Advanced technologies for precise viticulture

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1. Introduction

Crop protection is a key issue in farm management. It involves dealing with important risks and expensive pesticide products. Most of these products are to be applied by means of sprayers. Spraying techniques have been continuously evolving in recent decades. However, it is not only the sprayer itself, but everything related to the application of plant protection products (PPP) that needs to be taken into account in order to improve the results obtained. What is the canopy like? What is the canopy volume? What is the leaf area to be sprayed? What technologies are available to help growers improve their spray applications in a more effective, efficient and sustainable way?

In the 1980s, the term "precision agriculture" was used for the first time. Sensors, agricultural and statistical techniques and technology were combined to improve farm management techniques. One of the contexts where precision agriculture has been widely implemented is vineyards, in what is known as "precision viticulture". After some decades of rapid development, in this day and age when people are carrying around extremely powerful microprocessors and GPS receivers in their pockets, it seems reasonable to consider using these technologies to turn spray applications into a more sustainable operation.

Apart from improving new solutions and developing cutting edge technology, there exists an important gap from science to industry that needs to be filled with more training and formative programs as well as easy access to the developed prototypes and methodologies.

This paper navigates through some of the important developments related to plant protection product application and spraying techniques with the objective of demonstrating that all means are there to improve the way crops are being protected and increasing sustainability of spraying techniques.

2. Canopy characterization: the key factor

The study and determination of canopy structure is a key parameter in viticulture for several reasons. Crop growth and vigour is closely related with grape quality and ripeness processes, but also impacts the performance of plant protection operations by allowing greater or lesser amount of plant protection products depositing in inner leaves and fruits. It is, therefore, the need of research and knowledge of vine growth dynamics and canopy characteristics what has boosted the use of sensors for data acquisition in the field. Three main types of sensors have been generally used: ultrasound sensors (US), laser scanner sensors (LIDAR) and optical sensors (cameras).

Ultrasound sensors (US) allow determining the distance between the sensor and a proximal object. In viticulture and orchards, US have been extensively used to determine the structural characteristics of vegetation [31; 16; 25; 13]. All these studies mounted the sensors on terrestrial vehicles (i.e. tractors) at different heights to scan the vegetation in divided into three or four sections along the row to better capture the possible changes in canopy width from the base to the tip of the tree. The conclusions reached by authors involved in these researches are that US are a reliable system for canopy characterization but limitations due to sensor resolution prevent for a fine delineation of the canopy leaf wall.

To overcome the limitations related to sensor resolution, light detection and ranging sensors (LIDAR) were introduced as a measure of ground truth for canopy monitoring. LIDAR sensors use infrared light beams to detect objects and calculate the distance to the sensor. The infrared light beams are emitted from the sensor in a fan shape with angular resolutions of less than 1º, and when hitting the canopy the beam spot has few millimetres which endow it with a great capacity for penetration through the canopy. Unlike US, LIDAR scanner can measure distances in several directions within a plane [6]. Although there are LIDARs embedded in aerial vehicles (aerial laser scanning or ALS) that are used in topography, geology and forestry, in agriculture the most common use of such a sensors is transported by a terrestrial vehicle (terrestrial laser scanning or TLS).

Terrestrial laser scanning has been commonly discussed during the recent years for 3D characterization of fruit trees (Rosell et al. 2009, Miranda-Fuentes et al. 2015) and also in vineyard [25]. While ultrasound sensors provided less precise information than LIDAR sensors, this fact can be compensated by a more user friendly working protocol, installation, calibration and data analysis given by US [25; 27].

In contrast with ground based sensors (i.e. LIDAR and US), remote sensing technology is best suited for large scale monitoring. The use of aerial remote sensing in agriculture started with the first launch of Landsat Multispectral Scanner System (MSS) satellite in 1972. From then, there has been a continuous deployment of earth observation satellites by public and private entities with the objective of providing timely and low cost multispectral images. However, until the last decade, the use of satellite imagery for precision agriculture has been only available to large-scale monitoring and restricted to broad acre crops due to the limited spatial and temporal resolution satellite data [22]. Recent advances in remote sensing techniques have allowed developing new types of aerial platforms (e.g. unmanned aerial vehicles or UAV) and more sophisticated sensors capable of offering image data at very high spatial resolution (centimetric). The two types of platforms offer clear differences in their management, accuracy and economical cost, which have been extensively discussed in research reaching various advantages and disadvantages of each platform depending of the canopy type, size and expected output. The resulting images from remote sensing systems provide spectral information at different wavelengths through the electromagnetic spectrum, with special importance to the chlorophyll absorption bands in the visible range of the spectrum (480 nm and 670 nm) as well as the green peak centred at 550 nm [14]. Furthermore, beyond the visible light there is relevant information offered by plant physiology which is also captured by multispectral sensors, especially in the Red Edge and NIR wavelengths (from 700 to 1000 nm). Combination of bands from the Visible and NIR range of the spectra allows for the calculation of vegetation indices which have been used to asses biophysical characteristics of vegetation as well as plant stress [19; 21; 30; 33; 34]. Some of the vegetation index reported in literature are especially sensible to vegetation-soil spectral mixing at pixel level but also are strongly affected by changes in LAI [20]. It is, therefore, important to consider spatial resolution as a key parameter in order to ensure reliable results when using remote sensing for canopy characterization. UAV offer a very high resolution allowing detection and discrimination of canopy rows in vineyards and reducing spectral mixing at pixel level [3; 5], or said in other words, higher number of canopy-pure pixels can be obtained when working with small pixel sizes. The impact of high resolution in the resulting maps is clear, but equilibrium has to be found with timeliness of data availability as well as economic aspects when comparing UAV and satellite based remote sensing in viticulture.

Taking benefit of the momentum that variable rate application of inputs is experiencing in broad acre crops, scientific developments in orchards aim to develop systems able to monitor and characterize the vegetation and apply fertilizers and PPP according to the needs in every area of the field. VRA of a PPP in a 3D crop represents a significant improvement on the sustainable use of pesticides, while ensuring accurate product deposition in the leaf and significant reduction of spray drift losses by adjusting the amount of PPP that are applied to every canopy structure in the field. Campos et al. [3] developed a methodology for image acquisition and analysis from UAV systems to collect spectral and geometric information from the vines that was later used to derive prescription maps based on the canopy characteristics in three vigour zones in which the fields were divided. In order to characterize each vigour area, field measurements of canopy height and width were collected and traduced to an average volume rate (l·ha-1) per vigour zone using the freely available DSS app DOSAVIÑA® (Figure 1). It was found clear differences between low, medium and high vigour zones in all three crop growth stages where measurements were carried out that ultimately impacted significantly on the volume rate per crop stage as well as per vigour area. An extension of this work, aimed to develop a regression model to predict the canopy characteristics per vigour zone based only on remote sensing data [5]. UAV as well as high resolution satellite information (3 m·pixel-1) showed good linear relationship with canopy parameters such as height, width, TRV and LWA, although the higher resolution data (i.e. UAV) significantly outperformed, especially when trying to apply the model to low vegetated canopies (i.e. at the beginning of the season) with coefficients of determination higher than 0,84. Other relevant information extracted from the cited research, is the improvement suffered by all regressions performed with drone based data when the value of vine projected area calculated from aerial imagery was included in combination with NDVI. Similar work has been proposed by Roman et al. [28] where vine LAI was estimated using remote sensing, and prescription maps were developed based on the LAI variability maps. Other studies using high-resolution NDVI maps have found significant differences between vines belonging to different vigour classes [1; 15]; however, none of them have related or modelled the structural characteristics of vines and the NDVI values in viticulture.

Other authors have tackled vine characterization through the use of the digital surface model (DSM) originated from the photogrammetric process used for generating the orthomosaic. This method allows for a robust estimation of the canopy height if UAV flight plan is carefully performed, ensuring sufficient overlapping between image frames to produce reliable and accurate data. The DSM united with image analysis techniques makes possible determining tree height, width and volume in a reliable way. Object based image analysis (OBIA) and DSM generation were used to characterize vines in two different moments in the season with RMSE below 20 cm for canopy height estimation, although better results were obtained when the estimation was made for each growth stage separately [7]. Similar approach was followed directly with the 3D point cloud generated after the photogrammetric process to differentiate between different management strategies conducted in vineyards (leaf removal and shot trimming) which allows for an automatic supervision of canopy management operations in the field [26]. Two important considerations can be extracted from the two previous research cited: 1) the need for a high resolution sensor that can provide dense point clouds in the photogrammetric process and 2) in order to ensure reliable results, it is recommended flying at low altitudes (about 30 m high) which compromises the working capacity with such an aerial platform.

Taking benefit from satellite's high temporal resolution, with revisit periods of less than a week, vineyard growth evolution has been mapped during the season. Devaux et al. [8] used temporal NDVI information from Sentinel 2 satellite imagery at 10 $m \cdot pixel^{-1}$ spatial resolution to track vineyard growth during the season, which provided a methodology to determine the approximate dates for conducting vine structure management operations. Similar methodology could be used to assess the general vigour of a vineyard to determine the most suitable volume rate to be used for spray application.

3. Decision tools for a better dose expression

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 [17; 12]. 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 [23]. 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.

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:

- In the majority of cases, the recommended volumes obtained after using DOSAVIÑA® are lower than the ones commonly selected by the farmers. This fact, coupled with a dose expression method based on concentration, leads to a consequent reduction in pesticide amounts.
- 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.
- 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® 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.

4. Variable Rate Application: a practical solution

Electronic canopy characterization allows the implementation of variable application rate techniques in fruit and vineyard crops, whereby pesticide application rates are modified according to crop characteristics [32; 2; 9; 24; 10; 12; 18]. In all cases, relevant benefits in terms of dose reduction, drift control and uniform deposition were achieved by all of the proposed methods. In the specific case of vineyards, the research group of Universitat Politècnica de Catalunya has developed a sprayer prototype that can apply a variable amount of liquid according to the canopy variability along the crop row [18]. The results indicated an average potential saving of 21.9%. There was a higher savings potential in the narrow canopy zones where the canopy width was below 0.22 m, which had an average savings of 31.4%. This value dropped to a 12.5% average for zones with a canopy width of over 0.22 m. These results indicated a similar response by the prototype that was independent of the canopy variation; instead, it was influenced by the crop stage and sensor position.

Following this line, EU founded Horizon 2020 project OPTIMA, has developed, tested and validated a smart sprayer for vineyard base on an existing air-assisted sprayer (Caffini Synthesis 1000 ATS102/E). This sprayer has been equipped with a GPS spray control unit enabling to manage in real-time the activation of each individual nozzle and the adjustment of the operating pressure, in order to adapt the spray volume according to a decision made based on the canopy characteristics, the disease spreading (downy mildew) detected by a DSS and an Early Detection System (EDS) in real time.

The latest trend in VRA is actually coming from what is already developed for broadacre crops regarding map based application of inputs. This has been transferred to specialty 3D crops where the fact of training the canopy in rows makes the challenge somehow more complicated. Map based VRA needs de determination of a prescription map that is normally done from remote sensing information. Once the canopy is characterized and the different homogeneous zones in the field are classified, the optimum volume rate is associated to each area. The machine is able to read in real time its position in the field and control the pressure to allow more or less rate to exit the nozzles. Campos et al. [3] showed that savings in water and pesticide over 40% could be obtained during the season using map based VRA of PPP. It was also tested the biological efficacy of the new proposed methodology, showing equivalent results as compared with a conventional pest application process [4]. Similarly, Roman et al. [28] demonstrated a reduction in sprayed volume of 25% compared to conventional practices, although the methodology is still not validated with biological efficiency.

4. Early detection Systems: the ideal devices

Early and accurate detection and diagnosis of plant diseases are key factors in plant production and the reduction of both qualitative and quantitative losses in crop yield. For this, a certain capability of prediction is needed in order to determine the best management actions to carry out in the field. Early detection of crop diseases in viticulture is a hot topic that has been developed for years but it still remains a challenge for farmers. One of the barriers for adoption is the way these models and their results are presented to the end user. Easy to access, user friendly and intuitive interfaces are key for success and adoption. Different platforms and software's are tackling this, and especially in viticulture there exists a broad range of options for modeling main pests and diseases.

In the frame of Project OPTIMA (http://optima-h2020.eu), four common existing models for predicting downy mildew infection in vineyards (vite.net, DMCast, DMEW and GVDM-infection) were implemented on an online DSS that is capable of achieving high prediction accuracy (up to site specific scale) based on past and current environmental data, community testimonies of farmers/advisors, detection data and geostatistical methods (Figure 2). Furthermore, another achievement of the project has been the creation of an image based Early Detection System capable of acquiring images at a high frame rate and analyzing the images by means of an artificial intelligence classification method developed within the project, reporting for each geolocalized frame the probability of incidence of the disease. This is later on interpolated offering the possibility of working with a probability disease map that is implemented in the smart sprayer to adapt the flow rate according to it. As the project is still ongoing, no definitive results can be reported.

5. Robots in agriculture

What is next? It is clear that future will involve robotics in viticulture. There are many research centers working in how robots can assists in yield prediction, weeding or even pruning (VINUM-Robot project) in viticulture, but it is especially in France, where this research is coming into the market with robust and commercial solutions. Mainly focused, for now, in weeding and harrowing operations, from 2020 a farmer can buy a robot that is capable of performing these operations unmanned. VitiRover in 2012 was the pioneer by developing a small robot intended for mowing the grass under the vines in an autonomous way. More ambitious projects followed, and robotics companies such as Naïo Technologies or VitiBot developed an 800 and 2500 kg robot respectively that is capable of performing harrowing under the wine. These robots are electric with more than 8 hours of autonomy. In the case of VitiBot they have recently developed an implement that allows for an autonomous spraying of the vineyard with a 400 liter tank attached to the robot.

Recent research is focusing on detecting clusters, counting them and allowing precise and early forecasting of yield. Small autonomous platforms fitted with different optical sensors and actuators are being used to determine phonological traits of the vines, detect clusters via image analysis algorithms and even in some cases act accordingly by harvesting the ripen fruits. To interesting projects working in this field of work are VineRobot and Bacchus where successful implementation of robotic platforms have been achieved.

In other kind of operations, the robots and humans will have to cooperate. In this case, the term robot suffers an adaptation to be transformed to *cobot*. This novel approach to the introduction of robots has been addressed mostly in indoor industrial settings, also because of the challenges raised by outdoor environments. Outdoor environments are particularly problematic for the deployment of autonomous robots due to the new degrees of environmental dynamics and unpredictability, such as variations of the illumination, changes in weather conditions, or temporary perceptual occlusions. The CANOPIES project (https://www.canopies-project.eu), founded by Horizon 2020 program, aims to develop a novel collaborative human-robot paradigm in the industry of table grape to address two major tasks carried out in the field namely harvest and pruning.

6. Technology ready to be used

INNOSETA (http://www.innoseta.eu) is an EU founded project (Nº 773864) that helps to bridge the gap between the farmer and the latest technological and knowledge developments in the sector. This platform is divided into four areas: projects, training material, industry solutions and articles. Each user can upload information relevant to the sector, which goes through a selection process and is published in 8 official EU languages, thus reducing the problem of only finding information material in a single language (Figure 3).

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FIGURES

Figure 1 – Working protocol for map based VRA of PPP in vineyard *(Source: [3])*.

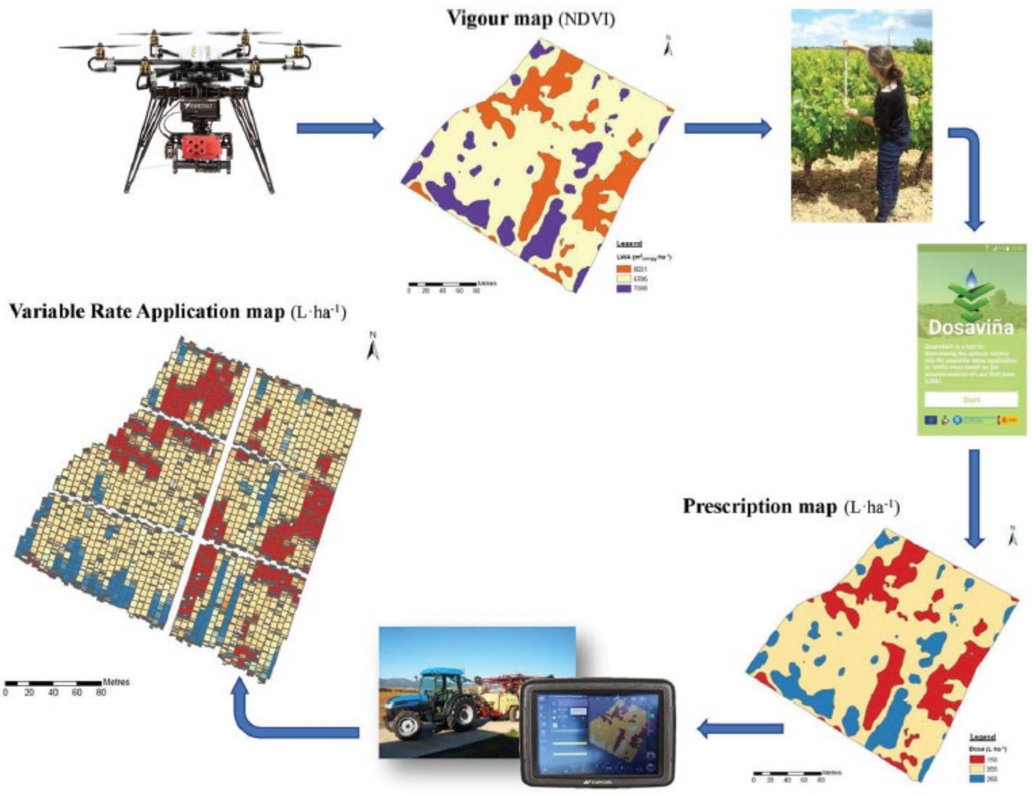

Figure 2 – DSS developed under the OPTIMA project available at http://dss.optima-h2020.eu/.

Figure 3 – INNOSETA platform available at https://platform.innoseta.eu/.