Variable rate dosing in precision viticulture: use of electronic devices to improve application efficiency

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Abstract

Two different spray application methods were compared in three vine varieties at different crop stages. A conventional spray application with a constant volume rate per unit ground area ($l\cdot ha^{-1}$) was compared with a variable rate application method designed to compensate electronically for measured variations in canopy dimensions. An air-blast sprayer with individual multi-nozzle spouts was fitted with three ultrasonic sensors and three electro-valves on one side, in order to modify the emitted flow rate of the nozzles according to the variability of canopy dimensions in real time. The purpose of this prototype was to precisely apply the required amount of spray liquid and avoid over dosing. On average, a 58% saving in application volume was achieved with the variable rate method, obtaining similar or even better leaf deposits.

Key words: Ultrasonic sensor; Vineyard; Canopy volume; Variable rate application; Precision Viticulture; Crop adapted spraying; Vine row volume (VRV).

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1. Introduction

The efficiency of plant protection products (PPP) depends on many interacting factors. Crop characteristics (canopy structure, vegetative stage, variety, etc.), application technique, weather conditions, applied dose rate and others are interdependent factors that allow, in an adequate combination, to achieve high efficacy and efficiency values.

Crop-adapted dosing of agrochemicals has been widely discussed in many publications (Furness, 2003; Walklate et al., 2003; Gil et al., 2005; Godyn et al., 2005; Viret et al., 2005; Pergher and Petris, 2008). In all cases the main goal has been to adapt the total amount of PPP to crop characteristics but difficulties were encountered in the selection of the most suitable crop parameters. The high degree of variability in crop characteristics has increased the difficulty in obtaining general solutions well adapted to all crops and situations.

The use of orchard canopy volume as a basis for chemical application rate calculation and system design was discussed and tested by Sutton and Unrath (1984, 1988). The tree row volume concept maintains that chemical rate recommendation and application should be based upon crop canopy volume rather than on land area. Following this methodology other trials have been conducted in order to adapt the spray volume to crop dimensions in vineyards (Siegfried et al., 2007; Pergher and Petris, 2008). In all cases, accurate measurements of crop dimensions are a key factor for final success. The use of electronic devices to measure crop dimensions is not a new idea. McConnell et al. (1983) proposed the use of a system with a vertical mast with range transducers to measure tree extension, from the trunk outward and towards the row middle. More recently, Giles et al. (1989), using a modified orchard air-blast sprayer equipped with three ultrasonic transducers, concluded that savings in pesticide application when using the electronic control system was strongly related to target crop architecture. The same authors concluded that sprayer control based upon target measurement, rather than simple target detection resulted in substantial increases in savings of applied spray liquid.

To solve the difficulties encountered in crop characterization and to accomplish the recent EU aim to reduce the total amount of PPP (COM, 2006), environmentally-safe spraying techniques have been developed to spray only when and where needed with reduced losses to the environment ((Doruchowski and Holownicki, 2000). Recent advances in computer hardware and software, global navigation satellite systems (GNSS), canopy sensors and remote sensing offer opportunities for fast and inexpensive measurements of tree canopy characteristics for variable rate technologies (VRT) (Zaman and Salyani, 2004). Walklate et al. (2006) using a LIDAR (LIght Detection and Ranging) concluded that area-density and height adjustments were the best crop structure parameters on which a simplified scheme for pome fruit spraying could be based on. Rosell et al. (2009) developed a LIDAR-based measurement system for the estimation of physical and structural characteristics of plants (plant volume, leaf area density and leaf area index). The different shapes, sizes and foliar densities found in tree crops during the same growing season, require a continuous adjustment of the applied dose rate to optimize the spray application efficiency and to reduce environmental contamination (Solanelles et al., 2002). Crop characteristics are directly related to the total amounts of deposit on leaves and values of leaf area and canopy dimensions (mainly height and width) can widely affect the efficiency values, as a relationship between the expected deposit and the actual one (Gil et al., 2005).

Target detection has been developed either by using advanced techniques, such as vision systems and laser scanning, or by ultrasonic and spectral systems. Gil et al.

(2007) obtained a significant reduction in the total amount of applied volume (57%) using a sprayer prototype with ultrasonic sensors able to measure the crop width variations and to apply a variable dose rate according to the instantaneous measured vine row volume (VRV), in comparison with a conventional and constant application volume rate. However, this reduction did not affect the results in terms of deposit, leaf coverage and penetration where similar normalized values were achieved.

Whitney et al. (2002) investigated the ultrasonic transducer's response to different parts of a citrus canopy and also examined the effect of the sampling frequency and the transducer spacing on canopy volume determination. More recently Balsari et al. (2008) using a crop identification system based on ultrasonic sensors, confirmed its suitability for detecting canopy characteristics in real time, independently of the forward speed, as previous studies already indicated (Zaman and Salyani, 2004).

It seems that any approach to adapt the spraying volume rate to crop characteristics will lead with a general principle that foliar application must results in similar deposits ($\mu g \cdot cm^{-2}$), independently of crop size or canopy density. That system would avoid the problem of over dosage of PPP detected as a frequent problem in the early crop growth stages, especially in orchards and vineyards where in most cases pesticide dose rate is expressed in many different ways (Koch, 2007).

But in any case selective application with a precise target detection system must assure uniform deposits and must guarantee that large savings in sprayed application volume rates will not affect biological efficacy. This assumption has been confirmed in trials using different electronic control strategies (Koch and Weisser, 2000) who obtained no significant differences between a sensor based and a conventional application technique for apple scab (Ventura inequalis), pear psylla (*Cacopsylla pyri xx*) and leaf and bud mite (*Aculus schechtendali xx*) control.

This paper describes the characteristics of a sprayer prototype able to automatically adapt the spray application rate according to the target geometry, using an adapted tree-row-volume (TRV) estimation method (Pergher and Petris, 2008; Rüegg et al., 1999). Results in terms of deposit of tracer ($\mu g \cdot cm^{-2}$) and leaf recovery (actual recovered tracer compared with the expected according leaf area) have been calculated and compared with those obtained with a conventional method based on a per land surface dosage system ($l \cdot ha^{-1}$). In order to evaluate the influence of the leaf morphology, research trials have been conducted in three representative vineyards (*cv. Merlot*, *cv. Cabernet Sauvignon* and *cv. Tempranillo*) at two growth stages.

The objectives of this research were: a) to analyze the ability of ultrasonic sensors in determining vineyard structure; b) to investigate the spray volume savings achieved through the use of a target measurement sprayer control system based on the instantaneous vine volume, *iVV* (an adapted VRV principle); to evaluate the efficiency of the proposed spraying system, in comparison with the conventional application based on land surface; and d) to determine the relationship between spray volume savings and canopy structure.

2. Material and methods

2.1. Sprayer design

The development and testing of the target measurement and sprayer control system used in this research have been previously described and discussed (Gil et al., 2007) and will only be briefly outlined in this article. The measurement system and the electronic process unit were mounted on an air-blast orchard sprayer (Hardi LE-600 BK/2 with a centrifugal fan of 400 mm diameter). The sprayer was equipped with six individual and adjustable spouts (three on each side of the machine) in which up to five nozzles could be arranged on each one. A mast was fitted on its left side to hold three ultrasonic sensors and a solenoid high frequency electro valve was in front of each of the three spouts linked to each ultrasonic sensor. The three sensors and electro valves were connected to the central control unit placed on the rear top of the sprayer on which a purpose developed software based on LabVIEW (National Instruments Corporation, Austin, USA) was used to transform the crop width measured by each sensor into flow rate at every nozzle set (Figure 1) according equation [1]:

$$q_u = \frac{C_w \times \frac{C_h}{3} \times v \times m \times 1000}{60 \times n} \qquad [1]$$

Where C_w is the half crop width (m), C_h crop height (m), v is forward speed (km·h^{-1}), m the application coefficient per unit vegetation volume (l·m-^{3}) and n the number of nozzles per manifold (equal to 2).

2.2. Experimental plots

Trials were conducted in three different grape varieties (*Merlot*, *Cabernet Sauvignon* and *Tempranillo*) and at two different growth stages (75 and 85 according to the BBCH-scale (Meier, 2001). In all cases a total length of at least 100 m of five rows were sprayed (1,500 m^2 of experimental plot), and sample leaves for deposit measurements were only taken from the three different blocks randomly established in the center row. In every block, a sample of 1 m length of row was established, on which plants were divided into four different zones according to height (every 0.40 m, ranging from 0.40 m to 1.60 m), and three zones according to depth within the crop (I: external left, II: centre; and III: external right). From each of the twelve sampling positions (Figure 2), three replicates of samples were collected after spraying and stored in plastic bags.

2.3. Treatments

A set of tests was arranged on each variety and growth stage in order to compare the efficiency of application of the variable rate system with a conventional spraying procedure based on a constant application volume rate ($l \cdot ha^{-1}$) selected for each situation according to the usual rates in the area and growth stage. For the variable rate system, the application coefficient of $m = 0.095\ l \cdot m^{-3}{}_{vegetation}$ was maintained in all cases. This application rate was selected according to previous research (Gil, 2001) where interest and benefits of this value in terms of efficacy and efficiency of applications were demonstrated. The sprayer settings (Table 1) were maintained as close as possible between treatments in order to avoid external sources of variability.

2.4. Leaf area measurements

The leaf area index (*LAI*) was measured for each variety after the trials. For this purpose, two replicates of 1.0 m length were randomly selected among the five treated rows and leaves were picked independently into four plastic bags, corresponding to the four crop sample zones from 0.4 m to 1.6 m height (Figure 2). The total weight of each individual leaf sample was determined in the laboratory. The leaf area index was determined by area: weight ratio estimation for each variety and crop stage (Gil et al., 2007; Cross et al., 2001). All the obtained relationships were determined by measuring the weight and surface area of 50 samples collected from the bottom, middle and top parts of the vine. Surface area (one side only) was measured with a LI-COR LI 3100C electronic planimeter.

2.5. Measurement of deposits

Deposit and spatial distribution of spray liquid was measured using EDTA metallic chelates (Mn for conventional application and Zn for the variable rate system) as spray tracers (Gil et al., 2005; Gil et al., 2007; Cross et al., 2001; Murray et al., 2000) at a rate ranging from 0.68 to 1.80 $g \cdot l^{-1}$ depending on treatment (Table 1) following the same protocol established by Gil et al. (2007). Spraying different tracers for each treatment allowed the same leaf samples to be used and reduces the effect of canopy variability (Murray et al., 2000; Solanelles et al., 2005). Prior to the application, 25 leaves were picked from every individual block as blank samples, in order to determine the possible presence of metals. In all cases values of tracer concentration in the blank samples were less than the detection limit of the spectrophotometer (< 0.01 ppm). Once collected, all plastic bags containing leaf samples were placed in a dark container and stored in a refrigerator until the extraction process. Collection of samples was completed within 2 hours after the last application. Tracer deposit d in $\mu g \cdot cm^{-2}$ was determined by adding an exact quantity of deionized water as extractant (100 ml) and the subsequent measurement of tracer concentration using an atomic absorption spectrometer (Variant Spectra 1100). Three samples of roughly 100 ml of the spray solution for each treatment were taken from the tank of the sprayer immediately before and after application in order to determine the real tank concentration for each metal.

2.6. Analysis and expression of results

Statistical analysis was performed using SAS system v.8 (SAS Institute Inc., Cary, NC, USA).The symbols used are reported in the notation table using a previously defined nomenclature (Pergher and Gubiani, 1995).

The amount of spray deposited per unit leaf area by a particular treatment (*d,)* was calculated by dividing the tracer concentration in the washing solution of sample (T_{cl}) by the total leaf area of the sample L_a , according equation [2]

$$d = \frac{T_{cl} \times w}{L_a} \qquad [2]$$

where d is the tracer deposit per unit leaf area ($\mu g \cdot cm^{-2}$), T_{cl} tracer concentration in washing solution of sample leaf ($\mu g \cdot l^{-1}$), w the amount of deionized water (ml) and L_a area of sample leaf (cm^2)

Since the tracer application rates (T_{cs}) were not the same for all treatments, a normalized deposit, d_n ($\mu g \cdot cm^{-2}_{leaf} / \mu g \cdot cm^{-2}_{ground}$) was then calculated according to equation [3], by dividing the actual deposit d by the amount of metal tracer applied per unit ground area:

$$d_n = \frac{d \times 10^5}{V \times T_{cs}} \qquad [3]$$

where d_n is the normalized tracer deposit rate per unit leaf surface ($\mu g \cdot cm^{-2}$), d the actual deposit per unit area of leaf surface ($\mu g \cdot cm^{-2}$), V the spray volume rate ($l \cdot ha^{-1}$) and T_{cs} the tracer concentration of spray mixture in the tank ($\mu g \cdot l^{-1}$)

The normalized deposit procedure enables comparisons between the different sprayers and/or the different technologies, and has been based on the total amount of tracer applied per ground area. This procedure has been previously applied (Cross et al., 2001; Viret el al., 2003; Siegfried et al., 2007) where comparisons between sprayers and/or field conditions were arranged.

At the same the proportion of spray retained on the leaves (D_l) was also calculated (equation [4]) according the equation used by Pergher and Gubiani (1995), Cross et al. (2001) and Gil et al. (2007):

$$D_l = \frac{d \times 10^7 \times LAI}{V \times T_{cs}} \qquad [4]$$

In all cases, values of tracer concentration measured on blank samples were included in the calculation and normalization procedure. Prior to statistical analyses, a normal adjustment of the obtained data using a logarithmic transformation was applied in order to stabilize variances (Doruchowski et al., 1996; Gil et al., 2007).

3. Results

3.1. Quantification of savings

One of the objectives of this research was to calculate the total savings in the applied liquid. According to the application rate adjusted for every individual test, Table 2 shows the individual and average saving of liquid for all varieties and crop stages. In all cases saving values are greater than 40%, with the highest value for *cv. Tempranillo* (77%) in the last growth stage (BBCH-scale 85). In this particular situation some pruning before the test probably affected the measurements obtained by the sensors, increasing the distance to the crop and reducing substantially the applied volume (86 $l \cdot ha^{-1}$) compared to previous applications, whereas the conventional application volume rate was increased according to the normal procedure in the area. In general, the average savings obtained were approximately 58%, being in accordance with previous research (Koch and Weisser, 2000; Gil et al., 2007; Moltó et al., 2000; Balsari and Tamagnone, 1998; Solanelles et al., 2005). A detailed reading of results shown in Table 3 indicates a good correlation between canopy volume and leaf recovery in variable rate application, giving better results for highest values of TRV (Figure 3) measured according the methodology proposed by Siegfried et al. (2007).

The spatial distribution of savings can be observed in Figure 4. As an example, this figure shows a sample of 20 meters of crop line (*cv. Merlot*) where all the measured points with ultrasonic sensors have been represented (every 80 ms corresponding to 10 cm along the crop line). For every measured point the applied volume in variable rate application mode, calculated according to the measured distance with sensors, can be compared with that applied with the conventional spraying mode. Differences between those two lines represent the savings of liquid. It is important to highlight the perfect similitude of liquid amount delivered by the variable application method with the crop profile line. In figure great differences can be observed between the two applied volume rates. However, in any case those savings must be analyzed and evaluated together with averaged deposit values obtained for the two tested methodologies.

3.2. Deposit on leaves

According to the obtained values of normalized deposit on leaves d_n, proportional leaf recovery D_l and spatial uniformity of deposit on the whole canopy measured by the coefficient of variation of total deposit samples (Table 3), the variable rate application method showed higher leaf deposits in all cases except for those obtained for *cv*. *Merlot*. For the remaining cases, differences in d_n between the two tested methods differ significantly in favor of the variable rate method. In terms of proportion of spray retained (D_l), the same tendency has been observed. In all cases, variable application method gave the highest values of retention, always greater than 40%. It is interesting to remark the highest value of proportional leaf recovery (86.85%)

obtained in cv. *Tempranillo* at 75 of BBCH-scale. On the contrary, retention values obtained with conventional applications were below 40%, except for *cv. Merlot*.

The spatial uniformity of leaf deposit in the whole canopy, measured by means of the coefficient of variation (CV %) of the total deposit samples on the crop (Table 3) indicates that in *cv. Tempranillo* and *Cabernet Sauvignon*, variable rate applications gave CV values under 50%, with a more uniform deposit than obtained for conventional applications. For *cv. Merlot*, the tendency was the opposite: conventional applications gave the most uniform results.

Graphics of the spatial distribution of leaf deposit within the canopy are shown in Figure 5. In general, high uniformity can be observed in all cases, independently of the spray method (conventional or variable), crop stage or crop variety. A deeper analysis of figure 5 indicates higher values of normalized leaf deposits for the variable rate application method than those obtained with the conventional method.

The effect of variable rate applications on the quality of leaf deposits measured by the coefficient of variation of the total sample zones on the vine (d_n) and the normalized leaf recovery expressed as a percentage of the total emitted output (D_l), are shown in Figure 6. The general tendency indicates a slow but homogeneous movement to the right of the graph, which means an increase in normalized leaf recovery, obtained in all cases with the lower volume rates. The diameter of each individual circle represents the average normalized deposit (d_n) on each treatment. Following the same trend as observed for leaf recovery, the variable rate technology gives the highest values of normalized deposit. And in terms of uniformity of deposits, in general all the circles are located close to the center line (horizontal), meaning similar values of uniformity (coefficient of variation).

A detailed analysis of the distribution of sample frequencies was conducted in order to compare the normalized deposit in both methods. It is interesting to notice that in all cases variable rate applications gave higher cumulative frequencies of leaf samples with higher deposits. Remarkable results have been obtained at the earlier crop stage (BBCH-75) in *cv. Cabernet Sauvignon* and *cv. Tempranillo*.

3.3. Crop profile and liquid distribution

Figure 7 shows the relation between crop profile (leaf surface distribution with height) and total deposits measured at each crop level. In general in all cases it can be observed how deposits for conventional application follow a vertical line, independently of leaf distribution on each level. Those lines must be compared with those related to variable rate application, which present in general better adaptation to leaf distribution. Quantification of this adaptation can be done by means of the coefficient of correlation (r) between profiles (Figure 7). In all cases, except in the latest crop stage in *cv. Tempranillo*, variable rate spraying offered better adaptation to crop profile or at least the same values as conventional spraying (i.e. *var. Merlot*).

Another important aspect regarding the relationship between crop structure and applied volume can be observed in Figure 8, representing values obtained in *cv. Merlot*. In that figure, variation of the real application coefficient m ($l \cdot m^{-3}$) has been plotted together with the obtained measures of canopy volume (m^3) with the ultra sonic sensors. Solid line on the graphic indicates the theoretical m value for which the variable rate sprayer was adjusted. Values of real m ($l \cdot m^{-3}$) rate delivered with the variable rate system have been represented with triangles on the same graphic. Results show a great coincidence with the objective, mainly in situations with a high canopy volume (right part of the figure). The most important deviations from the intended objective can be observed for situations with low or very low crop canopy (left part of the figure). This behavior is due to spraying those areas with the minimum established pressure (sometimes overdosing) to ensure the quality of the droplets. Obtained results in conventional application (represented by square points on the graph) indicates that the objective is only achieved for canopy values over 0.04 m^3 with high overdose generated in case of lower canopy volumes. In fact, this behavior is the expected in a constant flow rate application. The selected flow rate is the one that best fits worst cases (highest canopy volumes) found in the vineyard. As the sprayed flow rate does not vary with canopy volume decrease, the result is an over sprayed canopy in situations different than the worst case. The application coefficient increases as the canopy decreases.

4. Discussion

Even in uniform vineyards, important differences can be observed in crop width and thus in canopy volume along the line. The use of electronic systems capable to determine these differences in real time and the ability to adjust the working parameters according to these variations is an interesting way to achieve savings in the total amount of sprayed pesticides.

The use of ultrasonic sensors together with variable rate electro-valves and the corresponding software for automation, made possible a real time modification of the spray flow rate according to the canopy volume. This allowed a significant reduction in spray volume while maintaining coverage and penetration rates similar or even better to conventional methods.

Ultrasonic sensors and their measurements of crop canopy allow tracer deposits to be varied according to leaf distribution in the crop profile. This fact is extremely important in order to obtain leaf deposits close to the intended threshold.

Results obtained in all crop conditions and varieties encourage the continuation of this research, maintaining as the main goal of increasing pesticide savings and improved liquid distribution according to the crop characteristics.

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TABLES

Table 1 Operational parameters during treatment applications

Variety and crop Stage*		Conventional application			Variable rate application (VRT)		
		Applied volume rate ($l \cdot ha^{-1}$)	Pressure (bar)	Tracer concentration ($mg \cdot l^{-1}$ Mn)	Application rate m ($l \cdot m^{-3}$)	Pressure (bar)	Tracer concentration ($mg \cdot l^{-1}$ Zn)
Merlot	85	266	7.0	1878	0.095	min = 3.0 max = 7.0	1568
Cabernet Sauvignon	75	299	7.0	741			1021
	85	373	11.0	735			680
Tempranillo	75	299	7.0	741			1021
	85	373	11.0	735			680

In all cases the sprayer was settled with 12 hollow cone nozzles (Albuz ATR brown) at a forward speed of 4.5 $km \cdot h^{-1}$

* Crop stage according to BBCH classification

Table 2 Percentage savings (VRT/conventional) for different cultivars and crop stages

Variety and crop stage*		Application rate ($l \cdot ha^{-1}$)		Total saving (%)
		Conventional	VRT	
Merlot	85	266	141	47.0
Cabernet Sauvignon	75	299	179	40.1
	85	373	111	70.2
Tempranillo	75	299	127	57.5
	85	373	86	76.9

* According to BBCH classification

Table 3 Normalized deposit average values, proportional leaf recovery and coefficient of variation for all varieties and crop stages analyzed

Variety and crop stage[1]		LAI	TRV[2] ($m^3 \cdot ha^{-1}$)	Actual deposit[3] d		Normalized deposit[4] d_n		Proportion of spray retained D_l (%)		Deposit uniformity (CV %)	
				CONV	VRT	CONV	VRT	CONV	VRT	CONV	VRT
Merlot	85	1.32	1880	2.30	0.77	0.46 **a**	0.35 **b**	60.85 **a**	47.14 **b**	28.00	54.00
Cabernet Sauvignon	75	1.08	1922	0.73	1.02	0.33 **b**	0.56 **a**	35.51 **b**	60.94 **a**	50.44	38.73
	85	0.99	1514	1.01	0.39	0.37 **b**	0.52 **a**	37.51 **b**	51.46 **a**	32.27	34.94
Tempranillo	75	1.24	2242	0.66	0.89	0.30 **b**	0.69 **a**	37.45 **b**	86.85 **a**	51.12	43.15
	85	1.50	1710	0.77	0.16	0.28 **a**	0.28 **a**	43.38 **a**	42.23 **a**	45.46	49.76

CONV: Conventional application; VRT: Variable Rate Technology

Values followed by the same letter in rows do not differ statistically (Student-Neuman-Keuls test, $p<0.05$)

[1] According to BBCH classification

[2] Calculated according methodology proposed by (Siegfried et al., 2007)

[3] Actual deposit (d) expressed as total amount of tracer per leaf surface e unit ($\mu g \cdot cm^{-2}$)

[4] Normalized deposit (d_n) is expressed by relation between the total tracer on the leaf surface and the total amount of tracer per ground unit ($\mu g \cdot cm^{-2}_{leaf} / \mu g \cdot cm^{-2}_{ground}$)

FIGURE CAPTIONS

Figure 1 Principle of functioning of the prototype (left) and prototype with electronic devices (right).

Figure 2 Sampling zone on the canopy (left) and defoliation procedure for the leaf area index determination (right).

Figure 3 Relationship between the measured tree row volume (Siegfried *et al*, 2007) and the proportion of spray retained (%) for conventional application (left) and variable rate application (right).

Figure 4 Variation of nozzle flow rate in variable rate application, according crop structure measured by the ultrasonic sensors. Horizontal line represents the constant nozzle flow rate emitted during conventional application.

Figure 5 Spatial distribution of normalized deposit (d_n) for conventional and variable rate application for different vines and crop stages within the canopy.

Figure 6 Relation between variable rate application, leaf recovery and uniformity of deposition. Circumference diameters are proportional to absolute values of leaf deposit.

Figure 7 Vertical profiles of normalized deposits (d_n) and its relation with leaf distribution (% of leaf area). r indicates the coefficient of correlation between profiles.

Figure 8 Actual application coefficients *i* obtained with the two evaluated methods and comparison with the intended value.

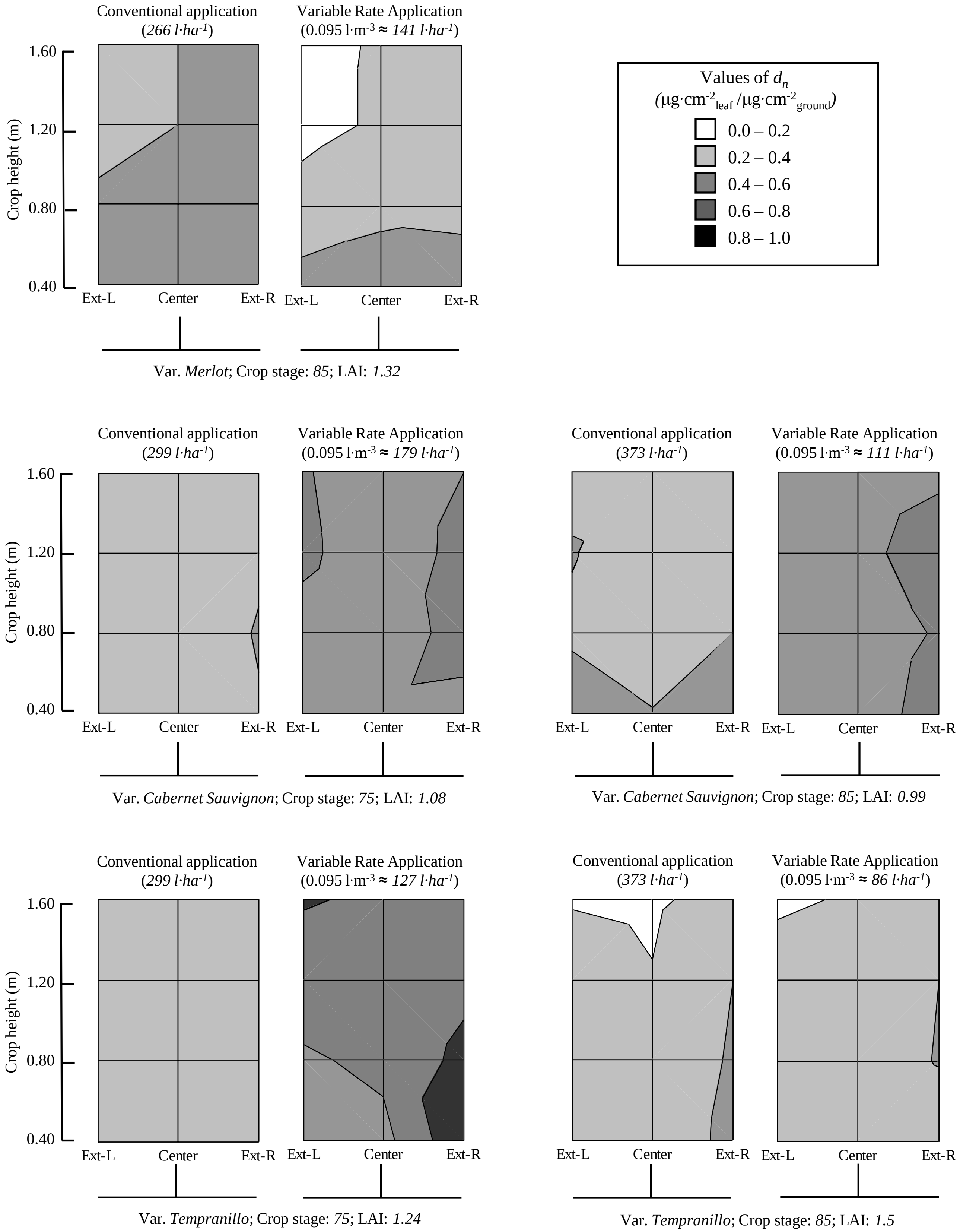
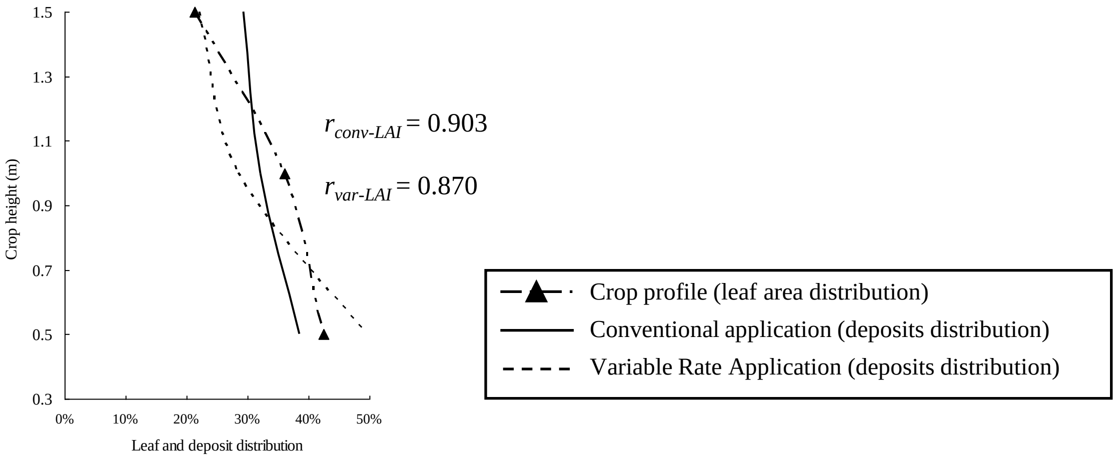
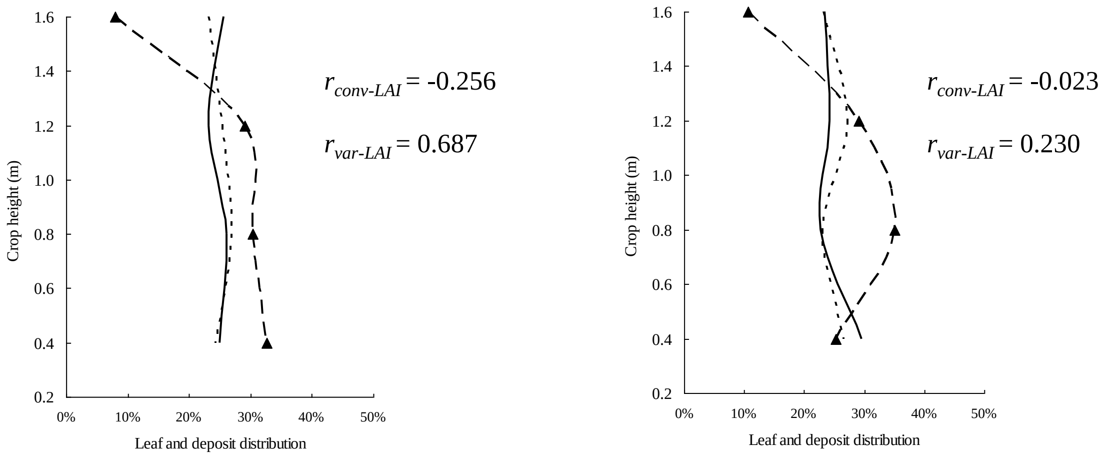

Conventional application
(266 l·ha-1)
Variable Rate Application
(0.095 l·m-3 ≈ 141 l·ha-1)
Crop height (m)
1.60
1.20
0.80
0.40
Ext-L
Center
Ext-R
Var. Merlot; Crop stage: 85; LAI: 1.32
Values of dn
(µg·cm-2leaf /µg·cm-2ground)
0.0 – 0.2
0.2 – 0.4
0.4 – 0.6
0.6 – 0.8
0.8 – 1.0
Conventional application
(299 l·ha-1)
Variable Rate Application
(0.095 l·m-3 ≈ 179 l·ha-1)
Var. Cabernet Sauvignon; Crop stage: 75; LAI: 1.08
Conventional application
(373 l·ha-1)
Variable Rate Application
(0.095 l·m-3 ≈ 111 l·ha-1)
Var. Cabernet Sauvignon; Crop stage: 85; LAI: 0.99
Conventional application
(299 l·ha-1)
Variable Rate Application
(0.095 l·m-3 ≈ 127 l·ha-1)
Var. Tempranillo; Crop stage: 75; LAI: 1.24
Conventional application
(373 l·ha-1)
Variable Rate Application
(0.095 l·m-3 ≈ 86 l·ha-1)
Var. Tempranillo; Crop stage: 85; LAI: 1.5

Figure 5

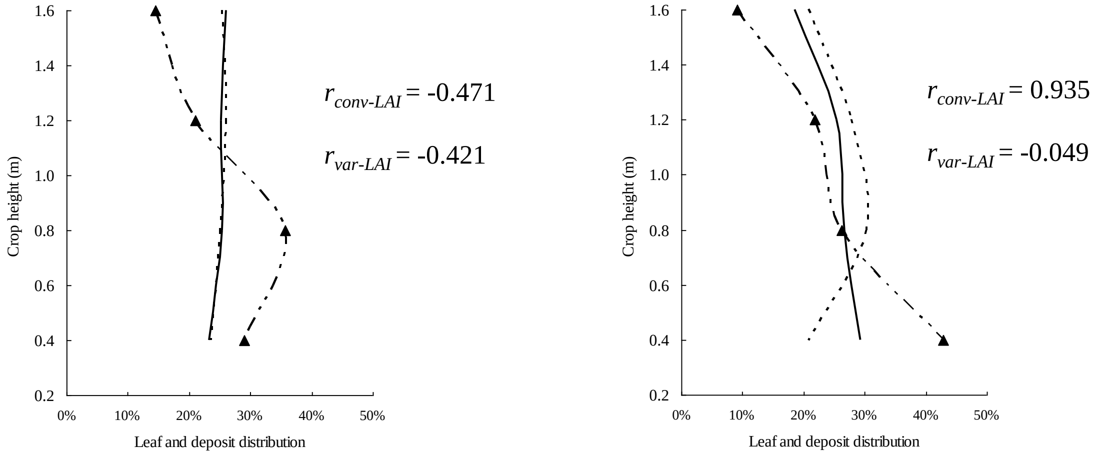


Var. *Merlot*; Crop stage: *85*; LAI: *1.32*



Var. *Cabernet Sauvignon*; Crop stage: *75*; LAI: *1.08*

Var. *Cabernet Sauvignon*; Crop stage: *85*; LAI: *0.99*



Var. *Tempranillo*; Crop stage: *75*; LAI: *1.24*

Var. *Tempranillo*; Crop stage: *85*; LAI: *1.5*

Figure 7

Figure(s)

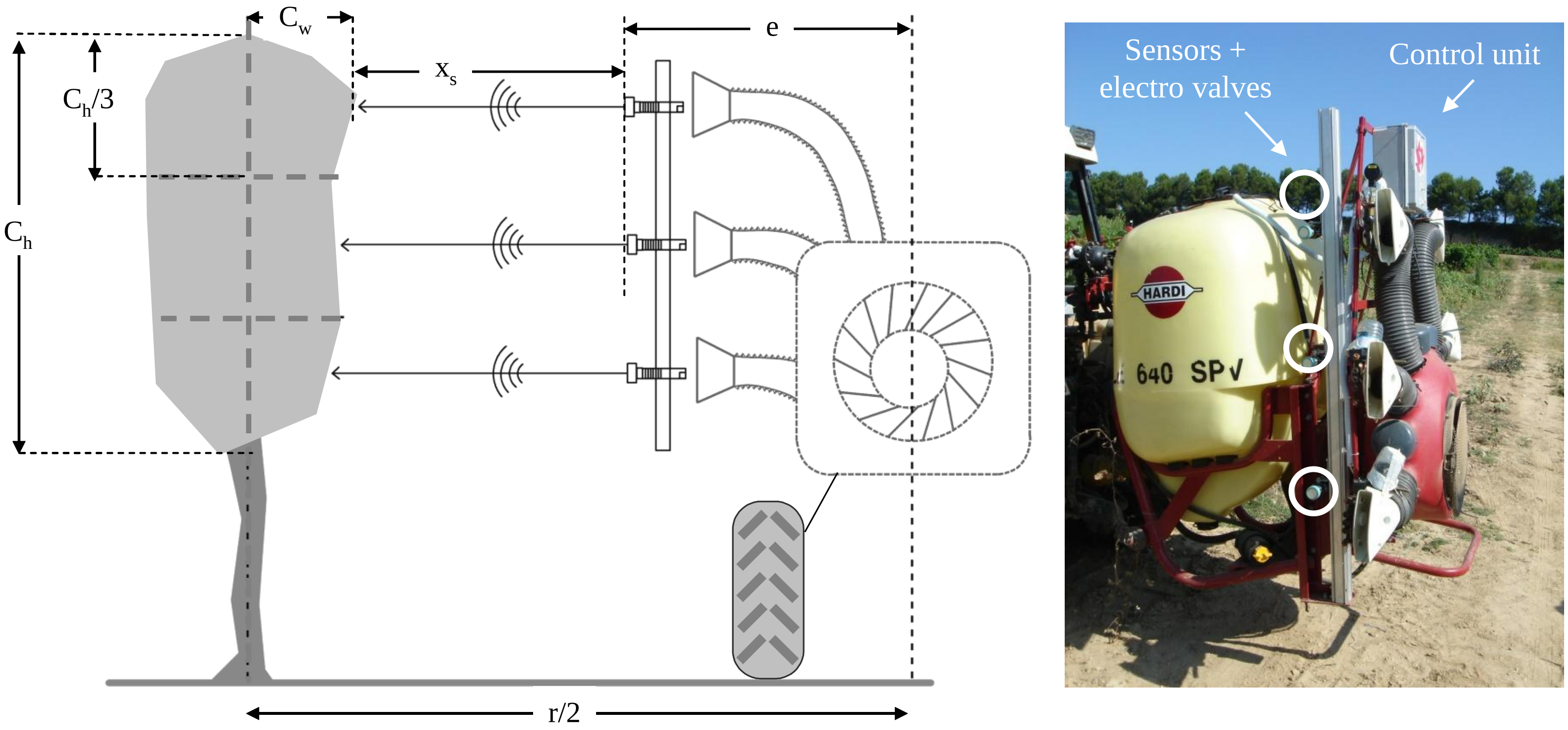


Figure 1

Figure 2

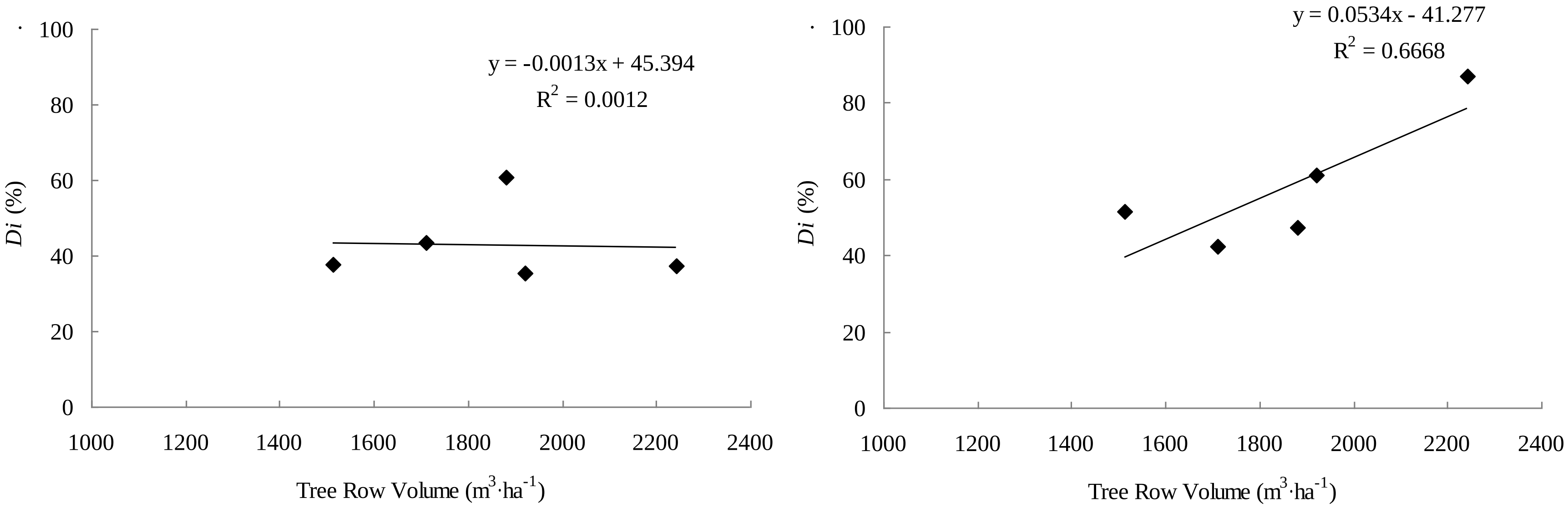
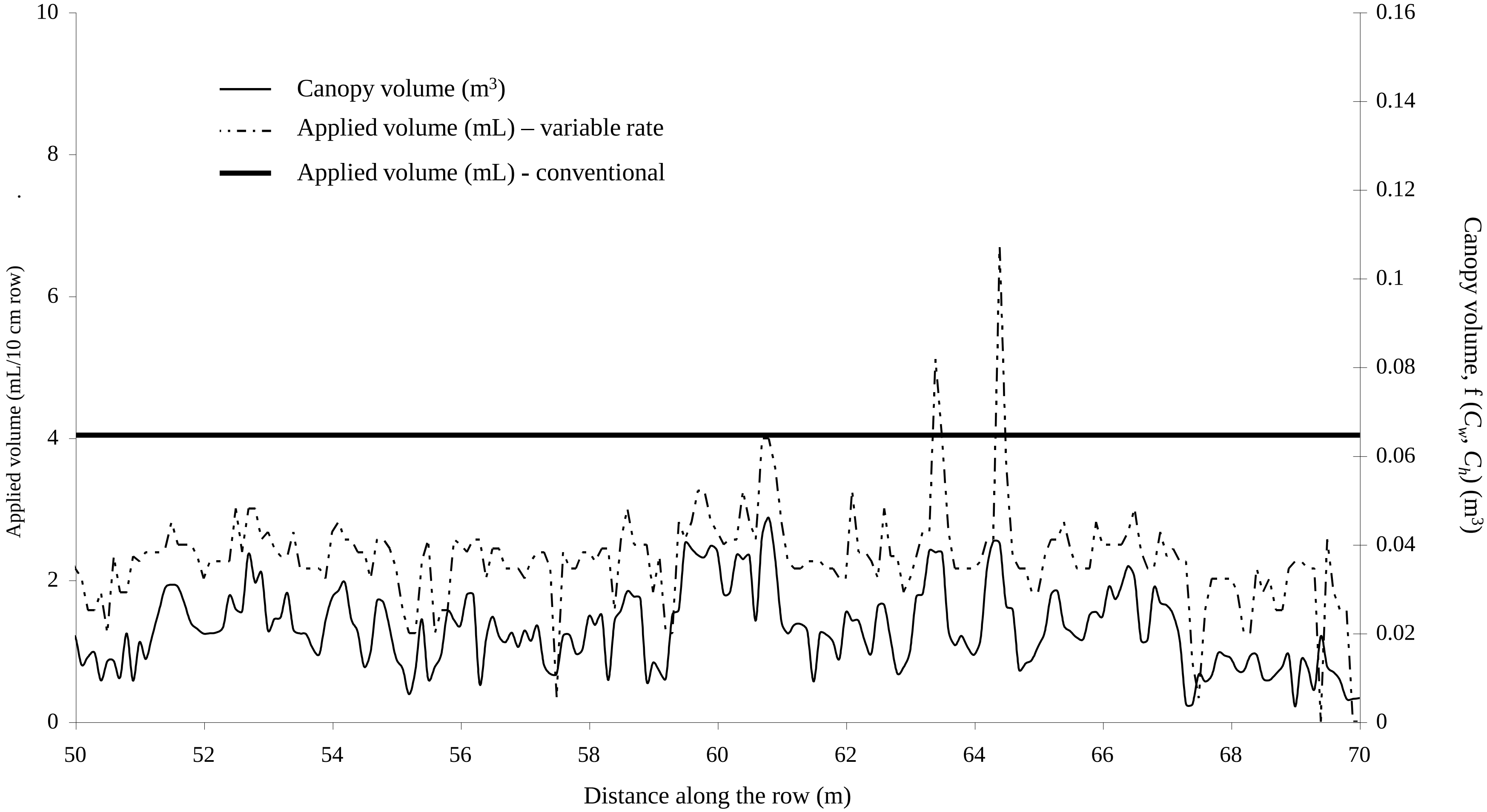

y = -0.0013x + 45.394
R2 = 0.0012
100
80
60
40
20
0
Di (%)
1000
1200
1400
1600
1800
2000
2200
2400
Tree Row Volume (m3·ha-1)
y = 0.0534x - 41.277
R2 = 0.6668
100
80
60
40
20
0
Di (%)
1000
1200
1400
1600
1800
2000
2200
2400
Tree Row Volume (m3·ha-1)

Figure 3



Canopy volume (m³)
Applied volume (mL) – variable rate
Applied volume (mL) - conventional
Applied volume (mL/10 cm row)
Canopy volume, f (Cw, Ch) (m³)
Distance along the row (m)
0
2
4
6
8
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
50
52
54
56
58
60
62
64
66
68
70

Figure 4

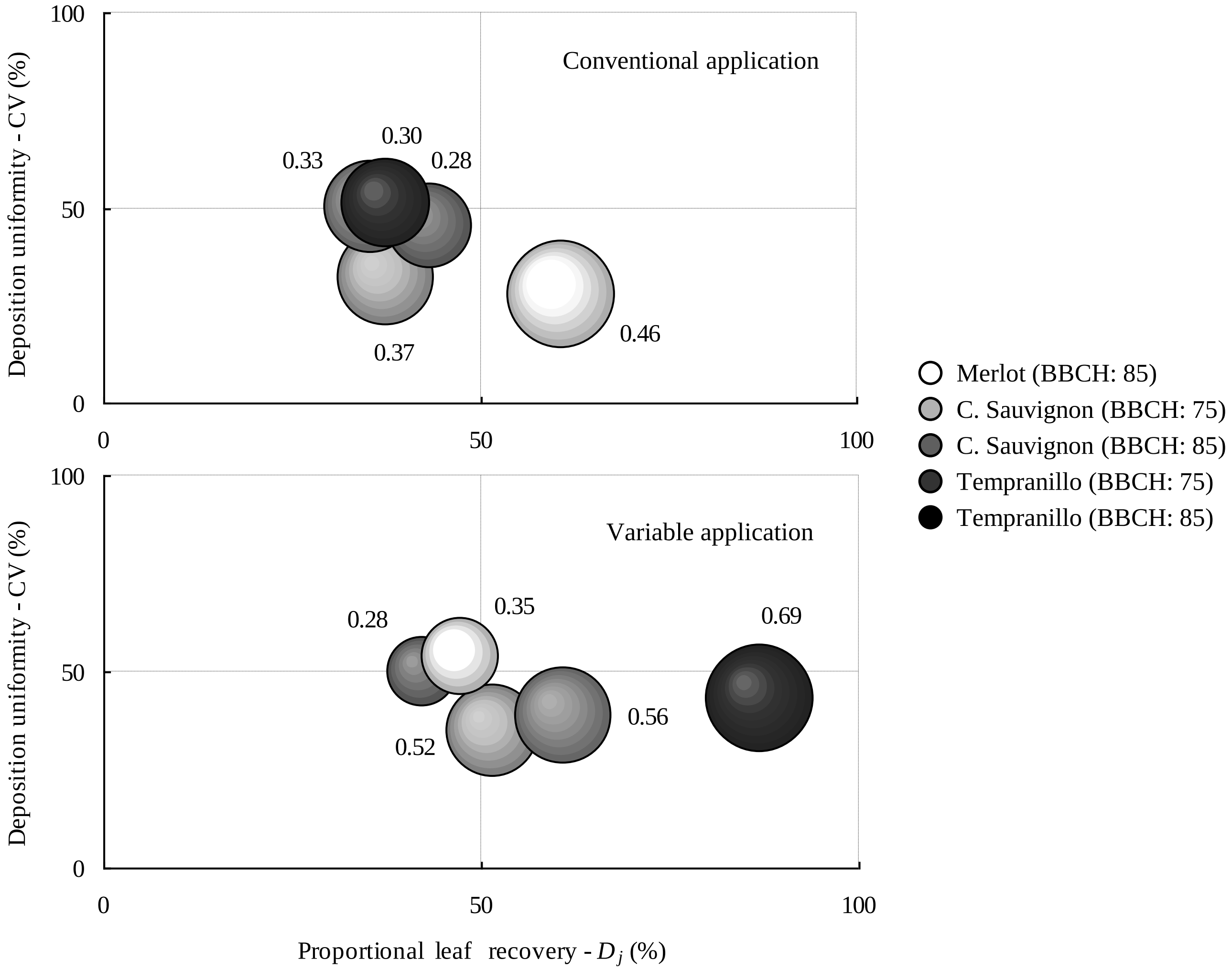

Conventional application
Variable application
Deposition uniformity - CV (%)
Proportional leaf recovery - D_j (%)
0
50
100
0.33
0.30
0.28
0.37
0.46
0.28
0.35
0.69
0.52
0.56
○ Merlot (BBCH: 85)
● C. Sauvignon (BBCH: 75)
● C. Sauvignon (BBCH: 85)
● Tempranillo (BBCH: 75)
● Tempranillo (BBCH: 85)

Figure 6

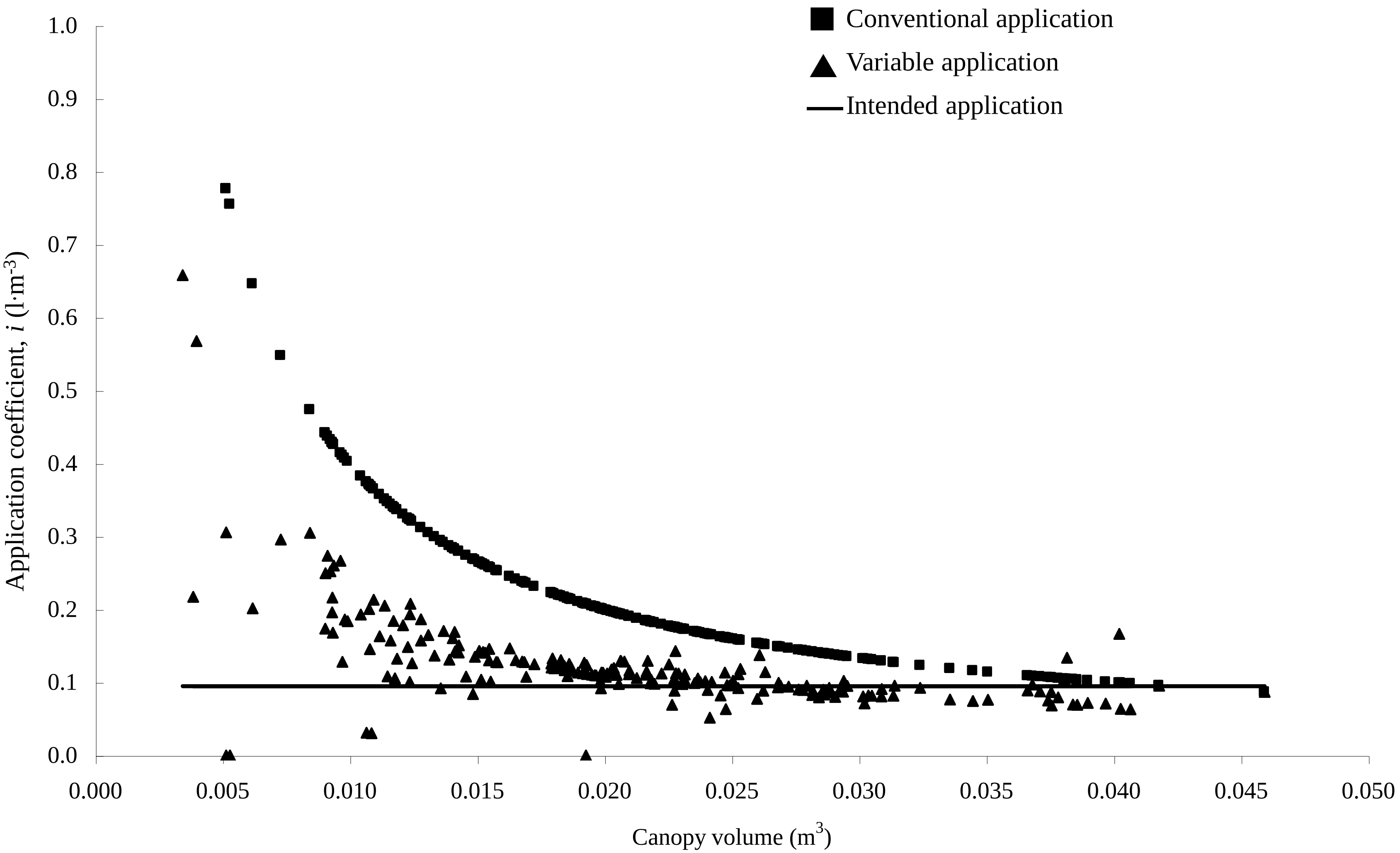

Conventional application
Variable application
Intended application
Application coefficient, i (l·m-3)
Canopy volume (m3)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
0.050

Figure 8