

39. Evaluating a smart sprayer for vineyards using remote sensors and mapping technologies: product savings and biological efficacy

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Abstract

Optimizing the use of plant protection products (PPP) is key in high-value crops like vineyards. This study evaluated a smart prototype equipped with adjustable pulse width modulation (PWM)-valves and GNSS tracking, integrated into a commercial sprayer, enabling variable-rate applications based on normalised difference vegetation indices (NDVI)-derived vigor maps from drone imagery (2023) and satellite data (2024). Trials in Penedès region (Barcelona) compared this approach to conventional spraying, assessing biological efficacy and PPP savings. Results showed up to 40% PPP reduction without compromising pest control. The results highlight the potential of satellite-based precision agriculture for efficiency and sustainability.

Keywords: drone, plant protection product, prescription map, satellite, variable rate application, vineyard

Introduction

Precision agriculture is revolutionizing modern farming by enabling growers to optimize inputs, reduce environmental impact, and enhance crop productivity. One of its key advancements is the improved application of plant protection products (PPPs) through technologies such as prescription maps and pulse-width modulation (PWM) valves. These innovations allow for a highly targeted and efficient use of PPPs, addressing the dual challenges of sustainability and profitability in agriculture. Variable rate application (VRA) technology in vineyards initially developed by adjusting sprayer flow rate to canopy characteristics using ultrasonic sensors (Gil *et al.*, 2007). This approach demonstrated a 40% reduction in PPP use compared to conventional uniform spraying. The integration of remote sensing further advanced VRA by enabling canopy vigor characterization through drone and satellite imagery (Campos *et al.*, 2021). Additionally, Decision Support Systems (DSS), such as DOSAVIÑA (Gil *et al.*, 2019), have been used to generate optimized prescription maps, based on remote sensors, achieving up to a 20% reduction in PPP usage. Similar studies have assessed the biological efficacy of VRA for controlling fungal diseases, finding no significant differences between conventional spraying and VRA-based applications (Garcia-Ruiz *et al.*, 2023).

These field works show the two alternatives available in VRA spray systems. On one side, real-time or on-line VRA systems, which utilize onboard canopy sensors to adjust application rates instantaneously as the sprayer moves through the field. Off-line modes, on the other hand, are based on information collected by remote sensors, mainly satellites and drones. While on-line VRA provides a dynamic and highly responsive solution, its effectiveness depends on sensor accuracy, calibration, and forward speed. Additionally, remote sensing-based VRA systems enable strategic planning with plant health and vigour data, optimizing applications based on agronomic trends rather than instant reactions. However, few field studies focused on remote sensing techniques individually compared their impact on product savings and biological efficacy when applied under similar conditions.

This study evaluated a smart sprayer prototype integrated into a commercial sprayer, implementing variable rate application (VRA) based on remote sensing data. The trials were conducted over two seasons, using different prescription mapping techniques: in 2023, maps were generated from high-resolution drone imagery, while in 2024, they were derived from satellite data. The study aims to compare the efficacy of these two remote sensing methods in optimizing product savings and biological control in vineyards.

Materials and methods

Prototype description

A Hardi Zatrurn Compact Cronos air-assisted multi-row vineyard sprayer (Ileemo Hardi, Lleida, Spain) (Figure 1a) was re-engineered to enable fully automated spray control via an on-board computer capable of interpreting prescription maps. Although the sprayer had a total of 6 vertical booms, only the 4 central ones were enabled to work. The sprayer was hydraulically upgraded with 24 solenoid shut-off valves (115880 e-ChemSaver, TeeJet Technologies, Glendale Heights, IL, USA), while retaining hollow-cone nozzles. A digital turbine flowmeter (FT-08NEXWULEE-5, FTI Flow Technology, Tempe, AZ, USA) was installed to measure the total flow rate. Additionally, the hydraulic circuit was equipped with digital manometers (1600B, Gems Sensors and Controls, Plainville, CT, USA) for continuous pressure monitoring at three points: the total system pressure before the flow splits into left and right sectors, and the inlet pressures for the left and right sectors. These sensors were integrated with the sprayer computer (Figure 1b) for real-time data acquisition and control.

The sprayer's control system was powered by two distinct sources. First, an independent internal battery supplying 12 V was dedicated to computer-controlled components, including an on-board computer, a data acquisition card, a voltage converter (12 VDC-24 VDC), a 14-inch touchscreen monitor for the graphical user interface (GUI), and a GPS receiver (SXblue, Anjou, QC, Canada). Additionally, an external power source was directly connected to the battery of the traction tractor, delivering 12 V and 30 A to operate the PWM valves. More details about the prototype and its operation are explained by Rovira-Mas *et al.* (2024).

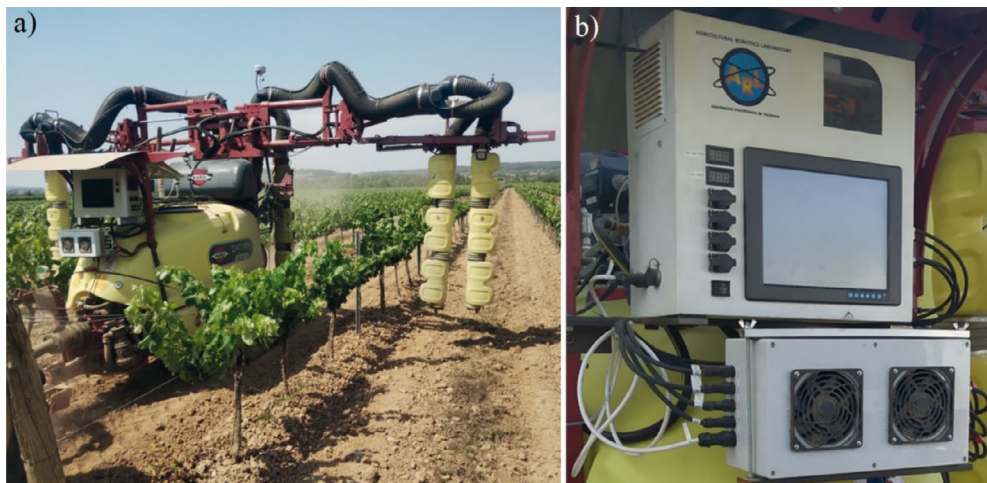


Figure 1. Commercial multi-row sprayer (a) and intelligent system control unit integrated into the sprayer (b).

The outgoing flow rate from the nozzles was regulated by PWM valves, thereby adjusting the spray flow to match the prescription map. This method was chosen for its ability to work at a constant pressure without altering the droplet spectrum. It was achieved by varying the pulse width or duty cycle (DUC), enabling precise flow control. A control algorithm was designed to operate within this effective range, ensuring precise flow delivery tailored to the needs of each area as specified in the prescription maps. The algorithm was designed after previous laboratory experiments, with the sprayer based on the methodology presented in Salcedo *et al.* (2022). The total flow rates generated were characterized according to the DUCs (from 0 to 100% at intervals of 10% DUCs) for different pressures (200, 400 and 600 kPa, respectively) and ISO nozzle sizes (codes 01, 015 and 02, respectively) (ISO, 2018).

Prescription map generation

The PPP prescription maps were generated using canopy maps (Campos *et al.*, 2021; Garcia-Ruiz *et al.*, 2023), obtained through aerial remote sensing imagery. For the 2023 campaign, high-resolution drone imagery was used. Very high resolution was desired in the first year of experiments to be able to eliminate all the artifacts and noise in the imagery and concentrate the analysis only in vine vegetation, therefore drone imagery was used to produce the maps. In the second campaign, based on the methodology used for the 2023 season, a prescription map was generated using data collected from satellite images. To enhance efficiency in image acquisition for the 2024 fungicide application campaign, high-resolution satellite imagery was tested to develop the canopy maps. For this, satellite imagery was collected from Dove nanosatellites (Planet Labs, San Francisco, CA, USA). The spatial resolution of drone imagery was about 5 cm/pixel, whereas satellite imagery provided 3 m/pixel spatial resolution.

In both campaigns, the analysis of images acquired by the remote sensors allowed for the evaluation of vineyard vigour through the calculation of the NDVI index from a false-color orthophoto (NIR, G, B), following a specific protocol proposed by Campos *et al.* (2021). After assigning the corresponding coordinate reference system, pixels were segmented into vineyard and ground using a threshold of 0.35, creating a binary mask. The vineyard rows were then divided into rectangular polygons representing individual plants, and the average NDVI value was calculated for each. The centroids of these polygons were interpolated using the Inverse Distance Weighting (IDW) method to produce a continuous raster image of NDVI, which was subsequently reclassified into two classes (high and low vigour) based on the median. Finally, vector polygons with vigour classes and a grid of points spaced 2.0 m apart were generated, assigning each point a vigour class compatible with the smart prototype, resulting in a vigour map ready for interpretation (Figure 2). The application rate volumes for each of the vigour zones were calculated using the Dosaviña[®] DSS (Gil *et al.*, 2019).

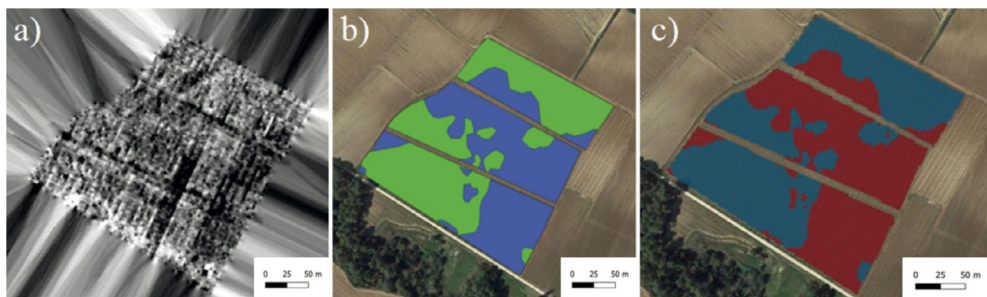


Figure 2. Phased map generation: Initial NDVI layer interpolated from vineyard vegetation pixels (a), obtained vector layer (b) and final prescription map with two vigour zones (c).

Field experiments

In this project, two fungicide treatments were carried out in both June and July of 2023 (using drone-based prescription maps) and 2024 (using satellite-based prescription maps), ensuring consistency in the application timeline across both years. The selected plot was located in the Penedès wine region (Barcelona, Spain) and covered an area of 5 hectares. The plot was planted with the Macabeo grape variety (*Vitis vinifera*), trained in a trellis system distributed across 92 rows. The planting frame consisted of 2.8 m spacing between rows and 1.2 m spacing between vines. The applications targeted the fungus *Plasmopara Viticola* (downy mildew), using 50% copper oxychloride as the fungicide. The phenological stages of the vineyard ranged between BBCH 75 (June) and BBCH 85 (July) (Meier, 1997).

For each month and year, two applications were conducted within the same plot. The farmer was driving directly the multi-row sprayer with the assembled intelligent control unit. Twenty consecutive rows (1 ha) were treated using the conventional method employed by the farmer, which involved a constant spray volume of 160 l/ha in 2023 and 200 l/ha in 2024 for both June and July (Table 1). In both campaigns, the twenty consecutive rows were confirmed to contain a similar proportion of high- and low-vigor zones. For the conventional application, the smart system was deactivated, and the PWM valves operated fully open (100% DUC) (Figure 3).

The remainder of the plot, excluding the last three rows on each end used such as control areas, was treated using the VRA methodology with the prototype activated. The flow rate was adjusted using PWM valves according to the prescription map, while maintaining a constant speed. Spray volumes ranged between 80 and 160 l/ha in 2023. The PWM nozzles operated with solenoids at a frequency of 10 Hz, within a duty cycle range of 20–80%, considered optimal for orchard applications in previous tests under laboratory conditions (Saiz-Rubio *et al.*, 2023).

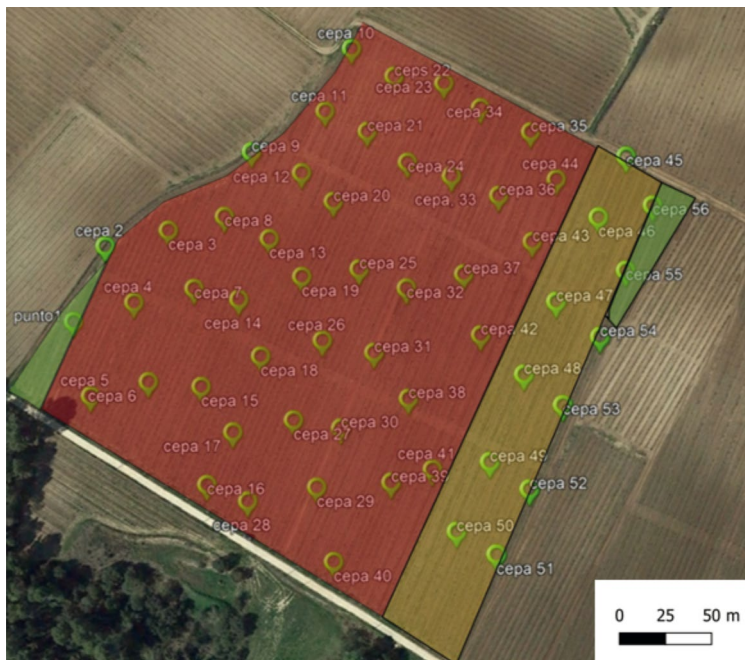


Figure 3. Representation of the treatment areas. Control (green), VRA (red) and conventional (yellow). Geolocation for the 56 sampled vines is represented as green pin in the map.

Table 1. Main working conditions during the field applications for the reference conventional spray mode (CON) and the VRA technology (VRA).

Parameter	Year 2023				Year 2024			
	June		July		June		July	
	CON	VRA	CON	VRA	CON	VRA	CON	VRA
Remote sensor	–	Drone	–	Drone	–	Satellite	–	Satellite
Application rate for low vigor (l/ha)	160	80	160	110	200	100	200	120
Application rate for high vigor (l/ha)	160	110	160	140	200	140	200	160
Forward speed (km/h)	6.0	6.0	6.0	6.0	7.0	7.0	7.0	7.0
Operating pressure (kPa)	600	600	600	600	550	550	550	550
Working width (m)	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6

The working pressure and travel speed were consistent between both methods, according to the working conditions chosen by the farmer himself for the reference treatment. The air flow rate (fan position and width of the individual air outlets) was calibrated according to the volume of the canopy mean, following previous air characterization tests (Vigo-Morancho *et al.*, 2024). Hollow-cone nozzles ISO 02 (ISO, 2018) were used in both years for the two spray modes.

During the two complete seasons, the savings in PPP and water were registered and quantified, comparing them with those obtained with conventional management without variable rate application. Furthermore, once the trials were completed, a biological efficacy evaluation was carried out one week after each of the treatments to check whether the treatments were effective against two usual fungal diseases. The methodology used consisted of sampling the vines that were previously marked following a systematic uniform random sampling scheme that was used for the two seasons. A total of 56 vines were monitored for every biological efficacy assessment that was carried on following the protocol proposed by the EPPO standard PP1/031(3) (EPPO, 2000).

Results and discussion

Product savings

In June 2023, 752 litres of spray liquid were consumed for the conventional treatment, while 448 litres were used for the entire plot with the VRA prototype, resulting in an approximate 40% product savings (Table 2). In July of the same year, 589 litres were applied with the VRA method, achieving a 20% product savings compared to the reference area. Similarly, in June 2024, 984 litres of pesticide were used with the conventional method, while the VRA method consumed 610 litres in June and 734 litres in July, achieving savings comparable to those obtained with the drone-based VRA method. It suggested that satellite imagery, like drone-based approaches, was able to achieve similar levels of product savings, while also contributing to reductions in other factors such as tractor fuel consumption and costs associated with PPP.

Table 2. Main estimated reductions in inputs between the conventional method and the VRA prototype.

Reduction	Year 2023 (drone)		Year 2024 (satellite)	
	June	July	June	July
Applied product (%)	36.7	16.7	37.7	25.1
Total fuel amount (l/100 ha)	32.0		21.3	

Biological efficacy

The biological efficacy against downy mildew was equal between the two treatments in both the 2023 and 2024 seasons. However, it should be noted that in 2023, the infestation level in the control area was very low (approximately 5%), whereas in 2024, up to 50% infestation was detected on leaves and 20% on grape clusters. This difference was due to the severe drought and higher temperatures in 2023, which were unfavourable for fungal diseases. In any case, the farmer had planned a minimum number of preventive treatments in 2023, meaning that product savings would have occurred regardless. In 2024, both spraying methods managed the pest achieving similar levels of infestation in both cases. However, the prototype displayed greater input savings. It is particularly noteworthy that the satellite-based method achieved comparable results to those of the drone-based VRA, demonstrating its effectiveness not only in maintaining pest control but also in optimizing input usage in a cost-efficient and environmentally sustainable manner. Nonetheless, further trials are necessary to explore this in greater depth, including new drone-based treatments under conditions more favourable for fungal development or applications in vineyards with different training systems.

Conclusions

This study compared drone-based prescription maps (2023) and satellite-derived maps (2024) to evaluate a smart sprayer prototype in vineyards. Both approaches achieved similar levels of product savings (up to 40% approximately) and biological efficacy against downy mildew, demonstrating that satellite imagery is a viable alternative to drones for VRA in precision viticulture. The reliability of this comparison is supported by the fact that the vineyard maintained similar vigour patterns across both seasons, as confirmed by NDVI analysis and field observations. Despite minor climatic variations, the spatial distribution of high- and low-vigour zones remained consistent, ensuring that differences in application outcomes were primarily due to the sensing approach rather than vineyard variability.

The experiment also showed that this technology can be effectively used and applied by farmers themselves, as the prototype was operated directly by the collaborating grower during the trials. However, further research is needed to validate its performance under diverse conditions and in vineyards with alternative training systems.

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