DOSAVIÑA: tool to calculate the optimal volume rate and pesticide amount in vineyard spray applications based on a modified Leaf Wall Area method

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Abstract

DOSAVIÑA is a new tool (website and app for smartphones) developed for calculating the optimal volume rates and pesticide doses to apply during spray application processes in vineyards. DOSAVIÑA also calculates and recommends the optimal working parameters for working pressure, forward speed, and number and types of nozzles. DOSAVIÑA was developed by the Unit of Agricultural Machinery at the Universitat Politècnica de Catalunya, and is available for iOS and Android devices. It is also available on the DOSAVIÑA website (https://dosavina.upc.edu). The developed tool can be used for the calibration of spray applications on fruit trees (as well as on citrus orchards, olive trees, almond trees, and many other vertical crops) once the volume rate has been established. The system, which is based on a modified version of the leaf wall area (LWA) method, calculates the optimal volume rate for vineyards by considering the effects of leaf density, canopy width, and sprayer type. System testing took biological efficacy into consideration and measured the main factors used for characterizing spray processes, coverage, and distribution over the entire canopy.

Results showed that water and pesticide use could be reduced by more than 20% while still meeting economic, environmental, and food quality requirements. The design of the tool is aligned with European requirements concerning pesticide use, as established in the European Directive for a Sustainable Use of Pesticides.

Keywords

Dose Expression, vineyard, volume rate, leaf wall area, DOSAVIÑA.

1. Introduction

During the pesticide application process, risk as a function of pesticide dose and harm to sensitive non-target areas are both related to a) spraying efficiency and b) the amount of plant protection products (PPPs) used 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. As a direct consequence of this complexity, different methods have been proposed for the establishment of dose expressions on pesticide labels; these different methods make various claims regarding improved efficiency of pesticide use (Koch et al., 2001; Walklate et al., 2003, 2006, 2011; Koch, 2007). In all cases, the proposed dose expression method has been linked to one or several canopy characteristics, with significant differences in measurement difficulty.

Attempts to improve dose expression procedures have included recommendations based on either two (leaf wall area) or three (tree row volume) dimensional factors related to the canopy structure (Gil et al., 2011, 2014; Walklate et al., 2011; Escolà et al., 2013). However, those efforts have led to a chaotic situation in which a comparison of label instructions for PPPs authorized in different European countries reveals remarkable differences in dose expression (Koch, 2007).

In Europe, the situation concerning the information available on pesticide labels, especially for those known as three-dimensional (3D) crops, remains unclear.

Considering the case of the southern regulatory zone (including Bulgaria, Greece, Spain, France, Italy, Cyprus, Malta, and Portugal), in most cases the pesticide dose is expressed as a concentration (%; rate/hL) and/or as the maximum dose of product per unit of ground surface (EC, 2009; Garcerá et al., 2017; Mironet et al., 2017). However, it is widely accepted that both the amount of pesticide and the applied volume during the spray application process should be calculated based on canopy structure. It is not appropriate to apply the same dosage of PPP in orchards with wide differences in canopy structure and dimension.

Other than the problem of the 'dose expression unit', which expresses the product quantity in relation to the treated area, the achievement of an adequate and optimal volume rate for an intended canopy must be established and determined separately (Koch, 2007). 'Dose adjustment', which reflects the adaptation of the product quantity to varying canopies, is directly linked to the criteria used to establish the total amount of liquid that is distributed into the canopy. This aspect has been widely discussed (Furness, 2003; Viret et al., 2007; Pergher and Petris, 2008; Codis et al.; 2012). In all cases, the main goal has been to adapt the total amount of PPP to the crop characteristics; however, difficulties have been encountered in selecting the most suitable crop parameter. The high degree of variability in the crop canopy has increased the difficulty of obtaining general solutions that could be successfully adapted to all crops and situations.

According to Manktelow et al. (2004), in research conducted in a vineyard, deposit variability between the outer and inner portions of the canopy tended to be reduced as application volume increased, especially when the outer parts of the canopy were wetted beyond the point of runoff, with associated reductions in spray efficiency. The same authors concluded that if the chemical application rate is held constant and the application volume is adjusted, the highest overall deposits will be achieved at low volumes (at which runoff losses are minimised).

These facts all suggest that accurately determining the spray volume rate based on canopy structure will improve the quality of pesticide application, resulting in better pest/disease control, reduced risk of contamination, and reduced amounts of pesticide, with the consequent economic, environmental, and social benefits. However, not all 3D crops have the same structure and uniformity. In some cases, it is difficult to characterize the geometric parameters of the intended target. Moreover, canopy characterization could range from very simple measurements of the main structural parameters (e.g. canopy height, canopy width) up to the most sophisticated ones (e.g. leaf area density, porosity, leaf area index). To allow the three-dimensional nature of the crop to be considered, it is possible to express the dose in kg or L per m^3 of tree row volume, or in kg or L per ha of leaf wall area, or in kg or L ha^{-1} per m tree height, or in kg or L per 100 m of plant row (EPPO, 2012). The EPPO Standard PP 1/239 Dose expression for plant protection products states that 'per treated leaf wall area (LWA) unit' is becoming a common dose expression method in three-dimensional crops. However, considering the great variability of those 3D crops in terms of structure and dimensions, it was recently concluded (EPPO, 2016) that the leaf wall area (LWA) method is an appropriate dose expression for plant protection products used on pome fruit, grape vineyards, and high-growing vegetables. In the same sense, the canopy characterization process has been proposed (EPPO, 2018) in order to guarantee an objective and reliable measurement process.

After reviewing substantive and widely disseminated research on this topic, it is clear that: a) determination of the optimal volume rate is not an easy task, and b) canopy characterization is not a simple and quick procedure, even when performed by users at a specific site and with simple tools. Those important reasons have been merged in order to explore the possibility of using new technologies to develop diverse decision support systems (DSS) that offer diverse alternatives for the intended topic. This development has focused on topics such as establishing an adapted volume rate according to crop structure (Siegfried et al., 2007; Furness and Thompson, 2008; Walklate et al., 2011; Garcerá et al, 2017), or calculating the total amount of PPP for any particular crop geometry (Furness, 2003; Siegfried et al., 2007; Cross and Walklate, 2008; Codís et al., 2012). In all cases, important improvements in the daily management of crop care activities have been detected after using the different devices.

Focused on the specific topic of vineyard, Optidose (Davy, 2007; Davy et al., 2010) and the tool *Dosage Adapté* (www.agrometeo.ch) have been proposed with similar objectives than Dosaviña. Optidose proposes an adaptation of the fungicide dose applied to protect the vineyard, based on the plant surface, the diseases pressure and the development stage. Field trials demonstrated an average reduction of 40% leading into a low increase of symptoms of downy and powdery mildew. Crop Adapted Spraying tool was developed (Viret et al., 2010) for the particular case of Swiss viticulture. The current Swiss dosage system consists in a linear adaptation, following the phenological development of the vine. Leaf area adapted dosage is aimed at delivering exactly the amount of product requested for a given leaf area present at the time of spraying. An easy and user-friendly calculation module is available on www.agrometeo.ch.. However, none of the previous described tools consider the influence of the sprayer type in the calculation of the recommended amount of pesticide. Even more, neither the applied volume rate nor the suggested working parameters are not included.

The objective of this research was to develop and test a new decision support system (app and website) for determining the optimal volume rate and amount of plant protection products (PPP) to be used during spray application in vineyard plantations constructed using a trellis system. A complementary objective was to determine whether the developed tool could help reduce the risk of environmental contamination in vineyard plantations by increasing the efficiency of PPP applications.

2. Fundamentals of Dosaviña

The principle used by Dosaviña for calculating the optimal volume rate is based on a modified method of the leaf wall area (LWA) principle, which has been recently proposed by EPPO (EPPO, 2016) as the recommended and harmonized method for dose expression in uniform wall 3D crops. This method has been widely tested in different conditions (Friessleben et al., 2007; Toews and Friessleben, 2012) and utilises structural canopy dimensions to determine the total canopy wall area per ground area (Eq. 1).

$$LWA = 2 \times 10^4 \times \frac{C_h}{r} \qquad [1]$$

Where:

LWA is the leaf wall area in both sides of the crop ($m^2\ ha^{-1}$); C_h is the canopy height (m); and r is the distance between rows (m)

However, the conventional LWA method, even if it is based on the canopy structure, does not consider other important and influencing parameters such as canopy width and leaf density, which both directly affect spray distribution quality. Foliar deposits at different locations across the canopy are directly influenced by canopy characteristics, mainly height and depth (Pergher and Zucchiatti, 2018). Furthermore, spray distribution quality, including losses to the ground and drift, is directly influenced by the type of sprayer. Models with internal tangential-flow fans (Siegfried and Hollinger, 1996) or axial-flow fans (Molari et al., 2005) have been proposed, owing to their potential to control air assistance. New developments such as automatic air assistance control (Garcerá et al., 2018) also reduce drift and improve canopy deposition. Neither the complementary canopy parameters (i.e. canopy width and leaf density) nor the type of sprayers are considered in the process for calculating the amounts of pesticide and liquid, based on the traditional LWA method. After a deep evaluation of canopy deposition in vineyards, Perguer and Petris (2008) found that the LWA method could be considered sufficiently accurate in a wide range of vineyards with a foliar area/canopy cross-section in the row direction ratio of lower than four. These results were also matched by Pergher and Zucchiatti (2018).

The proposed modified method for determining the optimal volume rate in uniform trellis vineyard plantations includes all the parameters previously considered. The proposed mathematic expression to calculate the optimal volume rate is shown in Eq. 2.

$$V\ (l\ ha^{-1}) = LWA \times\ [f_{cw}] \times [f_{cd}] \times [f_s] \times i\ \left(l\ {m_{LWA}^{2}}^{-1}\right)\ [2]$$

Where:

V is the calculated amount of liquid to be sprayed (l ha^{-1}); f_{cw} is the canopy width factor (dimensionless); f_{cd} is the leaf density factor (dimensionless); f_s is the factor considering the type of sprayer (dimensionless); and i is the unit volume rate per LWA canopy surface (l/m^2_{LWA}).

The unit volume rate per LWA canopy surface i (l/m^2_{LWA}) was previously established after more than 20 years of field trials combining different canopy structures, crop stages, and application rates (Gil et al., 2011), resulting in a recommended value of 0.037 l/m^2_{LWA}. This value, based on the LWA concept, was also converted into the corresponding value for the TRV (tree row volume) method, establishing a reference canopy width of 0.8 m in the full growth stage. The obtained result was 0.1 l m^{-3} TRV, very similar to recommended values established by other researchers (Byers, 1987, Viret et al., 2007).

2.1 Quantification of leaf density

Leaf density was included in the volume rate calculation procedure owing its substantial effect on spray distribution quality. The amount of leaves per unit of canopy volume varies greatly, along with crop stage development. According to Da Silva et al. (2010), the evolution of the geometry and density of canopies in grape plantations is important during the first months. On the other hand, the leaf area per unit of surface area can experience significant variations depending on variety, crop layout, and the trellis system. Codis et al. (2012) found that the aforementioned factors could cause fifteen-fold differences in leaf surface areas. This increase in leaf surface generates a progressively negative effect on canopy deposition and the penetration of droplets into the internal parts of the crop. Da Silva et al. (2002) found a linear correlation between the leaf area index and deposits, meaning that the deposit per leaf surface unit should be constant for an average tree representing the entire vineyard. In order to quantify this effect, a large database of field trials combining different varieties, growth stages, canopy dimensions, leaf densities, row distances, and locations, and the corresponding values for spray deposition on leaves and penetration of the canopy (Gil, 2001 and 2003; Gil et al., 2005), was used to propose a numerical factor to quantify the effect of leaf density in the calculation of the optimal amount of spray liquid. Figure 1 shows the relationship between leaf density (Da Silva et al., 2002), expressed as leaf density (LD) (m^2/m^3), and canopy height (m), as the main representative parameters of the LWA method.

[insert Fig. 1]

The proposed calculation procedure in Dosaviña calculates the optimal volume rate by considering four different leaf density ranges based on four different pictograms (Table 1), which are associated with four numerical factors included in the mathematical formula. An estimation of leaf canopy density by means of pictographs has previously been used in apple orchards (Chemicals Regulation Directorate, 2006).

[Insert table 1]

The assigned values for the four different pictograms included in the Dosaviña were estimated considering the effect of different leaf density values (LD m^2/m^3) on canopy height (Table 1). Figure 1 shows the influence of the four assigned values in canopy height.

2.2 Quantification of canopy width

Canopy width represents one of the most representative parameters used for alternative dose expression methods such as tree row volume (TRV) (EPPO, 2012). As stated previously, the original LWA method does not consider this parameter when determining the amount of pesticide/water to be applied over a certain canopy. Dosaviña introduces this parameter in order to improve the process of calculating the optimal amount of water to be delivered during the spray application. However, this value has been included as a 'qualitative' factor for considering three canopy width levels representing the widths most commonly found during the period of most intensive spray application in vineyards. The three selected levels were: 1. Less than 0.5 m; 2. Between 0.5 and 0.8 m; 3. Higher than 0.8 m. The proposed methodology was adopted in order to simplify the measurement procedure by reducing the heterogeneity and subjectivity of individual/manual canopy measurements (Bailey and Mahaffee, 2017). The three intervals characterizing the canopy width were established after a numerical analysis of the relationship between canopy width and canopy height, considering the latter parameter as the canopy measurement that most influences the LWA method. The relative influence of canopy width was determined as established in Table 2, which shows the percentages of influence of the three different canopy width classes. The relative values assigned to all the three canopy width classes were estimated by considering their effect on canopy height (Fig. 2).

[insert figure 2]

[insert table 2]

2.3 Quantification of efficiency of spray application depending on sprayer type

As factors affecting the calculation of the optimal volume rate, Dosaviña considers the type and characteristics of the sprayer used. It has been widely demonstrated that the type of sprayer has a significant influence on the final success of the spray process

(Whitney et al., 1989). According to Duga et al. (2015), tree characteristics such as total leaf cover, leaf wall porosity, and tree volume strongly affected the total on-target deposition, further confirming previous claims that ground surface area alone is an incorrect measure for dose calculation in fruit trees. Depending on the selected technology, values for deposition into the canopy, losses to the ground, and drift losses can vary significantly. Based on results obtained to quantify the efficiency of different type of sprayers (Gil 1998; Gil 2001; Gil 2002), three categories/typologies of sprayers were selected as the most representative ones used in vineyards: conventional mistblowers, individual outlet sprayers, and multi-row sprayers. In all cases, the selected sprayer type represents the most widely used technology in terms of conventional nozzles and air assistance needed for transporting droplets to the canopy structure. Then, following the same principle described for the analysis of leaf density, the same large database of field experiments was used to assign a numerical value to each selected sprayer typology: 1. Conventional mistblower – 1.20; 2. Individual outlet sprayer – 1.00; 3. Multi row sprayer - 0.80.

After the previously described parameters have been introduced into the system, the optimal spray volume is then calculated and used in subsequent steps to determine the amount of PPPs to be added into the tank.

3. Determining the amount of pesticide

Pesticide label information was established as the baseline for the functionality of Dosaviña. Because they are based on legal requirements, the recommended doses are always strictly respected when using the proposed tool. Following that, and considering that the dose expression method most widely used in many vineyard pesticides particularly in South European Zone countries (Bulgaria, Cyprus, France, Greece, Italy, Malt, Spain and Portugal) is based on a concentration of PPP (% or rate/hL) (Codis and Douzals, 2012), the Dosaviña tool uses this recommended concentration value along with the maximum amount of pesticide allowed per unit of area (L or Kg ha^{-1}) to calculate the absolute amount per ha, while always respecting the official recommendations and maximum limitations per unit of surface. Based on this principle, and considering the calculated optimal spray volume rate (l ha^{-1}), the developed tool also calculates the total amount of PPP to be distributed per ha, and the amount of pesticide to be added to the spray tank, while considering the tank capacity and/or the amount of water added by the user.

4. Tool for sprayer adjustment

In addition to determining the optimal volume/PPP rate, it is crucial to establish an accurate sprayer adjustment to guarantee the success of the process (Gil et al., 2013). It has been widely demonstrated that, when the intended volume rate to be sprayed is calculated based on certain canopy characteristics instead of the actual ground area-based procedure, recommended applied volume rates tend to be lower than those traditionally applied by farmers (Gil et al., 2018). Thus, in order to guarantee an accurate and efficient spray distribution, it is necessary to follow a complete sprayer adjustment process, which includes forward speed selection, choosing a nozzle (number and size), and adopting a reasonable working pressure (Landers, 2016). An inadequate selection of any of these parameters will lead to unnecessary losses of PPP, environmental contamination, and poor pest/disease control (Otto et al., 2015). A complete sprayer calibration process, which was previously developed and tested, was incorporated into the developed device to guide users through the process of selecting the most important parameters and calculating the optimal working pressure (while respecting the main recommended values), in order to guarantee a precise and efficient droplet size distribution.

Droplet size is related to spray pressure, and it is well known that as higher is working pressure as lower is the droplet size. Consequently, and considering that small droplets generate high risk of drift ((Gil et al., 2014), Dosaviña includes an automatic algorithm to calculate the working pressure, in combination with the selected number of nozzles and the intended forward speed. The calculation procedure varies depending on the nozzle size distribution selected on the sprayer. Two different situations have been considered, and consequently, two different calculation processes have been developed: a) assuming all the nozzles installed in the sprayer have the same size (the general strategy selected for a uniform distribution over the canopy); b) allowing a combination of different nozzle sizes to be installed in the sprayer (when using a liquid distribution strategy based on the heterogeneity of the canopy). In both cases, the nozzle selection process in Dosaviña is based on ISO colour code nozzles (ISO, 2005).

Calculation of the recommended working pressure is based on the following process. The starting point is the relationship between the pressure (bar) and flow rate (l min^{-1}) defined for every single ISO colour code nozzle. This relationship is calculated in two different directions (Table 3).

[insert table 3]

Dosaviña tool calculates the recommended pressure for a single nozzle size according to Eq. 3:

$$p_i = a_i \times \left[\frac{Q_T \times f}{n_i \times 100}\right]^{b_i} \qquad [3]$$

Where:

p_i is the calculated pressure for a single nozzle of size *i* (bar); a_i is the coefficient for a nozzle of size *i* as provided in Table 3 (dimensionless); Q_T is the total flow rate calculated to achieve the intended application volume rate (l min^{-1}); b_i is the coefficient for a nozzle of size *i* as provided in Table 3 (dimensionless); n_i is the number of nozzles of size *i* (dimensionless); and *f* is a defined factor for automatic pressure calculation (see below).

Factor *f* was included to balance out the pressure calculation when different nozzle sizes are used. This *f* factor is calculated following Eq. 4:

$$f = \frac{c_i \times n_i \times 100}{\sum_{i=1}^{n} c_i \times n_i \times 100} \qquad [4]$$

Where:

c_i is the coefficient for nozzle size *i* provided in Table 3 (dimensionless); and n_i is the number of nozzles of size *i* (dimensionless).

The final pressure in the case of combination of different nozzle sizes is then calculated following Eq. 5:

$$P_T = \frac{\sum_{i=1}^{n} p_i}{N} \qquad [5]$$

Where:

P_T is the final working pressure recommended (bar); p_i is the calculated pressure for a single nozzle of size i (bar); and N is the number of different nozzle sizes selected (dimensionless).

5. Structure and main characteristics of Dosaviña app for smartphones

Dosaviña was designed for use with the two main mobile platforms, IOS and Android. A web-based version of Dosaviña has also been developed (https://dosavina.upc.edu). The main characteristics of the newly developed app are shown in Table 4.

[insert table 4]

The new device has been developed using React-Native framework. This solution, developed by the engineer's team from Facebook, allows the development of new apps for the two main platforms, IOS and ANDROID. React-Native offer the possibility to write the entire code only once, being totally compatible with the two main Operational Systems (OS). Additionally, another advantage of React-Native is that all the developed appS are native and originals, then their usability and efficiency are higher than the non-native ones.

By sharing the development tool between the two platforms, it has been possible to use the same functional codes, which allowed to save development cost and time, while maintaining the same or even higher quality level. React-Native has been programmed using Javascript ®, widely used all over the world. An internet website version of the newly developed app has been created using React-Native tool as well. This harmonization between the app and website versions of the new device concerning the programming language used allow to share most of the critic code (calculations, decisions…) avoiding differences in the obtained results.

The app is structured into several correlated packages (Fig. 3), covering settings for the device, canopy characterization, sprayer type, and pesticide information.

[insert figure 3]

Once the settings have been selected (language, unit system, location, etc.) the process starts with two options: a) calculation of the optimal volume/PPP rate for a trellis vineyard; and b) calibration of the sprayer. These two steps are directly linked in cases involving wall trellis systems in vineyards. The device can also be used in calibrations for other 3D canopy crops (e.g. orchard fruits, citrus, almonds, olive trees, etc.) where users shall first introduce the desired amount of liquid per hectare (Fig. 4).

[insert figure 4]

Following the previous description and in accordance with the BMP (Best Management Practices) (Gil et al., 2013), working pressure is automatically. The system calculates the requested working pressure to achieve the desired volume rate with the number and size of nozzles previously selected. When the calculated pressure falls out of the recommended pressure range for a particular type of application, a warning message appears on the screen.

Nozzle selection is directly linked with the intended vertical distribution of the liquid. For this reason, Dosaviña allows selection of two different nozzle types, depending on the canopy characteristics (Fig. 5). The app allows adjustment of the sprayer when using nozzles of the same size, or when using a combination of different nozzle sizes, with the goal of mimicking the vertical leaf distribution.

[insert figure 5]

At the end of the process, a complete report with detailed information (Table 5) is generated; users can save the report in a favourites folder and/or send the report as a pdf file.

[insert table 5]

The entire process, including determination of the optimal volume rate, the amount of pesticide (per hectare and per tank), and the calibration procedure, was developed to provide an interactive and easy flow, including several warning messages aimed at avoiding the selection of parameter values (forward speed, working pressure, number of nozzles, droplet size) that do not conform to those recommended by best management practices (Gil et al., 2013). The entire flow chart is shown in Fig. 6.

[insert figure 6]

6. Evaluation of spray distribution and coverage using Dosaviña

Previous versions of Dosaviña were evaluated in terms of biological efficacy with interesting results (Gil et al., 2011; Landers, 2011). Following the same procedure, and with the aim to evaluate the improvements included in the new version of the tool, during crop seasons of 2017 and 2018 several field trials were arranged in order to evaluate the spray distribution quality (coverage) obtained following the recommendations generated by Dosaviña. For this purpose, four representative commercial parcels containing different vineyard varieties (i.e. Merlot, Chardonnay, and Cabernet Sauvignon) were selected inside the Penedès region, one of the largest wine production zones in Spain. All four parcels belong to the Official Recognized Wine Production Zone DO Penedès. The main characteristics of the selected parcels are shown in Table 6.

[insert table 6]

In every parcel, three different zones (low, medium, and high leaf density) were identified and classified according to their previously measured leaf density (Fig. 8). For every single canopy zone on the parcel, the recommended volume rate was defined using Dosaviña. During the entire 2018 season, a total of seven spray applications were arranged, starting in early May and finishing in late July, using a conventional mistblower with a 1000 l tank and equipped with vertical deflectors (SAHER Maquinaria Agrícola S.L., Vilafranca del Penedès, Barcelona, Spain). Calculated spray application volumes and specific working condition for every single combination are shown in Tables 7a and 7b. During the entire season, on the spray dates selected by the farmer, a randomized sampling selection process was conducted in the aforementioned three zones with the four varieties, defining a total of 36 sampling points (3 zones x e replicates x 4 varieties) (Fig. 7). A total of nine Water Sensitive Paper (WSP) strips were located at every single sampling point, covering the internal and external parts of the canopy (external and internal layouts, top, middle, and bottom part of the canopy), in accordance with previous research findings (Gil et al., 2007, Miranda-Fuentes et al., 2015). The purpose of the water sensitive papers was to define the spray coverage and the spray distribution over the entire canopy. Coverage values were obtained using a macro developed for use with ImageJ software, as established by Llop et al. (2015).

[insert figure 7]

[insert tables 7a and 7b]

8. Results of spray evaluation

Results obtained in terms of coverage (Table 8) indicated good spray coverage results in all the evaluated conditions, with an average value of 33.5 %. The lowest coverage value (27 %) was obtained at BBCH 79-81 (majority of berries touching – beginning of ripening, July 12th) when leaf density was at its maximum (and before manual intervention to reduce the canopy); the largest value was obtained during the second spray application (beginning of flowering – end of flowering, BBCH 61-69, June 1st), where canopy height increased faster than leaf density. In general, the average obtained coverage values can be considered adequate in terms of minimum requirements to assure pest/disease control in any spray application process. Figure 8 shows a sample of spray distribution obtained over water sensitive paper for four specific cases during the field trials. A quick view of the spray droplets distribution indicates uniform coverage over the entire canopy structure.

[insert table 8]

[insert figure 8]

A deep analysis comparing coverage and applied volume rate can be observed in Fig. 9, where the relationship between applied volume rate (L ha^{-1}) and obtained coverage (%) has been calculated. In general, the obtained coverage values fell within an even range (25 % - 45 %) independent of the applied volume rate. This situation occurred in 76.8 % of the evaluated data. The obtained coverage value was lower than 25 % in only 13.6 % of cases, while the coverage value exceeded 45 % in only 9.8 % of cases. These findings indicate that the developed tool accurately calculated the optimal volume rate, thereby maintaining a good level of coverage (according to Chen et al. (2013)) independent of the canopy characteristics.

[insert figure 9]

To illustrate the quality of the spray distribution, measured through the uniformity of coverage over the entire canopy, a deep analysis of encountered results is provided in Fig. 10. Standard deviation values of the coverage obtained in all nine sample points (water sensitive papers) placed in the canopy (external and internal parts, high, medium, and low positions) were not affected by the applied volume calculated using Dosaviña. This indicates that in all cases, ranging from low to high spray volumes, similar values of spray uniformity were obtained, indicating a successful determination of the most accurate volume rate according to the canopy structure. Fig. 11 show the average coverage values (%) obtained for the three established canopy developments (low, medium, and high). The same level of coverage was achieved independent of the canopy development, allowing the potential efficacy of the spray application to be maintained independent of the canopy structure. According to Fig. 11, the most heterogeneous coverage values were obtained in cases with high dense canopies, as expected. However, these differences are minimal among the three defined canopy classes.

[insert figure 10]

[insert figure 11]

9. Conclusions

Dosaviña was developed with the aim of helping farmers in the important process of determining optimal volume rates for spray applications in vineyards. The final developed tool resulted a good example of bringing research to potential daily application by end users. The new app is based on a modified method of LWA and includes spray calibration support. This last consideration regarding the calibration process is properly highlighted in the app, as one of the conditions for a good success of the entire process. After extensive testing and dissemination of the tool, the following conclusions are drawn:

- Dosaviña is an intuitive tool for determining recommended volume rates, especially for uniform vineyard trellis systems, and represents a good example of bringing research to end users.

- In the majority of cases, the recommended volumes obtained after using Dosaviña are lower than those commonly selected by the farmers. This fact, coupled with a dose expression method based on concentration, leads to a consequent reduction in pesticide amounts, in line with the main objective established in Europe after the official publication of the Sustainable Use Directive (EU, 2009).

- The sprayer adjustment tool included in Dosaviña represents a convenient complement to the establishment of the optimal volume rate. The automated calculation process allows selection of the most suitable values for the most important working parameters, particularly working pressure. This calibration/adjustment process is also included in the requirements established by the Sustainable Use Directive, and represents a key procedure guaranteeing good spray distribution while reducing water use.

- Results obtained in terms of coverage and uniformity of deposition demonstrated a high level of performance, even if low spray volumes were recommended. In all cases, good coverage values were obtained, independent of the recommended volume rate. Results of field trials demonstrated that an accurate calibration process allows similar levels of coverage to be obtained, even with low amounts of spray liquid.

- Dosaviña allows users to follow the best management practices recommended for pesticide application in vineyards; it allows the average amount of liquid and pesticide to be reduced by assuring correct selection of the most recommended working parameter values.

- Additionally, Dosaviña can be used for other type of orchard trees, offering to the users an accurate tool to arrange a precise calibration process of the sprayer, guarantying a good spray application process. However, in this case the recommended volume rate shall be calculated separately.

- Dosaviña includes, all in the same too, a methodological process to calculate the optimal amount of water to be applied, following the actual tendency for uniform and vertical crops based on leaf Wall Area, the recommendations about the amount of PPP to be applied, and a complete engine to follow a proper sprayer's adjustment. Those specific characteristics allow to differentiate Dosaviña from the other similar tools already developed.

Through analysis of the obtained results described herein, together with other previous research works, it is concluded that the use of the newly developed app could be an effective tool for stakeholders involved in pesticide use, achieving potential reductions in pesticide amounts while maintaining the efficacy/efficiency of crop care activities. This important conclusion represents a clear contribution toward addressing general European goals to reduce PPP use, and enhancing efforts to reduce environmental contamination.

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Author's contribution

Emilio Gil developed the original device; Emilio Gil and Javier Campos conceived and designed the experiments; Emilio Gil, Javier Campos, Jordi Llop, Montserrat Gallart, Ramón Salcedo, and Enric Armengol performed the experiments; Paula Ortega, Ramón Salcedo, Montserrat Gallart, and Anna Gras contributed laboratory analysis and statistical data management; Emilio Gil wrote the paper. All authors have read and approved the manuscript.

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FIGURES AND FIGURE CAPTIONS

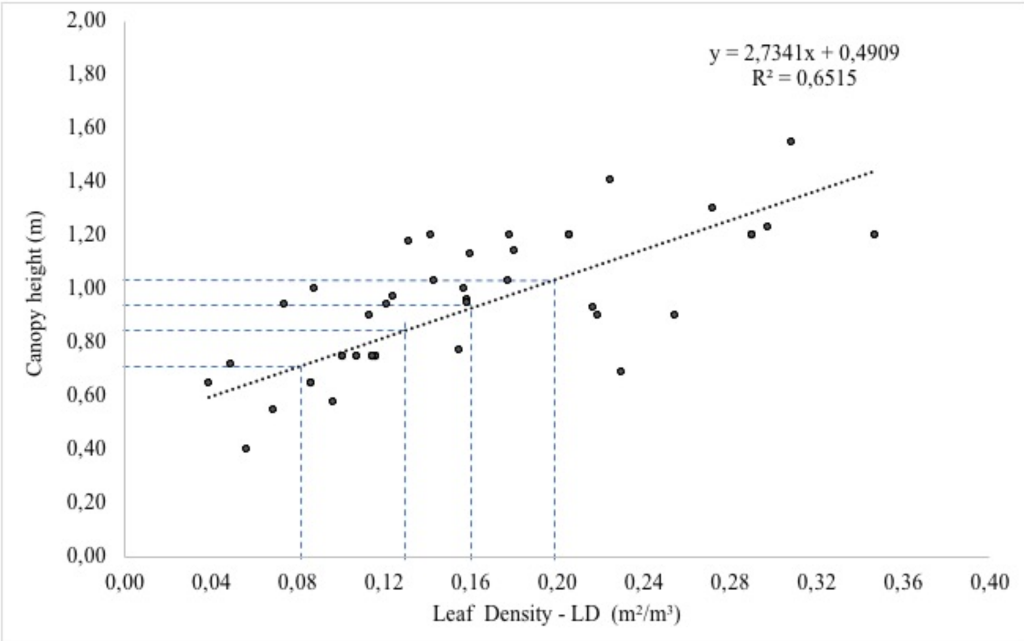

Figure 1. Relationship between leaf density – LD (m^2/m^3) and canopy height. Representation of the four zones corresponding to each of the density pictograms included in Dosaviña.

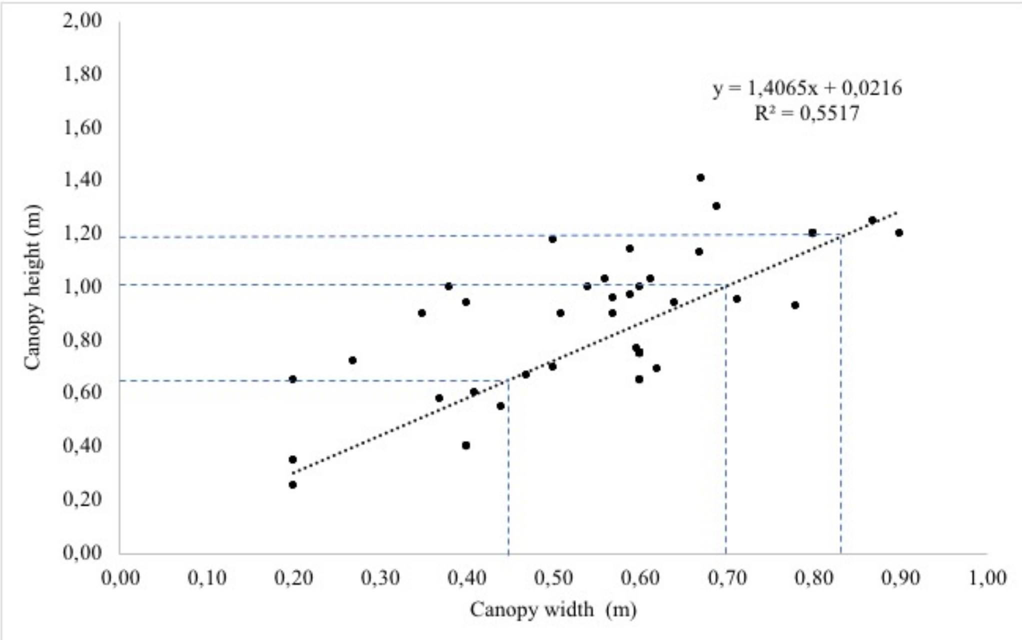

Figure 2. Relationship between canopy width (m) and canopy height (m). Representation of the four zones corresponding to each of the three canopy width intervals included in Dosaviña.

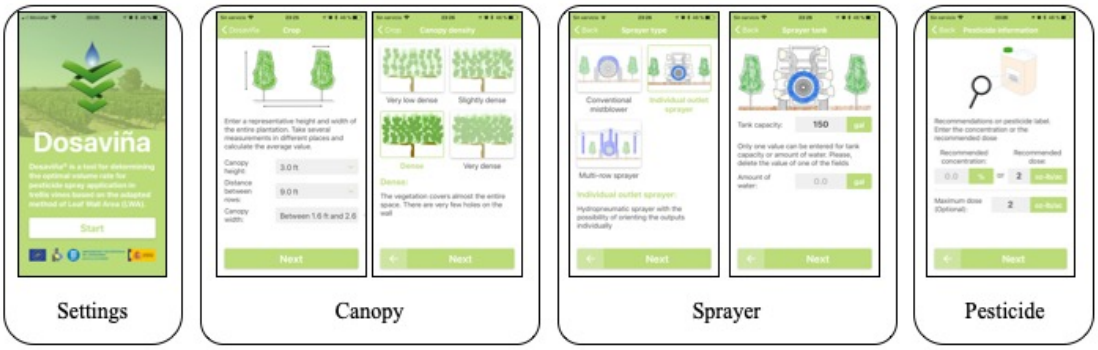

Figure 3. Dosaviña includes four different packages: settings, canopy characteristics, sprayer, and pesticide information

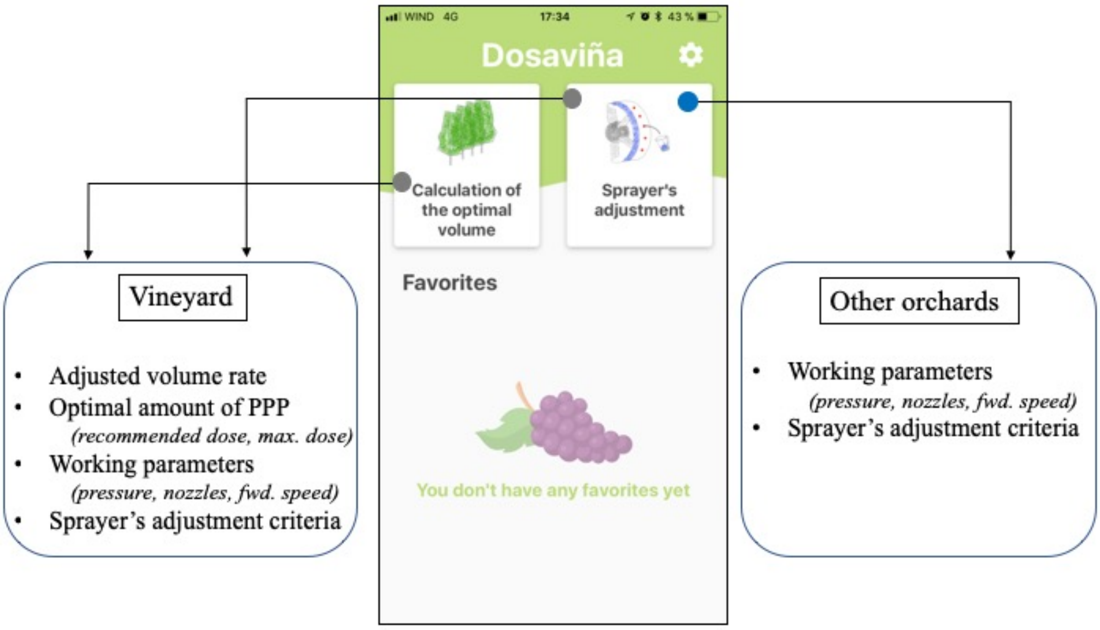

Figure 4. Dosaviña has been developed as a tool to determine optimal volume rate (and pesticide amount) for trellis vineyards. It is also useful for sprayer calibration processes in all orchard plantation types.

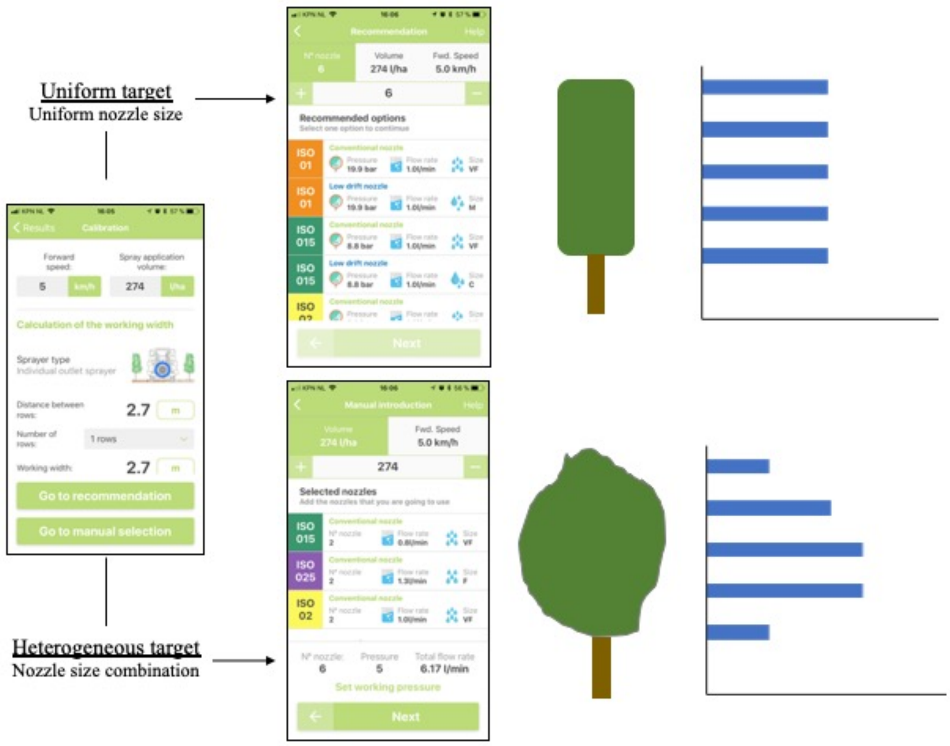

Figure 5. Spray adjustment and nozzle selection options included in Dosaviña, depending on the canopy structure: a) all nozzles are the same size and code, for uniform canopy distribution (upper graph); b) combination of nozzle sizes for heterogeneous liquid distribution (lower graph).

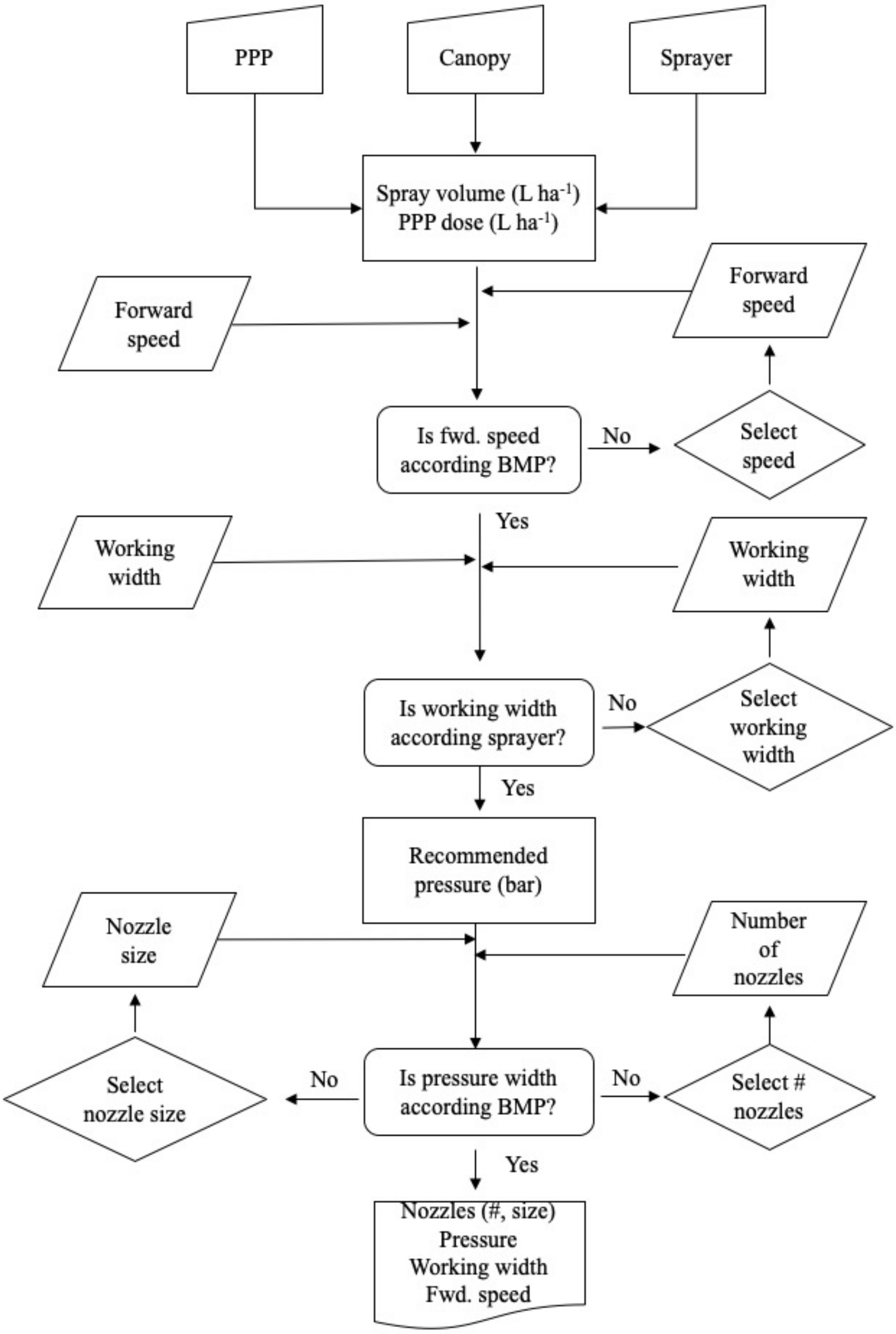

Figure 6. Flow chart of the entire Dosaviña process, including the procedure for determination of the most suitable working parameters.

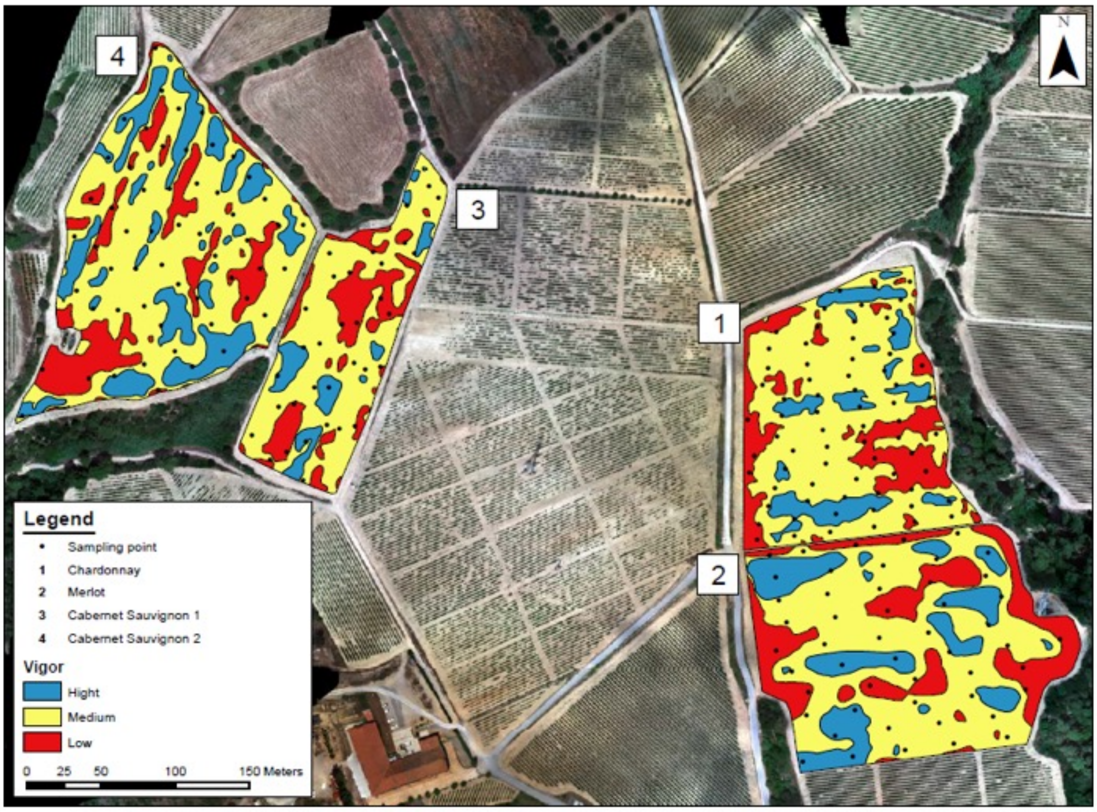

Figure 7. Four commercial vineyard parcels with different varieties (Chardonnay, Merlot, and Cabernet Sauvignon) were selected at Jean Leon winery (Vilafranca del Penedès, Barcelona, Spain). On each selected parcel, three different zones were established according to different canopy development types. Sample points were randomly distributed among each of the zones.

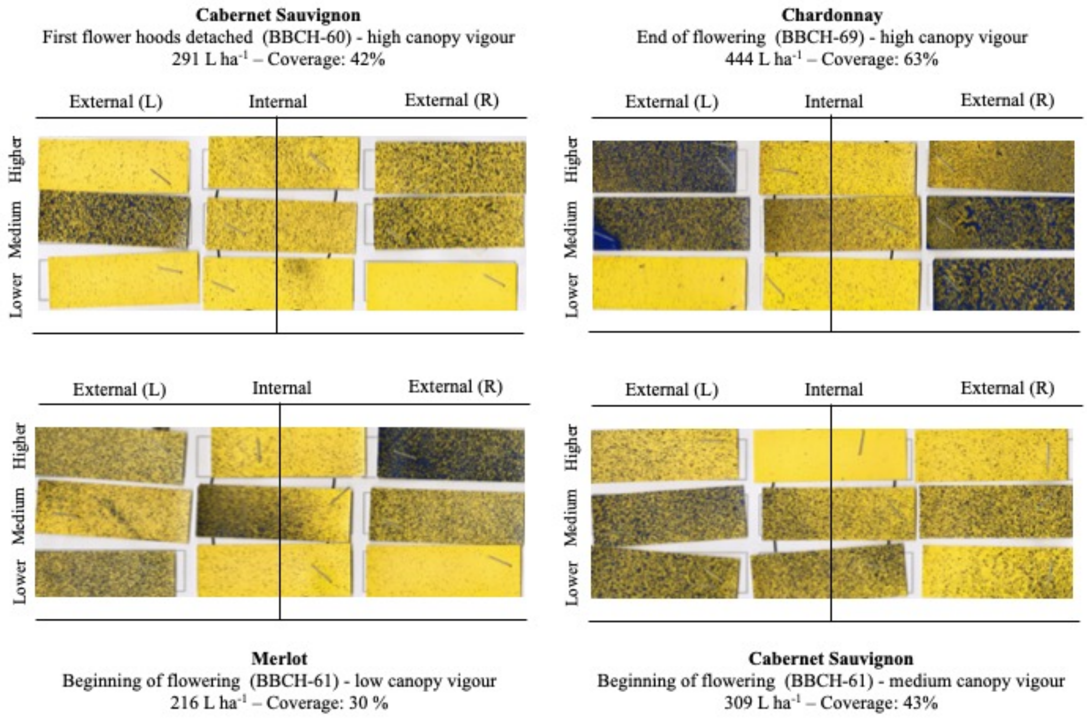

Figure 8. Example of results obtained on water sensitive paper strips placed on the canopy. Nine sampling points were defined on each sample point covering the external and internal parts of the canopy, as well as the entire canopy height.

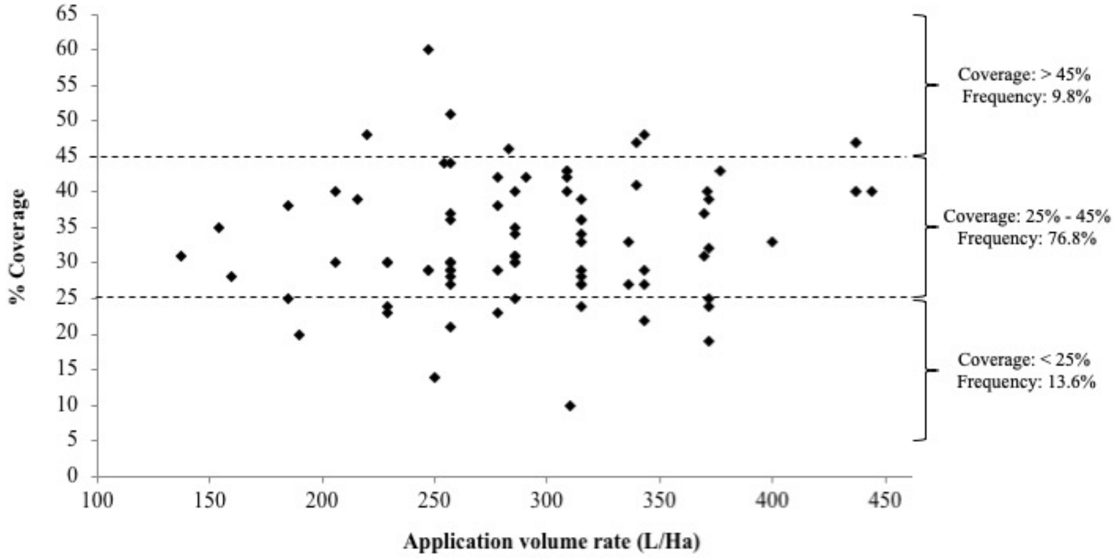

Figure 9. Relationship between application rate recommended by Dosaviña and % of coverage measured at water sensitive papers.

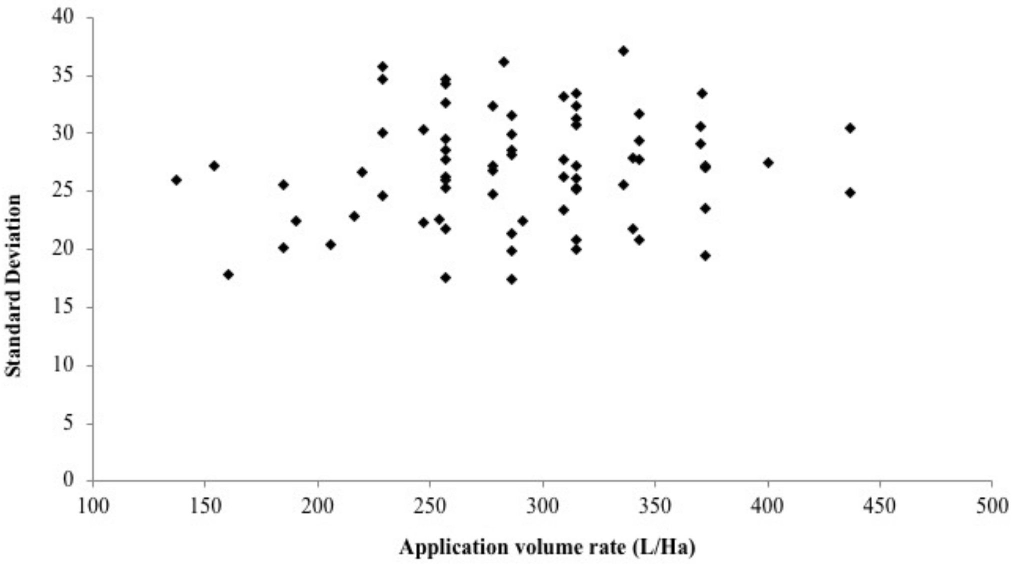

Figure 10. Relationship between application rate (L ha^{-1}) recommended by Dosaviña, and the standard deviation of all the coverage values (%) obtained at the nine sample points on each selected plant.

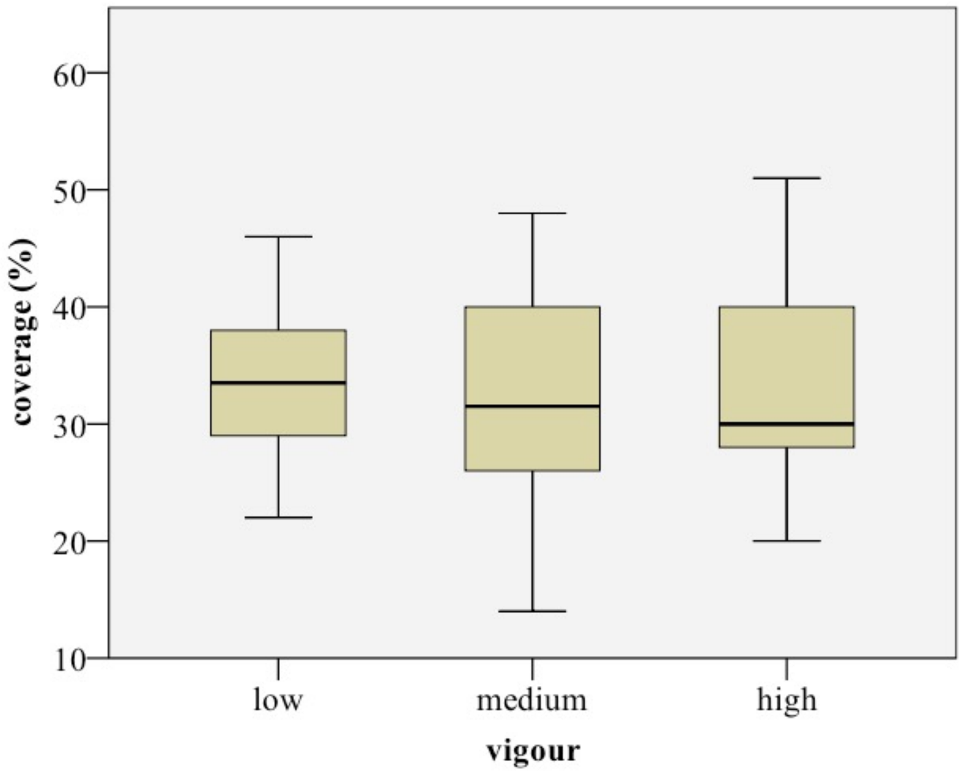

Figure 11. Average percentage of coverage obtained at the three different canopy vigour zones that were identified (low, medium, and high). Recommendations obtained after using Dosaviña concerning the optimal spray volume rate allowed very similar deposition values and similar spray distribution uniformity to be obtained, independent of the canopy characteristics.

TABLES

Table 1. Procedure to estimate the assigned value for density pictograms included in Dosaviña. Quantification of leaf density and its effect on canopy height

Dosaviña pictogram	**LD (m^2/m^2)**	**Canopy height (m)**	**Relative variation (%)**	**Dosaviña assigned value**
Very low dense	0.083	0.719	85	0.8
Low dense	0.125	0.833	94	0.9
Dense	0.143	0.881	100	1.0
Very dense	0.196	1.038	110	1.1

Table 2. Procedure to estimate the assigned value for canopy width intervals included in Dosaviña. Quantification of canopy width and its effect on canopy height

Canopy width intervals	**Assigned canopy width (m)**	**Canopy height (m)**	**Relative variation (%)**	**Dosaviña assigned value**
< 0.5 m	0.45	0.65	65	0.85
0.5 m - 0.8 m	0.70	1.01	100	1.00
> 0.8 m	0.82	1.17	117	1.15

Table 3. Mathematical relationships between working pressure and flow rate for all ISO colour codes.

ISO code	$p\ (bar) = a \times q^{b} (\frac{l}{min})$		$q\ (\frac{l}{min}) = c \times p^{d} (bar)$	
	a	**b**	**c**	**d**
ISO 01	18.793	2.0040	0.2314	0.4989
ISO 015	8.3358	2.0020	0.3468	0.4994
ISO 02	4.6903	1.9967	0.4612	0.5008
ISO 025	2.9949	2.0050	0.5786	0.4987
ISO 03	2.0817	2.0002	0.6931	0.4999
ISO 04	1.1740	1.9983	0.9229	0.5004
ISO 05	0.7540	1.9945	1.1521	0.5014
ISO 06	0.5190	2.0023	1.3875	0.4994
ISO 08	0.3054	1.9632	1.8322	0.5086
ISO 10	0.1967	1.9642	2.2912	0.5083

Table 4. Technical characteristics of Dosaviña app

Concept	**Characteristics**
OS compatibility	IOS and ANDROID
Languages	English, Spanish, French, Italian, Greek, Catalan
Units	IS (International System) and US-Imperial
Country identification	Yes
IOS link download	https://itunes.apple.com/es/app/dosavi%C3%B1a/id1413664423?mt=8
ANDROID link download	https://play.google.com/store/apps/details?id=edu.upc.deab.uma&hl=es
Web site version	https://dosavina.upc.edu
Developer	UPC - https://uma.deab.upc.edu
Price	Free

Table 5. Technical information included in the final report generated after using Dosaviña (app or website version)

Concept	**Units/Classes**
Canopy characteristics	
Row distance	m
Canopy height	m
Canopy width	Low, medium, high
Leaf density	Very low dense, slightly dense, dense, very dense
Sprayer adjustment	
Sprayer type	Conventional mistblower, individual outlet, multi-row
Volume rate	L ha^{-1}
Forward speed	Km h^{-1}
Working width	m
Total flow rate	L min^{-1}
Nozzle flow rate	L min^{-1}
Recommended pressure	bar
Nozzle type	Conventional or AI
Nozzle size	ISO colour code
Nº of nozzles	-
Droplet size	VS, S, M, C, VC, XC
PPP dose recommendation	
Dose	L ha^{-1}
Max. dose	L ha-1
Amount of PPP per sprayer tank	L

Table 6. Main characteristics and location of the four selected parcels

Variety (parcel)	**Merlot (1)**	**Chardonnay (2)**	**Cabernet Sauvignon (3)**	**Cabernet Sauvignon (4)**
Size (ha)	2.97	2.35	1.53	3.14
Row distance (m)	2.20	2.20	2.20	2.20
X coordinate	392234	392194	391856	391744
Y coordinate	4587843	4587999	4588055	4588107
Trellis system	Double Royat			
Location	Torrelavit (Barcelona, Spain)			
Reference system	ETRS89 UTM 31			

Table 7 a. Volume rate (L ha-1) calculated with the developed Dosaviña tool for each combination of grape variety and canopy development (low, medium, high). Selected working conditions (size and number of nozzles, and working pressure) for every test (trials 1 to 4)

Variety	**Canopy develop.**	May 24th BBCH: 60 (CS-MT); 61 (CH) 60: First flower hoods detached 61: Beginning of flowering			June 1st BBCH: 61 (CS-MT); 69 (CH) 61: Beginning of flowering 69: End of flowering			June 6th BBCH: 69 (CS-MT); 75 (CH) 69: End of flowering 75: Berries pea-size			June 20th BBCH: 75 (CS-MT); 77 (CH) 75: Berries pea-size 77: Berries beginning to touch		
		Volume (L ha $^{-1}$)	**Nozzles (size & nº)**	**Pressure (bar)**	**Volume (L ha $^{-1}$)**	**Nozzles (size & nº)**	**Pressure (bar)**	**Volume (L ha $^{-1}$)**	**Nozzles (size & nº)**	**Pressure (bar)**	**Volume (L ha $^{-1}$)**	**Nozzles (size & nº)**	**Pressure (bar)**
Merlot	*Low*	137	Brown (6)	6.7	216	Yellow (6)	7.6	206	Yellow (6)	6.9	229	Brown (4) Yellow (4)	7.1
	Medium	160	Brown (6)	9.1	247	Yellow (6)	10.0	247	Yellow (6)	10.0	257	Brown (4) Yellow (4)	9.0
	High	190	Brown (6)	12.8	278	Yellow (6)	12.7	278	Yellow (6)	12.7	315	Brown (4) Yellow (4)	13.6
Chardonnay	*Low*	185	Brown (8)	5.7	278	Yellow (8)	7.1	309	Yellow (6) Orange (2)	7.4	257	Yellow (8)	6.0
	Medium	250	Brown (8)	10.3	309	Yellow (8)	8.8	377	Yellow (6) Orange (2)	11.2	315	Yellow (8)	9.2
	High	310	Brown (8)	15.9	371	Yellow (8)	12.8	444	Yellow (6) Orange (2)	15.6	372	Yellow (8)	12.8
Cabernet Sauvignon 1	*Low*	154	Brown (6)	7.0	247	Brown (4) Orange (4)	8.3	206	Brown (4) Yellow (4)	5.7	257	Yellow (8)	6.0
	Medium	185	Brown (6)	10.1	309	Brown (4) Orange (4)	13.1	283	Brown (4) Yellow (4)	10.9	315	Yellow (8)	9.2
	High	220	Brown (6)	14.2	340	Brown (4) Orange (4)	15.9	315	Brown (4) Yellow (4)	13.6	372	Yellow (8)	12.8
Cabernet Sauvignon 2	*Low*	216	Brown (8)	7.7	278	Yellow (8)	7.1	286	Yellow (6) Orange (2)	6.3	257	Yellow (6) Orange (2)	5.1
	Medium	254	Brown (8)	10.7	309	Yellow (8)	8.8	336	Yellow (6) Orange (2)	8.8	286	Yellow (6) Orange (2)	6.3
	High	291	Brown (8)	14.0	340	Yellow (8)	10.7	437	Yellow (6) Orange (2)	15.1	437	Yellow (6) Orange (2)	15.1

All nozzles used were hollow cone Albuz (Albuz Saint-Gobain Desmarquest, Evraux, France) ATR models; size selected is shown in the table; forward speed during all the treatments was 6.8 km h^{-1} except for those marked (*) where forward speed was 6.0 km h^{-1}; CS: Cabernet Sauvignon: MT: Merlot; CH: Chardonnay.

Table 7 b. Volume rate (L ha-1) calculated with the developed Dosaviña tool for each combination of grape variety and canopy development (low, medium, high). Selected working conditions (size and number of nozzles, and working pressure) for every test (trials 5 to 7)

Variety	Canopy develop.	July 2nd BBCH: 77 (CS-MT); 79 (CH) 77: Berries beginning to touch 79: Majority of berries touching			July 12th BBCH: 79 (CS-MT); 81 (CH) 79: Majority of berries touching 81: Beginning of ripening			July 20th BBCH: 81 (CS-MT); 83 (CH) 81: Beginning of ripening 83: Berries developing colour		
		Volume ($L\ ha^{-1}$)	**Nozzles (size & nº)**	**Pressure (bar)**	**Volume ($L\ ha^{-1}$)**	**Nozzles (size & nº)**	**Pressure (bar)**	**Volume ($L\ ha^{-1}$)**	**Nozzles (size & nº)**	**Pressure (bar)**
Merlot	*Low*	257	Brown (2) Yellow (6)	7.4	229	Brown (2) Yellow (6)	5.8	229	Brown (2) Yellow (6)	5.8
	Medium	286	Brown (2) Yellow (6)	9.2	-		-	-		-
	High	315	Brown (2) Yellow (6)	11.2	370	Brown (2) Yellow (6)	15.6	336	Brown (2) Yellow (6)	12.8
Chardonnay	*Low*	257	Brown (2) Yellow (6)	7.4	257	Yellow (8)	6.0	229	Brown (4) Yellow (4)	7.1
	Medium	286	Brown (2) Yellow (6)	9.2	286	Yellow (8)	7.5	286	Brown (4) Yellow (4)	11.2
	High	343	Brown (2) Yellow (6)	13.3	370	Yellow (8)	12.7	315	Brown (4) Yellow (4)	13.6
Cabernet Sauvignon 1	*Low*	315	Yellow (8)	9.2	257	Yellow (8)	6.0	257	Yellow (8)	6.0
	Medium	343	Yellow (8)	10.9	286	Yellow (8)	7.5	286	Yellow (8)	7.5
	High	372	Yellow (8)	12.8	372	Yellow (8)	12.8	400	Yellow (8)	14.9
Cabernet Sauvignon 2	*Low*	257	Yellow (8)	6.0	257	Yellow (8)	6.0	257	Yellow (8)	6.0
	Medium	315	Yellow (8)	9.2	315	Yellow (8)	9.2	315	Yellow (8)	9.2
	High	372	Yellow (8)	12.8	343	Yellow (8)	10.9	343	Yellow (8)	10.9

All nozzles used were hollow cone Albuz (Albuz Saint-Gobain Desmarquest, Evraux, France) ATR models; size selected is shown in the table; forward speed during all the treatments was 6.8 km h^{-1} except for those marked (*) where forward speed was 6.0 km h^{-1}; CS: Cabernet Sauvignon: MT: Merlot; CH: Chardonnay.

Table 8. Average coverage values (%) measured over water sensitive paper in each of the conducted trials

Variety	Canopy development	BBCH 60-61 May 24th Coverage (%)	BBCH 61-69 June 1st Coverage (%)	BBCH 69-75 June 6th Coverage (%)	BBCH 75-77 June 20th Coverage (%)	BBCH 77-79 July 2nd Coverage (%)	BBCH 79-81 July 12th Coverage (%)	BBCH 81-83 July 20th Coverage (%)
Merlot	*Low*	31	-	30	30	29	24	23
	Medium	28	29	29	30	31	-	-
	High	20	38	23	33	27	31	27
Chardonnay	*Low*	25	29	68	44	51	28	30
	Medium	14	43	43	39	40	30	34
	High	10	40	40	39	45	37	36
Cabernet Sauvignon 1	*Low*	35	60	40	30	36	27	37
	Medium	38	42	46	34	29	25	31
	High	48	41	24	25	19	24	33
Cabernet Sauvignon 2	*Low*	39	42	30	29	30	21	36
	Medium	44	43	33	35	27	28	29
	High	42	47	47	40	32	22	27
Average		**31.1**	**41.2**	**37.7**	**34.0**	**33.0**	**27.0**	**31.1**