Variable rate application of Plant Protection Products in vineyard using ultrasonic sensors

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Abstract

The changes in the shape and size of vines during the growing season, requires a continuous adjustment of the applied dose to optimize spray application efficiency. Target detection with ultrasonic sensors can be used to adapt the applied dose following the principles of the variable rate technology. A multi-nozzle air blast sprayer was fitted with three ultrasonic sensors and three electro-valves, to modify the flow rate from the nozzles in real time, in relation to the variability of crop width. A constant application rate of 300 l·ha^{-1} was compared with a variable rate application using the tree row volume principle at a 0.095 l·m^{-3} canopy. The total flow rate sprayed by the nozzles was modified according to the variations of crop width measured by the ultrasonic sensors. On average 58% less liquid was applied compared to the constant rate application, with similar deposition on leaves with both treatments. A detailed analysis of savings indicates differences between the lower, middle and top part of the crop, in accordance with the leaf area distribution with crop height. No significant differences between

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treatments were detected in uniformity of liquid distribution and capability to reach the inner parts of the crop. This important reduction in spray volume could be followed by an equivalent reduction of plant protection products but further research work is needed to guarantee biological efficacy of a reduced dose.

Key words: spray, vineyard, variable rate, electronic control, dose adjustment, ultrasonic sensors, precision viticulture, tree row volume.

1. Introduction

Environmentally safe spray techniques have been developed to reduce the use of plant protection products (PPP) and apply them only when and where needed with reduced losses to the environment (Doruchowski and Holownicki, 2000). In this sense the effort invested in developing new technologies to adjust the dosage to the characteristics of the vegetation is very well known. Measurements recorded using 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 (Walklate *et al*, 2006). The different shapes and sizes found in tree crops, even during the same growing season, requires a continuous adjustment of the applied dose to optimize the spray application efficiency and to reduce environmental contamination (Solanelles *et al.*, 2002). Target detection has been developed either by using very advanced techniques, such a vision systems and laser scanning, or with ultrasonic and spectral systems. According to Doruchowski and Holownicki (2000), ultrasonic and optic sensors can be used with sprayers that produce an air flow which is more or less horizontal, such as cross-flow fan sprayers or directed air-jet sprayers. In this case, the signal from the sensors, together with data on the sprayer's forward speed and the constant distance between the sensors and the nozzles are used in an optimized algorithm to open and close individual nozzles according to the detected presence or absence of the crop.

The performance of an electronic sprayer prototype was initially tested by Giles *et al.* (1987 and 1988). The system was based on ultrasonic range transducers and was mounted on an orchard air-blast sprayer. Ultrasonic transducers measured the distance to the canopy foliage and their performance was not affected by ground speed. Later applications were focused on interrupting the spray output when there was no vegetation by means of different technologies to detect vegetation. Jaeken *et al.* (1997) used a spectrum analysis system to switch individual nozzles on and off. Balsari and Tamagnone (1998) also undertook a similar approach with an ultrasonic control system fitted on an air-assisted sprayer, reporting some difficulties in identifying small gaps in vegetation due to the wide field of view of the sensors. The potential application of ultrasonic sensors includes orchard management based on rapid quantification of tree volume and, according to Zaman and Salyani (2004), the information could also be used in variable rate application of agrochemicals. Moltó *et al.* (2001) developed a prototype able to turn off the spray in the gaps between tree canopies and also to accommodate the variation of canopy volume at the beginning and at the end of each tree making it possible to spray two different flow rates depending on the vegetation volume. The first approach to continuous proportionality was developed by Rosell *et al.* (1996). They built a prototype with proportional response operating on a 3-nozzle boom section as a first attempt to test the feasibility of such a technology. Following this work, in 2001 a sprayer was fitted with sensors and electro valves to achieve proportional spraying as described in Solanelles *et al.* (2002). In that work a conventional application was compared with an application proportional to the canopy volume, using two ultrasonic transducers and solenoid valves. The arrangement saved 65 and 30% of spray liquid in olive and pear orchards respectively. Whitney *et al.* (2002) investigated the ultrasonic transducer's response to different parts of a citrus canopy and also examined the effect of sampling interval and transducer spacing on canopy volume determination.

Selective application with a precise target detection system must assure uniform efficacy of application, and must guarantee that large savings on sprayed liquid will not affect biological efficacy. This assumption has been confirmed by Koch and Weisser (2000) who obtained no significant differences between the sensor technique and conventional application in control for apple scab, pear psylla (*Cacopsylla pyri*) and leaf and bud mite (*Aculus schechtendali*).

Therefore, this work was designed to:

1. Evaluate an alternative methodology that applies an optimal volume rate based on the crop structure, Tree Row Volume (TRV), in comparison with the traditional methodology based on the amount of product per unit ground area.
2. Quantify the total savings, in terms of liquid and plant protection product (PPP), from the use of the electronic control system;

Following from these general objectives, two particular objectives are also proposed:
1. Develop an electronic system to determine the variability of crop structure in vineyards;

2. Evaluate the application quality of the new versus conventional methodologies.

2 Materials and methods

2.1. Electronic devices

Following the work of Escolà *et al.* (2003), an electronic control system was developed to allow measurement of changes in the crop structure and modification of the total applied volume according to those changes. An air assisted sprayer (model LE-600 BK/2 from ILEMO-HARDI, S.A.) with a centrifugal fan (400 mm diameter) was equipped with six individual and adjustable sets of nozzles (three on each side of the machine) where up to five nozzles could be arranged. A mast was fitted on its left side with three ultrasonic sensors (Sonar Bero-Compact) and three solenoid electro valves (Asco/Joucomatic). These were at the same level of each nozzle set (figure 1). All three sets were connected to the central control unit placed on the top rear of the sprayer. The signal obtained from the sensors (voltage) was converted into distance to the crop (m) following Eq. (1) obtained by Escolà *et al.* (2003):

$$d_i = 250 - 21 \times v_i \tag{1}$$

Where d_i: distance between sensor i and crop (cm); v_i: value of voltage measured by sensor i (V) ($r^2 = 0.9986$). Individual values of d_i were used to calculate the crop width and, together with values of the crop height and forward speed, variations in crop volume were then calculated. Ultrasonic transducer distance measurements exceeding one half of the row width were eliminated from the calculation with an "IF" logical statement in the calculation process (Shumann and Zaman, 2005).

Previous to the treatment, the spray parameters (forward speed, row distance and spray application rate) must be entered manually. When the application begins, the signals from the ultrasonic sensors are acquired and the volume of vegetation is determined by the controller. To convert volume of vegetation into flow rate, the spray volume rate per unit canopy volume (l·m^{-3}) must be previously selected. Finally, the estimated flow rate is converted into voltage to be sent to the valves (figure 2) according to Eq. (2):

$$v_i = 2.2952 \times e^{1.0925 \times Q_i} \qquad (2)$$

Where v_i: voltage to be sent to the electro valve (V); Q_i: estimated flow rate on the nozzle set (l·min^{-1}).

2.2. Principle of function

The performance of the sprayer was based on the estimation of the canopy volume at cross sections every 10cm and at three different heights, similar to what Wheaton *et al.* (1995) proposed, and spraying the appropriate flow rate proportionally to the measured volume. Figure 3 shows the principle of operation of the prototype. Distance from the sensor to the crop (d_i) was measured by each sensor, obtaining the crop width for each third of the total crop height. These measures were automatically introduced into the software based on Labview® allowing the calculation of corresponding flow rate for every set of nozzles according to Eq. (3):

$$q\ (l\,\mathrm{min}^{-1}\ ) = \frac{[D - d_i - e_i](m) \times {}^{h}\!/_{3}\ (m) \times v(km\,h^{-1}) \times i\ (l\,m^{-3}) \times 1000}{60} \tag{3}$$

Where q: flow rate to be sprayed per nozzle set (l·min^{-1}); D: distance between axis of the sprayer and axis of the tree row (m); e_i: distance between sensor i and the axis of the sprayer (m); d_i: distance between sensor i and crop (m); h: measured crop height (m); v: forward speed (km·h^{-1}); i: established application volume rate per unit vegetation volume (l·m^{-3}).

2.3. Field tests

The experiments were conducted in Torre Marimon, a research farm belonging to the Polytechnic University of Catalonia, in Barcelona (Spain), in a Royat trellis vineyard (cv: Cabernet sauvignon). Row spacing was 3 m and the spacing between poles on the row was 2.0 m; thus density was 1.666 vines ha $^{-1}$. Experiments were performed during the last week of July 2004 in the verison stage, one of the most important from the point of view of PPP applications.

Three blocks were established on a central row of a 50 m wide vineyard parcel. Every block was separated from each other by 40 m. A total length of circa 120 m was sprayed from both sides according to the recently developed ISO FDIS 22522 – *"Crop protection equipment – Field measurement of spray distribution in tree and bush crops"* and following the normal procedure during PPP applications in vineyard. On every block, a sample 1 m length of row was established, in which plants were divided into five different zones according to height (A: from 0.60 to 0.90 m; B: from 0.90 to 1.20 m; C: from 1.20 to 1.50 m; D: from 1.50 to 1.80 m; and E: over 1.80 m), and three zones according to depth within the crop (I: external left, II: centre; and III: external right). From each of the fifteen sampling positions, a variable number of leaves (between 2 and 5) were collected after spraying and stored into a plastic bag.

To assess losses to the ground, four wooden frames (50 cm x 20 cm) containing three round pieces (5.5 cm ∅) of absorbent paper were placed on the ground in each block (Pergher *et al.*, 1997) to collect spray deposits over a width of 3.0 m, that is 1.5 m on each side of the sample vine (figure 4).

2.4. Treatments

Two different treatments were established. In the first one, a conventional sprayer was calibrated to apply a constant rate of 300 l·ha^{-1}, according to the results obtained by Gil (2003). In the second treatment, the application rate was varied according to crop structure using the Tree Row Volume method of dose expression (Byers *et al.*, 1971, 1984; Sutton and Unrath, 1988; Hall and Cooper, 1991; Doruchowski *et al.*, 1997; Heijne *et al.*, 1997; Walklate *et al.*, 2003). First, the total volume of vegetation (m^3·ha^{-1}) was calculated according to the crop dimensions (1.4 m height, 0.67 m width and 3.0 m row distance) by applying the TRV method , Eq. (4):

$$TRV\ (m^3\ ha^{-1}) = \frac{h\,(m) \times w\ (m)\ \times 10.000\ (m^2\ ha^{-1})}{r\ (m)} \qquad (4)$$

Where *TRV*: total volume of vegetation per unit ground area ($m^3 \cdot ha^{-1}$); *h*: height of crop wall (m); *w*: crop width (m); *r*: row distance (m). The obtained value of TRV (3126 $m^3 \cdot ha^{-1}$) was then used to transform the constant application rate of 300 $l \cdot ha^{-1}$ of the conventional application, into a constant volume rate per unit vegetation volume (i = 0.095 $l \cdot m^{-3}$) based on crop structure, following Eq. (5):

$$i\,(l\,m^{-3}) = \frac{App.rate\ \ (l\,ha^{-1})}{TRV\ \ (m^3 ha^{-1})} \qquad (5)$$

Where *i*: established spray volume rate per unit vegetation volume ($l \cdot m^{-3}$); *App. rate:* fixed application rate per unit area ($l \cdot ha^{-1}$); *TRV*: total volume of vegetation per unit ground area ($m^3 \cdot ha^{-1}$). Maintaining this ratio of 0.095 $l \cdot m^{-3}$ as a goal in this second treatment the flow rate of nozzles was continuously modified according to the variations of crop width measured by the three ultrasonic sensors.

In order to avoid external sources of variability, all the working parameters were maintained as close as possible in both treatments, with especial interest in nozzle type (ATR brown: 0.57 $l \cdot min^{-1}$ at 7.0 bar pressure) and pressure. According Escolà *et al* (2003), values of VMD obtained with the same electronic device in variable application rate in apples, were not significantly different (156 µm) than those obtained for the conventional application (148 µm), using in both cases the same type of nozzles (orange hollow cone ATR), No differences were observed in values of D_{10}, D_{90}, CU and SPAN. The sprayer settings (Table 1) were the same for both treatments, except that the values are the maximum for the variable rate sprayer.

2.5. Spray tracer and sampling

EDTA chelates of metals were used as spray tracers (Cross *et al*., 2001; Murray *et al*., 2000; Gil *et al*., 2005) at a rate of approximately 400 $g{\cdot}ha^{-1}$. Concentration of tracers ranged from 1.313 $g{\cdot}l^{-1}$ of Mn^{2+} for conventional application to 1.588 $g{\cdot}l^{-1}$ of Zn^{2+} for variable application (table 2). Spraying different tracers on each treatment allowed to use the same leaves samples.

On every block three replicates were arranged, resulting in a total of 135 samples (3 blocks x 3 replicates x 5 heights x 3 depths). 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 the samples was completed within 2 hours after the application of the last spray.

Deposits of spray tracers were determined ($\mu g{\cdot}cm^{-2}$) using an ICP-atomic emission spectrometry (ICP-AES). Prior to statistical analyses, a transformation of the obtained data using a logarithmic transformation (Doruchowski *et al.*, 1996; Gil, 2001) was applied, in order to stabilize the variance.

2.6. Leaf area determination

The surface area of leaves samples was determined by area - weight ratio estimation (Cross *et al.*, 2001). This ratio (Eq. 6) was determined by measuring the weight and surface area of 25 samples collected from the bottom, middle and top part of the vine.

Surface area (one side only) was measured with a LI-COR LI 3000 electronic planimeter.

$$A = 41.741 \times g + 13.279 \qquad (6)$$

Where A: leaf surface (cm^2); g: leaf weight (g); ($r^2 = 0.97$) (figure 7). For samples of deposition on ground surface, the calculated area of each piece of absorbent paper was 23.75 cm^2.

3. Results

3.1. Crop characterization

Value of the Leaf Area Index was 1.40. Leaf surface distribution across height presents an expected profile (figure 6), with the maximum amount of leaves (31.6 %) in the middle part of the canopy (C level) and the minimum (7.2 %) at the bottom part (0.60 m height or less). There is a high concentration of leaves in the middle and upper part of the canopy, with great variability of leaf density. This variability is measured by the ultrasonic sensors, and justifies the need of a variable application rate along the crop wall.

The crop profile data at the different levels on the left and right side respectively of the transformed from the ultrasonic sensor output (Figures 7 and 8) show important differences in the crop width (table 3) as well as variations on the TRV values along the crop line, in accordance with the heterogeneous distribution of the leaf surface.

3.2. Efficiency

Efficiency of applications can be estimated by relating the total deposit obtained on each treatment with the theoretical applied volume and tracer concentration in the tank, according to Eq. 7 (Gil, 2001):

$$E = \frac{C \times 10^5 \times LAI}{[T_r] \times Ap} \tag{7}$$

Where *E*: efficiency of the application; *C*: average of deposited metal tracer (µg) per unit leaf area (µg·cm^{-2}); *LAI*: Leaf Area Index (adim.); *[Tr]*: real concentration of metal in the tank sample (mg·l^{-1}); and *Ap*: application rate (l·ha^{-1}). Efficiency obtained with proportional application (0.31) was more than double than the obtained with conventional one (0.15). Averaged application rate in proportional test (125.7 l·ha^{-1}) was calculated for an estimated average flow rate of 2.83 l·min^{-1}.

3.3. Savings

According to the crop profile variations, the total flow rate to be applied by every set of nozzles was then established following Equation 3. This variable flow rate for each one of the three nozzle sets was then compared with the constant flow rate applied in the conventional test.

The total amount of liquid applied in both treatments was then calculated, allowing estimation of the total saving of liquid at each level. On the 100 m length a total of 9.12

l were applied (both sides of the row) during conventional application (1.52 l on each nozzle set). With the proportional system only 3.76 l were applied, representing 41.2% of the conventional one. Thus, the potential averaged saving can be estimated at about 58.8%, in accordance with other research projects (Koch and Weisser, 2000; Moltó *et al.*, 2000; Balsari and Tamagnone, 1998; Solanelles *et al.*, 2002).

On the right side of the crop (table 4), the most important saving was observed in the lower level of crop (83.9 %). Also 32.7% and 48.0% savings were measured for top and middle part of the crop, respectively. Results on left side differed, with the highest savings (86.9 %) at the top of the crop, and a similar value in the middle (48.7 %). This difference can be explained by the fact that, due to the heavy weight of the crop structure, and the slight but regular ground slope from left to right, the leaf mass at the top was somewhat inclined to the right side, creating as a consequence a deviation between the theoretical and real placement of the crop axis. This fact probably affected the measures obtained by the top sensors, increasing the distance on the left side and reducing it on the right. Moreover, these results are in accordance with the leaf distribution presented above.

On average, the most important saving (68.1 %) occurs at the bottom level. The area covered by this sensor ranges approximately from the bottom part of the crop (0.60 m.) up to 1.06 m, covering one third of the total height of the crop (1.41 m). In this lower third of the canopy, only 21% of leaf surface is found (7.2% at 0.6 m and 13.3% at 0.9 m). On the other hand, the lowest saving occurred in the middle part of the canopy (48.4 %), monitored by sensor 2 (the second third of the canopy range from 1.06 m to 1.52 m). Is in this area, leaf density is higher (31.6 % of leaves at 1.20 m height and 26.6 %

at 1.50 m). Finally at the top part of the crop, where only 21.2% of the leaf was found, saving was 59.8%, similar to that obtained at the bottom level of the crop. These different results obtained on the left and right sides are in accordance with Zaman and Salyani (2004), who concluded that trees are generally asymmetrical and should be scanned from two sides to obtain more accurate results.

3.4. Deposit on crop

Differences in average values (tables 5 and 6) obtained with conventional application (0.42 $\mu g \cdot cm^{-2}$) and the variable one (0.44 $\mu g \cdot cm^{-2}$) are not significantly different ($p<0.05$). In terms of uniformity of distribution, values of the coefficient of variation (CV) of deposition obtained on the fifteen measured points show similar values, ranging from 28.49 % for variable application to 29.50 % for the conventional one. This higher uniformity was observed also in the average values of deposition obtained at the different heights. For variable application, there were no differences between crop heights, with the only exception in the highest part of the crop where deposition (0.32 $\mu g \cdot cm^{-2}$) was significantly lower than in the rest of areas. This can probably be explained by the low position of the nozzle set in relation with the high development of the crop in the top zone, or even because of the inclination of the crop structure. The result of these factors is poor coverage in that area (figure 9).

3.5. Penetration

Capability of the two different methods in terms of deposition in the inner part of the crop has also been evaluated (figure 10). For conventional application, the average value of deposit in the inner part of the crop (0.34 $\mu g \cdot cm^{-2}$) was significantly lower ($p<0.05$) than those measured on left (0.49 $\mu g \cdot cm^{-2}$) and right (0.44 $\mu g \cdot cm^{-2}$) side of the crop using the variable rate application. For variable application deposition was more uniform on the right (0.39 $\mu g \cdot cm^{-2}$) and centre (0.35 $\mu g \cdot cm^{-2}$), and the only significant differences were observed on the left side of the crop (0.58 $\mu g \cdot cm^{-2}$).

In general, results obtained with the two different applications were very close in terms of deposition and uniformity. It is important to reiterate that when spraying with the prototype, the total amount of liquid applied was only 41.22 % from that of conventional sprayer. Variations on nozzle flow rates due to modifications in crop structure allow the reduction of the total amount of applied liquid while maintaining the quality of applications.

3.6. Losses to the ground

Losses on the ground (figure 11) indicate that higher values were observed under the line of the crop, especially when the prototype was used (sampling positions II and III). Statistical analysis shows no differences between depositions in all the sampling areas for conventional application (table 7). This fact can be explained as a consequence of some leakages produce in nozzles when turning off the proportional valves.

4. Conclusions

Tree Row Volume method can be used for calibration procedures in PPP applications in vineyard. This method allows improving values of efficiency in comparison with the traditional calibration procedure based on unit ground area approaches.

Even in uniform vineyard lines, important differences can be observed in crop width 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 save important amounts of PPP.

The use of ultrasonic sensors and proportional electro-valves and the corresponding software and automation allowed real time modification of the sprayed flow rate well adapted to the crop structure. This allowed a significant reduction in spray volume while maintaining coverage and penetration rates similar to conventional methods.

Thus the farmer can benefit by using less PPP, in this case a 57% reduction but further research must be carried out in order to confirm the biological efficacy when such an important reduction of pesticide is proposed.

This saving was observed in the very late crop stage, but more detailed field trials through the crop development season and with different trellis systems is needed to characterize the overall benefits of reduced PPP usage with the development of this new electronic technology.

5. Acknowledgements

This work was funded by the Spanish Ministry of Education and Science, and it is part of the funded research project AGL2002-04260-C04-03.We are grateful to Ilemo-Hardi, S.A. for the loan of the centrifugal fan mist blower sprayer used in this work.

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Table 1. Operational parameters during treatments

	Operational parameters
[a] Nozzle serial number	210
[a] Color	Brown
No. of active nozzles per side	6
Pressure (bar)	0 – 7.0[b]
Spray flow rate per nozzle ($l \cdot min^{-1}$)	0 – 0.57[b]
Spray flow rate all nozzles ($l \cdot min^{-1}$)	0 – 3.44[b]
Forward speed ($km \cdot h^{-1}$)	4.5
[c] Working width (m)	1.5
Reference application rate ($l \cdot ha^{-1}$)	300
Reference spray volume coefficient ($l \cdot m^{-3}{}_{canopy}$) PTO speed ($rev \cdot min^{-1}$)	0.095 540
Volumetric air flow rate ($m^3 \cdot s^{-1}$)	1.76

[a] Albuz ceramic hollow cone ATR series (black ringed tip)

[b] Values on variable application ranged from 0 to maximum according to crop width

[c] Only one side of the prototype was spraying at a time (tree-row spacing: 3.0 m)

Table 2. Dose of tracer and actual tank concentration for the different treatments

Treatment	Metal	D_T ($g \cdot ha^{-1}$)	D_R ($g \cdot ha^{-1}$)	$[T_R]$ ($g \cdot l^{-1}$)	F (D_T/D_R)
Conventional	Mn^{2+}	400	401.32	1.313	0.9967
Variable rate	Zn^{2+}	400	431.95	1.588	0.9260

D_T: theoretical dose of tracer

D_R: Actual dose of tracer

T_R: Actual concentration of tracer in the tank

Table 3. Statistical parameters of crop measurements (average width, standard deviation and coefficient of variation) for both sides of crop.

	Left side				Right side			
	Top	Middle	Bottom	Total left	Top	Middle	Bottom	Total right
Values with all data								
Average width (m)	0.04	0.17	0.16	**0.13**	0.23	0.18	0.05	**0.15**
Standard deviation (σ_{n-1})	0.09	0.12	0.10	**0.10**	0.19	0.11	0.08	**0.13**
Coefficient of variation (CV %)	213.48	67.25	58.69	**113.14**	81.91	65.27	149.72	**98.97**
Values with data > 0								
Average width (m)	0.28	0.20	0.10	**0.19**	0.13	0.19	0.17	**0.17**
Standard deviation (σ_{n-1})	0.17	0.10	0.09	**0.12**	0.12	0.11	0.09	**0.11**
Coefficient of variation (CV %)	59.20	52.07	83.23	**64.84**	93.48	54.81	49.83	**66.04**
Nº data > 0*	337	896	929	**2162**	810	893	523	**2226**
% data > 0**	33.7	89.5	92.8	**71.99**	80.9	89.2	52.2	**74.12**

* Figures calculated using only values of crop width > 0

** According the total measurements recorded from each sensor (= 1001)

Table 4. Percentage of savings (variable/conventional) at different heights

	Left	Right	**Total**
Top	86.9%	32.7%	**59.8%**
Middle	48.7%	48.0%	**48.4%**
Bottom	52.2%	83.9%	**68.1%**
Total	**62.6%**	**54.9%**	**58.7%**

Table 5. Tracer deposition ($\mu g \cdot cm^{-2}$) on different parts of the crop obtained with conventional application. Values followed by the same letter (in rows), do not differ statistically. Values followed by the same letter in brackets (in columns) do not differ statistically (Student-Neuman-Keuls test, $p<0.05$).

Crop height (m)	**Left**	**Centre**	**Right**	**TOTAL**
1.80	0.25	0.20	0.34	*0.26 [c]*
1.50	0.45	0.20	0.46	*0.37 [b]*
1.20	0.63	0.40	0.49	*0.51 [a]*
0.90	0.58	0.47	0.41	*0.49 [a]*
0.60	0.55	0.43	0.49	*0.49 [a]*
TOTAL	*0.49 a*	*0.34 b*	*0.44 a*	**0.42**

Table 6. Tracer deposition ($\mu g \cdot cm^{-2}$) on different parts of the crop obtained with proportional application. Values followed by the same letter (in rows), do not differ statistically. Values followed by the same letter into brackets (in columns) do not differ statistically (Student-Neuman-Keuls test, $p<0.05$).

Crop height (m)	**Left**	**Centre**	**Right**	**TOTAL**
1.80	0.44	0.22	0.31	*0.32 [b]*
1.50	0.59	0.27	0.40	*0.42 [a]*
1.20	0.68	0.36	0.43	*0.49 [a]*
0.90	0.62	0.45	0.36	*0.48 [a]*
0.60	0.56	0.46	0.46	*0.49 [a]*
TOTAL	*0.58 a*	*0.35 b*	*0.39 b*	**0.44**

Table 7. Tracer deposit on ground samples ($\mu g \cdot cm^{-2}$). Values followed by the same letter (in rows) do not differ statistically. Values followed by the same letter in brackets (in columns) do not differ statistically (Student-Neuman-Keuls test, $p<0.05$).

Treatment	**I**	**II**	**III**	**IV**	**Average**
Conventional	0.09 a	0.58 a	0.55 a	0.33 a	*0.36 [a]*
Proportional	0.08 b	0.73 a	0.93 a	0.16 b	*0.43 [a]*

Figure 1. Sprayer prototype with ultra sonic sensors and electro valves

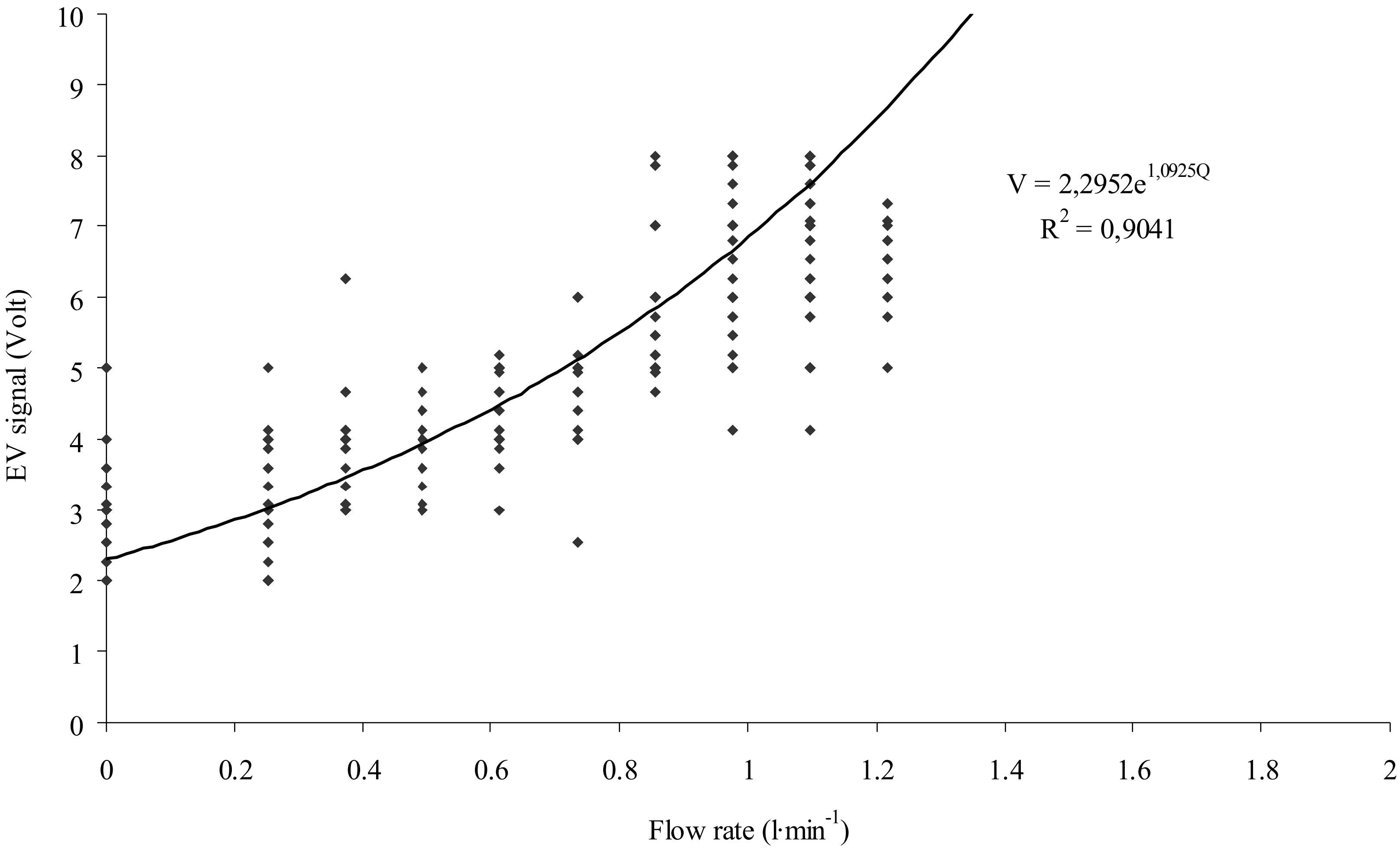

Figure 2. Relationship established in laboratory to convert the appropriate flow rate into voltage to be sent to the electro valve

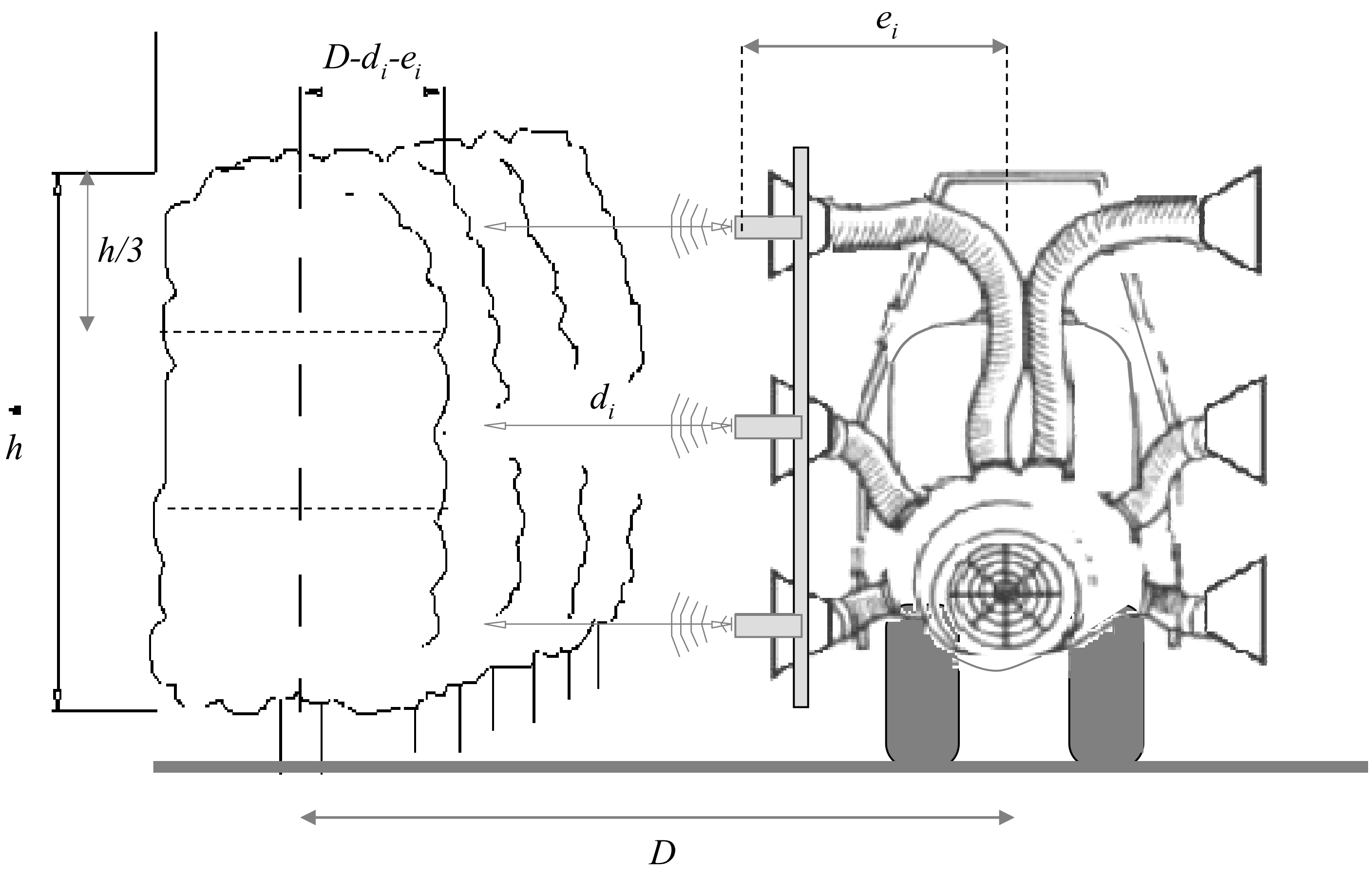

Figure 3. Principle of operation of the prototype

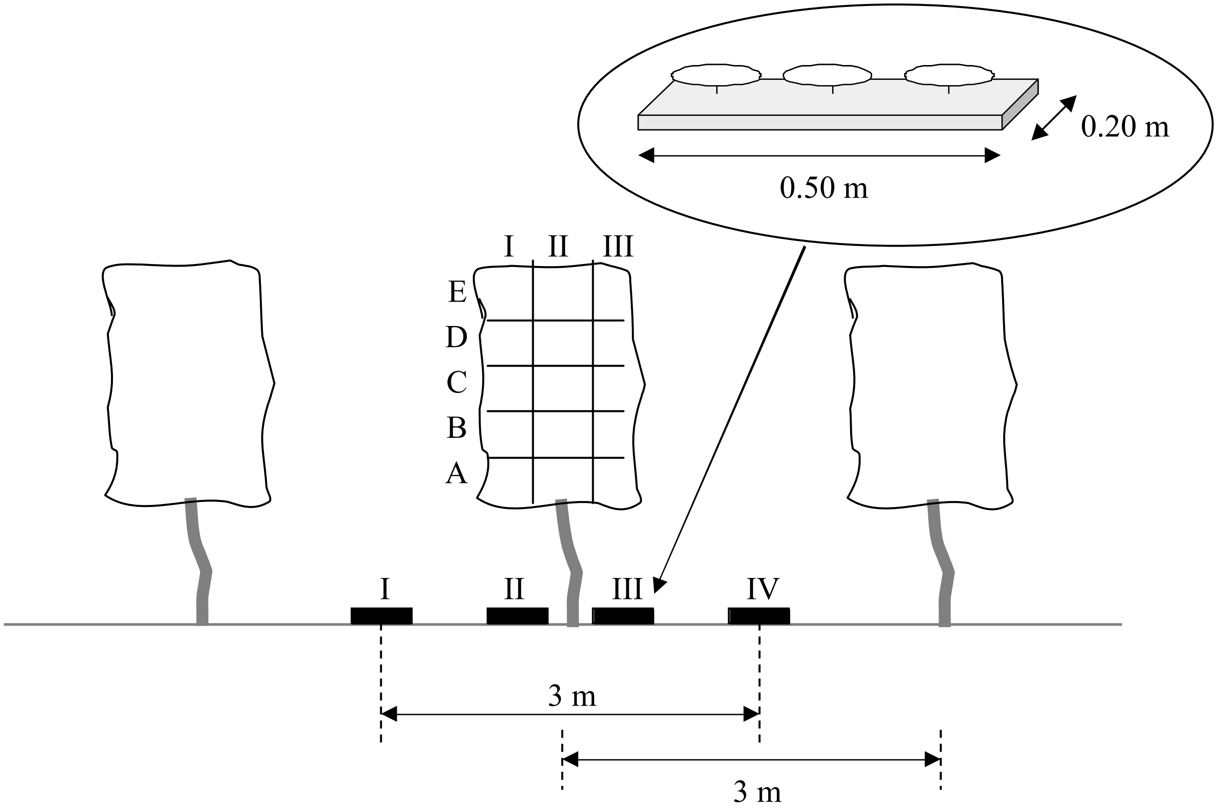

Figure 4. Distribution of sampling areas into the crop and soil

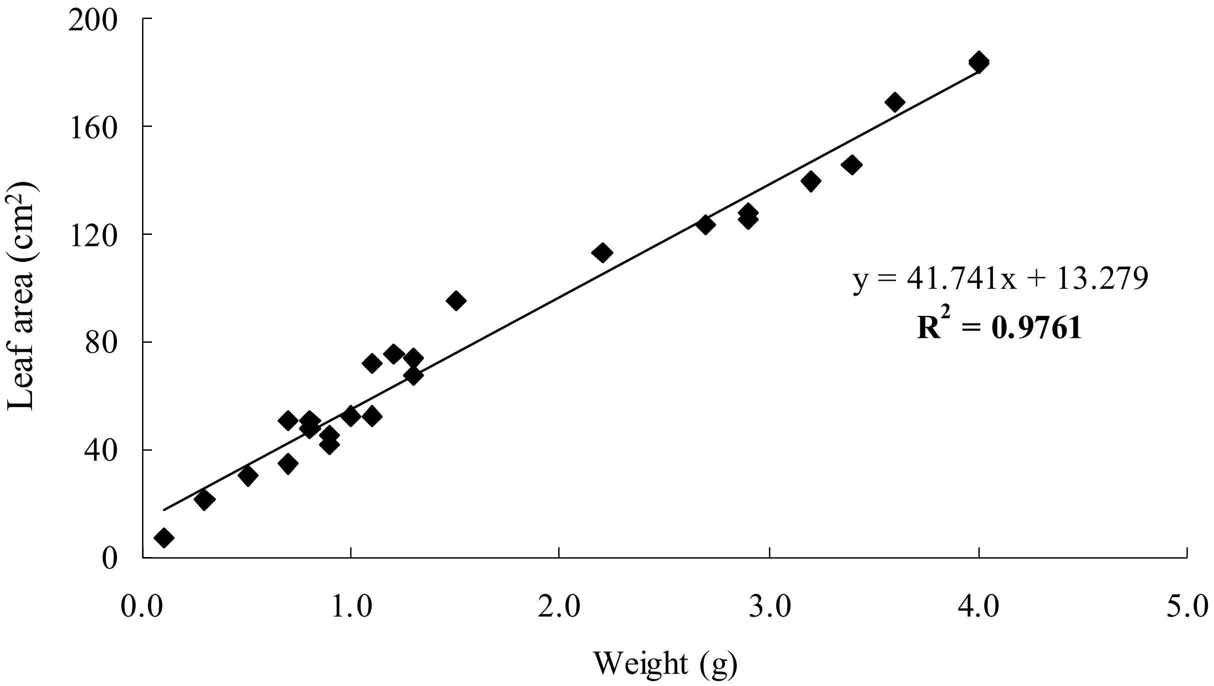

Figure 5. Relation between weight and leaf area

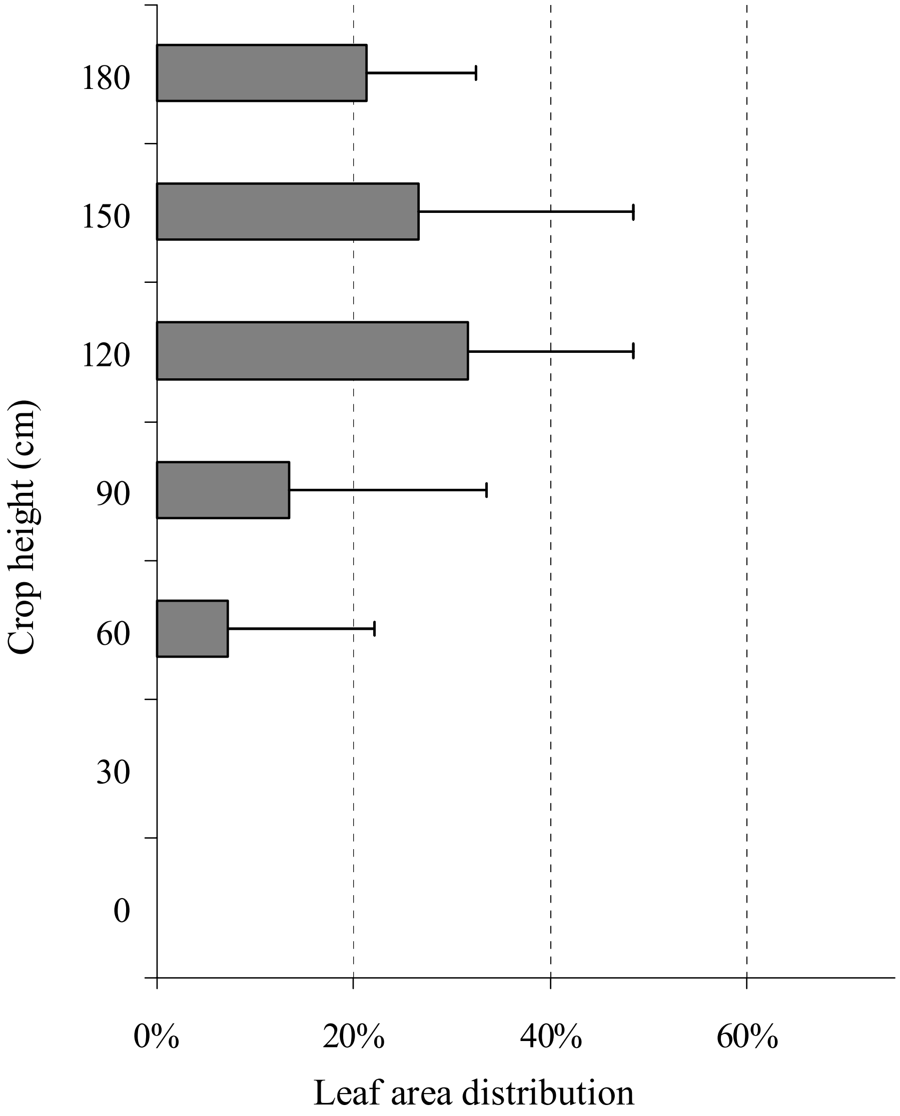

Figure 6. Leaf area distribution oh height. Lines on each point indicates the variability (CV) of all measurements

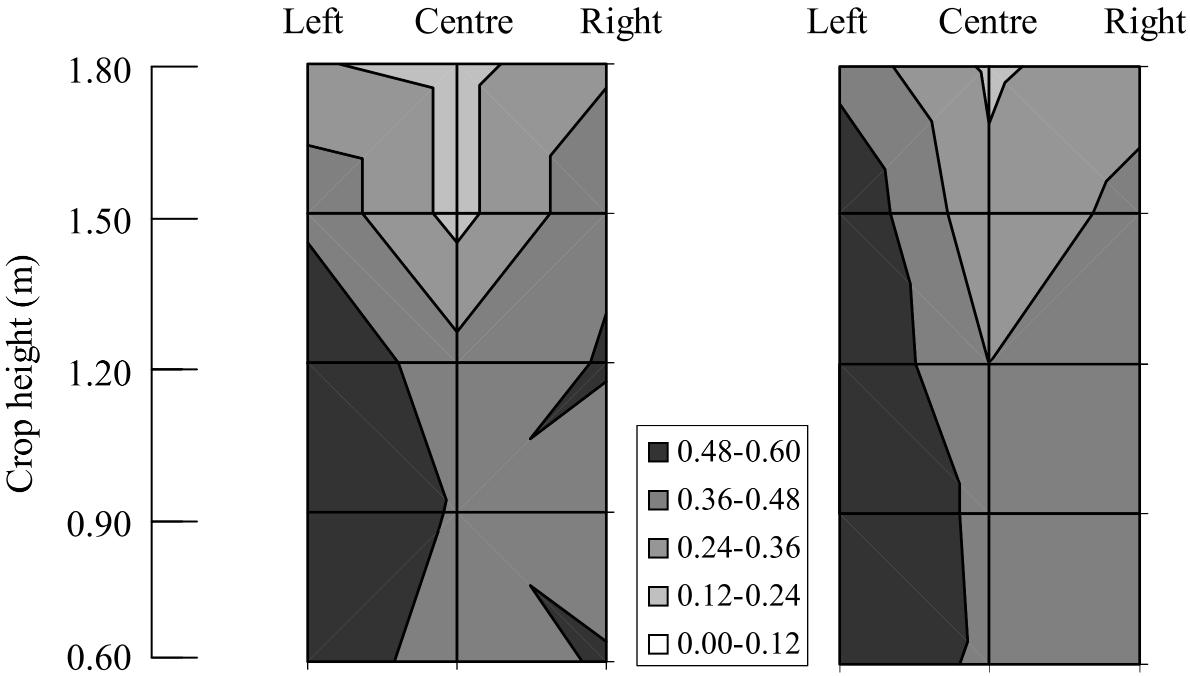

Figure 9. Spatial distribution of deposition (μg·cm^{-2}) obtained with conventional application (left) and with variable application rate (right)

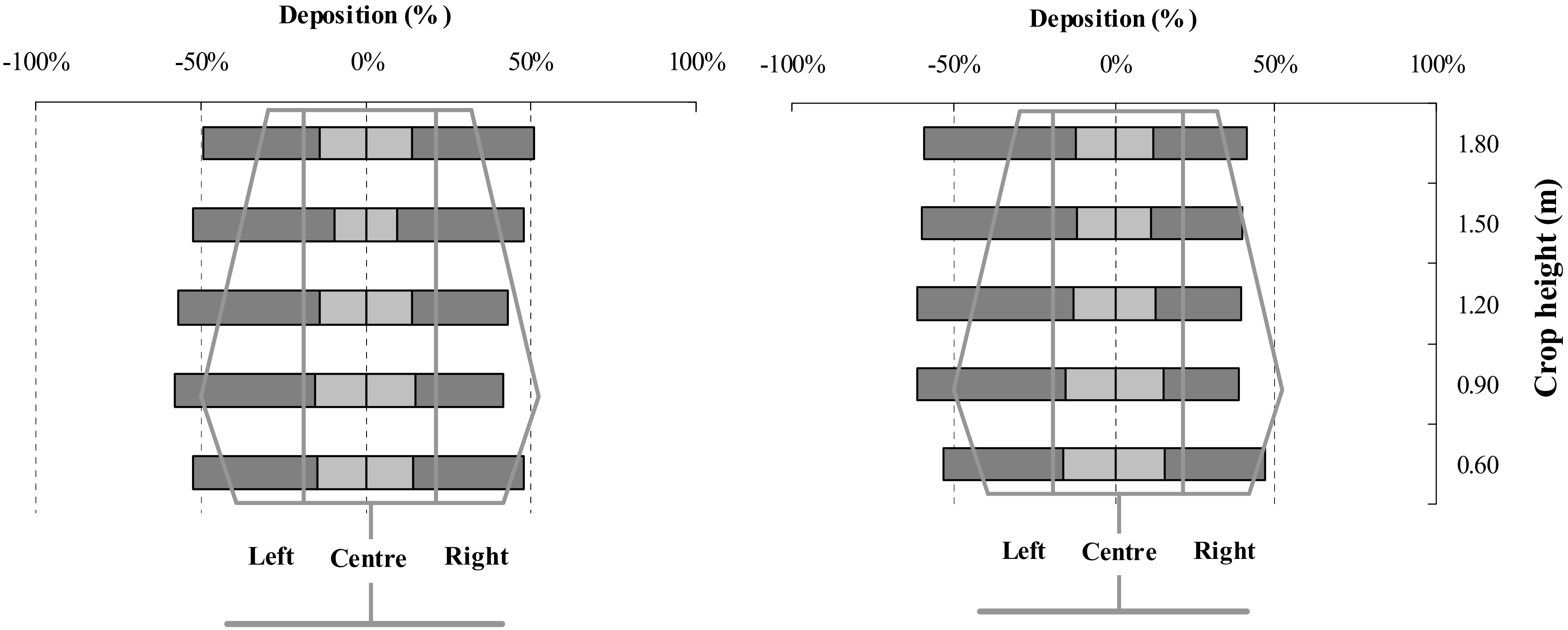

Figure 10. Relative deposition on the three sample crop zones. Conventional application (left) and variable application rate (right)

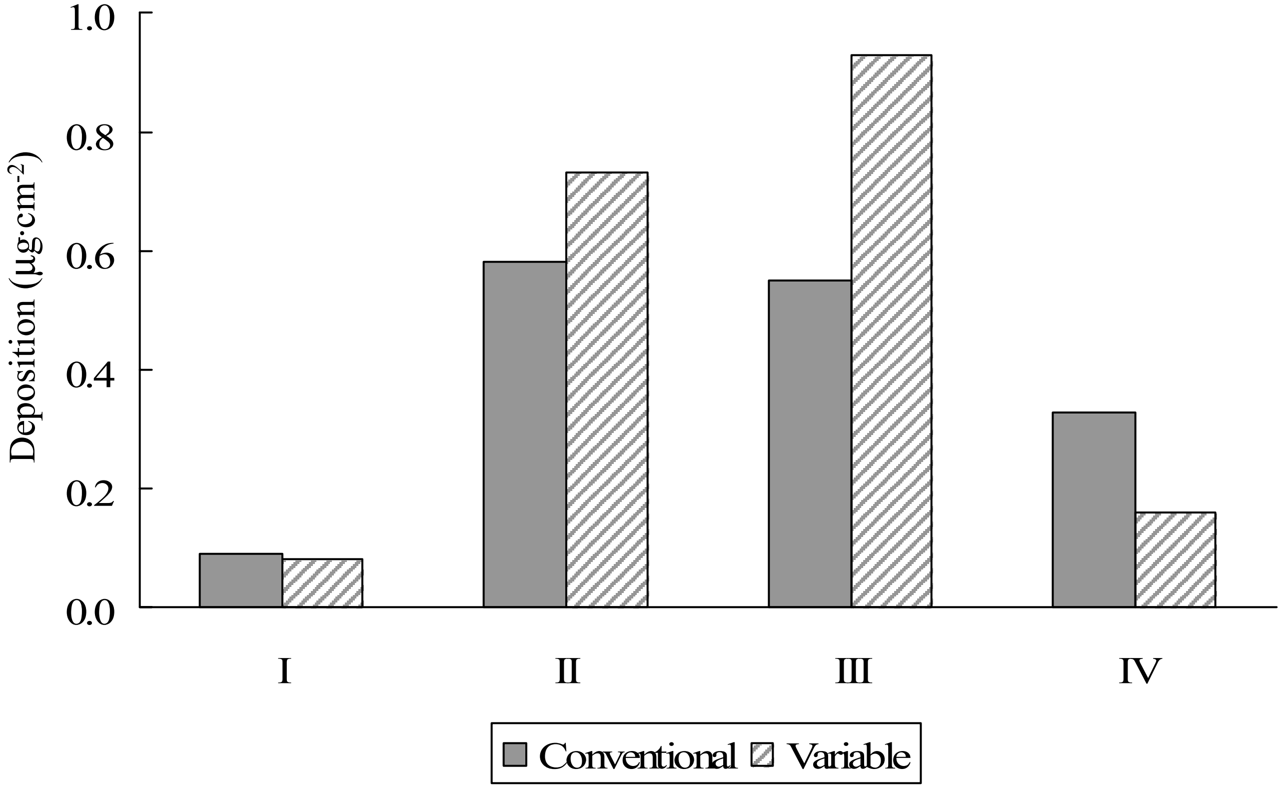

Figure 11. Distribution of losses to the ground for the different treatments

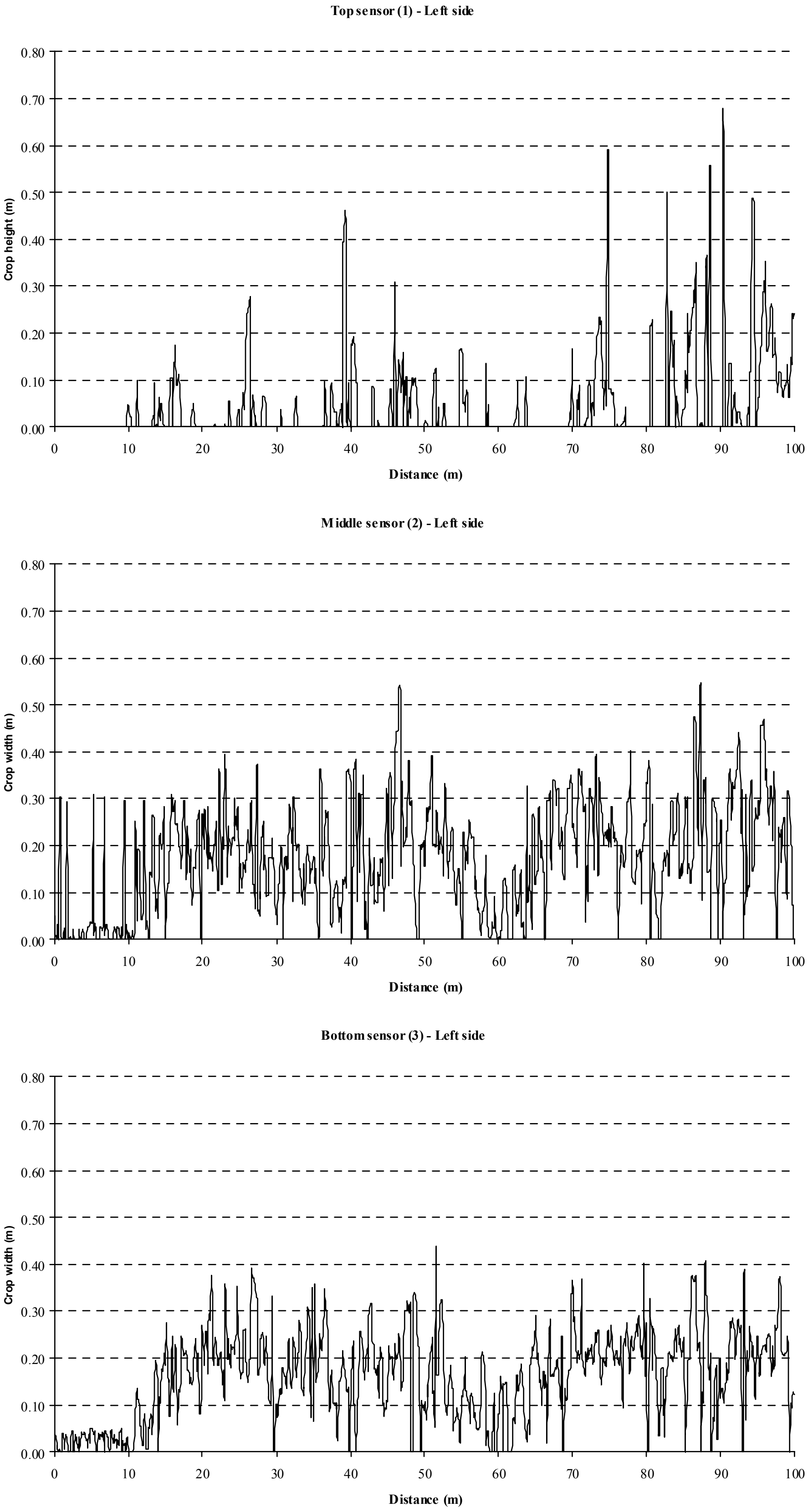

Figure 7. Crop width variations at three measured levels. Left crop side.

Figure(s)

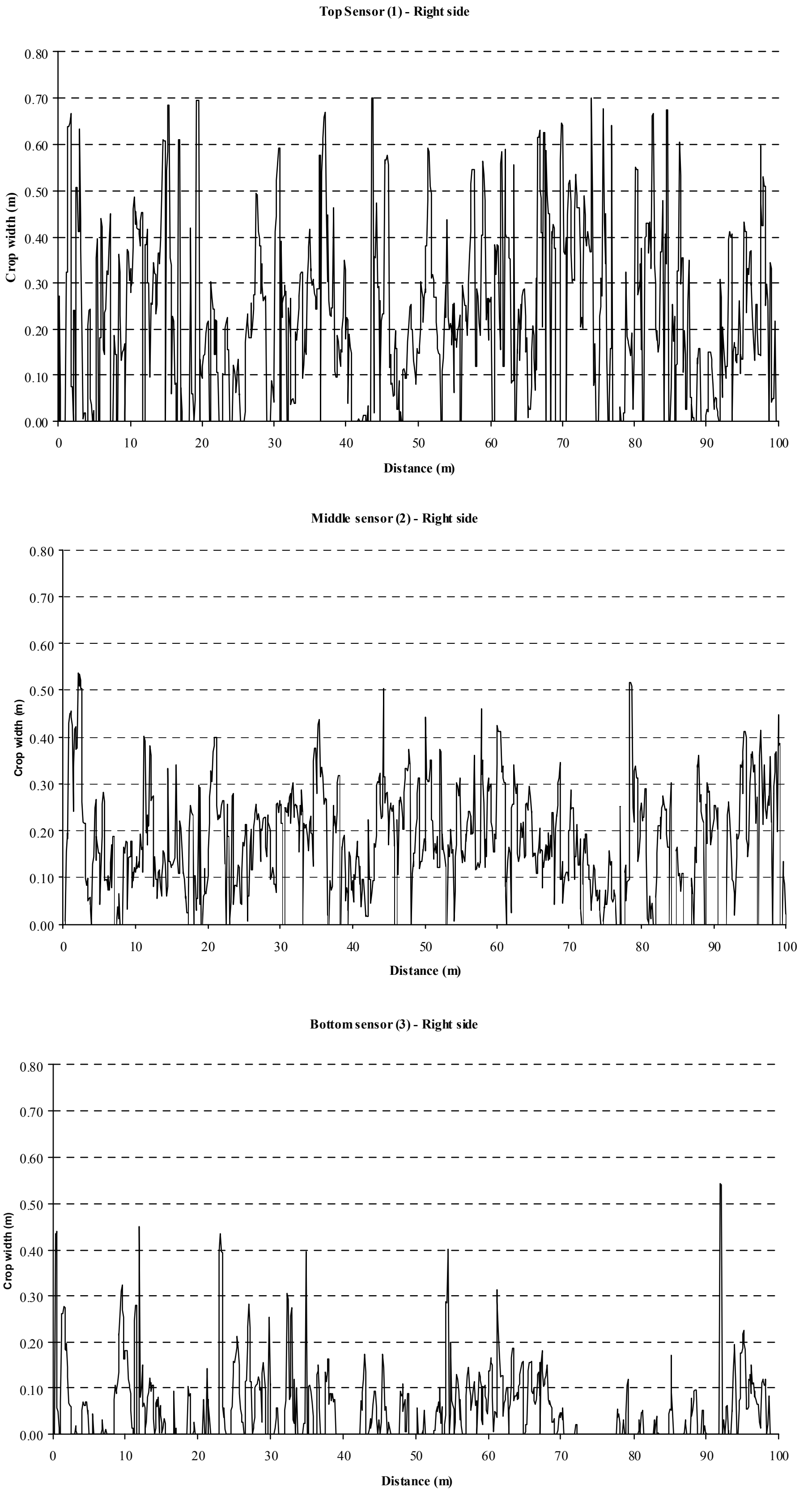

Figure 8. Crop width variations at three measured levels. Right crop side.