 11,43% p/p	30	1000	450	0.30	0.14	55%
27-May.	Kresoxim-Metil 50% p/p (WG)	20	1000	450	0.20	0.09	55%
3-Jun.	Difenoconazol 25% p/v (EC)	20	1000	450	0.20	0.09	55%
9-Jun.	Kresoxim-Metil 50% p/p (WG)	20	1000	450	0.20	0.09	55%

Table 4 summarizes the actual pesticide application plan, the established applied volume rate for conventional and alternative spray techniques evaluated, and the corresponding PPP amount per unit area. A volume rate reduction of 75% and 55% depending on the time of the season was achieved. Consequently, as the pesticide doses in all cases were based on concentrations (g or cc per 100 L of water), following the pesticide label recommendation, the same reduction in terms of applied pesticides was achieved at the end of the season.

Table 5 Biological efficacy for rosy apple aphid (*Dysaphis plantaginea*) as a percentage (%) of living aphids. Data from in-field monitoring in 2020.

Date	DALA[a]	CONTROL	REF	REF-BMP	MULTIFAN	VERTICAL	PNEUMATIC
19-May	1	100% a*	<5% b	100% a	100% a	100% a	100% a
22-May	4	100% a	<5% c	66% b	33% c	69% b	24% c
29-May	11	89% a	<5% c	23% c	13% c	39% b	0% c
02-Jun	15	83% a	<5% c	10% b	13% b	15% b	0% c

[a] Days After the Last Application.
* Values not followed by a common letter (in rows) are significantly different according to Student–Newman–Keuls test (P < 0.05).

The results of the control efficacy of rosy apple aphid (*Dysaphis plantaginea*) are displayed in Table 5. The control plots showed 100% of aphids alive (Brown and Mathews, 2014) at the beginning of the spray season, experiencing a natural decrease down to 83%. On the other hand, in experimental plots treated with the conventional sprayer, the samples yielded less than 5% of aphids alive on the four dates when the inspection was carried out. The experimental plots treated with the rest of the evaluated sprayers started with 100% of the presence of the pest but showed a decrease to an average of 48% in three days, 18% in ten days, and 9% in 14 days, indicating that rosy apple aphid was successfully controlled, even though the amount of pesticide was significantly reduced. The changes in the applied volume rate did not influence the final control of the aphid for the REF and PNEUMATIC treatments. For the rest of the tests, even assuming that statistically differences were found in practice, the average level of living aphids found (10-15%) can be considered as acceptable to ensure a reasonable agronomic control of the pest.

Table 6 Level of infection of powdery mildew **(***Podosphaera Leucotricha***)** in field monitoring in 2020. Incidence level in the scale of 1 (no presence) to 5 (severe infection).

Date	DALA[a]	CONTROL	REF	REF-BMP	MULTIFAN	VERTICAL	PNEUMATIC
19-May	1	5.0 a*	5.0 a	5.0 a	5.0 a	5.0 a	5.0 a
02-Jun	15	5.0 a	2.2 bc	2.6 b	2.0 bc	1.3 c	1.1 c

[a] Days After the Last Application.
* Values not followed by a common letter (in rows) are significantly different according to Student–Newman–Keuls test ($P < 0.05$).

The control efficacy of powdery mildew (*Podosphaera leucotricha*) (Table 6) between the control plot and the experimental plots treated with the five sprayers showed significant differences in the last evaluation date, two weeks after the last pesticide application. Non sprayed control area presented a severe infection level while, for the evaluated sprayers, powdery mildew presence was classified as no presence or light infection with values of incidence lower than 20% in all the cases, according to EPPO evaluation guidelines (OEPP/EPPO, 1988). A detailed analysis showed the best results obtained with sprayer equipped with vertical boom and pneumatic sprayers, both with significantly higher efficacy values than the other three evaluated techniques. In any case, none of those values showed important damage, as it was observed for the control plot. Among the sprayers, VERTICAL and PNEUMATIC resulted in the lowest incidence of powdery mildew, being significantly different from the REF-BMP treatment. Even that, a consistent decrease was observed in all treatments from the first to the second evaluation date, leaving the incidence below 25% and indicating the control of the disease according to the EPPO guide evaluation scale (OEPP/EPPO, 1988).

The presence of apple scab (*Venturia inequalis*) was very low for all treatments including the control plot. During the 2020 season, apple scab was present in less than 2.2% of the fruits in the experimental plots, considered as a low level of incidence of this specific disease (Chatzidimopoulos et al., 2020). There was no presence of codling moth in the control plot, nor was it in the rest of the low-volume-rate experiments carried out.

The results obtained concerning the pest and disease control efficacy in most of the cases were similar to those obtained with the conventional spraying process (REF), even with the substantial reduction in the total amount of pesticide. These results aligned with the European objective to reduce pesticide usage by 50% by 2030 (European Commission, 2020).

4. Conclusions

The results obtained after the complete field evaluation of the four selected spray technologies allow the following conclusions to be drawn:

- Results observed in values of pest/disease control level among the five evaluated tests, do not justify the high amount of pesticides applied in the conventional mode, as it is used by the farmer; additionally, normalized spray deposits on the canopy do not increase compared with those using low volume application rates.
- Adjustment of sprayers and selection of the optimal operational parameters according to the canopy characteristics allow to improve the quality of the pesticide application process, generating the same, or better, coverage in all zones of the canopy, with a considerable improvement in spray efficiency.
- A proper adjustment of the sprayers based on canopy characteristics allow to reduce the total amount of applied pesticide in accordance with the established requirement of the European Farm to Fork

Strategy. This reduction implies economic benefits and directly influences the environmental benefits of the spray process.

- A considerable pesticide dose reduction, ranging from 55% to 75% depending on the canopy development, has been achieved resulting in similar pest and disease control. This pest/disease control did not affect the quantity nor the quality of apple production.
- The pesticide dose for orchards in general, should not be based on the ground area. A proper recommendation should be implemented based on the canopy structure and dimensions.
- The optimal volume rate during spray application in orchards should be defined based on the canopy structure, with consideration of the sprayer technical characteristics. This conclusion implies that the recommendation of 1000 L ha^{-1} for some pesticide labels should be reviewed.

In general, this research underlined the difficulties to arrange field trials to evaluate effectiveness of different spray application techniques combining at the same time a proper evaluation of the spray distribution quality. However, obtained results demonstrated the great influence of the selected technology and, more than this, the extreme importance of a proper adjustment and selection of the operational parameters, demonstrating once more the importance of an accurate training.

CRediT authorship contribution statement

Emilio Gil: Conceptualization, Methodology, Resources, Investigation, Writing - Review & Editing, Supervision. Lu Xun: Investigation, Data Curation, Formal analysis, Visualization, Writing- Original draft preparation. Francisco García-Ruiz: Data Curation, Visualization, Writing - Review & Editing. Xavier Fàbregas: Investigation, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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