



RESEARCH ARTICLE

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Description of the airflow produced by an air-assisted sprayer during pesticide applications to citrus

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Abstract

Atmospheric drift of plant protection products is considered a major source of air pollution during pesticide applications. Citrus protection against pests and diseases usually requires application of these products using air-blast sprayers. Many authors have emphasized the influence of vegetation on the risk of spray drift. The aim of this work was to describe in detail how the airflow from an air-blast sprayer behaves when it reaches citrus trees and, in particular, the effect that the tree canopy has on this flow. Tests were conducted at a commercial citrus orchard with conventional machinery, placed parallel to a row of trees. Air velocity and direction was measured using a 3D ultrasonic anemometer in 225 points situated in three parallel planes perpendicular to the equipment. The stability of the airflow at each measuring point was studied and the mean velocities were graphically represented. Two vortices, one behind the canopy, and another over the tree, have been deduced and never been reported before. Both may have an important influence on the trajectories of the sprayed droplets and, as a consequence, on the way in which plant protection products are diffused into the atmosphere. Observed turbulence intensities were higher than in similar experiments conducted in other tree crops, which may be attributable to the higher air volume generated by the machinery used for citrus protection and to the higher foliage density of citrus orchards.

Additional key words: environment; axial fan; drift; risk; CFD; *Citrus sinensis*

Abbreviations used: CFD (computational fluid dynamics); IPM (integrated pest management). **Parameters:** I (intensity of turbulence, %); u_x (instantaneous wind speed in the x direction, m/s) U_x (mean wind speed for a period of time in the x direction, m/s), u'_x (difference between the u_x and U_x in the x direction).

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Introduction

Drift is recognised as being the most important source of diffuse environmental contamination caused by pesticide application (Jong *et al.*, 2008; Maski & Durairaj, 2010). ISO Standard 22866 defines spray drift as the quantity of plant protection product that is carried out of the sprayed (treated) area by the action of air currents during the application process (ISO, 2005). Drifting material may take the form of droplets, dry particles or vapour. It has potential negative effects on living organisms in areas adjacent to treatment, particularly water surfaces, affecting nearby residents, bystanders and fauna and flora (Hamey, 1999; Ver-

cruysse & Sterbaut, 2002; De Schamphelre *et al.*, 2007). Thus, this should be minimized as much as possible.

The amount of drift generated during plant protection treatments depends, among other factors, on the characteristics and geometry of the culture (foliage density, dimensions, etc.) (Raupach & Leys, 1999; Praat *et al.*, 2000; Gil & Sinfort, 2005; Endalew *et al.*, 2006, 2009) and the machinery setup, *i.e.* sprayed volume, use of fans, tractor speed, etc. (Farooq & Salyani, 2002; Van de Zande *et al.*, 2004; Derksen *et al.*, 2007; Zhu *et al.*, 2008; Nuytens *et al.*, 2011). The importance of using such specific information has been highlighted also for assessing environmental and health risks of

the use of plant protection products (Ramos *et al.*, 2000).

In order to understand how the spray drifts, it is important to study the behaviour of the airflow around the canopy. Airflow will affect the trajectory that the droplets will follow (Fox *et al.*, 2008). For this reason, several studies have investigated the air velocities generated by the fan (Hetherington, 1997). Some of them have placed anemometers at different distances and heights from the air output and measured air velocities in a stationary position (García-Ramos *et al.*, 2012), as a first step to understand the air movement during the spray. It is well known that these stationary measures should be different from those taken when the sprayer moves. However, some authors have reported that they have a close relationship (De Moor *et al.*, 2002). At the same time, physical-mathematical models based on the theory of the turbulent jet (Abramovich, 1963) have been developed to characterise this airflow (Reichard *et al.*, 1979; Brazee *et al.*, 1981; Fox *et al.*, 1992).

Leaves and branches generate aerodynamic resistance to the passage of air. It results in additional flow turbulence both within the canopy and at its boundaries (Su *et al.*, 2008; Finnigan *et al.*, 2009). Vegetation dissipates the kinetic energy of the air, causing a reduction on its speed (Belcher *et al.*, 2003; Yi, 2008; Yue *et al.*, 2008). Studies of the turbulent nature of fan airflow as it passes through foliage have confirmed reductions in momentum and turbulent kinetic energy (Walklate *et al.*, 1996). Vegetation absorbs part of the energy produced by the fan, which can help to reduce spray drift (Hofman & Solseng, 2001).

Spain is the leading citrus producer in Europe and the fifth worldwide. Cultivated surface in Spain is around 330,000 ha, which highlights its economic importance. At present, citrus protection against pests and diseases is based on integrated pest management (IPM). IPM is a combination of biological, biotechnological and crop growing measures that include the use of chemical plant protection products. These are normally applied using air-blast sprayers. The application volume ranging between 1,000 and 5,000 L/ha, depending on the pest or disease and on tree size.

In air-blast sprayers, the mixture of plant protection product and water passes, under pressure, through nozzles which fragment the liquid into multiple droplets. These are transported to the target by the effect of the pressure itself and a turbulent air current generated by an axial fan. This air current also serves to move the leaves and helps the mixture to penetrate the canopy. The air volumes that are currently applied range between 40,000 and 100,000 m³/h.

It is estimated that losses due to atmospheric drift in the case of citrus applications amount to as much as

17% of the total quantity of mixture employed (Chueca *et al.*, 2011).

The influence of vegetation on the risk of spray drift has been demonstrated in vineyard treatments (Balsari & Marucco, 2004; Pergher & Petris, 2007). In the case of citrus, several studies have been conducted to enable a better understanding of droplet deposition within the tree canopy (Juste *et al.*, 1990; Farooq & Salyani, 2002). Others have assessed the risk of spray drift based on the characteristics of the machinery used for spraying and/or on environmental considerations (Farooq & Salyani, 2004; Cunha *et al.*, 2012). To the best of our knowledge, no previous studies have described the influence of canopies on the air currents induced by the fan around the canopies. Vegetation has been shown, however, to be the most influential factor affecting drift in grapefruit treatments. The importance of understanding the interaction between trees and air currents has been highlighted (Stover *et al.*, 2002).

Computational fluid dynamics (CFD) is a computer-based tool that makes it possible to represent flows through making numerical approximations of the equations that govern fluid motion (Versteeg & Malalasekera, 1995). It has been used to model the spray drift generated by air-assisted sprayers (Weiner & Parkin, 1993; Walklate & Weiner, 1994). Over time, CFD has been shown to be a useful and complementary tool for carrying out the complex and costly tests required to investigate the phenomenon of drift (Dekeyser *et al.*, 2013). In recent years, the use of CFD for the simulation of spray behaviour has noticeably intensified. This has been the case of studies involving spray treatments applied to vineyards. Furthermore, all of these studies that have taken into account the effect of vegetation have been focused on crops whose structures and foliage densities are very different from those of citrus trees. Citrus crop has a very dense vegetation and produces a high resistance to airflow.

Before generating a CFD model for air movement during spraying, field tests must be performed to have an approximate idea of the actual airflow. The air current generated by machines similar to those used in Spain in citrus cultivation has already been studied (Pascuzzi & Guarella, 2008). However, this work did not study the effect of vegetation on the air current.

For all the above reasons, the aim of the present work was to describe how the airflow from an air assisted sprayer behaves in a citrus orchard and, in particular, the effect that the tree canopy has on this flow and its turbulence.

The work was based on conditions relating to orange orchards in Spain. It was intended to serve later as a basis for generating CFD models of the behaviour of spray drift during treatment applications.

Material and methods

The main experiment was conducted at a commercial orchard growing 'Lane Late' oranges (*Citrus sinensis* (L.) Osb), in order to describe the major flow structures of the air movement. In this orchard, the mean canopy diameter was 3.8 m and the mean tree height was 2.6 m; the row separation was 6 m. It is worth noting that the apparent density of the canopy of some trees as seen from a moving sprayer increases with travel speed (Panneton *et al.*, 2005). In this work, this has been considered not to be a major factor as the canopy was already very dense.

Data from an additional lower scale experiment were used to confirm if the proposed airflow could be acceptable (hereafter referred as Confirmation experiment). These data came from an orchard with similar characteristics (variety, tree volume and spacing).

A conventional air-blast sprayer (Futur 1500, Pulverizadores Fede, S.L., Cheste, Spain) was used in all the experiments. The mean airflow rate provided by the fan under the test conditions was estimated to be 24.4 m³/s. This figure was calculated by multiplying the average air speed (m/s), measured at different points of the air outlet, and the surface of the air outlet (m²).

Velocity measurements

Some authors have analysed air currents within the vegetation with a view to understanding how droplets penetrate foliage (Svensson *et al.*, 2003; Panneton *et al.*, 2005). However, this has been considered out of the scope of this work, which is concentrated in the general movement of the air around the canopies, because it was assumed to have more influence on droplet drift.

The equipment was always placed parallel to a row of trees with the fan outlet in line with the trunk of a representative tree, because this is the zone where the airflow is more affected by the tree, since it is the widest and the densest part of the canopy. The minimum distance between the closest canopy point to the sprayer and the fan air outlet was 1.05 m (Fig. 1a). For practical reasons (the large number of measuring points and the availability of anemometers), air velocity measurements were taken without advancing the tractor.

In the main experiment, air velocity was measured in three parallel planes running perpendicular to the theoretical trajectory of the tractor: a central plane, hereafter called 'Plane $x = 0$ ', which coincided with the central plane of the air outlet and subsequently that of the trunk; and two other planes, which were located

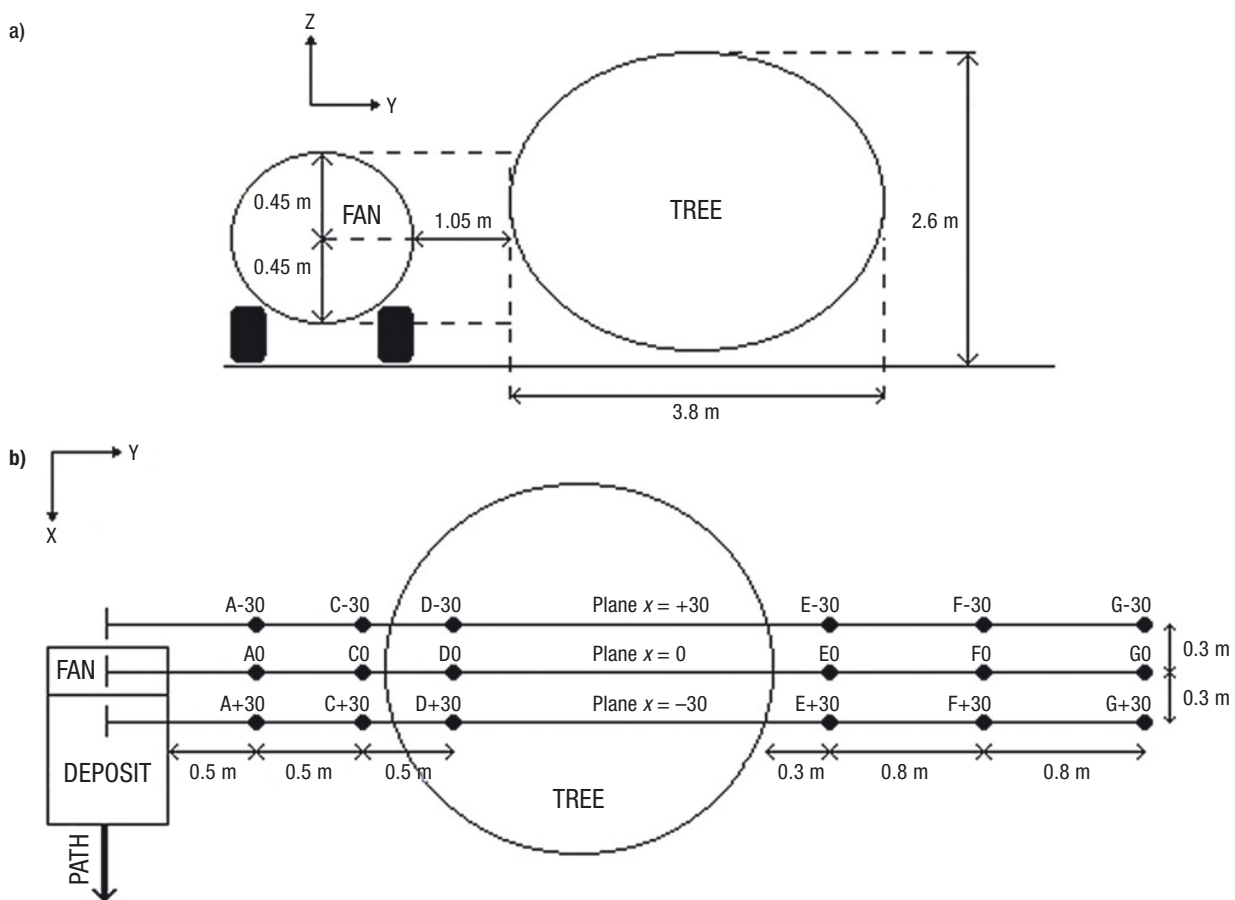


Figure 1. Elevation view of the fan position with respect to the tree (a); plan view of the layout of the measuring points (b).

30 cm before (Plane $x = +30$) and after this position (Plane $x = -30$) on the tractor path (Fig. 1b).

In this experiment, measurements were taken in each plane using a series of vertical metal posts positioned at specific locations (labelled A, C, D, E, F and G). The layout of the measuring points was the same in each plane (Fig. 2a). The posts labelled A were placed 50 cm from the equipment and measurements were taken at 20 cm intervals, starting at a height of 40 cm above the ground and continuing up to a height of 2.0 m. From this point upwards, measurements were taken at 50 cm intervals, up to a maximum height of 4.5 m. The posts labelled C were positioned 55 cm from each of the A posts and measurements were taken at 50 cm intervals, starting at a height of 25 cm above the ground and up to a maximum height of 4.5 m. The D posts, which were positioned 50 cm from the C posts, were placed inside the tree canopy and measurements were taken at 50 cm intervals, starting from a height of 3.0

m and up to a maximum height of 4.5 m. Posts labelled E, F and G were positioned behind the canopy. The E posts were positioned 30 cm from the canopy edge, the F posts were positioned equidistant between the rows, and the G posts were positioned 30 cm before the next canopy. Measurements relating to these three sets of posts were taken at 30 cm intervals, starting from a height of 30 cm above the ground and continuing to a height of 3.0 m and then at 50 cm intervals up to a maximum height of 4.5 m. Additional horizontal posts (labelled B), positioned at a height of 1.8 m, were used to take measurements at 20 cm intervals from the centre of the fan to the position corresponding to post A. Measurements were taken at a total of 201 different points (67 points per plane, in three planes). In similar studies, only one side of the sprayer was considered (Da Silva *et al.*, 2006; Endalew *et al.*, 2010a,b, 2011, 2012; Duga *et al.*, 2013), although it is well known that air distribution of axial fans is asymmetric. This as-

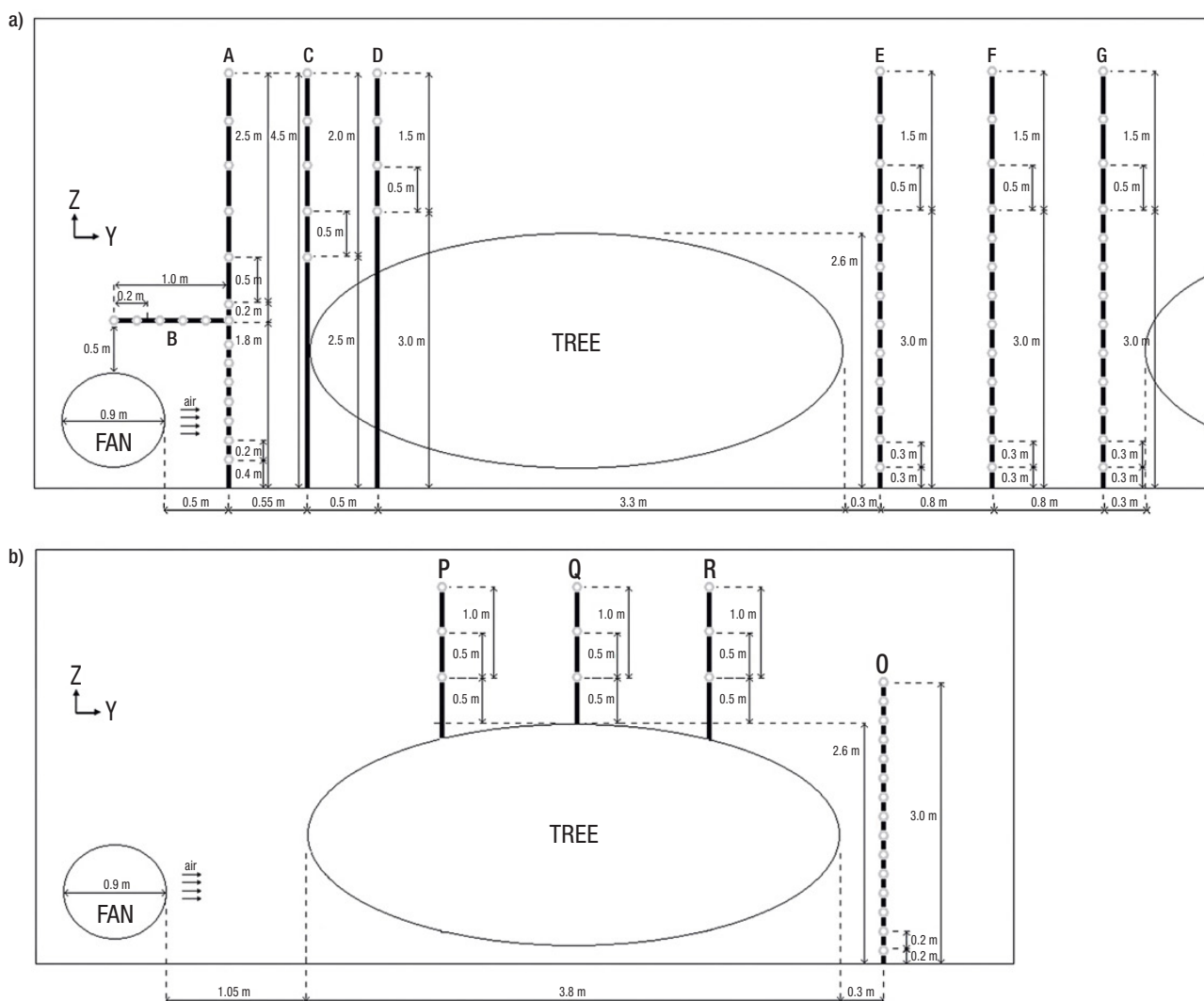


Figure 2. Elevation view of a measuring plan showing location of the sensors (a); setup of the confirmation experiment (b).

sumption is made not only to reduce the costs of assays but also because manufacturers are making an important effort to reduce this asymmetry by including air deflectors and improving the design of their fans.

Data from the confirmation experiment came from Plane $x = 0$. In this setup, post O was located 30 cm after the canopy and air velocities were measured from a height of 20 cm above the ground and continuing to a height of 3.0 m. Three additional posts were used (P, Q and R) (Fig. 2b). On these, air velocities were measured at 50 cm, 100 cm and 150 cm above the top of the canopy. The number of measuring points was 24.

Air velocity and direction were measured at each point using a 3D ultrasonic anemometer (WindMaster 1590-PK-020, Gill Instruments Ltd., Hampshire, UK) which was fixed to the post in a horizontal position and in such a way that it did not interfere with the air current. The accuracy was 1.5 % and the resolution was 0.01 m/s. The acquisition time was 60 s at each measuring point, with a sampling frequency of 1 Hz (60 samples). The three instantaneous components of air velocity were recorded, with U_x as the horizontal direction parallel to the row of trees, U_y as the perpendicular horizontal direction and U_z as the vertical direction.

During the experiments, the meteorological conditions were recorded using a 2D ultrasonic anemometer (WindSonic, Gill Instruments Ltd., Hampshire, UK) and with a thermo-hygrometer (Log32, Data logger, Dostmann Electronic GMBH, Wertheim-Reicholzheim, Germany), positioned at a height of 5.0 m above the ground. The sensors were located close to the orchards, without obstacles between them and the experiments and avoiding any kind of mutual interference. Sampling frequency was 1 Hz. Tests were conducted over four days with atmospheric conditions that were as similar as possible. The average air temperature was 26.3°C and the average relative humidity was 67.9 %. Table 1 shows the average module and direction of wind during the experiments. Wind directions were measured anti-clockwise from Plane $x = 0$, in such a way that 0° represents the main direction of air leaving the fan and 90° the theoretical tractor path. During the experiment wind speed vectors had low magnitudes and ranged between 0.8 m/s and 1.2 m/s.

Influence of wind in the air speed produced by the sprayer below 4.0 m was assumed to be negligible due

to the low magnitudes of measured wind speed, although it is acknowledged that there is some effect of natural wind in the air speed measurements that depends on height (Georgiadis *et al.*, 1996). Furthermore, Endalew *et al.* (2009) indicated that typically it is assumed that the effect is only significant above 1.5 times the height of the trees (in our case this equals 3.9 and for this reason we assumed negligible effect below 4.0 m).

Data processing and representation of results

Firstly, the stability of the airflow at each measuring point was studied. For this, the average of each air velocity component was calculated every 10 s during 1 min (6 measures). Then, the coefficient of variation of these 6 measures was calculated per each velocity component at each point. Flow was considered to be stable at a given point if the coefficients of variation of all the components of the air velocity were below an arbitrary value of 30 %.

The mean velocities were then graphically represented. To do this, three vector diagrams were generated, coinciding with each of the measurement planes ($x = -30$, $x = 0$ and $x = +30$) and using the coordinates of the mean velocities U_y and U_z . A further 6 diagrams were generated: one for each set of vertical posts, which reflected the average wind speeds U_x and U_z perpendicular to these planes.

Estimation of turbulence intensity

Turbulence intensity is a parameter that quantifies the fluctuations of the airflow. It is a scaled measurement of turbulence, since it is calculated with respect to the average air speed, and it is expressed as a percentage. An airflow without any fluctuation of the air speed or direction would have 0 % turbulence intensity. However, due to the way that this parameter is calculated, values greater than 100 % are possible. This happens, for example, when the average air speed is very small and there are large fluctuations of air speed.

To estimate its value, we started with the following equation for wind speed at a specific location:

$$u = U + u' \quad [1]$$

where u is the instantaneous wind speed (data provided by the anemometer), U the mean value of the velocities at that point and u' the fluctuation, or difference, between the instantaneous speed and the mean value.

Table 1. Wind speed module and direction (Wind direction is referred to the fan outlet, measured anti-clockwise from Plane $x=0$)

Measured plane	Wind speed	Wind direction
$x = -30$	0.8 m/s	60°
$x = 0$	0.9 m/s	74°
$x = +30$	1.2 m/s	216°

Based on Eq. [1], it is possible to calculate the intensity of turbulence (I , %). This parameter compares the significance of the components of the fluctuating wind speed with the module of the average air velocity. It is defined as:

$$I(\%) = 100 \sqrt{u_x'^2 + u_y'^2 + u_z'^2} / \sqrt{U_x^2 + U_y^2 + U_z^2} \quad [2]$$

It should be noted that instead of using Eq. [2], other authors (Delele *et al.*, 2005; Endalew *et al.*, 2009) have averaged the values of the three components of the fluctuating velocity. Their values therefore differ from ours by a factor of $\sqrt{3}$.

Results and discussion

Velocities analysis of the main experiment

The conditions for stable air velocity were met at all points on the vertical posts below a height of 3.0 m and at all points on the D posts. However, stability was not attained at all the points above this height, and particularly not on the A and C posts, which were closer to the fan and therefore strongly affected by it (Table 2). Stability was observed at all points on the B posts and they have therefore been excluded from this table.

Fig. 3 represents measured air velocity in Planes $x = -30$, $x = 0$ and $x = +30$. Figs. 4 and 5 represent air velocity vectors (before and after the tree respectively) in perpendicular planes that include the posts with the same label letter. In the following paragraphs we will explain the results taking referring to both perpendicular sets of planes in order to have a three-dimensional idea of the air movement.

Fig. 3a shows the velocity vectors in Plane $x = -30$ (components U_y and U_z). In the area before the first tree (posts A-30, B-30 and C-30), the vectors of air velocity on post A-30 pointed at the sprayer, probably due to a combined effect of the aspiration of the fan and the high speed of the airflow in Plane $x = 0$ (Fig. 3b), which

may also cause aspiration. In Fig. 4a (components U_x and U_z for post A), most part of the U_x components were positive, pointing out in the direction of the theoretical movement of the tractor. Fig. 4a also confirmed that vectors on post A-30 were oriented towards the aspiration of the fan. In Fig. 3a, the vectors from the first metre above the ground of post A-30 suggested that the air could have been turning in an anticlockwise direction, indicating the possible presence of a small vortex next to the fan. The lower halves of posts C-30 and D-30 were also affected by suction, presenting negative vertical and horizontal components. As in the case of posts labelled A (Fig. 4a), Figs. 4b and 4c confirmed the aspiration effect and a large anti-clockwise vortex perpendicular to the direction of the main airflow. Fig. 5a also showed an anticlockwise reflux after the first tree (posts E-30, F-30 and G-30) and 2.7 m below the top of the canopy; this was fed by the air current which arrived from below the canopy. The width of the vortex was close to the distance between the canopies. On post E-30, above a height of 1.2 m, the vectors pointed towards the first canopy. This suggests that the vegetation barely allowed the air current to cross it and, at the same time, that suction took place, probably due to the effect produced by the current below the canopy. From heights above 3.0 m, the directions of the velocities on posts E-30 and F-30 were mostly oriented towards the sprayer. This could be due to the existence of a vortex on the surface of the canopy of the first tree. Horizontal average air speeds measured in posts E and F were around 1.1 m/s, which were three times higher than the component of the average wind in the same direction, and for this reason wind was considered negligible. In the other hand, Figs. 5a and 5b showed a large clockwise reflux perpendicular to the direction of the main airflow (circulating in the opposite direction to the one observed before in Figs. 4a, 4b and 4c).

Fig. 3b shows the velocity vectors in the central Plane $x = 0$. It can be observed that the horizontal component U_y was positive and dominant below a height of 1.8 m on post A0, which was the area closest to the fan air outlet. For post B0, the vertical component U_z got larger when closer to the centre of the fan. For posts C0 and D0, the current followed the contour of the canopy. For posts E0, F0 and G0, however, it was again possible to observe the vortex between the trees. It was also possible to observe a reflux above the canopy, but this was less intense than the one observed in Plane $x = -30$ (Fig. 3a). In Plane $x = 0$, only the vectors of post E0 were orientated towards the canopy. The horizontal components of the velocities, U_y , were again almost always positive in F0 and G0 at heights above 2.1 m. Again, the wind was considered negligible compared to air velocities recorded in points above the canopies.

Table 2. Measuring points where stability was not attained (marked with ‘•’)

Planes	Height (m)	Masts					
		A	C	D	E	F	G
$x = -30$	4.0						
	4.5	•				•	•
$x = 0$	4.0	•	•				
	4.5	•	•		•	•	•
$x = +30$	4.0						
	4.5	•					

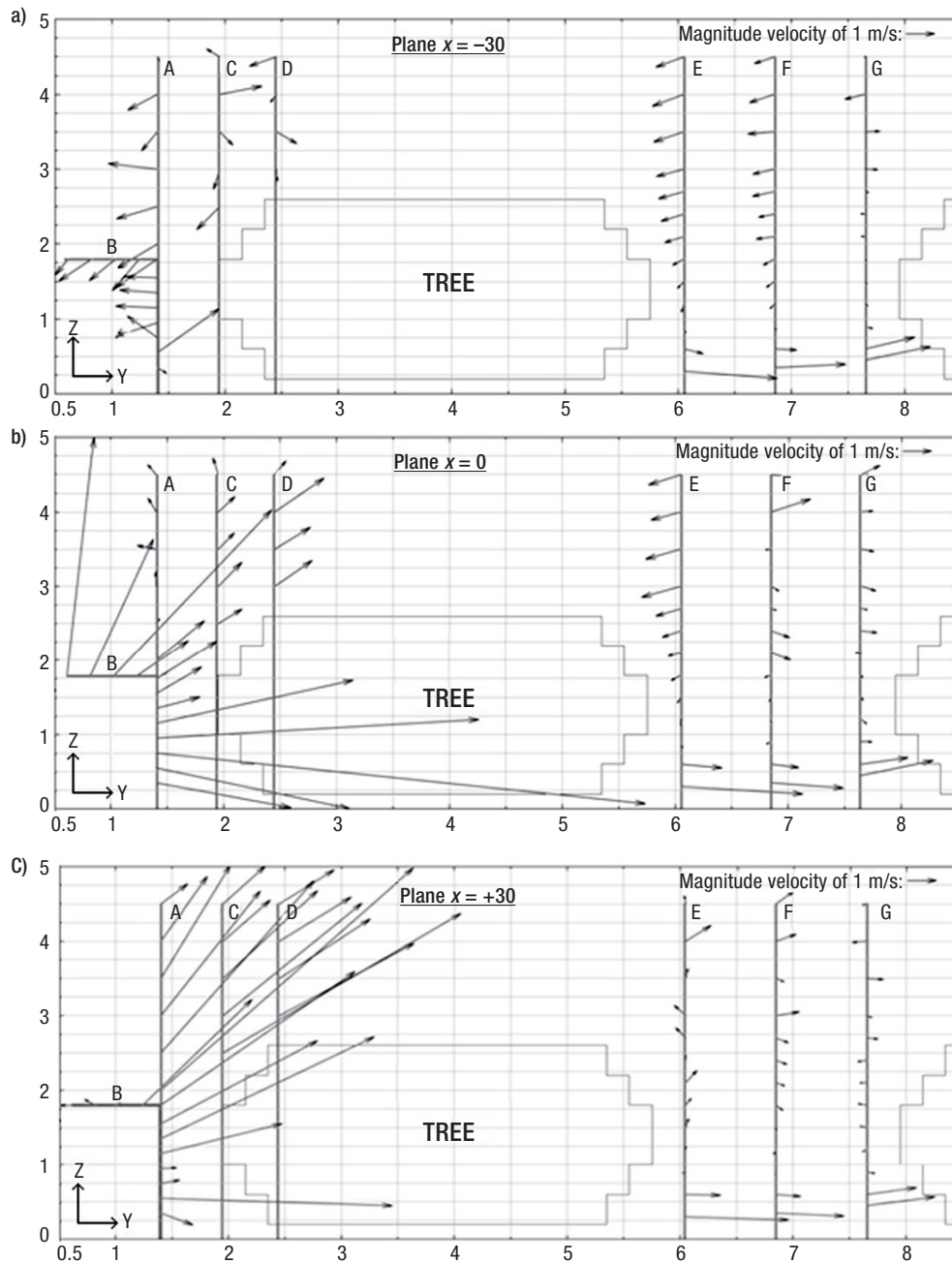


Figure 3. Horizontal U_y and vertical U_z velocities in a) Plane $x = -30$, b) Plane $x = 0$ and c) Plane $x = +30$. Distances in metres.

For Plane $x = +30$, the velocities were more intense in front of the tree (Fig. 3c). The U_z component was larger at points on posts A+30, C+30 and D+30 that were closer to the upper half of the canopy. All the components of the velocities were positive on these three posts. In this plane, as in Plane $x = 0$, the tree canopy increased the fluctuations of the air as it modified its trajectory. The existence of a vortex between the tree canopies was still perceptible, but its intensity decreased to the extent that the centre of the reflux was found to be located between posts F+30 and G+30. Meanwhile, the velocity vectors below 60 cm of height on these three

posts exhibited the same behaviour as in the other two planes, reflecting a strong air current under the canopy. After this zone, the velocity vectors pointed towards the first canopy up to a height of 3.5 m for post E+30. For posts F+30 and G+30, the velocity vectors displayed a similar trend to that observed in Plane $x = 0$. The vertical velocities in the area between the canopies were negative on posts G0 and G+30, as also observed for posts E-30, E0, F-30, F0 and F+30. In general, air speed above 4 m was higher than measured wind.

Observing the plane formed by the E posts (Fig. 5a), situated after the canopy, all the vectors in E-30 and

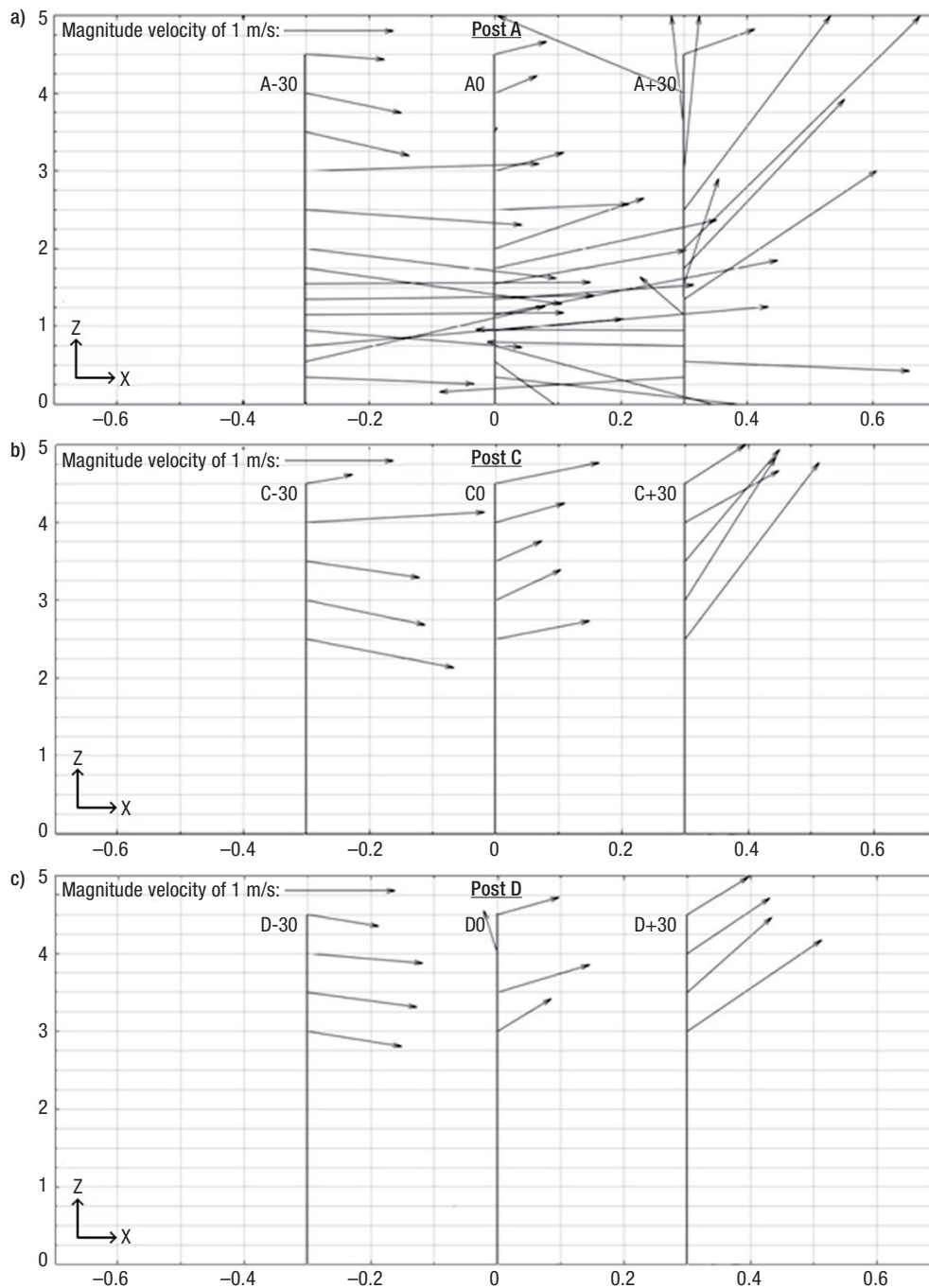


Figure 4. Horizontal U_x and vertical U_z velocities for a) posts A-30, A0 and A+30; b) posts C-30, C0 and C+30 and c) posts D-30, D0 and D+30. Distances in metres.

E+30 had negative horizontal components, U_x , while in Plane $x = 0$, the signs of U_x varied up to a height of 3.0 m. The influence of the vortex above the first tree (Figs. 3a and 3b) can be clearly appreciated. The U_z component was negative at heights above 3.0 m for posts E-30 and E0 as a result of the direction of the reflux, whereas the vertical velocity was positive on post E+30 because there was no vortex in the Plane $x = +30$. The U_x velocities for post F-30 had similar directions as for post E-30 (Fig. 5b). U_x for points on

posts F0 and F+30 were more variable than for those on E0 and E+30. In the plane formed by the G posts (Fig. 5c), a change in the direction of the velocities was observed at points on post G-30 with respect to points on post F-30. The velocities for posts G0 and G+30 were, to a certain extent, similar to those for posts F0 and F+30, and they were in the opposite direction in the horizontal component, thus giving an idea of how the vortex above the trees rotates in the direction of the major flux. The vertical component U_z prevailed over

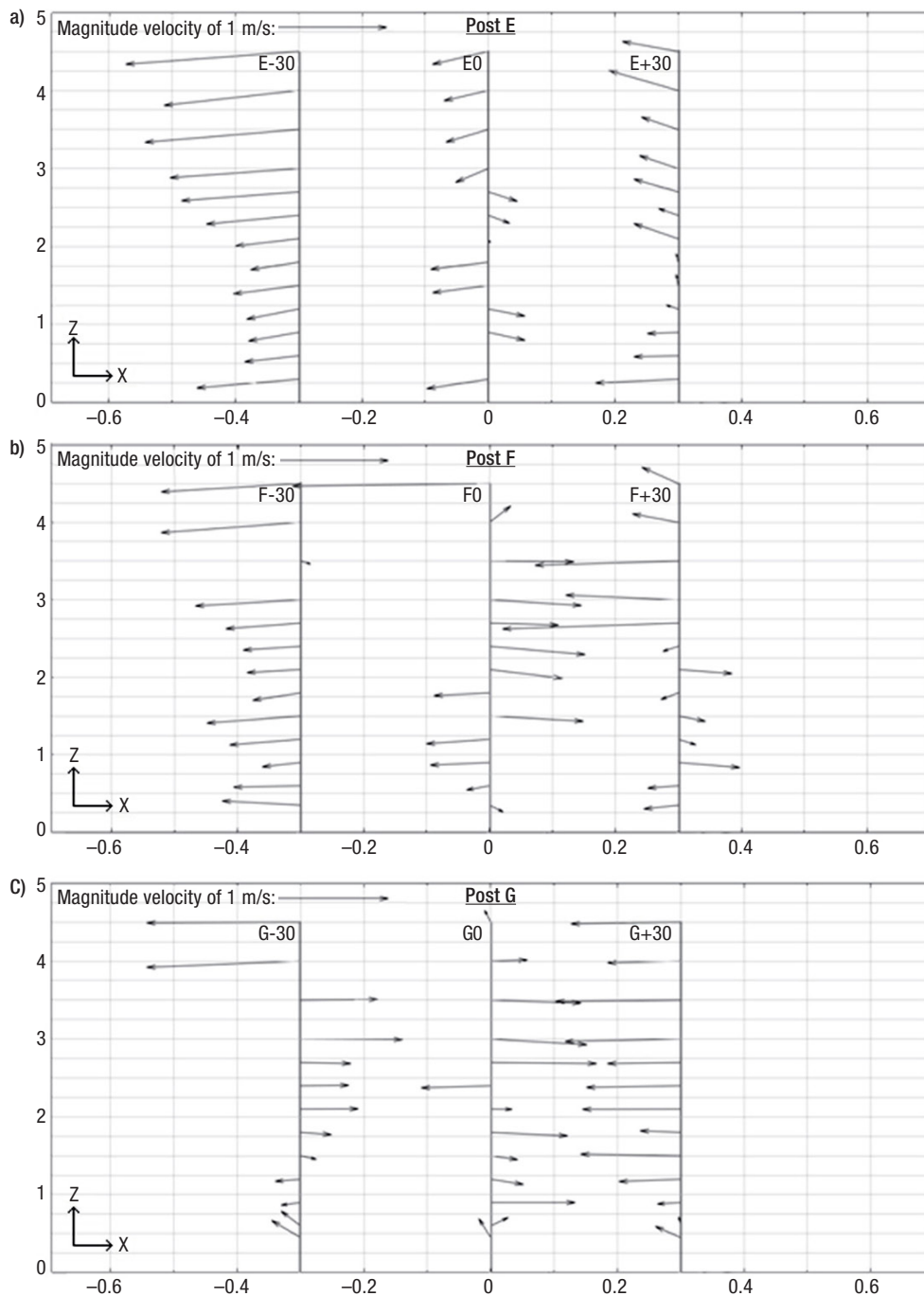


Figure 5. Horizontal U_x and vertical U_z velocities for a) posts E-30, E0 and E+30; b) posts F-30, F0 and F+30 and c) posts G-30, G0 and G+30. Distances in metres

the first 60 cm, most probably because of the small 45 cm elevated platform of soil on which the second tree was standing. Above a height of 90 cm, the U_x component was larger than for the previous posts.

It is important to note that in tests performed in other crops such as vineyards (Da Silva *et al.*, 2006) and pear orchards (Endalew *et al.*, 2010a,b), it was observed that the airflow crossed the vegetation in the horizontal component. Therefore, U_y was positive both when entering and leaving the vegetation. However, in our

experiments, we observed the presence of a reflux, spanning the full height of the trees, after the canopy. Below the canopies, the air current was only horizontal and positive up to a height of 60 cm, which was where the vegetation presented least resistance.

To the best of our knowledge, the generation of a vortex over the canopy of the first row of trees has never been previously reported. This reflux may affect drift even more than the one between the canopies, since according to its intensity and size, it could condi-

tion the time during which the sprayed droplets would remain in the air and also their trajectories.

One explanation for this behaviour of the air in citrus groves is that the density of the vegetation is generally greater than in vineyards or pear orchards. The absorption of momentum and the drop in pressure were much higher, so the airflow would only have found an escape route below the canopy. It is also observed in the field that as the velocity of the air current over vegetation increases, tree leaves tend to show greater resistance to the air, assuming vertical positions and moving with the branches. This would have produced a shear load on the flow, making air circulation difficult and forcing the air to alter its trajectory with the result of only a small part of the current managing to cross the canopy.

Results from the confirmation experiment

Fig. 6 shows the vector velocities found in the confirmation experiment. Part of the vortex between the canopies of the next row can be observed in points of post O, as it was in Figs. 3a and 3b. The vortex is fed by the air passing below the canopy and the upward air current produced by the fan above the canopy of the first tree. All the vertical values U_z were also negative, whereas horizontal component changed the direction from 1.2 m. The lower part of the vortex above the canopy of the first tree is also observed from the direction of the velocity vectors on points of posts P, Q and R.

Estimation of turbulence intensity

Fig. 7a shows the values of turbulence intensity versus height. For post A-30, which was the closest to

the aspiration zone, the intensity of the turbulence significantly decreased between heights of 40 cm and 60 cm and then gradually increased above 300 cm. The same tendency was observed at post C-30, as the aspiration current remained stable. As the height increased, the air current became more vulnerable to the effects of external forces and the intensity of turbulence increased. The high turbulence intensity registered in the first 60 cm at post A-30 may have been due to the small vortex that was described in Fig. 3a.

On the other side of the canopy, the airflow produced little turbulence in the first 30 cm from the ground. This was probably because it was a current with only slight vertical variations and had few obstacles in its path and because the air currents that passed above the tree canopy had little effect on the flow. Turbulence intensity increased and was greater at post G-30, which was closer to the second tree than the other posts. This was probably because the modules of the velocities were close to zero and, therefore, they were more susceptible to external factors. Above a height of 4.0 m, and above the canopies, the intensity of turbulence registered at the three posts seemed to increase. This was probably due to fluctuations in the second reflux above the canopy (Fig. 3a).

In Plane $x = 0$, the flow was more stable at the sprayer air outlets (Fig. 7b). It should be noted that in these areas the velocities were very high (Fig. 3b) and so were only minimally modified by their surroundings. Turbulence intensities were the highest at the points furthest from the fan.

After the first canopy, the flow was more stable over the first 30 cm above the ground. As for Plane $x = -30$, the fluctuations in turbulence intensity for post E0 were lower than for the other two posts. The air velocities at the different points on post G0 were very low and therefore more susceptible to surrounding influences.

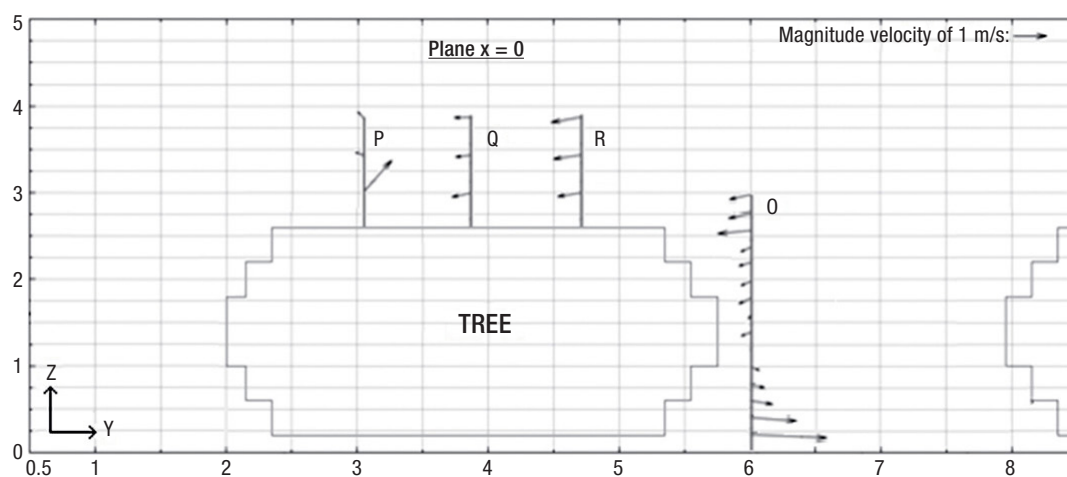


Figure 6. Confirmation experiment results: Air velocities in Plane $x = 0$.

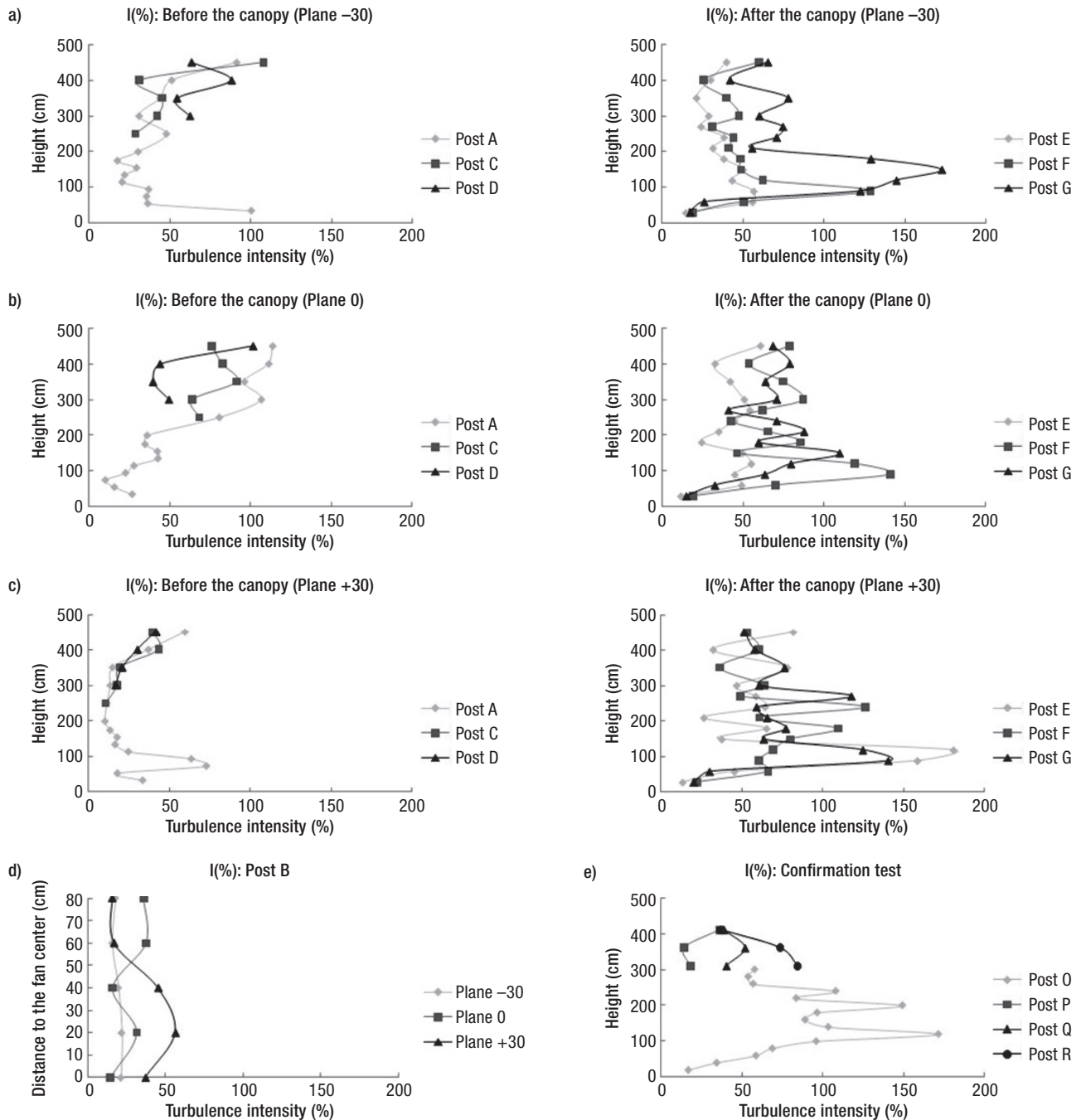


Figure 7. Turbulence intensity of the vertical posts for a) Plane $x = -30$, b) Plane $x = 0$, c) Plane $x = +30$ before and after the tree canopy; d) for the horizontal post B in the different planes; e) turbulence intensity for Plane $x = 0$ in the confirmation experiment.

At a height of 4.5 m, the values for the three posts converged. Above 3.0 m, posts E0 and F0 displayed lower intensities of turbulence than the corresponding posts in Plane $x = -30$ (E-30 and F-30 in Fig. 7a); this may have been related to a lower intensity of reflux above the tree canopy.

The airflow in Plane $x = +30$ (Fig. 7c) was less turbulent than in the two previous planes. As previously in Fig. 7b, the velocities at the three posts: A+30, C+30 and D+30 were very high, so the perturbations would

not have influenced the velocity components very much. The high turbulence intensity observed at heights of 60 and 80 cm coincided with the smallest module vectors of Fig. 3c.

Behind the canopy, the flow displayed little turbulence over the first 30 cm of height. For post E+30, the turbulence intensity greatly varied between heights of 90 and 120 cm above the ground, where the lowest velocities were recorded for this post. Air velocities increased above 150 cm and at these points the turbu-

lence intensity decreased. A more turbulent flow was recorded for posts F+30 and G+30, which appeared to become steadier at heights above 3.0 m. No specific flow structure was apparent in Fig. 3c. In addition, the velocity vector modules were smaller than in the other planes and with many variations in the signs of their vertical components.

The air turbulence intensity for horizontal post B is shown in Fig. 7d. The area with less turbulence was found in Plane $x = -30$. In Plane $x = 0$, the current was less turbulent in the central area of the fan and at a distance of 40 cm, which coincided with the highest recorded velocities in this plane. The velocity at 20 cm was lower than at 0 or 40 cm, with this difference in velocities on either side, making the turbulence intensity at 20 cm greater. Turbulence was high in the Plane $x = +30$ and then decreased beyond 60 cm for the central plane of the fan because the velocities were close to zero over the first 40 cm.

It was observed that the intensity of turbulence varied greatly between planes, which would suggest that the flow studied in this work was very anisotropic. All of these differences were probably attributable to the divergences with the previously referenced works having studied applications on pear trees. Machines used for spray applications in pear orchards have fans that produce smaller volumes of air than in our case, while pear trees have far less vegetation than orange trees.

Fig. 7e shows the values of turbulence intensity versus height obtained in the confirmation test. At post O, low turbulence values were observed close to the ground (as in Fig. 7b). Turbulence intensity increased until the top of the canopy (2.6 m of height). The modules of the velocities were still close to zero. Turbulence intensity at post E was found to be larger than in the main experiment (Fig. 7b), although the velocity profiles were very similar. These differences were probably due to the low air speed and the effect of vegetation. Post P presented the intensity more stable over the canopy, influenced for the proximity to the strong air currents from the fan. At the posts Q and R, turbulence intensities were larger at points closer to the canopy, probably because they were in a transition region over the canopies in which the wind started having an effect, as Georgiadis *et al.* (1996) reported, and the height of this region depended on the particular tree.

It is important to remark that the turbulence intensities observed immediately behind the tree in a wind tunnel have been reported to be 10-20% (Endalew *et al.*, 2009). However, as already commented, these turbulence intensities were not calculated using Eq. [2]. If this equation had been used, the values of the turbulence intensity would have been 17-34%. In another study, Delele *et al.* (2005) used a uniform turbulence intensity

value of 30% at the fan outlet; this would equate to 52% if Eq. [2] was used. In the present work, it was shown that the turbulence intensities varied considerably with height and that the values for posts A were lower than those proposed by these other authors. Authors also acknowledge that the actual values of turbulence intensities may have been higher if higher sampling rates of air speed would have been employed.

This work presents the first general description of the airflow generated by the axial fan of an air-assisted sprayer in a citrus orchard, based in field measurements of air speed in multiple points. It has been demonstrated that the air current from the fan was split into two currents: one that passed, in an upward direction, over the closest vegetation surface and another which passed below the tree canopy.

For the current that passed below the canopy, friction with the ground and the presence of a second row of trees generated a large vortex, or reflux, in the row parallel to the trajectory of the tractor. The width of this reflux was equivalent to the open space between the canopies and it was as high as the trees. In our reference system, the vortex moved in an anticlockwise direction.

The ascending current, which passed over the canopy, produced another vortex above the canopy which had not previously been reported in other studies on the application of treatments to fruit trees. This reflux affected at least half the tree height and may have a major influence on the trajectories of the sprayed droplets that pass above trees and, as a consequence, on the way in which plant protection products are diffused into the atmosphere.

The high velocity at which the air was emitted from the fan meant that the velocities recorded under our test conditions fluctuated least in the areas with the highest air current intensities, as they were strong enough to withstand any possible variations due to external causes. This occurred in the area closest to the sprayer and where the air passed around the tree at the greatest velocity. Greater variations in velocity were produced behind the tree because the air current velocities in these sheltered areas were close to zero and were therefore more susceptible to effects from their surroundings.

It can be envisaged from this work that, during the application of citrus treatments, the droplets that are sprayed and suspended in the air close to the central part of the canopy would be less susceptible to deviations from their initial path than those whose paths take them directly to the upper part of the canopy. This would underline the importance of correctly orientating the nozzles of sprayers towards the vegetation in the upper part of the nozzle manifold in order to reduce drift risk.

The airflow behaviour observed in this study, relating to the application of treatments to orange trees, has not been previously described in any other fruit orchard or vineyard, nor has such a high level or variation in the intensity of flow turbulence intensity. Differences in the intensity of the turbulence observed may be attributable to the higher air volume generated by the machinery used in citrus tree treatments compared to that used with other fruit trees and also to the very high foliage density of citrus trees. It was also observed that in the field the leaves of citrus trees tended towards the vertical when exposed to strong air currents. All of the above would entail the generation of a more turbulent flow in citrus orchards and the presence of specific vortexes not described in other scenarios. These turbulence intensity values can be used as an input in later CFD simulations.

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