# Variable rate sprayer. Part 2 – Vineyard prototype: Design, implementation, and validation

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## *Abstract*

The structural characteristics of the canopy are a key consideration for improving the efficiency of the spray application process for tree crops. However, obtaining accurate data in an easy, practical, and efficient way is an important problem to be solved. This paper describes the technical characteristics of a sprayer prototype developed for vineyards, following the principles and previous laboratory tests described in the complementary paper *Variable rate sprayer. Part 1 - Orchard prototype: design, implementation and validation*. This prototype can modify the sprayed volume application rate according to the target geometry by using an algorithm based on the canopy volume inspired by the tree row volume (TRV) model. Variations in canopy width along the row crop are electronically measured using several ultrasonic sensors placed on the sprayer and used to modify the emitted flow rate from the nozzles in real time; the objective during this process is to maintain the sprayed volume per unit canopy volume (L $m^{-3}$). Field trials carried out at different crop stages for Merlot and Cabernet Sauvignon vines (*Vitis vinifera*) indicated a good relationship between the applied volume and canopy characteristics. The potential pesticide savings were estimated to be 21.9% relative to the costs of a conventional application. This conclusion is in accordance with the results of similar research on automated spraying systems.

Keywords: Variable rate application, ultrasonic sensors, canopy geometry, vineyard

## Nomenclature

| | |
|---|---|
| $C_{Hj}$ | Canopy height at sector $j$ (m) |
| $C_{Vj}$ | Canopy volume to spray per unit time at sector $j$ ($m^3$ $min^{-1}$) |
| $C_{Wj}$ | Canopy width (semi-width) for sector $j$ (m) |
| $D$ | Sprayer output, amount of product per unit row length of application (L $m^{-1}$) |
| $d_j$ | Measured distance from sensor to the external layout of the canopy (m) |
| $d_{max}$ | Maximum measured distance by ultrasonic sensor (m) |
| $Dv0.1$ | Volumetric diameter percentile 10 (μm) |
| $Dv0.9$ | Volumetric diameter percentile 90 (μm) |
| $e$ | Distance between sensor and central axis of sprayer (m) |
| $f$ | Sampling frequency of the system (Hz) |
| $i_a$ | Application coefficient - actual (L $m^{-3}$) |
| $i_o$ | Application coefficient - objective (L $m^{-3}$) |
| $NMD$ | Numeric median diameter (μm) |
| $p_j$ | Pressure on sector $j$ (bar) |
| $p_{max}$ | Maximum working pressure of the system (bar) |
| $p_{min}$ | Minimum working pressure of the system (bar) |
| $q_j$ | Flow rate at section $j$ (L $min^{-1}$) |
| $q_n$ | Individual nozzle flow rate (L $min^{-3}$) |
| $r$ | Row spacing (m) |
| $S_{Lj}$ | Canopy slice length at sector $j$ (m) |
| $v$ | Forward speed (km $h^{-1}$) |
| $V_{in}$ | Electrical output signal emitted by ultrasonic sensor (V) |
| $V_{out}$ | Electrical output signal sent to electromagnetic valve (V) |
| $VMD$ | Volume median diameter (μm) |

## 1 INTRODUCTION

In the last few years, improvement of the pesticide application process has been established as a major objective of the official regulatory bodies of the European countries. The European Union legislation for the sustainable use of pesticides was implemented with the publication of Directive 128/2009/CE (European Parliament, 2009), which established the reduction of risk during the pesticide application process as the main objective.

During the pesticide application process, risk as a function of pesticide dose and harm to sensitive non-target areas are both related to the total amount of plant protection products (PPP) and the spraying efficiency during the distribution process over the entire canopy. However, for orchard and vineyard applications, the different methods commonly used to determine the most suitable amount of PPP and the corresponding application volume rate are difficult to understand in most cases. A direct consequence of this complexity is that different methods have been proposed for the establishment of label dose expression; these different methods make various claims for the improved efficiency of pesticide use (Koch *et al.*, 2001; Walklate *et al.*, 2003; Walklate *et al.*, 2006; Koch, 2007; Walklate *et al.*, 2011). In all cases, the proposed alternative for dose expression has been linked to one or several canopy characteristics with great differences in the measurement difficulty. Among the available crop parameters, the canopy volume is one of the most commonly used for dose expression (Byers *et al.*, 1971; Byers, 1987; Furness and Magarey, 2000; Bjugstad and Stensvand, 2002; Montermini *et al.*, 2007; Viret and Höhn, 2008). However, in most cases, establishing a method for canopy measurements has been the most difficult aspect of improved methodologies for PPP application. Once the canopy characteristics have been measured and introduced in the dose adjustment process, the result is a homogeneous and uniform dose distribution per canopy unit.

Advances in electronics and in information and communication technologies have permitted new developments in specialty crop production around the world (Lee *et al.*, 2010), with a wide range of purposes and applications. In the particular case of PPP application, ultrasonic sensors began to be used in crop production in the 1980s (McConnell *et al.*, 1983). Giles *et al.* (1988 and 1989a) used commercial ultrasonic sensors to estimate the tree canopy volume in apple and peach orchards. This information was used to adapt the application volume rate to the canopy characteristics. Through the use of this method, savings ranged from 28% to 52%. Since then, the use of electronic devices for canopy characterisation has increased in the last few decades. Different authors have used sensors for canopy characterisation of citrus trees (Tumbo *et al.*, 2001; Whitney *et al.*, 2002; Zaman and Salyani, 2004), fruit trees (Balsari *et al.*, 2008; Escolà *et al.*, 2011; Hocevar *et al.*, 2011), and vineyards (Landers, 2008). In all of these cases, a high degree of concurrence between the manual and automated measurements was reported. The potential savings in pesticide use determined during the tests are of interest.

The use of electronic devices for canopy characterisation and the need to clarify the dose expression concept have given rise to the concept of the variable application method (Zheng *et al.*, 2005). Several groups have developed prototypes to adapt the application volume rate to the variations in canopy characteristics using ultrasonic and LIDAR sensors (Balsari *et al.*, 2008; Brown *et al.*, 2008; Doruchowski *et al.*, 2009; Escolà, 2010). Relevant benefits in terms of dose reduction, drift control, and uniform deposition were achieved by all of the proposed methods.

The objective of this research is to develop a prototype that can apply a variable amount of liquid according to the canopy variability along the crop row for PPP applications in vineyards. This paper has two parts: a) a detailed description of the electronic system for canopy measurements and the calculation of the adapted flow rate; and b) an evaluation of the benefits one of the variable application method over the conventional method.

## 2 MATERIAL AND METHODS

### *2.1. Description of the principle*

According to the recently developed Pesticide Adjustment to the Crop Environment (PACE) tool (Cross and Walklate, 2008) one of the European methods of label dose rate expression is based on the tree row volume (TRV) concept, which is defined as the amount of product applied per unit ground area for a given tree row volume per unit ground area. The typical unit used in this method is litre per hectare of ground area for a TRV of 10,000 $m^3$ $ha^{-1}$. The TRV concept was also considered as an alternative in the conclusions of the Dose Expression Group at their first meeting (Wohlhauser, 2009), where the major agrochemical manufacturers of Europe proposed to harmonise data submissions in support of the leaf wall area (LWA) dose rate for evaluating the efficacy of pesticide registration. The TRV expression method has been previously adopted for pesticide registration in some European countries, and some website tools have been developed to calculate the total amount of pesticide per unit ground area based on this principle (www.agrometeo.ch).

However, different dose expression methods are used in different EU member nations and even within the same country. Assuming that $D$ (L $m^{-1}$ or kg $m^{-1}$), as the sprayer output, expresses the amount of product per unit row length of application (Walklate and Cross, 2011), the influence of every single canopy parameter in the dose expression is clear (Table 1). The establishment of a relationship among the different options is also of interest. These relations are linked to the canopy structure and principal parameters, and determining them seems to be a key point to achieving an accurate spray application process.

According to Table 1, among the other dose expression methods already in use in Europe, the TRV concept requires a standard measurement of the canopy width (Walklate *et al.*, 2011). Some attempts to improve the electronic measurements of canopy parameters, such as canopy width, to adapt the applied volume to the variable characteristics of the canopy have already been developed (Solanelles *et al.*, 2006). The prototype developed in this research is based on the electronic method for canopy width measurements; the variability along the crop line is considered, and the amount of spray liquid is modified accordingly in order to achieve a proportional spray distribution based on canopy geometry.

The control algorithm (explained in Part 1 of this research) is based on the measurement of canopy width ($C_{Wj}$) at section $j$, and its variations along the crop line. Once that parameter is electronically determined, information about the tractor forward speed along the row ($v$) and canopy height ($C_{Hj}$) of every single section $j$ is added; the algorithm was developed in order to calculate the canopy volume to be sprayed per unit time ($C_{Vj}$), which is expressed in cubic metres per minute (see nomenclature). Equation [1] indicates the relationship applied for this process:

$$C_{Vj} = \frac{1{,}000}{60} \times C_{Wj} \times C_{Hj} \times v \qquad [1]$$

where $C_{Vj}$ is the unit canopy volume to be sprayed per unit time ($m^3\ min^{-1}$); $C_{Wj}$, the canopy width at a certain position (m); $C_{Hj}$, the canopy height (m); $j$ is the intended section; and $v$, the tractor forward speed ($km\ h^{-1}$).

The main objective of the algorithm was to modify the emitted nozzle flow rate based on the measurements of canopy volume along the crop line and its variations in order to maintain a constant (as named in part 1) objective application coefficient ($i_o$). In this research, the objective was to maintain a constant value for the application coefficient ($i_o$) of 0.095 $L\ m^{-3}$, which was selected according to previous research (Byers *et al.*, 1971; Gil, 2001). Equation [2] indicates the established relation between parameters:

$$q_j = C_{Vj} \times i_o \qquad [2]$$

where $q_j$ is the flow rate ($L\ min^{-1}$); $C_{Vj}$, the canopy volume to be sprayed per unit time ($m^3\ min^{-1}$) at section $j$; and $i_o$, the objective application coefficient ($L\ m^{-3}$).

The prototype was developed to be capable of a variable application rate according to the canopy variations along the crop line by proper modification of the nozzle flow rate. This fundamental concept is opposite to that widely used in the conventional spray application process, where the nozzle flow rate is maintained constant along the track independent of the canopy characteristics. The conventional spray application process produces an uneven liquid distribution in relation with canopy variations to result in different values of the actual application coefficient ($i_a$) and to generally create an overdose where the canopy volume is low and deficiencies when it is high.

### *2.2. Sprayer design*

A conventional air-blast orchard sprayer (Hardi LE-600 BK/2 with a centrifugal fan having a 400-mm diameter) was used as the prototype for variable application. The sprayer was equipped with a 600-L tank capacity and six individual and adjustable outlets (three on each side of the machine); up to five nozzles could be arranged on each outlet. A stainless steel mast was fitted in the front part of the sprayer as close as possible to the centre axis of the machine (Figure 1). Three ultrasonic sensors were fitted to the mast, and the distance between them could be adjusted according to the canopy dimensions. A GPS antenna was also installed on top of the mast so that a GPS receiver could be used to evaluate the uniformity of the forward speed along the track and to record geographical coordinates. The sensors continuously estimated the canopy width from only the left side of the sprayer. All the sensors were connected to a controller placed in a waterproof box located on the rear right side of the sprayer. The controller was a Compact Field Point (National Instruments, Austin, TX, USA) equipped with analogue and digital input/output modules (see part 1). A rugged computer and wireless router were also connected to remotely monitor and control the system. A box containing three sets of electrovalves (proportional and on-off), an electronic flow meter, and a general pressure sensor were installed on top of the sprayer at the rear. Individual pressure sensors were also placed at every single manifold.

FIGURE 1

The operational parameters for each intended spray application were first selected and transmitted wirelessly to the system through a laptop placed in the tractor cab (Figure 2). Specific software programmed in Labview® (National Instruments, Austin, TX, USA) was developed to control and program the entire system. The technical specifications of the components (Table 2) were selected according to the particular working conditions in the field (e.g. working temperature, vibration, protection against liquids and dust) and their capacity for data acquisition and management. Figure 3 shows the connection scheme for all the components.

FIGURE 2 AND FIGURE 3

## 2.3. Function of the prototype

The principle of functioning is as follows. The entire canopy structure was divided into three levels: low, medium, and high. For each individual level (Figure 4), variations in the canopy width were measured and recorded. The variations in canopy width for half of the row were measured by every single ultrasonic sensor at different heights following Equation [3]:

$$C_{Wj} = {}^{r}\!/_{2} - d_j - e \qquad [3]$$

where $C_{Wj}$ is the canopy width (m) for half of the row at height $j$; $r$, the distance between crop rows (m); $d_j$, the distance measured from the sensor to the external layout of the canopy (m) at height *j*; and *e*, the distance between the sensor and central axis of the sprayer (m), assuming an equidistant displacement of the sprayer between two adjacent crop lines.

FIGURE 4

According to the principle for functioning of the ultrasonic sensors, the electrical output signal for each single measurement was transformed into distance based on an calibration curve (see Part 1) obtained experimentally under laboratory conditions. Equation [4] presents that relation:

$$d_j = -14{,}215 \times V_{in} + 181{,}21 \qquad [4]$$

where $d_j$ is the measured distance from the sensor to the external layout of the canopy (m) at height *j* and $V_{in}$, the electrical output signal (V) emitted by the ultrasonic sensor.

The sampling frequency of the sensor (*f*) was adapted to 12.5 Hz (80 ms between two consecutive measurements) in order to obtain an average of at least 10 measurements per metre of travel distance for proper adjustment of the sprayer (Balsari *et al.*, 2002). This sampling frequency resulted in a canopy volume slice length ($S_L$) of 0.1 m for an average forward speed of 1.25 m $s^{-1}$ (maximum: 1.38 m $s^{-1}$; minimum: 1.11 m $s^{-1}$; CV: 4.06%) according to the GPS data. This value was then used to estimate the canopy volume to be sprayed for each single measurement. For each single value, the system then calculated the canopy volume at different heights ($C_{Vj}$). Consequently, the independent flow rate to be delivered individually by each of the three manifolds is shown in Equation [5]:

$$q_j = 60 \times C_{Wj} \times \frac{1}{3} C_H \times S_{Lj} \times f \times i_o \qquad [5]$$

where $q_j$ is the individual flow rate (L min$^{-1}$) at manifold $j$ (two nozzles); $C_{Wj}$, the canopy width (m) for half of the row at height $j$; $C_H$, the total canopy height (m); $S_{Lj}$, the canopy length according to the sampling resolution (m) corresponding to the sampling frequency; $f$, the sampling frequency (Hz); and $i_o$, the objective application coefficient (0.095 L m$^{-3}$). The principle of the variable rate application prototype was to adapt the emitted flow rate for every manifold to the variations in canopy geometry along the vine row. To assess the capabilities of the prototype, all the actual application coefficients ($i_a$) were compared with the objective coefficient ($i_o$) for the entire range of canopy width measurements.

Variations in the flow rate for each manifold were controlled by three electromagnetic high frequency solenoid variable rate valves. This valve modified the flow rate in a continuous manner according to an external control signal (0–10 V) provided by the controller depending on the canopy volume (all voltages appearing in this paper are DC quantities). The chosen valve was a normally closed Posiflow ¼″ (ASCO/JOUCOMATIC S.A., Rueil-Malmaison, France) placed on top of the sprayer at the rear (Figure 5).

FIGURE 5

The solenoid of the valve was supplied with a 300 Hz Pulse Width Modulate (PWM) 24-V signal with a duty cycle proportionally modified according to the external control signal. This operation was performed by the driver of the valve to result in a continuous variation of the position of an internal plunger causing a variation in the flow rate. The intended flow rate, calculated according to equation [5], was then converted into an electrical control signal to be delivered to each variable rate electrovalve. The conversion of the desired flow rate into the electrical control signal was performed according to the calibration curve (Figure 6), which is represented by equation [6], experimentally obtained for the solenoid valves (see part 1):

$$V_{out} = 0.2354 \times e^{5.4304 q_j} \qquad [6]$$

where $V_{out}$ is the electrical control signal sent to the electrovalve (V) and $q_j$ is the desired flow rate to be delivered at manifold $j$ (L min$^{-1}$).

FIGURE 6

Because of the technical characteristics of the electromagnetic valves and ultrasonic sensors and their locations relative to the centre of the sprayer (see Figure 1), the maximum ranging distance of the sensors ($d_{max}$) was limited to 0.7 m for a row spacing ($r$) of 3.0 m. The system could not estimate the distance for values higher than 0.7 m (corresponding to thin row semi-widths) because this exceeded the measurement range of the ultrasonic sensors. In these situations, the electrovalves turned off automatically to interrupt the spray emission. All measured distances below 0.7 m were then transformed into the required flow rate ($q_j$) following equation [5], and the corresponding working pressure was then calculated. Because of the hydraulic requirements of the solenoid valves, the differential pressure (max $\triangle$p = 8.0 bar) had to be limited so that the system could be turned off completely when no vegetation was detected. This meant that the maximum working pressure ($p_{max}$) was initially set at 8.0 bar. On the other hand, the lower limit working pressure ($p_{min}$) on the system was established at 3.0 bar in order to guarantee that the nozzles generated an adequate spray pattern and droplet size spectrum. As a consequence of these two limitations and with the aim of maintaining the working pressure within the most suitable range for optimal actuation of the solenoid valves, three pressure intervals were established in order to adjust the final emitted flow rate to the crop width: lower than 3.0 bar ($p_{min}$), between 3.0 and 11.0 bar, and higher than 11.0 bar ($p_{max}$). The system was implemented with three on-off electrovalves to allow the complete closure of the system for locations without a canopy. Canopy width measurements obtained with the three ultrasonic sensors and the working pressure detected by the three pressure sensors in the system were automatically recorded and related in pairs. In order to quantify the ability of the system to modify the applied volume according to the canopy geometry variations, the measured canopy volumes and corresponding working pressure selected by the prototype were compared separately for each individual ultrasonic sensor in every test.

Based on this scenario, the theoretical and practical ranges of actuation for the two brown hollow cone Albuz ATR nozzles on each manifold are shown in Figure 7. For the pressure range between 3.0 and 11.0 bar, the combination of the nozzle flow rate for the selected nozzles, technical characteristics of the ultrasonic sensors, and objective application coefficient ($i_o$) resulted in a crop width range ($C_{Wj}$) of 25.0–40.0 cm, which is equivalent to a canopy volume ($C_{VJ}$) of 0.22–0.525 m$^3$. Thus, the prototype was adjusted so that the nozzle flow rate could be automatically modified only for a canopy width ($C_{WJ}$) of 25.0–40 cm. Crop zones with a measured crop width ($C_{Wj}$) less than 25.0 cm but more than 0 cm (no crop) were sprayed at a constant pressure ($p_{min}$) of 3.0 bar; crop zones with a measured canopy width greater than 40.0 cm were sprayed at a constant pressure ($p_{max}$) of 11.0 bar.

FIGURE 7

### 2.4. Flowchart and system management process

The system starts to run when the control unit is turned on (Figure 8) and prompts for the introduction of specific spraying parameters related to the crop characteristics (row distance, objective application coefficient, forward speed, and maximum crop height). The data acquisition system begins to receive information from the ultrasonic sensors ($V_{in}$), electronic flow meter, and pressure sensors installed in the system. All data are then managed and processed in the controller, where signals acquired from each of the ultrasonic sensors are transformed first into canopy volume, then into intended flow rate, and finally into an electric control signal ($V_{out}$) to be sent to the corresponding solenoid valve.

FIGURE 8

The algorithm flowchart (Figure 9) illustrates the following description. A reading of the ultrasonic sensors is performed every 0.1 m along the row. At an average forward speed of $v$ = 4.5 km·h$^{-1}$, the period of the software loop is t = 80 ms. For each measured data, the system determines the distance from the sensor to the nearest vine foliage. According to equation [3], this value is transformed into crop width ($C_{Wj}$). All conversions are based on a defined vine row-to-row spacing distance ($r$) and the assumption that the sprayer travelled along the centre line between rows (Giles *et al.*, 1989b); potential errors were assumed to derive from the difficulty in maintaining the tractor in the exact centre of the row (Zaman *et al.*, 2007). Once the distance ($d_j$) has been determined by each of the ultrasonic sensors and the range readings are converted into crop width ($C_{Wj}$), the system transforms those values into the required flow rate per manifold ($q_j$) according to equation [5] in order to apply the required amount of liquid in proportion to the vine row width variations. As every manifold was equipped with two

Albuz ATR brown hollow cone nozzles (Saint-Gobain Ceramiques Advancees Desmarquest, Evreux, France), the flow rate for a single nozzle was calculated according to equation [7]:

$$q_n = 0.2262 \times p_j^{0.4487} \qquad [7]$$

where $q_n$ is the individual flow rate per nozzle (L min$^{-1}$) and $p_j$ is the working pressure on sector $j$ (bar).

The previously described pressure range of actuation of the prototype and the pre-established maximum and minimum values need to be included in the mathematical expression to convert the intended flow rate into the needed working pressure for the selected nozzles. Equation [8] indicates this relationship and was the criterion in the software for selecting among the different options regarding the pressure range for actuation of the prototype (Figure 7):

$$p_j = 24.336 \times q_n^{2.0655} \qquad [8]$$

where $p_j$ is the working pressure on sector $j$ (bar) and $q_n$ is the individual flow rate per nozzle (L min$^{-1}$).

FIGURE 9

*2.4. Characterisation of droplet size spectrum*

In order to evaluate the influence of pressure variations on the droplet size spectrum generated by the prototype, a replicate of a single element of the sprayer composed of a manifold, two brown ATR hollow cone nozzles, one proportional electromagnetic valve, and one on-off valve was assembled and tested at the Department of Agriculture, forestry and Food (DiSAFA) of the University of Turin. A Malvern Spraytec (Malvern Instruments Ltd., Worcestershire, UK) was used to measure the droplet size (Dodge *et al.*, 1987). The purpose was to determine the droplet size variations in the previously defined range of variable working pressure of the prototype. The entire replicate was installed in the centre of the laser chamber and fed with water at different working pressures (3.0–11.0 bar). The working pressure was adjusted in stepwise fashion (1.0 bar increments) by modification of the electric signal (V) received by the electromagnetic valve. The measurements were performed three times at every pressure value with the objective of determining the droplet spectra and its variation for the entire pressure range.

### *2.6. Field trials*

In order to evaluate the performance and accuracy of the developed prototype, different field trials were arranged at *Castell del Remei*, a 70-ha wine farm, in Lleida, Spain. A conventional application procedure at a constant application volume rate (L ha$^{-1}$) according to the most commonly adopted practices at the farm was compared with the variable application volume rate using the prototype. Two vine varieties (Merlot and Cabernet Sauvignon) were sprayed in 2009 and 2010 at two different growth stages: BBCH- 75 and BBCH-85 (Meier, 2001). Both the variable application procedure and the conventional procedure were carried out using the same tractor and sprayer. The use of the same sprayer was possible because the device was installed on the control system of the prototype, which allowed the proportional or conventional application procedure to be selected. Table 3 lists the working parameters for the field tests. In addition to the engineering and electronic parameters explained and discussed in the previous sections, the spray deposition on the canopy was comprehensively evaluated during the field trials (Gil *et al*, 2007; Llorens *et al*., 2010).

## 3 RESULTS AND DISCUSSION

### *3.1. Droplet size measurements*

The results (Table 4) showed a uniform droplet size (*VMD*) with a narrow variation from 109.71 µm (3.0 bar) to 88.70 µm (11.0 bar). The droplet sizes for the entire measured range were from fine-F (3.0–4.0 bar) to very fine-VF (4.0–11.0 bar) according to BCPC classification (Doble *et al*., 1985). Table 4 lists additional information about *Dv0.1* and *Dv0.9* the relative span values to characterise the variation in droplet size for the spray spectrum. The obtained results indicate that the working pressure influenced the average droplet size but was not as important as initially expected.

### *3.2. Accuracy of measurements and system response*

The theoretical working pressure range on the circuit was established according to the technical characteristics of the ultrasonic sensors and selected nozzle type. The prototype was developed with the aim of modifying the working conditions based on the ultrasonic sensor's measurements. The delay between the data acquisition from the sensor and the system response (solenoid electrovalve actuation) implied an elapsed time during which the theoretical pressure was different from that intended (see the explanation about laboratory measurements in part 1). Even after experimental calibration of the system, which included this calculated elapsed time on the software, some deviations were observed and quantified. These differences can be represented as the comparison between the electrical signal sent to the electromagnetic valve and the measured pressure achieved in the system (Figure 10). In general, a small diminution in the obtained pressure was detected during the process. Of interest was the high variability of the pressure in the system compared with the more stable electrical signal received by the electrovalves, as a consequence of the stabilization time required by the prototype.

FIGURE 10

### *3.3. Distribution of canopy measurements obtained with ultrasonic sensors*

Figure 11 graphically represents all the measurements made separately for each vine variety, crop stage, and year. In all cases, a great similitude was observed with the expected theoretical curve (Figure 7) independent of the sensor placement (bottom, middle, or top). Most of the actual working pressure values achieved in the system during the variable application process were close to the theoretical line established in Figure 7. This effect is shown in Figure 11, where only few points are far away from the intended curve. It is also interesting to note that the lack of differences in the amount of 'failed points' can be attributed to the different placements of the sensors (top, middle, or bottom). In terms of the measurement distribution, the results corresponding to the early canopy stage, BBCH 75 in 2009 and 2010, indicated a low measurement density in the zones corresponding to high canopy width (over 0.40 m width); the lowest measurement density occurred at the upper and lower levels of the canopy. The differences in slope in the variable segment of the curve (pressure range of 3.0–11.0 bar) indicated that there was less variability in the canopy width in the early stages of the 2009 and 2010 field trials for the two vine varieties. Regarding the relative distribution of the measurement points in the defined intervals (Table 5), around one-fourth of the points (23.14%) were classified in the variable range of actuation of the prototype, and around one-half of the measurements (46.0%) were classified with narrow canopy geometry (canopy width < 25 cm). The percentage of zero values (zones without vegetation) was very similar among all varieties and crop stages.

FIGURE 11

### *3.4. Application coefficient: actual versus objective*

Results were grouped according to the sensor placement (top, middle, and bottom positions); for each group, the values of the actual application coefficient ($i_a$) were compared with the intended values, i.e. objective application coefficients ($i_o$). This comparison was done not only with the results obtained with the prototype using variable rate technology but also with the actual application coefficient values ($i_a$) generated during the conventional application process. Figure 12 plots the results for every variety, crop stage, and year. A detailed analysis of those curves indicates that, in all cases, the resulting application rate for conventional spraying was close to the intended value ( horizontal line on the graphics) only for large canopy widths (right-hand side part of the curves). Meanwhile, the actual application coefficient ($i_a$) delivered with the prototype acting as a variable rate technology (point clouds) was much closer to the objective, especially in the previously defined canopy width range corresponding to the variable application. Differences among varieties and crop stages were observed in the zones corresponding to very low and very high canopy widths (left- and right-hand side parts of the curves, respectively). For those cases, a spray overdose was detected in the narrow canopy areas as a consequence of the previously established minimum working pressure of the system (3.0 bar). However, the differences were much smaller than those observed for the conventional application. On the other hand, the pre-established maximum working pressure on the system ($p_{max}$ = 11 bar) resulted, in some cases, in a deficit of the spray delivered (right-hand side part of the curves) with some values under the horizontal line representing the objective application coefficient ($i_o$).

FIGURE 12

*3.5. Quantification of potential pesticide saving*

A mathematical analysis of these results was used to estimate the potential pesticide savings. These savings were represented by the area between the curve formed by the actual application coefficient ($i_a$) for conventional application and the curve plotted with the $i_a$ generated with the proportional application method. Because of the influence of the canopy geometry on the obtained results, two different zones were independently evaluated (Figure 13): the first corresponded to canopy volumes smaller than 0.22 $m^3$ ($C_{Vj} \leq 0.22$ $m^3$) and the second corresponded to zones with canopy volumes greater than 0.22 $m^3$ ($C_{Vj} > 0.22$ $m^3$). These intervals in canopy volume ($C_{Vj}$) were respectively linked to canopy widths ($C_{WJ} \leq 0.25$ m and $C_{WJ} > 0.25$ m) measured by ultrasonic sensors. The mathematical expression of the curves was obtained for these two intervals (Table 6), and the potential savings were estimated by integration of the area between these two curves using the basic statistic package R® (R Development Core Team, 2010). The results indicated an average potential saving of 21.9% (Figure 14). There was a higher saving potential in the narrow canopy zones of $C_{Wj} \leq 0.22$ m (upper graphic), which had average savings of 31.4%. This value dropped to 12.5% average for zones with a canopy width of over 0.22 m (lower graphic on Figure 14). These results indicated a similar response by the prototype that was independent of the canopy variation; instead, it was influenced by the crop stage and sensor position. In general, these estimated saving values correlated with the results of previous research (Escolà *et al.*, 2007; Llorens *et al.*, 2010), and can be directly related with more precise and safe use of plant protection products in accordance with the new European Directive for the sustainable use of pesticides (European Parliament, 2009).

FIGURES 13 AND 14

## 4. Conclusions

Canopy characteristics have a substantial influence on spray deposition, and some of the main parameters in the crop structure must be used to define the optimal application volume rate. The prototype developed in this research allows ‘real-time’ quantification of the canopy volume being sprayed during the application process. Our results demonstrated that this prototype can measure the canopy and instantly modify the working parameters (pressure and nozzle flow rate) for a more accurate and safe liquid distribution.

The sensing and control systems of the developed prototype are efficient and reliable enough to detect minor variations in canopy structure, and these measurements can be used to establish a more suitable amount of pesticide according to the target characteristics. Based on the results of this study, a considerable amount of pesticides can be saved using available new technologies for characterising the canopy structure along the row. This conclusion is in concordance with those obtained in other similar works (Jeon *et al.*, 2011; Zaman *et al.*, 2011).

Difficulties encountered during canopy measurements because of technical limitations of the devices (principally, the ultrasonic sensor and solenoid valves) can be avoided by replacing them with similar tools with higher accuracy. Other external factors such as the maintenance of the driving path along the vine row (Zaman *et al.*, 2007) or the influence of external conditions (Jeon *et al.*, 2011) can have a greater influence in some instances than the internal error resulting from the instrument itself. Further development of the prototype should consider implementation with a precise guidance tool such as RTK GPS.

The potential savings in the amount of PPP when using the developed prototype were demonstrated. However, the system needs to be improved in order to achieve a more robust and user-friendly sprayer for variable dosage of PPP. The problems encountered during the field trials demonstrated a need for developing an easy-to-use and low-cost commercial unit that growers can adopt without too many difficulties (Lee *et al.*, 2010).

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## References

Balsari, P., Doruchowski, G., Marucco, P., Tamagnone, M., van de Zande, J.C., Wenneker, M., 2002. A system for adjusting the spray application to the target characteristics. Agricultural Engineering International: the CIGR Ejournal. Manuscript ALNARP 8, 1-12.

Balsari, P., Marucco, P., Tamagnone, M. 2008. Variable spray application rate in orchards according to vegetation characteristics. In: International Conference on Agricultural Engineering AgEng2008 "Agricultural and Biosystems Engineering for a Sustainable World", Creta, Grècia.

Bjugstad, N., Stensvand, A., 2002. Pesticide dosage in three-dimensional crops in Norway. Aspects of Applied Biology 66, 345-352.

Brown, D.L., Giles, D.K., Oliver, M.N., Klassen, P., 2008. Targeted spray technology to reduce pesticide in runoff from dormant orchards. Crop Protection 27, 545-552.

Byers, R.E., 1987. Tree-row-volume spraying rate calculator for apples. HortScience 22, 506-507.

Byers, R.E., Hickey, K.D., Hill, C.H., 1971. Base gallonage per acre. Virginia Fruit 60, 19-23.

Cross, J., Walklate, P. 2008. The UK PACE scheme for adjusting the dose to suit apple crops. Agricultural Engineering International: The CIGR Ejournal. Manuscript ALNARP 08 003, Vol. X. May, 2008

Doble, S.J., Matthews, G.A., Rutherford, I., Southcombe, E.S.E. 1985. A system for classifying hydraulic nozzles and other atomizers into categories of spray quality. In: Proceedings British Crop Protection Conference - Weeds, 3, 1125-1133.

Dodge, L.G., Rhodes, D.J., Reitz, R.D. 1987. Drop-size measurement techniques for sprays: Comparison of Malvern laser-diffraction and Aerometrics phase/Doppler. Applied Optics 26, 2144-2154

Doruchowski, G., Balsari, P., Van de Zande, J.C. 2009. Development of a crop adapted spray application system for sustainable plant protection in fruit growing. In: International Symposium on Application of Precision Agriculture for Fruits and Vegetables, Orlando, Florida, USA, pp. 251-260.

Escolà, A., Planas, S., Rosell, J.R., Pomar, J., Camp, F., Solanelles, F., Gracia, F., Llorens, J., Gil, E., 2011. Performance of an ultrasonic ranging sensor in apple tree canopies. Sensors 11, 2459-2477.

Escolà, A., 2010. Method for Real-Time Variable Rate Application of Plant Protection Products in Precision horticulture/fructiculture. Thesis. Universitat de Lleida. Department of Agricultural and Forest Engineering.

Escolà, A., Camp, F., Solanelles, F., Llorens, J., Planas, S., Rosell, J.R., Gràcia, F., Gil, E. 2007. Variable dose rate sprayer prototype for tree crops based on sensor measured canopy characteristics. In: Precision Agriculture '07. Papers presented at the 6th European Conference on Precision Agriculture, Skiathos, Greece, pp. 563-571.

European Parliament, 2009. Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for Community Action to Achieve the Sustainable Use of Pesticides. 2009/128/EC.

Furness, G.O., Magarey, P.A., 2000. Unit canopy row calibration and a new pesticide label format to improve dose consistency on different canopy sizes with spray application to fruit. Aspects of Applied Biology 57, 309-312.

Gil, E., 2001. Metodología y Criterios Para La Selección y Evaluación De Equipos De Aplicación De Fitosanitarios Para La Viña. Thesis. Universitat de Lleida.

Gil, E., Escolà, A., Rosell, J.R., Planas, S., Val, L., 2007. Variable rate application of plant protection products in vineyard using ultrasonic sensors. Crop Protection 26, 1287-1297

Giles, D.K., Delwiche, M.J., Dodd, R.B., 1989a. Method and apparatus for target plant foliage sensing and mapping and related materials application control. 66137.

Giles, D.K., Delwiche, M.J., Dodd, R.B., 1989b. Sprayer control by sensing orchard crop characteristics: Orchard architecture and spray liquid savings. Journal of Agricultural Engineering Research 43, 271-289.

Giles, D.K., Delwiche, M.J., Dodd, R.B., 1988. Electronic measurement of tree canopy volume. Transactions of the ASABE 31, 264-272.

Hocevar, M., Sirok, V., Godesa, T., Lesnik, M., Stajnko, D., 2011. Design and testing of an automated system for targeted spraying in orchards. Journal of Plant Diseases and Protection 117, 71-79.

Jeon, H.Y., Zhu, H., Derksen, R., Ozkan, E., Krause, C., 2011. Evaluation of ultrasonic sensor for variable-rate spray applications. Computers and Electronics in Agriculture 75, 213-221.

Koch, H., 2007. How to achieve conformity with the dose expression and sprayer function in high crops. Bayer CropScience Journal 60, 71-84.

Koch, H., Weisser, P., Knewitz, H. 2001. Sprayer adjustment in orchards - from dose to deposit. In: VI Workshop on Spray Application Techniques in Fruit Growing, Leuven, Belgium, pp. 28.

Landers, A.J., 2008. Innovative technologies for the precise application of pesticides in orchards and vineyards. Aspects of Applied Biology 84, 411-416.

Lee, W.S., Alchanatis, V., Yang, C., Hirafuji, M., Moshou, D., Li, C., 2010. Sensing technologies for precision specialty crop production. Computers and Electronics in Agriculture 74, 2-33.

Llorens, J., Gil, E., Llop, J., Escolà, A., 2010. Variable rate dosing in precision viticulture: Use of electronic devices to improve application efficiency. Crop Protection 29, 239-248.

McConnell, R.L., Elliot, K.C., Blizzard, S.H., Koster, K.H., 1983. Electronic measurement of tree row volume. Agricultural Electronics 1, 85-90.

Meier, U., 2001. Growth stages of mono and dicotyledonous plants. BBCH Monograph.

Montermini, A., Casoli, L., Salgarollo, V., Prencipe, N., Wolhauser, R., Wolf, S. 2007. Verification of the adaptability of the method TRV (crop adapted spraying) to the Italian viticulture for management of pesticide dosages in relation to the vegetative development of the crop. In: 9th Workshop on Sustainable Plant Protection Techniques in Fruit Growing (SuProFruit), Alnarp, Sweden, pp. 27-28.

R Development Core Team, 2010. R: A language and environment for statistical computing.

Solanelles, F., Escolà, A., Planas, S., Rosell, J.R., Camp, F., Gràcia, F., 2006. An electronic control system for pesticide application proportional to the canopy width of tree crops. Biosystems Engineering 95, 473-481.

Tumbo, S.D., Salyani, M., Whitney, J.D., Wheaton, T.A., Miller, W.M. 2001. Laser, ultrasonic and manual measurements of citrus tree canopy volume. In: ASAE Annual International Meeting, Sacramento, California, USA.

Viret, O., Höhn, H., 2008. Application de la dose selon la méthode du TRV. Revue suisse de Viticulture, Arboriculture et Horticulture 40, 50-51.

Walklate, P.J., Cross, J.V. 2011. An examination of Leaf-Wall-Area dose expression. Crop Protection 35, 132-134.

Walklate, P.J., Cross, J.V., Pergher, G., 2011. Support system for efficient dosage of orchard and vineyard spraying products. Computers and Electronics in Agriculture 75, 355-362.

Walklate, P.J., Cross, J.V., Richardson, B., Baker, D.E., Murray, R.A., 2003. A generic method of pesticide dose expression: Application to broadcast spraying of apple trees. Annals of Applied Biology 143, 11-23.

Walklate, P.J., Cross, J.V., Richardson, G.M., Baker, D.E., 2006. Optimising the adjustment of label-recommended dose rate for orchard spraying. Crop Protection 25, 1080-1086.

Whitney, J.D., Tumbo, S.D., Miller, W.M., Wheaton, T.A., 2002. Comparison between ultrasonic and manual measurements of citrus tree canopies. ASAE Paper Nº 0210512.

Wohlhauser, R., 2009. Dose rate expression in tree fruits – the need for harmonization approach from a chemical producer industry perspective. In: Paper Presented at the Tree Fruit Dose Adjustment Discussion Group Meeting, Wageningen, The Netherlands, September 29

Zaman, Q.U., Salyani, M., 2004. Effects of foliage density and ground speed on ultrasonic measurement of citrus tree volume. Applied Engineering in Agriculture 20, 173-178.

Zaman, Q.U., Schumann, A.W., Hostler, H.K., 2007. Quantifying sources of error in ultrasonic measurements of citrus orchards. Applied Engineering in Agriculture 23, 449-453.

Zaman, Q.U., Esau, T.J., Schumann, A.W., Percival, D.C., Chang, Y.K., Read, S.M., Farooque, A.A., 2011. Development of prototype automated variable rate sprayer for real-time spot-application of agrochemicals in wild blueberry fields. Computers and Electronics in Agriculture 76, 175-182.

Zheng, J., Zhou, H., Xu, Y., Zhao, M., Zhang, H., Ge, Y., Xiang, H., Chen, Y., 2005. Toward-target precision pesticide application and its system design. Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering 21, 67-72.

Table 1 Canopy parameters and their relationship with diverse dose expression models. Relationship among diverse dose expression models

| | GA[1] | LWA[2] | TRV[3] |
|---|---|---|---|
| *Factors affecting dose expression* | | | |
| *r* | $D_{GA} = {}^{D}/_{r}$ | | |
| $C_h$ | | $D_{LWA} = \frac{D}{C_h}$ | $D_{TRV} = \frac{D}{C_h\ x\ C_W}$ |
| $C_w$ | | | |
| *Relation between dose expression modes* | | | |
| *GA* | | | |
| *LWA* | $D_{GA} = \frac{D_{LWA}\ x\ C_h}{r}$ | | |
| *TRV* | $D_{GA} = \frac{D_{TRV}\ x\ C_h\ x\ C_W}{r}$ | $D_{TRV} = \frac{D_{LWA}}{C_W}$ | |

[1] Litres per hectare of ground area

[2] Litres per hectare of leaf wall area

[3] Litres per hectare of ground area for a tree volume of 10,000 $m^3$ $ha^{-1}$

Table 2 Technical specifications of the components used in the prototype

| Components | Model<br>Manufacturer | Characteristics | Signal characteristics | Accuracy | Power supply |
|---|---|---|---|---|---|
| Ultrasonic sensor | Sonar-Bero Compact II<br>3RG6115-3GF00<br>Siemens | 400÷3,000 mm | 0÷10 $V_{DC}$ | 1.5% | 24 $V_{DC}$ |
| Variable rate valve | SCG202A052V<br>Asco Joucomatic | Internal diameter 2.4 mm | 0÷10 $V_{DC}$ | 3% | 24 $V_{DC}$ |
| ON/OFF valve | SC8374S402<br>Asco Joucomatic | ON/OFF | 12 $V_{DC}$ | --- | 24 $V_{DC}$ |
| Pressure sensor | 1000BGB2502A3UA<br>GEMS Sensors | 0÷25 bar | 4÷20 mA | 0.25% | 8÷30 $V_{DC}$ |
| Electromagnetic flow meter | Flow sensor-15 mm<br>RS Amidata S.A. | 1.50÷30.0 L/min | 1,200 pulses/litre | 1.5% | 12 $V_{DC}$ |
| Compact field Point controller | cFP-2120<br>National Instruments | 188 MHz processor<br>128 MB SDRAM | 1 Ethernet port<br>3 RS232 ports<br>1 RS485 port | --- | 11÷30 $V_{DC}$ |
| Analogue input module | cFP-AI-100<br>National Instruments | 8 voltage or current input channels | -30÷30 $V_{DC}$<br>-20÷20 mA | --- | 11÷30 $V_{DC}$ |
| Analogue output module | cFP-AO-210<br>National Instruments | 8 analogue output channels | 0÷10 $V_{DC}$ | --- | 11÷30 $V_{DC}$ |
| High-speed counter module | cFP-CTR-50<br>National Instruments | 12 input channels<br>4 output channels | Input: 5÷30 VDC<br>Output: 5÷30 VDC | --- | 0÷30 $V_{DC}$ |
| Digital input output module | cFP-DIO-550<br>National Instruments | 8 inputs. 8 outputs | 11÷30 $V_{DC}$ | --- | 11÷30 $V_{DC}$ |
| GPS | Trimble agGPS332 | 12 channels | NMEA sentences | <1 m | 12 $V_{DC}$ |
| Rugged computer | ARK 3384.<br>ADVANTECH |  | 3 USB 2.0 ports<br>1 RS232 port | --- | 12 $V_{DC}$ |

Table 3 Application parameters during the field tests

| | | | | Conventional application | | | Variable application | | |
|---|---|---|---|---|---|---|---|---|---|
| Variety | Year | BBCH[1] | LAI[2] | Fwd. speed (km h$^{-1}$) | Pressure (bar) | Volume (L ha$^{-1}$) | Fwd. speed (km h$^{-1}$) | Pressure (bar) | Volume (L ha$^{-1}$) |
| Merlot | 2009 | 85 | 1.45 | 4.5 | 9.0 | 285 | 4.5 | 3–11 | 0.095 |
| Cabernet Sauvignon | 2009 | 85 | 0.89 | 4.5 | 10.0 | 283 | 4.5 | | |
| Merlot | 2010 | 75 | 1.75 | 4.6 | 7.0 | 297 | 4.6 | 3–11 | 0.095 |
| | 2010 | 85 | 1.52 | 4.6 | 7.0 | 265 | 4.6 | | |
| Cabernet Sauvignon | 2010 | 75 | 1.06 | 4.6 | 7.0 | 302 | 4.6 | | |
| | 2010 | 85 | 1.31 | 4.6 | 7.0 | 270 | 4.6 | | |

[1] Crop stage according to Meier (2001); [2] Leaf area index

Table 4 Characterisation of the spray spectrum (brown ATR hollow cone nozzles). Values measured using a Malvern Spraytec

| Pressure (bar) | $D_V0.1$ | *VMD* | $D_V0.9$ | Relative Span[1] | Droplet Size Classification[2] |
|---|---|---|---|---|---|
| 3 | 66.59 | 109.71 | 168.00 | 0.92 | Fine |
| 4 | 60.99 | 103.79 | 163.06 | 0.98 | Fine |
| 5 | 56.89 | 99.66 | 160.14 | 1.04 | Very Fine |
| 6 | 55.79 | 97.93 | 157.60 | 1.04 | Very Fine |
| 7 | 47.56 | 90.87 | 157.83 | 1.21 | Very Fine |
| 8 | 48.05 | 91.05 | 157.26 | 1.20 | Very Fine |
| 9 | 44.86 | 88.33 | 157.35 | 1.27 | Very Fine |
| 10 | 45.62 | 88.88 | 157.16 | 1.25 | Very Fine |
| 11 | 45.51 | 88.70 | 156.86 | 1.26 | Very Fine |

[1] Relative span: (Dv0.9 - Dv0.1)/VMD

[2] Droplet size classification is based on BCPC classification (Doble *et al.*, 1985)

Table 5 Percentage of measurements for each range of actuation of the prototype

| Variety (crop stage)* | | Year | US sensor actuation range (cm) | | | |
|---|---|---|---|---|---|---|
| | | | $C_{Wj} = 0$ (p = 0) | $0 < C_{Wj} \leq 25$ (p = 3 bar) | $25 < C_{Wj} \leq 40$ (p = $f$(q)) | $C_{Wj} > 40$ (p = 11 bar) |
| Merlot | 85 | 2009 | 10.97 | 50.01 | 28.42 | 10.60 |
| Cabernet Sauvignon | 85 | 2009 | 23.53 | 41.77 | 19.73 | 14.97 |
| Merlot | 75 | 2010 | 11.60 | 40.01 | 34.03 | 14.35 |
| | 85 | 2010 | 15.27 | 50.12 | 20.44 | 14.17 |
| Cabernet Sauvignon | 75 | 2010 | 23.64 | 52.28 | 17.41 | 6.67 |
| | 85 | 2010 | 19.99 | 41.78 | 18.79 | 19.44 |
| Average | | | 17.50 | 46.00 | 23.14 | 13.37 |

*Crop stage according to Meier (2001)

Table 6 Calculated coefficients for all integrals belonging to conventional and proportional application methods and individual saving values, which are represented as the area between the curves ($v$ represents the canopy volume ($C_{Vj}$) calculated after the ultrasonic sensor measurements).

| | | Conventional function | | | | | | Prototype function | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\int_{0}^{0.22} (\boldsymbol{m}v^{\boldsymbol{n}})dv$ | | | $\int_{0.22}^{0.525} (\boldsymbol{m}v^{\boldsymbol{n}})dv$ | | | $\int_{0}^{0.22} (\boldsymbol{m}v^{\boldsymbol{n}})dv$ | | | $\int_{0.22}^{0.525} (\boldsymbol{s}v^{2} + \boldsymbol{t}v + \boldsymbol{u})dv$ | | | | |
| Variety (BBCH) Year | Sensor placement | $m$ | $n$ | Integral (a) | $m$ | $n$ | Integral (b) | $m$ | $n$ | Integral (c) | $s$ | $t$ | $u$ | Integral (d) | Area (saving) [(a) - (c) + (b) - (d)] |
| Cs (85) 2009 | US top | 0.08 | -0.81 | 0.079 | 0.08 | -0.81 | 0.055 | 0.03 | -1.05 | 0.050 | -1.06 | 0.72 | 0.04 | 0.046 | 0.038 |
| | US middle | 0.08 | -0.81 | 0.079 | 0.08 | -0.81 | 0.055 | 0.03 | -0.97 | 0.042 | -1.07 | 0.72 | 0.03 | 0.042 | 0.050 |
| | US bottom | 0.08 | -0.81 | 0.079 | 0.08 | -0.81 | 0.055 | 0.03 | -0.99 | 0.044 | -1.02 | 0.62 | 0.08 | 0.048 | 0.042 |
| Me (85) 2009 | US top | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.02 | -1.13 | 0.042 | -0.69 | 0.3 | 0.13 | 0.042 | 0.016 |
| | US middle | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.02 | -1.03 | 0.032 | -0.79 | 0.38 | 0.11 | 0.041 | 0.028 |
| | US bottom | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.02 | -1.14 | 0.041 | -0.3 | -0.05 | 0.2 | 0.041 | 0.018 |
| Cs (75) 2010 | US top | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.03 | -1.06 | 0.052 | 0.18 | -0.43 | 0.26 | 0.038 | 0.011 |
| | US middle | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.03 | -0.96 | 0.041 | -0.08 | -0.22 | 0.23 | 0.041 | 0.019 |
| | US bottom | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.04 | -0.87 | 0.045 | -0.09 | -0.23 | 0.22 | 0.036 | 0.020 |
| Me (75) 2010 | US top | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.05 | -0.94 | 0.066 | 0.7 | -0.87 | 0.36 | 0.041 | -0.006 |
| | US middle | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.04 | -1.03 | 0.064 | 0.87 | -0.98 | 0.38 | 0.042 | -0.006 |
| | US bottom | 0.06 | -0.81 | 0.059 | 0.06 | -0.81 | 0.042 | 0.06 | -0.78 | 0.055 | 0.91 | -0.98 | 0.35 | 0.035 | 0.010 |
| Cs (85) 2010 | US top | 0.07 | -0.81 | 0.069 | 0.07 | -0.81 | 0.048 | 0.03 | -1.06 | 0.052 | 0.18 | -0.43 | 0.26 | 0.038 | 0.028 |
| | US middle | 0.07 | -0.81 | 0.069 | 0.07 | -0.81 | 0.048 | 0.03 | -0.96 | 0.041 | -0.08 | -0.22 | 0.23 | 0.041 | 0.035 |
| | US bottom | 0.07 | -0.81 | 0.069 | 0.07 | -0.81 | 0.048 | 0.04 | -0.87 | 0.045 | -0.09 | -0.23 | 0.22 | 0.036 | 0.036 |
| Me (85) 2010 | US top | 0.07 | -0.81 | 0.070 | 0.07 | -0.81 | 0.048 | 0.04 | -0.88 | 0.046 | 0.19 | -0.45 | 0.28 | 0.042 | 0.030 |
| | US middle | 0.07 | -0.81 | 0.070 | 0.07 | -0.81 | 0.048 | 0.03 | -1.02 | 0.047 | 0.14 | -0.39 | 0.26 | 0.048 | 0.023 |
| | US bottom | 0.07 | -0.81 | 0.070 | 0.07 | -0.81 | 0.048 | 0.04 | -0.89 | 0.047 | 0.19 | -0.42 | 0.25 | 0.036 | 0.035 |

FIG1


GPS
On/OFF valves
Flow meter
US Sensors
Solenoid valves
Pressure sensors
Router Wi-Fi
Computer
cFP
Rugged computer

FIG2

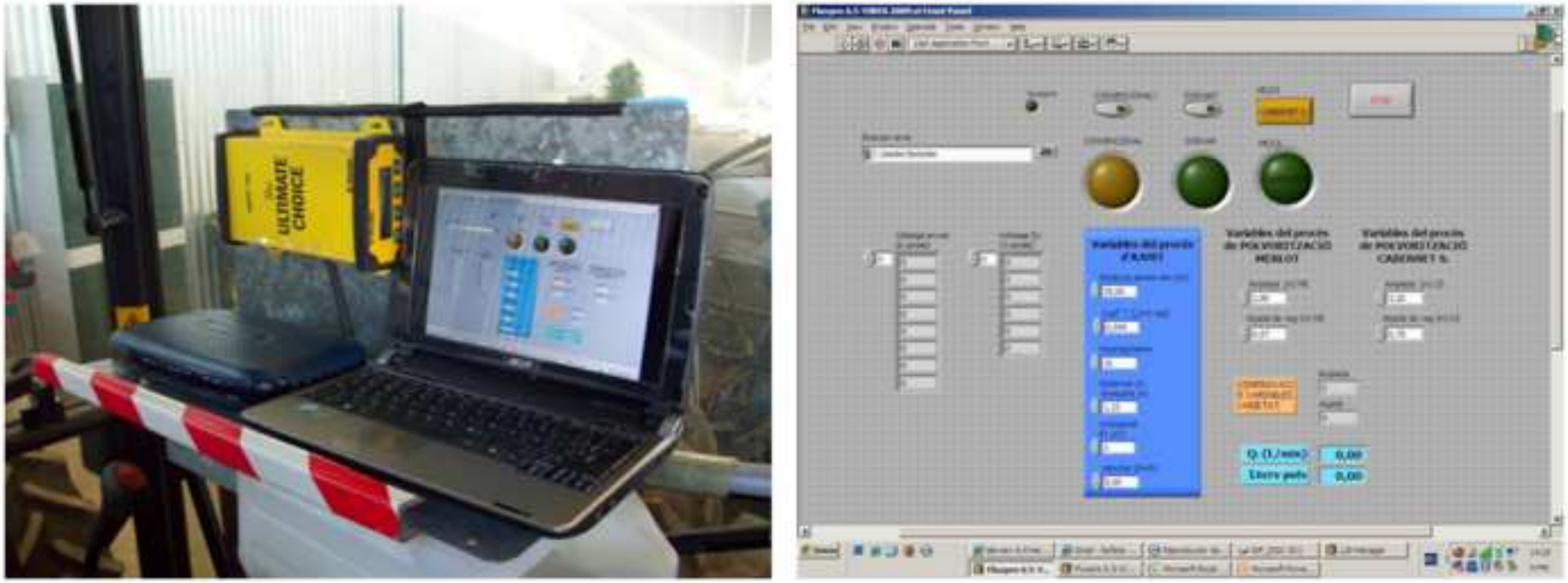

ULTIMATE CHOICE
Variables del procés de POLVORITZACIÓ MERLOT
Variables del procés de POLVORITZACIÓ CABERNET S.
Q (L/min)
0,00
0,00

FIG3

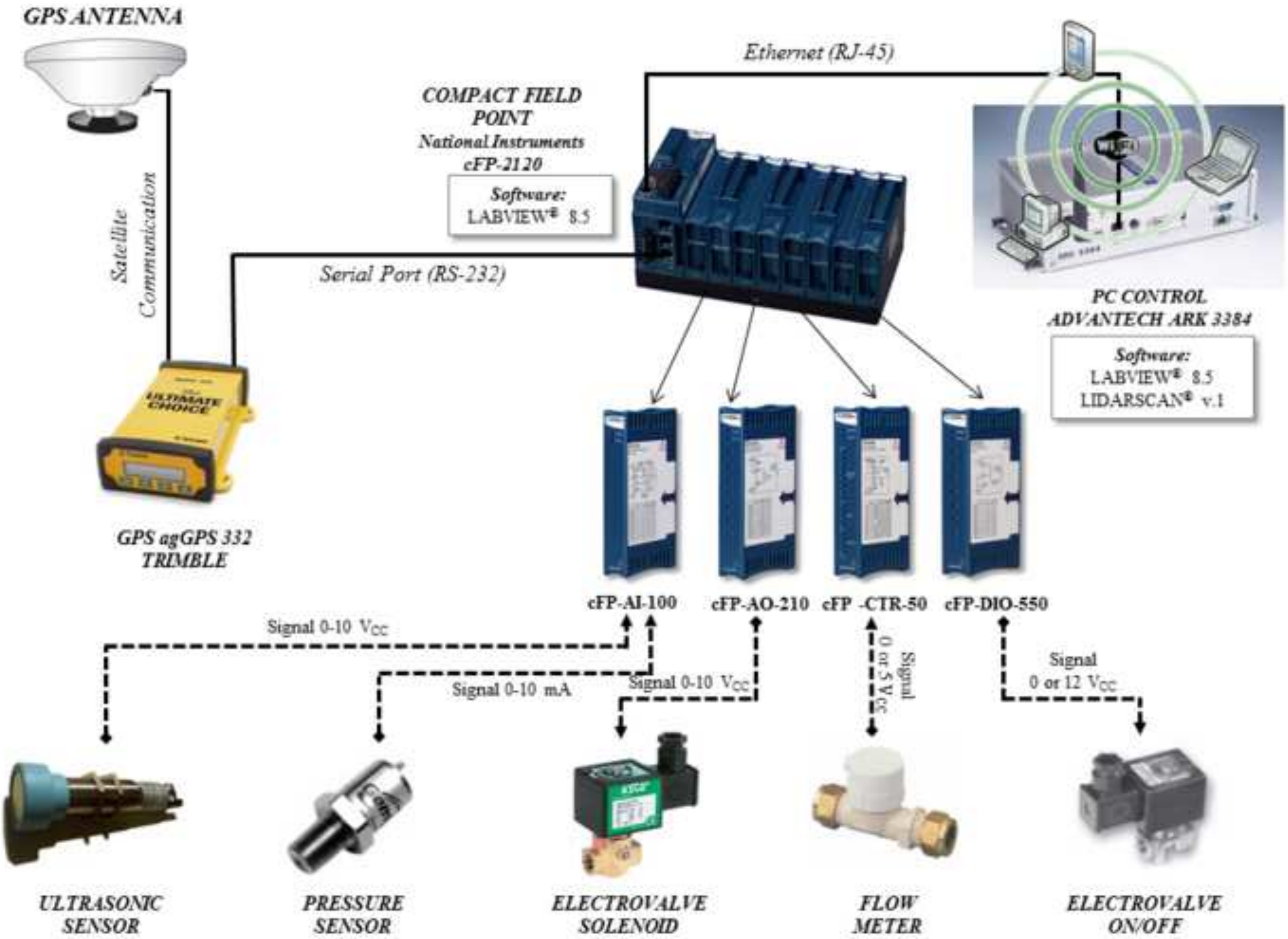

GPS ANTENNA
Satellite Communication
GPS agGPS 332
TRIMBLE
Serial Port (RS-232)
COMPACT FIELD POINT
National Instruments
cFP-2120
Software:
LABVIEW® 8.5
Ethernet (RJ-45)
PC CONTROL
ADVANTECH ARK 3384
Software:
LABVIEW® 8.5
LIDARSCAN® v.1
cFP-AI-100
cFP-AO-210
cFP -CTR-50
cFP-DIO-550
Signal 0-10 Vcc
Signal 0-10 mA
Signal 0-10 Vcc
Signal 0 or 5 Vcc
Signal 0 or 12 Vcc
ULTRASONIC SENSOR
PRESSURE SENSOR
ELECTROVALVE SOLENOID
FLOW METER
ELECTROVALVE ON/OFF

FIG4

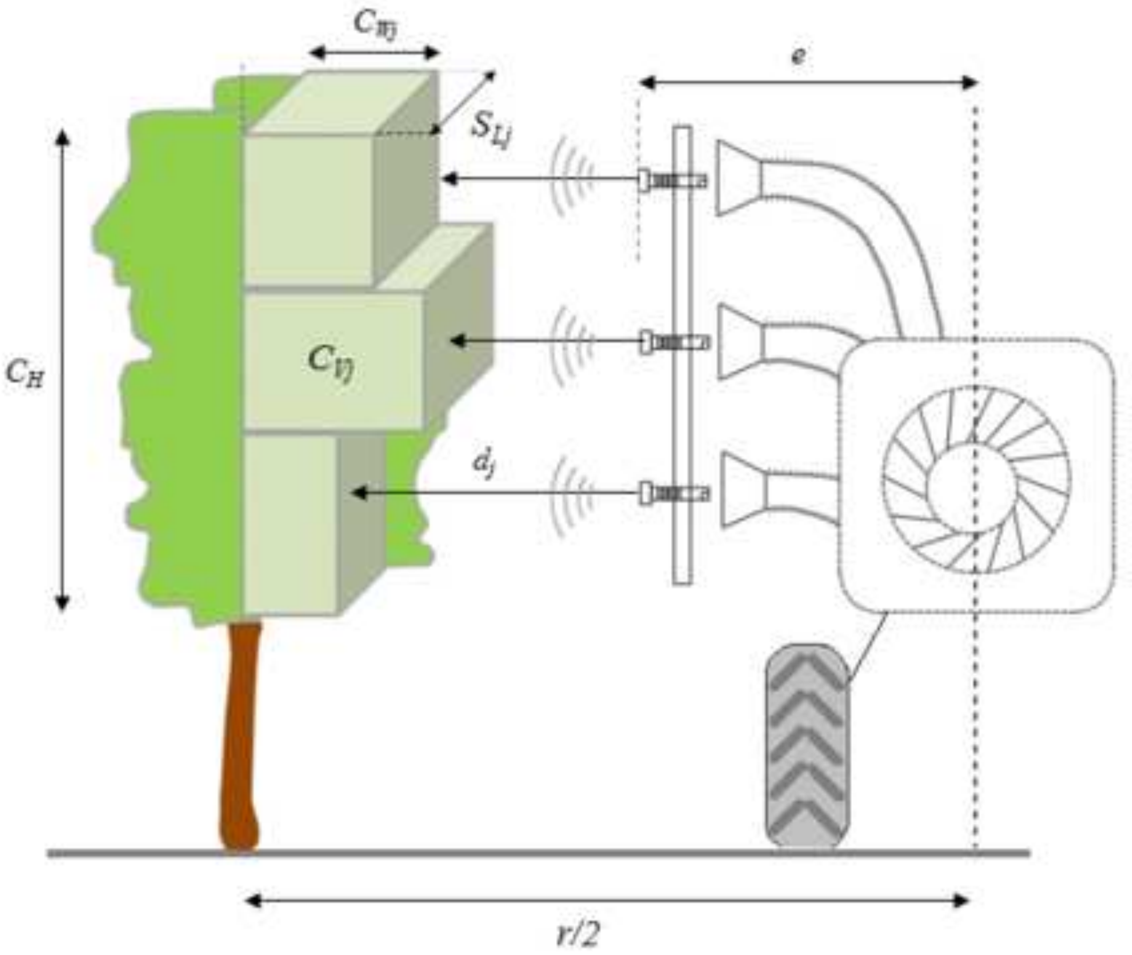
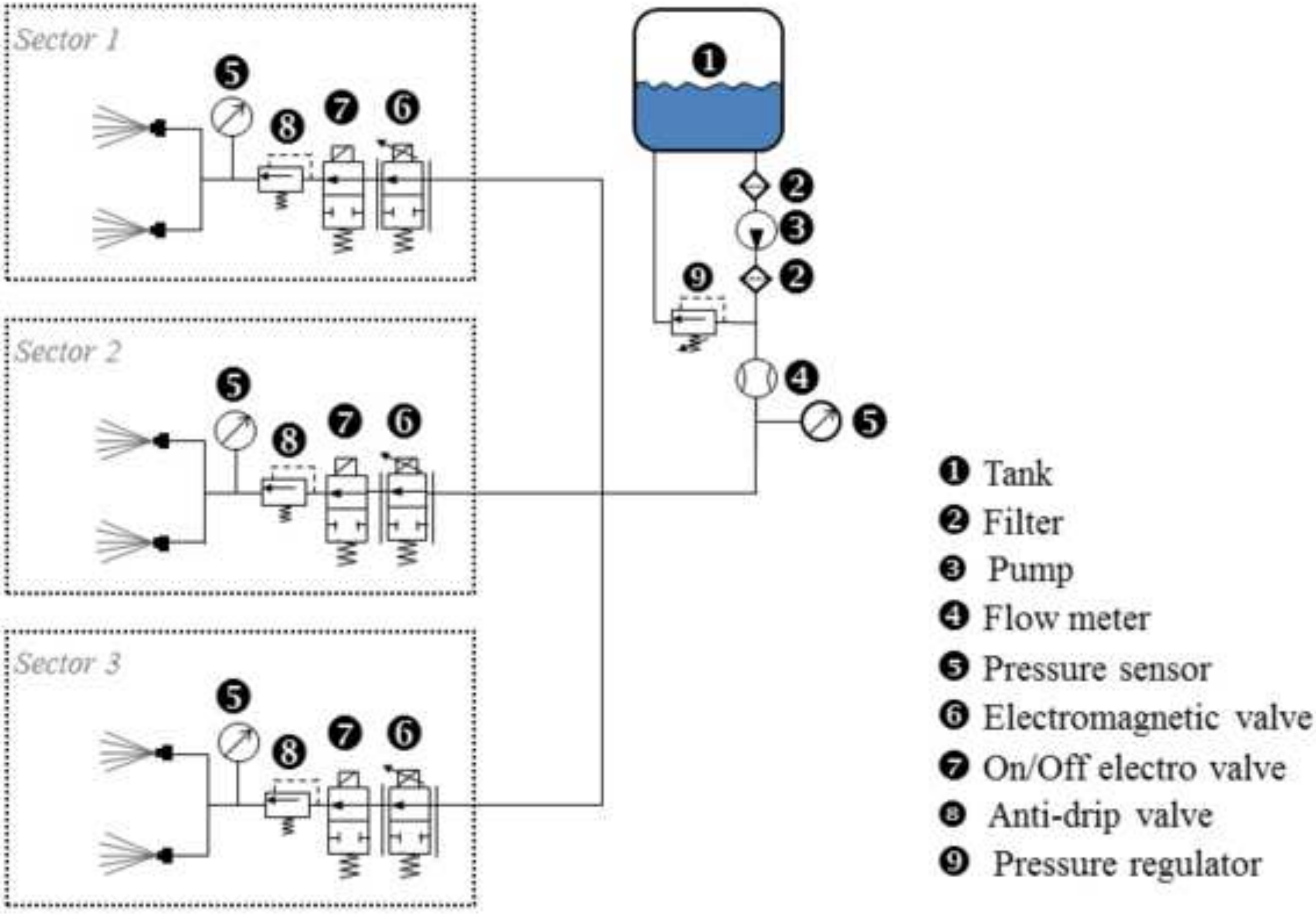


FIG5


Sector 1
Sector 2
Sector 3
❶
❷
❸
❹
❺
❻
❼
❽
❾
❶ Tank
❷ Filter
❸ Pump
❹ Flow meter
❺ Pressure sensor
❻ Electromagnetic valve
❼ On/Off electro valve
❽ Anti-drip valve
❾ Pressure regulator

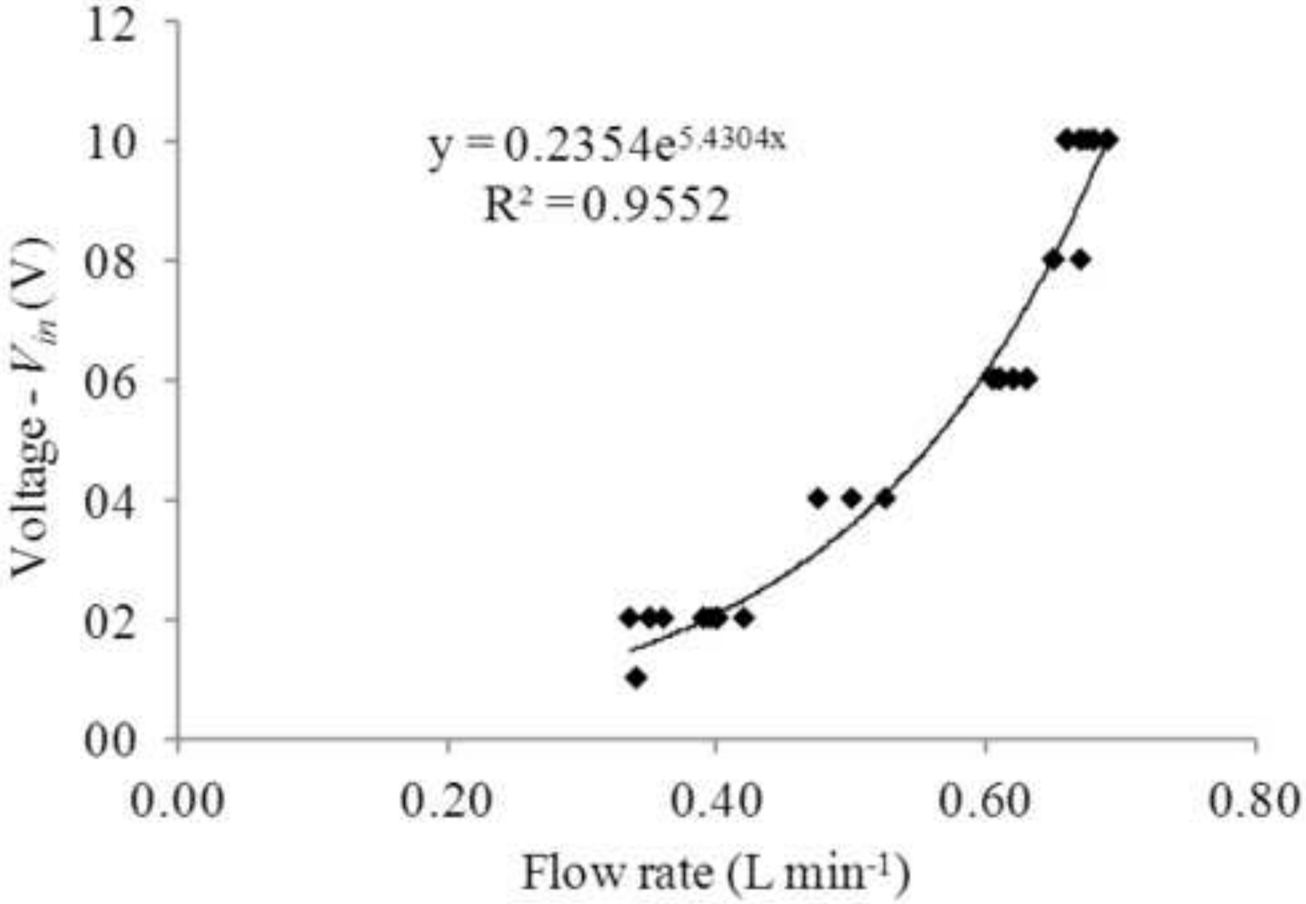

y = 0.2354e^5.4304x
R² = 0.9552
12
10
08
06
04
02
00
0.00
0.20
0.40
0.60
0.80
Voltage - V_in (V)
Flow rate (L min⁻¹)

**FIG7**

Click here to download high resolution image

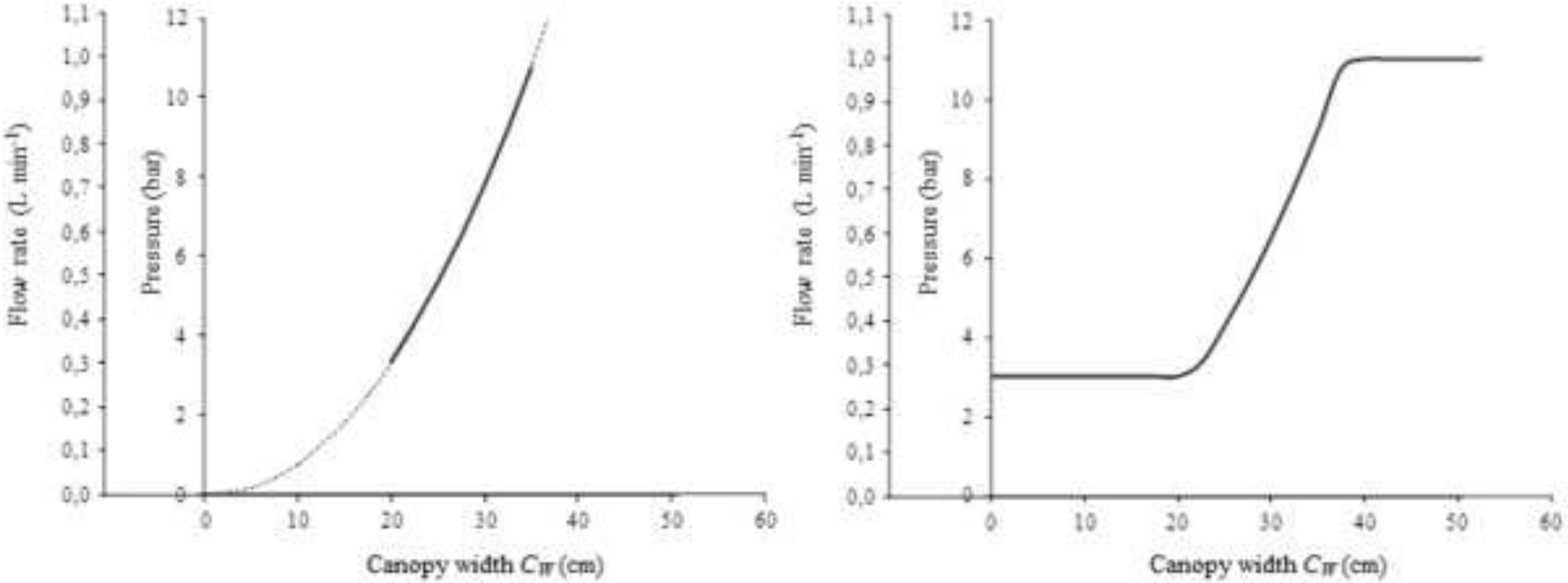


FIG8

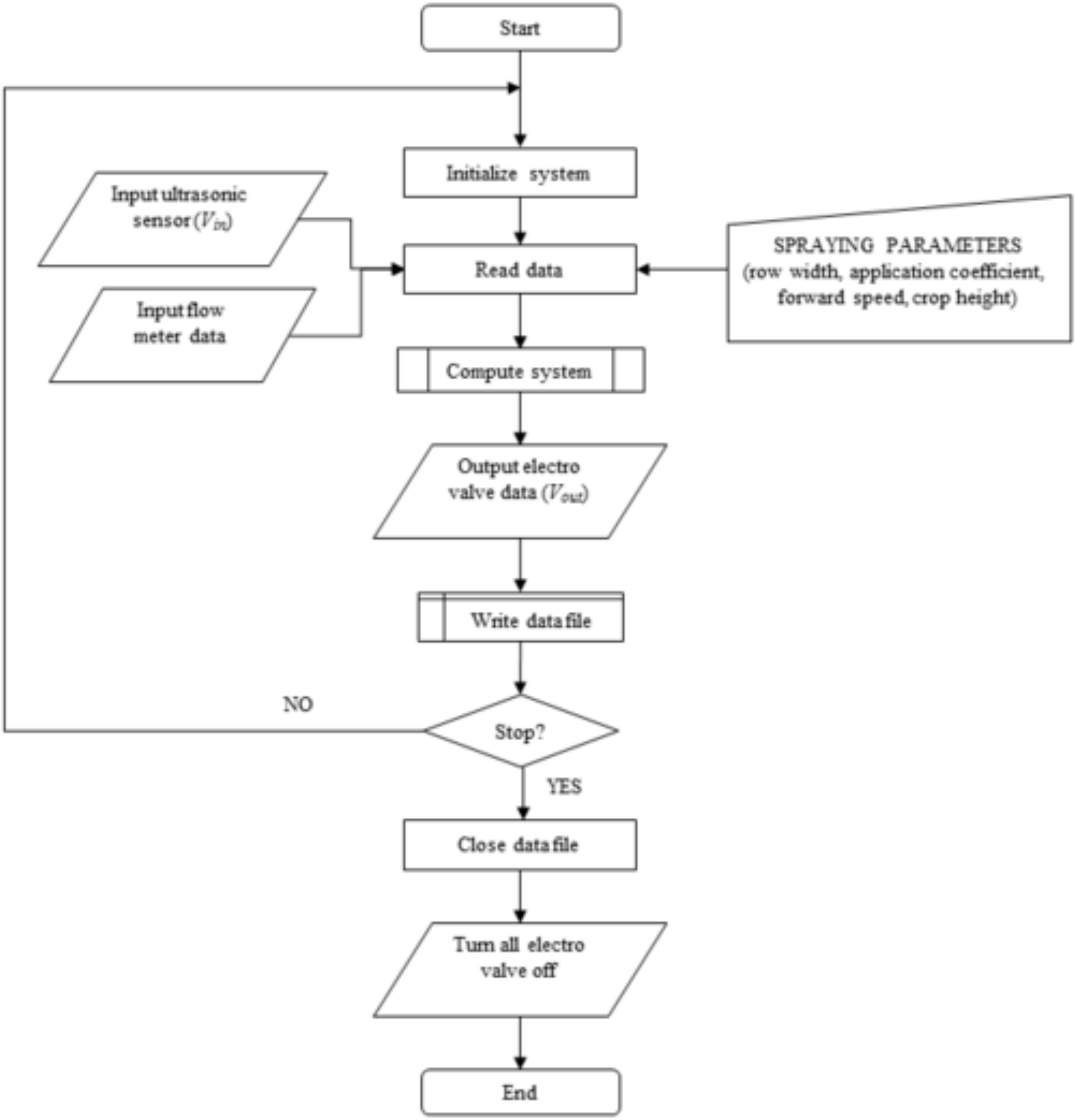

Start
Initialize system
Input ultrasonic sensor ($V_{in}$)
Input flow meter data
Read data
SPRAYING PARAMETERS (row width, application coefficient, forward speed, crop height)
Compute system
Output electro valve data ($V_{out}$)
Write data file
NO
Stop?
YES
Close data file
Turn all electro valve off
End

FIG9

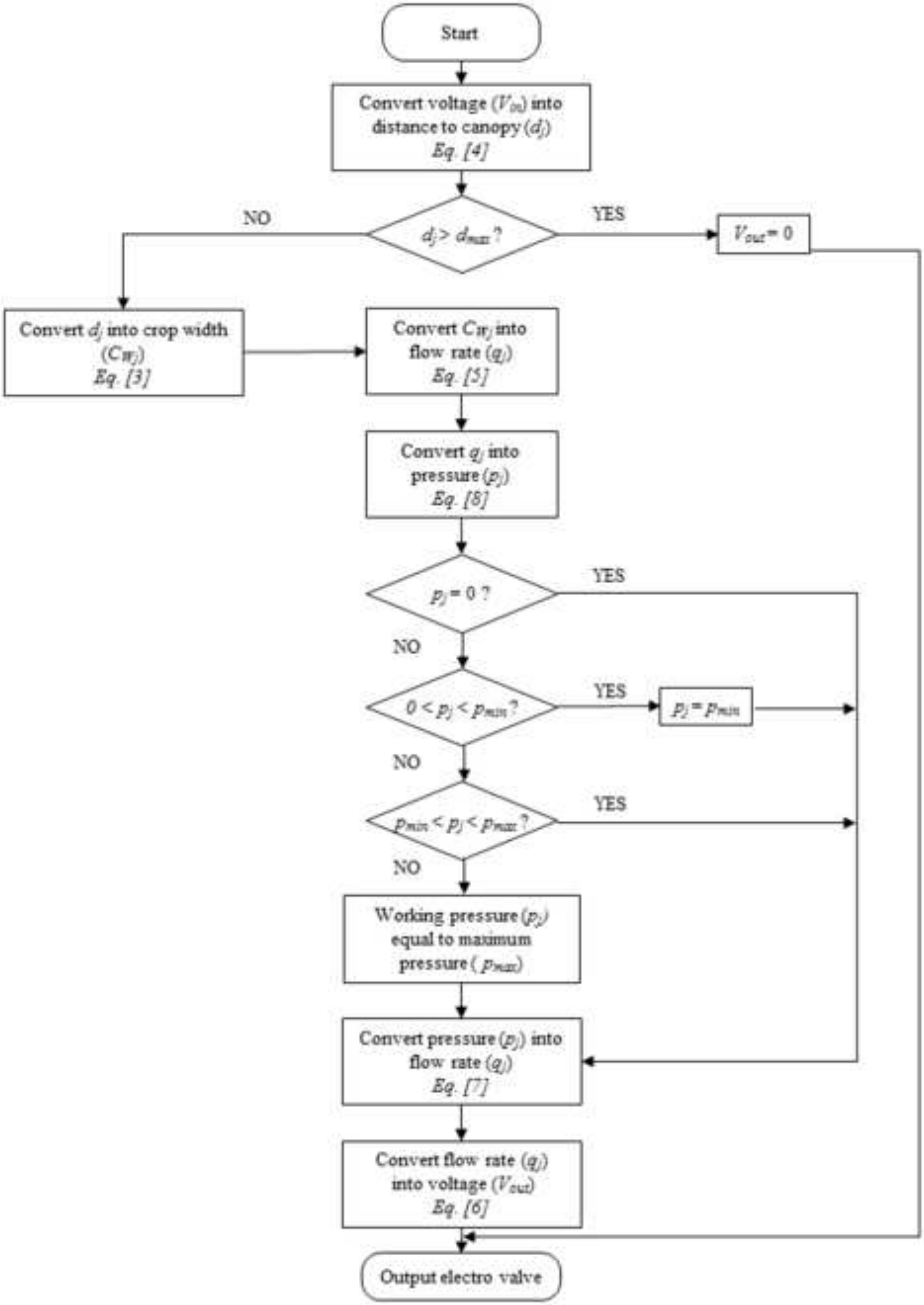

Start
Convert voltage ($V_{in}$) into distance to canopy ($d_j$) Eq. [4]
$d_j > d_{max}$?
NO
YES
$V_{out} = 0$
Convert $d_j$ into crop width ($C_{W_j}$) Eq. [3]
Convert $C_{W_j}$ into flow rate ($q_j$) Eq. [5]
Convert $q_j$ into pressure ($p_j$) Eq. [8]
$p_j = 0$ ?
YES
NO
$0 < p_j < p_{min}$?
YES
$p_j = p_{min}$
NO
$p_{min} < p_j < p_{max}$?
YES
NO
Working pressure ($p_j$) equal to maximum pressure ( $p_{max}$)
Convert pressure ($p_j$) into flow rate ($q_j$) Eq. [7]
Convert flow rate ($q_j$) into voltage ($V_{out}$) Eq. [6]
Output electro valve

FIG10

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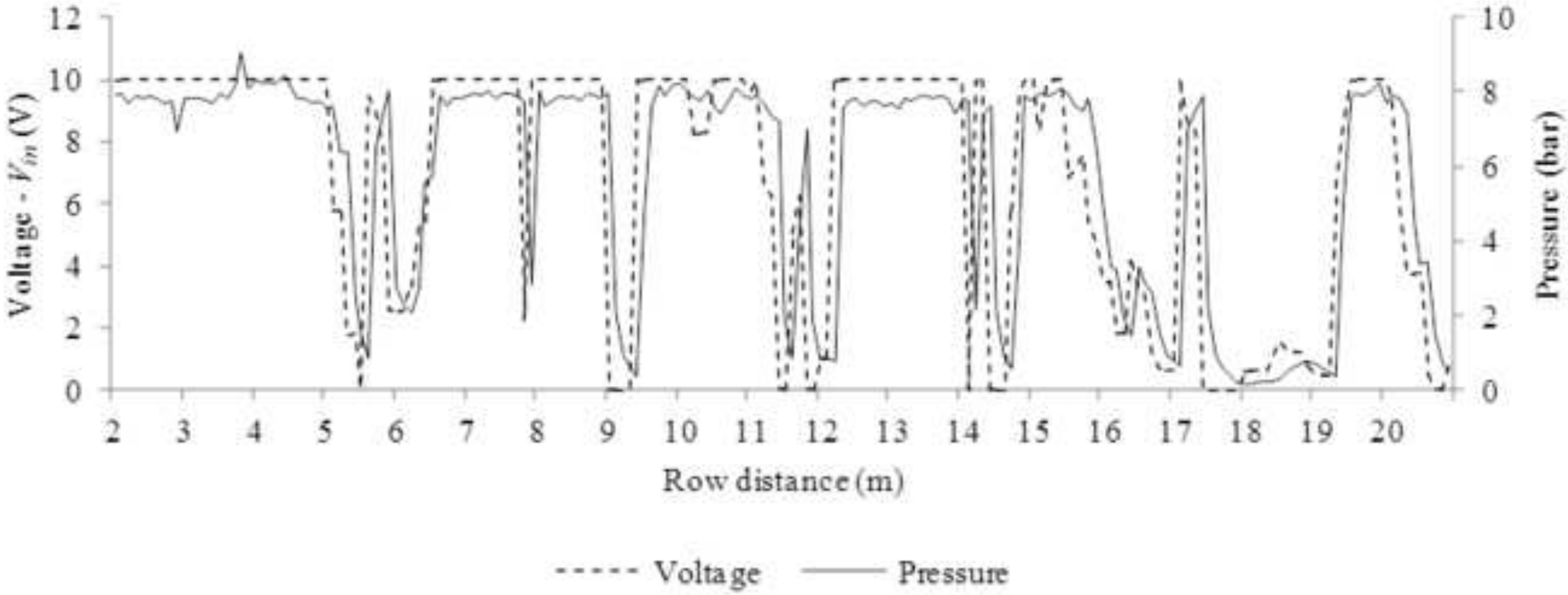

FIG11

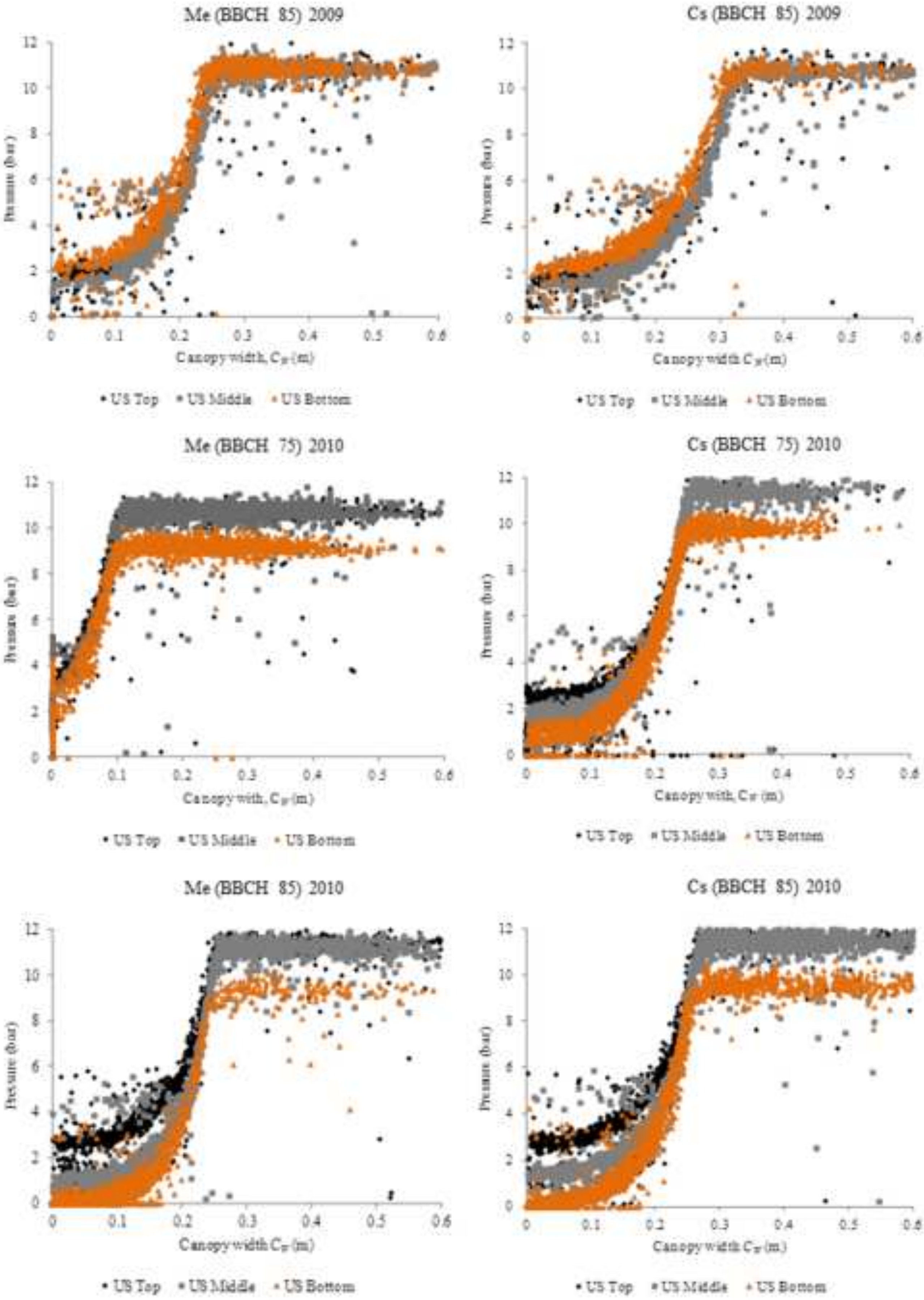
Me (BBCH 85) 2009
Cs (BBCH 85) 2009
Me (BBCH 75) 2010
Cs (BBCH 75) 2010
Me (BBCH 85) 2010
Cs (BBCH 85) 2010
Pressure (bar)
0
2
4
6
8
10
12
0
0.1
0.2
0.3
0.4
0.5
0.6
Canopy width, C_W (m)
Canopy with, C_W (m)
• US Top
• US Middle
• US Bottom

FIG12

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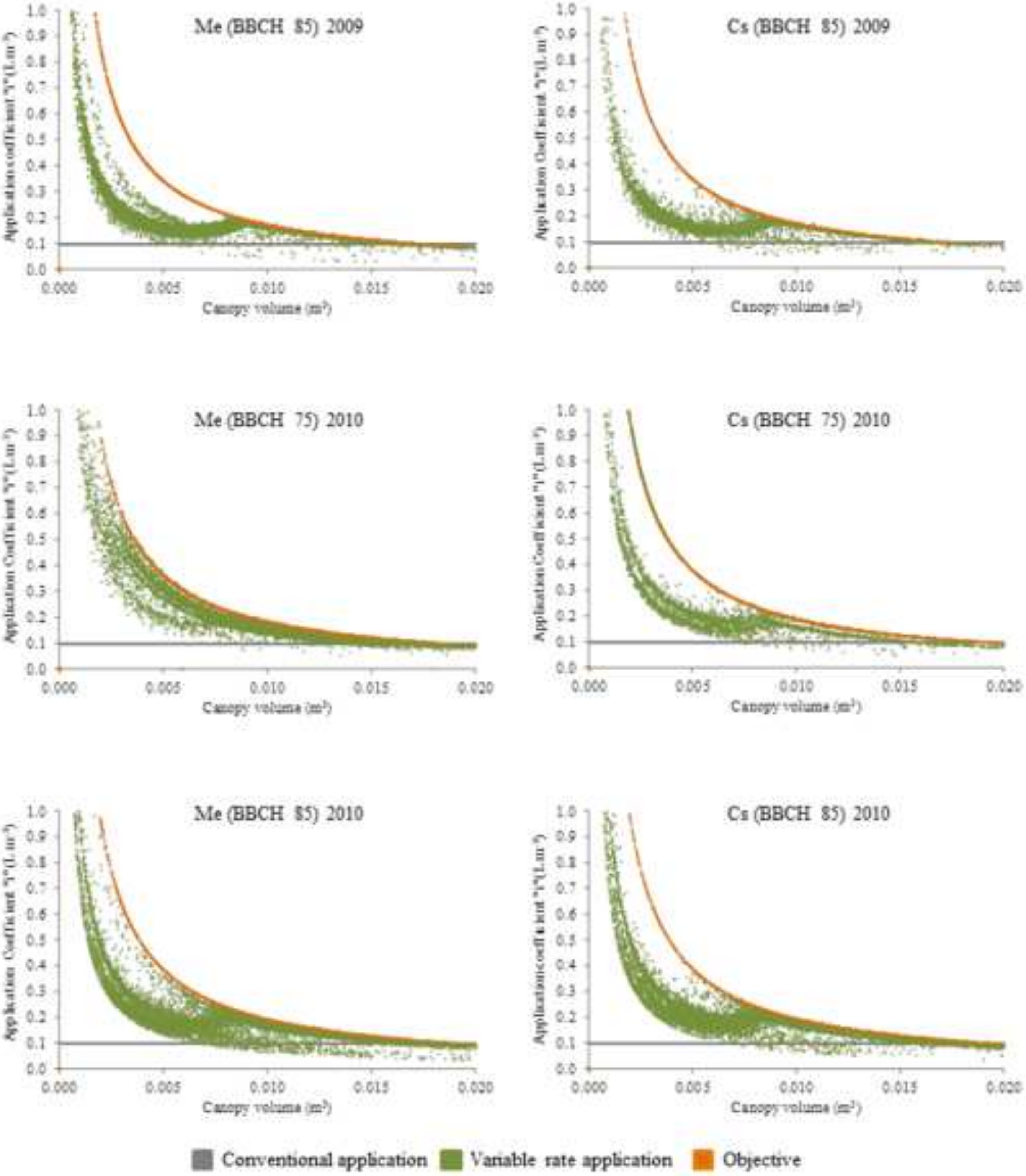

FIG13

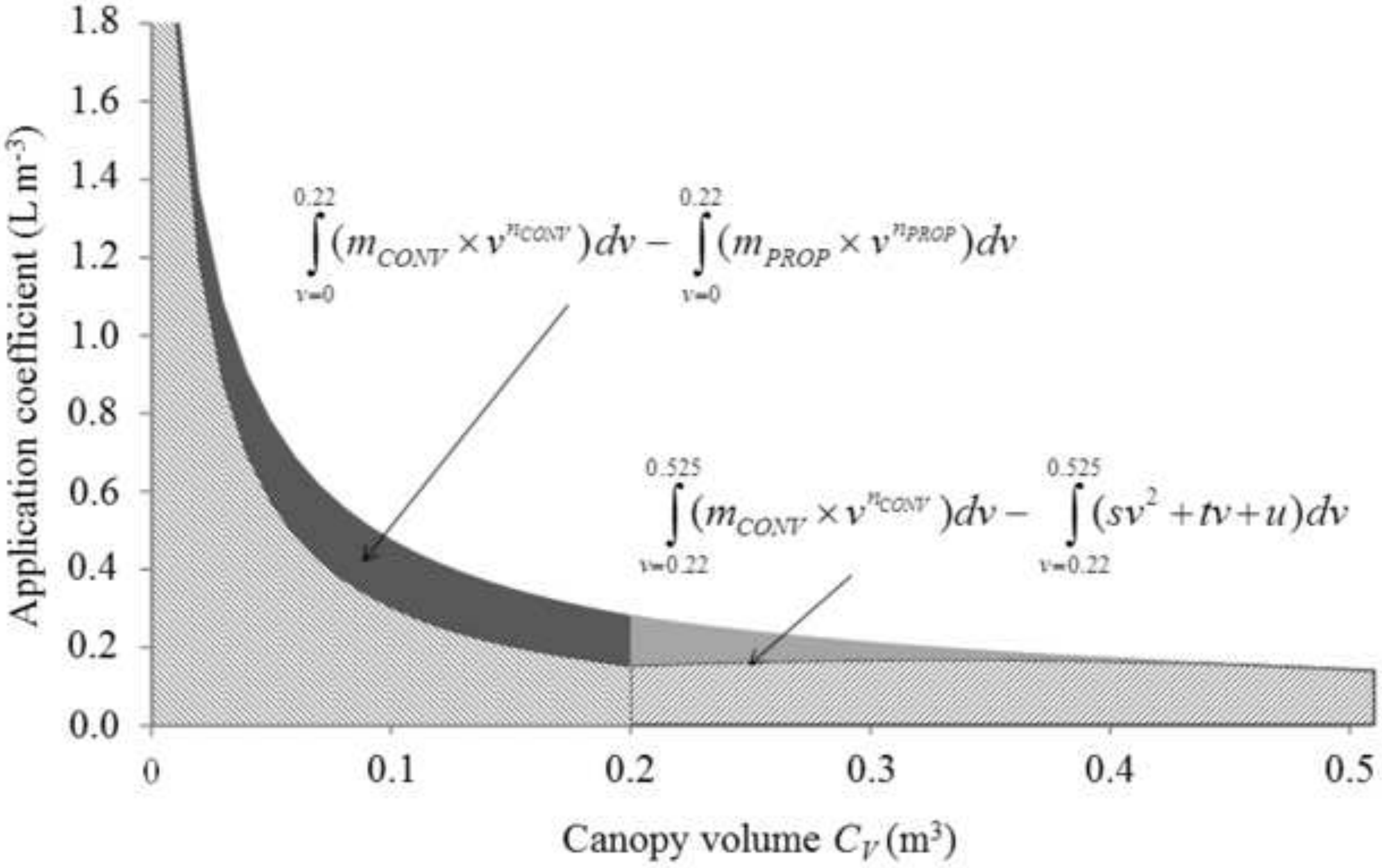
Application coefficient (L m$^{-3}$)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$\int_{v=0}^{0.22}(m_{CONV} \times v^{n_{CONV}})dv - \int_{v=0}^{0.22}(m_{PROP} \times v^{n_{PROP}})dv$
$\int_{v=0.22}^{0.525}(m_{CONV} \times v^{n_{CONV}})dv - \int_{v=0.22}^{0.525}(sv^2 + tv + u)dv$
0
0.1
0.2
0.3
0.4
0.5
Canopy volume $C_V$ (m$^3$)

FIG14

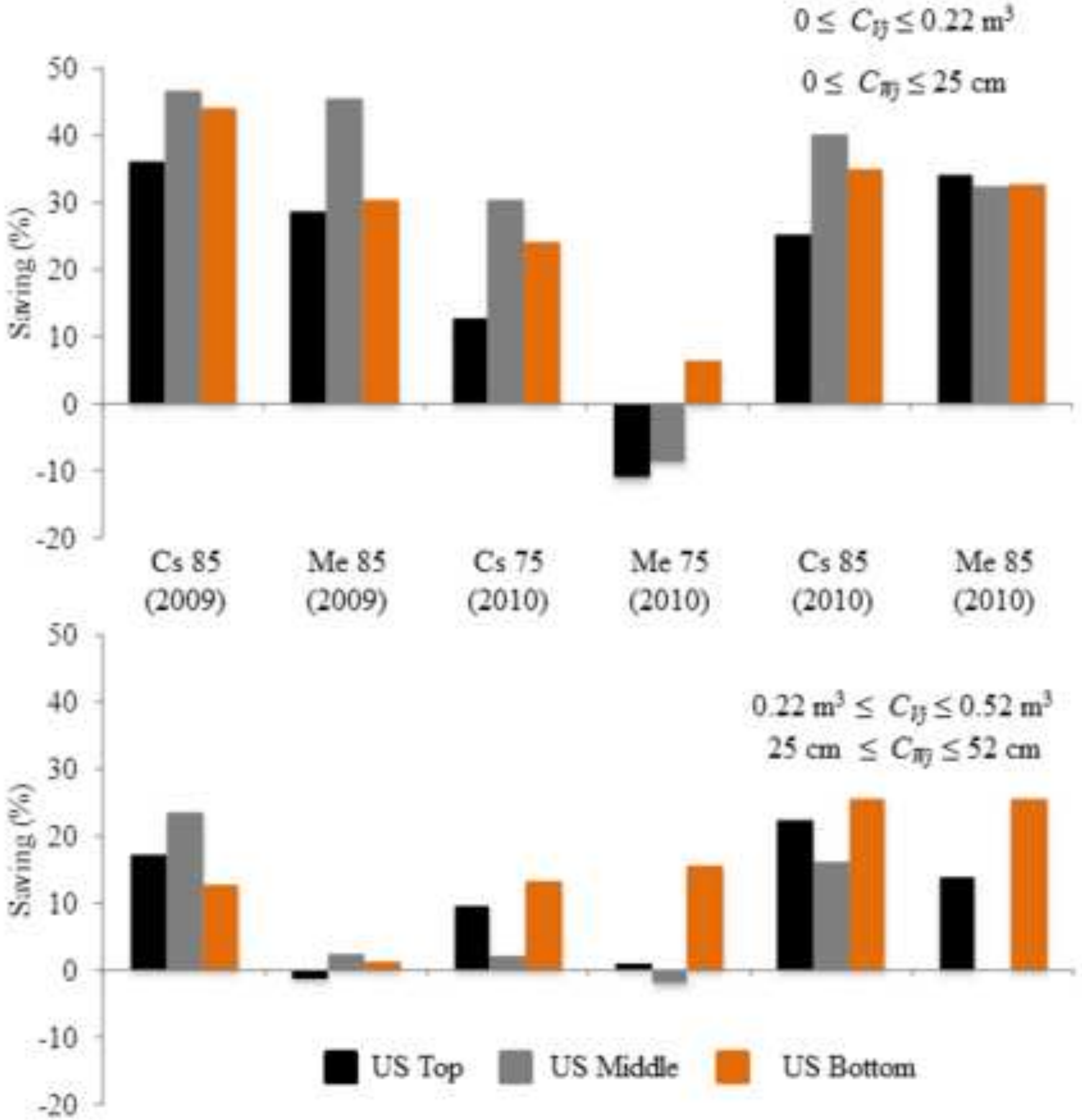
0 ≤ $C_{IJ}$ ≤ 0.22 m³
0 ≤ $C_{HJ}$ ≤ 25 cm
Saving (%)
50
40
30
20
10
0
-10
-20
Cs 85 (2009)
Me 85 (2009)
Cs 75 (2010)
Me 75 (2010)
Cs 85 (2010)
Me 85 (2010)
0.22 m³ ≤ $C_{IJ}$ ≤ 0.52 m³
25 cm ≤ $C_{HJ}$ ≤ 52 cm
Saving (%)
50
40
30
20
10
0
-10
-20
US Top
US Middle
US Bottom

**Figure captions**