37. Second-generation ultrasonic sensor in precision spraying: testing and actuation range refinement

A. Pagliai*, D. Sarri, C. Perna and M. Vieri
University of Florence, Department of Agriculture, Food, Environment and Forestry, Piazzale delle Cascine 15, 50144 Florence, Italy; andrea.pagliai@unifi.it

Abstract

The reduction of pesticide use in agriculture is one of the main goals of the European Union and it can be achieved with new technologies. This work aimed to test in the field a 2nd generation ultrasonic sensor (US), able to directly distinguish foliar layers and density, and to verify its working performance. Field trials were carried out in a vineyard and in different phenological phases. The best correlations were found between the canopy volume and the US Envelope parameter, and between the canopy height and the US Density parameter, R^2 of 0.67 and 0.73 respectively. Therefore, US parameters can estimate canopy characteristics with good reliability and thanks to the actuation-range refinement, this system can be implemented in conventional sprayers, improving their environmental sustainability.

Keywords: proximal sensing, sustainable pesticide management, spray coverage, deposit, viticulture

Introduction

One of the most environmentally impacting factors in crop production is plant-protection product management and distribution. The reduction of pesticides is considered a fundamental process by the European Union, as stated in the 'Farm to Fork' strategy. The European Union addresses, as a viable solution, the application of precision agriculture (PA) techniques. In viticulture, and generally in perennial crops, various planting layouts, different canopy management and shapes can be considered sources of variability. All these aspects must be carefully considered in the management of operations like crop protection (Miranda-Fuentes *et al.*, 2018).

Variable Rate Application (VRA) is a technique capable of taking into account these aspects and, at the same time, reducing the environmental impacts by adjusting, in real-time, the amount of spray distributed based on the volume of canopy that has to be treated (Gil *et al.*, 2013). A sensing system able to detect the canopy is necessary to carry out VRA management. In general, sensors such as ultrasonic sensors (US) or laser scanners (LS), which provide direct measurements of the canopy, are more reliable than sensors that measure the reflectance of visible and infrared light for obtaining three-dimensional characteristics of canopies and therefore for performing real-time VRA (Abbas *et al.*, 2020). In addition, LS performance is significantly weakened in high-light intensity and dusty environments (Rosell and Sanz, 2012). Instead, the robustness and low price of a US make it more suitable for agriculture purposes (Rosell and Sanz, 2012). In recent decades, many authors have used US to assess canopy characteristics, using various sensors to characterise the whole canopy and the time of flight (TOF) as a sensing parameter (1st generation) (Gil *et al.*, 2014; Llorens *et al.*, 2010). However, in recent years, new integrated US capable of managing TOF of different echoes and wavelengths, have been developed (2nd generation). Those sensors can distinguish foliar layer and canopy density. Some studies have shown promising results for real-time canopy characterisation with these new sensors, but linking these results to spray quality and quantity parameters to improve VRA is lacking (Palleja and Landers, 2017).

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The present work aimed to test in-field a second-generation ultrasonic sensor, able to directly determine foliar layers and density, to verify the canopy detection reliability performances of the sensor and to fine tune the spray actuation range.

Materials and methods

Experimental site and design

*Fie*ld trials were carried out in a cordon spur vineyard, located in Castellina in Chianti, Siena, Italy (43°27'39.27'N; 11°13'22.51'E), in the middle of Chianti Classico. The vineyard had a density of 5,000 pl/ha and followed the traditional Tuscan planting layout, with a planting distance of 2.5×0.8 m and a cordon mean height from the ground of 0.8 m. The cultivar was *Vitis vinifera* L. cv. 'Sangiovese'. The experimental site covered around 0.5 ha, where 20 vines were sampled and data were collected at three phenological phases (BBCH 61, BBCH 73, BBCH 81), both for canopy characterisation and for refining the spraying range (Lorenz *et al.,* 1995). Since the vineyard was located on a hillside and showed important vigour variability along the vine row, a completely randomized design was performed with three repetitions. The main characteristics of the trials were reported in Table 1.

Data acquisition for canopy characterisation

For canopy manual measurements, a revised Tree Row Volume (TRW) was adopted: the canopy height (H) and thickness (T) were measured for each sampled vine, and the volume of the canopy (V) was calculated as meter cubic of vegetation per meter of vine row (m^3/m). To ensure good reliability of measurements three repetitions were taken. A second-generation ultrasonic sensor was used for canopy instrumental measurement assessment. The instrumentation (Figure 1) used was a NORAC Ultrasonic sensor (Topcon Positioning Group, Tokyo, Japan). The sensor features a 1 mm resolution, a measurement range of 0.15 m to 10 m, a maximum acquisition frequency of 30 Hz, and it generated 50 kHz ultrasound waves. The sensor was integrated with a microprocessor capable of performing all computations onboard, i.e. selecting the range of interest (ROI) and outputting the final values in a .csv file (comma-separated values). This sensor was able to measure the number of echoes and their intensity in a pre-selected ROI and it provided three simplified values of readings (Edges, Envelope and Density). Considering the canopy layout in the involved vineyard, the ROI was set at 1 m and the relative ultrasonic cone diameter was around 0.50 m.

Table 1. Main characteristics of trials and spray volumes applied.

Trials	Phenological phase (BBCH)	Tree row volume (m^3/pl) ± sd	Sampled vines	Artificial target per plant and per side	Levels	Application volume (l/ha) ± sd
1°	61	0.258±0.08	20	3	L_1	150±0.5
					L_2	200±0.8
					L_3	175±0.7
2°	73	0.311±0.10	20	4	L_1	200±0.8
					L_2	225±0.8
					L_3	250±0.9
3°	81	0.334±0.10	20	5	L_1	275±1.1
					L_2	250±0.8
					L_3	225±0.4

a) b)

Figure 1. (a) Schematic representation of NORAC ultrasonic sensors (NORAC – Datasheet); (b) Sensors used in the experimentation.

Data acquisition for spray quality and quantity

To perform the calibration of the actuation range, a study of spray distribution for each phenological stage was conducted on the same day of the canopy data acquisition. The profile sampling strategy of the British Standard ISO 22522/2007 was followed. Particularly, both plastic sheets (50×90 mm, SEFAR NITEX) and water-sensitive papers (WSPs, 26×76 mm, Syngenta, Switzerland) were arranged on the canopy on both sides and in various positions, following the plant growth in the three trials (Table 1). To verify the right amount of spray volume in relation to the canopy dimensions, the sampled vines were sprayed at three different application levels in each phenological phase, with an 8 g/l concentrated solution of water and yellow Tartrazine (Andrea Gallo S.r.l., Genova, Italy). To analyse spray distribution reliability, normalized deposit and spray coverage have been taken into account. A well-known spectrophotometer methodology was used to quantify the Tartrazine concentration in plastic sheets (Gil *et al.,* 2007). In particular, Equation 1 was applied to obtain the normalized deposits.

$$d_n = \frac{\left[\dfrac{\dfrac{(A_r - A_b)}{\alpha} \times V_{dil}}{S_{ps}}\right] \times 100}{A_{vol} \times c_{tar}} \qquad (1)$$

where: d_n is the normalized deposit expressed in mg/cm^2; A_r is the absorbance value of the sample; A_b is the absorbance of the blank sample; α is the calibration curve coefficient; V_{dil} is the amount of washing solution; S_{ps} is the area of plastic sheet; A_{vol} is the applied spray volume expressed in l/ha; c_{tar} is the concentration of tartrazine.

Instead, an image analysis technique was used to measure the spray coverage from the WSPs. First of all, the collected WSPs were digitized with a professional scanner at a resolution of 600 dpi. Finally, the WSP images were analysed by the Deposit Scan software to extract the spray coverage values.

Instrumentation

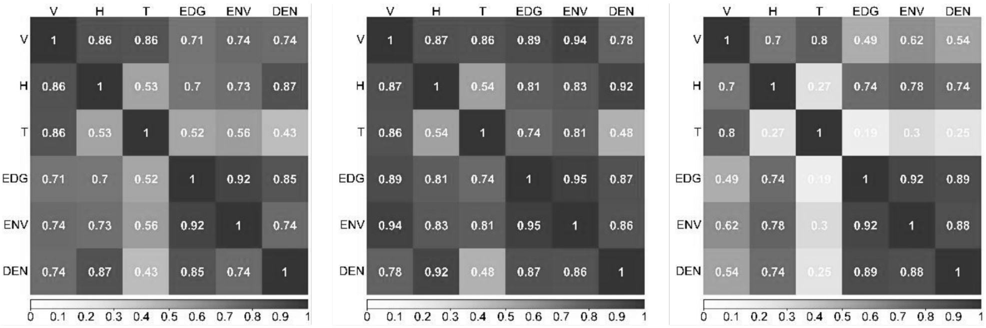
Both the canopy characterisation studies and the spray tests were conducted with the same equipment. A Lamborghini RF90 tractor coupled with a drawn pneumatic sprayer (Martignani M612 Whirlwind, Ravenna, Italy) was used. The main characteristics of the sprayer were: a 1000 l tank, a centrifugal fan capable of generating a homogeneous air flow of about 26,000 m^3/h, a centrifugal pump, and 6 nozzles per side (4 mm) located inside two radial fans. In addition, two US sensors were mounted in the front part of the sprayer and the maximum acquisition frequency (30 Hz) was set in all the canopy characterisation sessions. Both for the instrumental characterisation and the spray tests the tractor speed was set at 1.4 m/s and the sprayer or the sensors sprayed/measured both sides of the vine rows. Before each spray test, the sprayer was accurately calibrated to ensure homogeneous depositions and coverages. During the tests, a weather station was placed inside the vineyard to record the main meteorological parameters (air temperature, air humidity, wind speed and direction).

Data analysis

The statistical analysis and the graphical representation were undertaken with the open-source statistical software R under an RStudio environment. All the variables were analysed to ensure the reliability and robustness of the linear model assumption. The normal distribution of errors and the respect of homoscedasticity were inspected using the Shapiro-Wilk test (*P*<0.05) and Levene's test, respectively. The coefficient of determination (R^2) was used to evaluate the model's goodness and reliability. R-software native functions, the 'corrplot' package and the 'ggplot' package were used to check the assumptions of the linear model, to visualize the R^2 matrix and to show the linear correlations with scatters-plots, respectively (Wickham, 2016).

Results and discussion

In Figure 2, the three correlation matrices for each phenological phase are shown. The matrices concern the canopy manual measurements (V, H, T) and the canopy instrumental characterizations (Edges – EDG, Envelope – ENV, Density – DEN). The second trial showed the highest values of R^2 between different combinations. Instead, the R^2 values of the third trial revealed the lowest performance in terms of correlation. Between the second and the third trial, a vertical and horizontal topping was carried out by the wine farm. Palleja and Landers (2017) highlighted that there is a correlation between manual measurements and envelope signal of the US but it is not constant and it could differ for many reasons, for instance the canopy management. On the basis of the BBCH 81 matrix, the canopy management (topping) could have affected the canopy measurements in the last trial. A common trend showed in the matrices was that the lowest R^2 values are shown between the canopy thickness and the US readings (EDG, ENV and DEN). Instead, the highest R^2 values are disclosed between canopy volume and the instrumental measurements, except for the last trial where the canopy height highlighted the highest values. However, the highest R^2 was observed between the canopy height and the US Density in the first trial (R^2=0.87), between the canopy volume and the US Envelope in the second trial (R^2=0.94), and between the canopy height and the US Envelope in the last trial (R^2=0.78).



	V	H	T	EDG	ENV	DEN
V	1	0.86	0.86	0.71	0.74	0.74
H	0.86	1	0.53	0.7	0.73	0.87
T	0.86	0.53	1	0.52	0.56	0.43
EDG	0.71	0.7	0.52	1	0.92	0.85
ENV	0.74	0.73	0.56	0.92	1	0.74
DEN	0.74	0.87	0.43	0.85	0.74	1

BBCH 61

	V	H	T	EDG	ENV	DEN
V	1	0.87	0.86	0.89	0.94	0.78
H	0.87	1	0.54	0.81	0.83	0.92
T	0.86	0.54	1	0.74	0.81	0.48
EDG	0.89	0.81	0.74	1	0.95	0.87
ENV	0.94	0.83	0.81	0.95	1	0.86
DEN	0.78	0.92	0.48	0.87	0.86	1

BBCH 73

	V	H	T	EDG	ENV	DEN
V	1	0.7	0.8	0.49	0.62	0.54
H	0.7	1	0.27	0.74	0.78	0.74
T	0.8	0.27	1	0.19	0.3	0.25
EDG	0.49	0.74	0.19	1	0.92	0.89
ENV	0.62	0.78	0.3	0.92	1	0.88
DEN	0.54	0.74	0.25	0.89	0.88	1

BBCH 81

Figure 2. R^2 matrix for all the involved canopy measurements. V, H and T represent canopy volume, height and thickness. EDG, ENV and DEN represent edges, envelope and density of US variables.

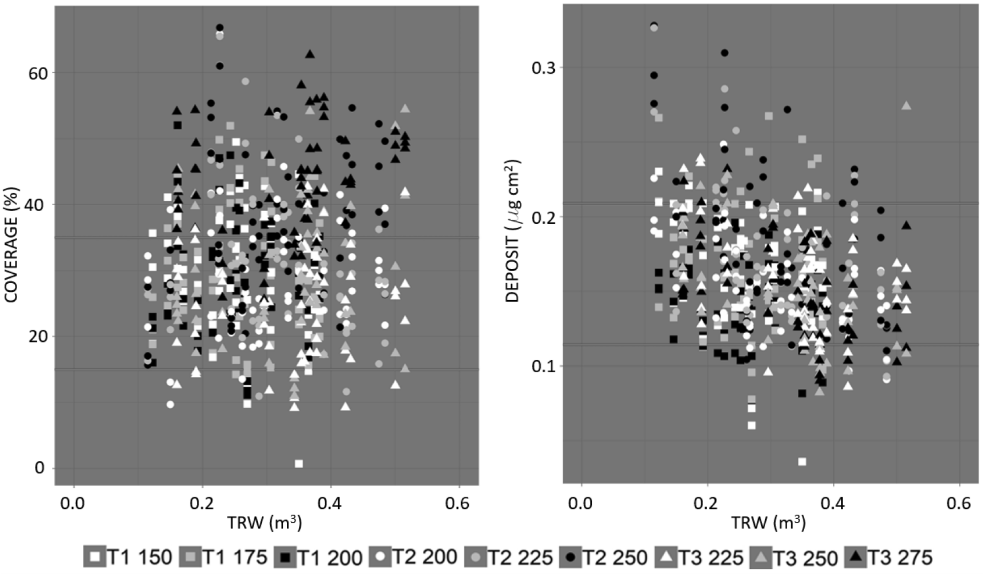
In Table 2, the linear relation of aggregated data (BBCH 61, BBCH 73, BBCH 81) were reported for all the involved measurements. Generally, a common decrease in the goodness of R^2 is shown in Table 2. The maximum achieved R^2 is 0.75, while in the previous matrices was 0.94. In particular, a significant decrease in goodness was disclosed between the canopy thickness and the US measurements, in which the maximum value of R^2 was 0.57 (T vs DEN). This is due to the values recorded in the last trial (BBCH 81). In fact, they showed the worst R^2 and they impacted on the correlation coefficients showed in Table 2. The maximum values of R^2 were shown between the canopy height and all the involved US measurements. In particular, the R^2 were 0.74, 0.75 and 0.73 between the H variable and EDG, ENV, and DEN respectively. Llorens *et al.,* (2010) showed the best R^2 between US parameters and canopy height (around 0.55) than the other manual canopy measurements. This trend is reported also in the present work, as shown in Table 2.

In Figure 3, the scatter plots between canopy volume (TRW) and spray parameters (spray coverage and normalized deposits) are shown. In particular, the points are represented in different shapes and colours depending on trials and applied volume levels. The horizontal lines represent the thresholds for filtering spray data in order to maximize the efficacy and minimize the over and under-spraying and the over and under-dosing of application (Grella *et al.,* 2022; Miranda-Fuentes *et al.,* 2016). In general, the spray coverage data exceeded significantly the thresholds related to the normalized deposits, especially for the highest applied volume (black triangle and black circle). In fact, the spray deposits are more concentrated in the region of interest. This is probably due to the type of analysis. Spray coverage values were extracted by WSPs. They are artificial targets very susceptible to external interference, such as the dislocation of collectors in the spraying moment or in general weather conditions (wind direction and intensity) (Grella *et al.,* 2022). Instead, the deposit values are more stable to external interferences and this is the reason many authors used this parameter than the spray coverage (Gil *et al.,* 2007; Llorens *et al.,* 2010; Miranda-Fuentes *et al.,* 2016). However, in the present work, both methods were presented and disclosed in order to provide a deeper analysis. The data showed in Figure 3 were used to refine the actuation range after filtering them according to the set thresholds. The filtered data was then portioned into ten subsets according to the canopy volume. This portioning has been necessary to create small datasets of homogeneous and representative vines regarding the canopy volume. Subsequently, the modal values of applied volume for each dataset were collected and plotted to build the actuation range. Finally, the equations of regression between the canopy volume and all the US parameters (EDG, ENV, DEN) were used to create and refine the actuation range for the US sensor. The actuation ranges, build according to

Table 2. Linear relation between all the involved canopy measurements for aggregated data.[1]

Sources	DF	p>(F)	Significance[a]	R^2	Equation
EDG ~ V	59	4.7E-13	***	0.59	y = 5.37x + 2.02
ENV ~ V	59	7.6E-16	***	0.67	y = 809.37x + 92.41
DEN ~ V	59	1.5E-11	***	0.54	y = 4355.1x + 3306.3
EDG ~ H	59	2.2E-16	***	0.74	y = 3.54x + 0.66
ENV ~ H	59	2.2E-16	***	0.75	y = 505.07x – 87.06
DEN ~ H	59	2.2E-12	***	0.73	y = 2994.1x + 2094.6
EDG ~ T	59	2.3E-09	***	0.46	y = 7.36x + 1.18
ENV ~ T	59	6.4E-09	***	0.44	y = 1020.87x – 3.14
DEN ~ T	59	2.7E-12	***	0.57	y = 6953.6x + 2268.9

[1] Statistical significance level: NS $P>0.05$; * $P<0.05$; ** $P<0.01$; *** $P<0.001$.



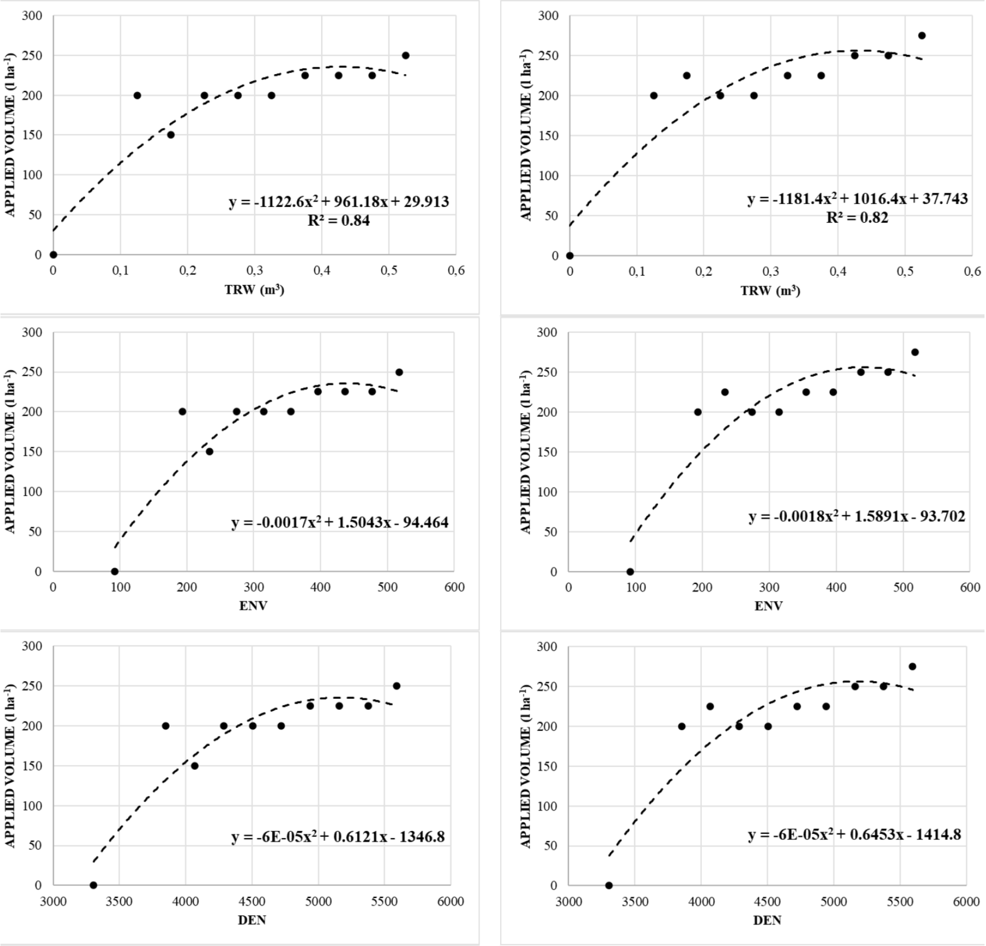
a) b)

Figure 3. (a) Scatter plot between spray coverage and canopy volume. (b) Scatter plot between normalized deposit and canopy volume. Different shape of points represent different trials and different colour represent different applied volumes.

spray coverage and normalized deposits, for the TRW and for the more reliable US measurements are shown in Figure 4.

Conclusions

The second-generation US sensor tested in this study opens new frontiers in precision spraying in terms of increasing environmental sustainability. In particular, concerning canopy detection reliability, the ultrasonic sensor showed good reliability in estimating canopy characteristics. Indeed, interesting correlations were found, especially between the canopy height and the US Envelope and Density parameters (R^2=0.94 and 0.92). On the basis of these results, two actuation ranges were reported according to the normalized deposit and spray coverage parameters. Thanks to them, it was possible to refine the spray volume application in compliance with good spraying thresholds. Moreover, thanks to these actuation ranges, this US sensor can be mounted in a sprayer, enabling the variable-rate application so as to improve the environmental footprint and meet European goals.



a) b)

Figure 4. Actuation ranges for the TRW and for the US measurements. (a) on the left, according to spray coverage; (b) on the right, according to normalized deposits.

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