Enhancing precision agriculture with cosmic-ray neutron sensing: monitoring soil moisture dynamics and its impact on grapevine physiology

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Abstract.

Cosmic-ray neutron sensing (CRNS) has emerged as a reliable tool for continuous, non-invasive soil moisture (SM) estimation across large areas and soil depths, aiding irrigation strategies. However, challenges like data interpretation and integration persist. This study examines CRNS's efficacy in monitoring SM and its impact on grapevine physiology. The study was conducted in a vineyard (Vitis vinifera L.) located at Imola (Bologna, Italy) within an area of approximately 12 ha and with two local grape varieties, Pignoletto (PG) and Trebbiano romagnolo (TR). The vineyard's irrigation system is a subsurface drip irrigation (SDI) located at 25 cm depth. A CRNS probe was installed and calibrated together with a static point-scale SM sensor for comparison. In addition, three campaigns with a portable point-scale sensor to assess SM spatial variability were carried out. Based on that, different SM zones have been identified and further investigated. Consequently, 80 vines were selected, equally proportioned between the two grape varieties, and considering the SM zones. Out of those vines, midday stem water potential (ψ_{stem}) was evaluated taking into account the irrigation management and grape ripening stage. After veraison, berry samples were analyzed, assessing the evolution of total soluble solids, pH, and titratable acidity. Empirical evidence confirms CRNS's effectiveness in detecting SM changes up to 25 cm deep from sub-surface irrigation. It correlates well with the point-scale sensor, reflecting SM dynamics accurately throughout the irrigation events. Variations within grape cultivars and moisture zones were discerned through grapevine physiological assessments. Despite the spatial variability observed, the results concerning vine water status and grape berries composition exhibited scarce variations. While highlighting CRNS's potential for water management support, this study underscores the need for integrated approaches in assessing spatial variability and tailoring irrigation strategies, particularly in extensive vineyards, considering vine physiological responses.

Keywords.
Soil Moisture, CRNS, Grapevine Physiology, Irrigation, VPD

Introduction

In the Mediterranean basin, optimizing water resources has become paramount nowadays, highlighting the central importance of precision agriculture and irrigation management. Besides, precision agriculture has emerged as a transformative approach in modern viticulture, seeking to optimize vineyard management. Vineyard operations depend significantly on effective water management, particularly in regions where water availability can notably impact grape quality and yield. In this scenario, soil moisture (SM), which is usually expressed as volumetric soil water content - SWC_v (m^3 m^{-3}), is a crucial variable in the soil-plant-atmosphere continuum, influencing not only the evapotranspiration process but also being strictly correlated with vine stress and growth (Pellegrino et al., 2005; Seneviratne et al., 2010). The co-occurrence of low SM and high vapor pressure deficits (VPDs) may trigger reductions in vegetation productivity driven by drought and heat (Zhou et al., 2019), a scenario particularly critical during the grapes ripening period. Despite grapevine is considered to be highly adaptable to water restrictions (Lovisolo et al., 2010), the growing season rainfall might be not sufficient to sustain the production, and grapevines are more often grown with supplemental irrigation. Moreover, providing irrigation during ripening has been proposed as an adaptation strategy to extreme conditions due to climate change (Allegro et al., 2023).Given this, the continuous and accurate monitoring of SM becomes essential for preventing water stress condition and programming irrigation. Numerous methods for assessing SM, ranging from point-scale, proximal-scale, to satellite remote sensing approaches have been devised (Susha Lekshmi et al., 2014). Ultimately, research interest is focused on the development and application of non-invasive proximal SM sensors based on cosmic-ray neutron sensing (CRNS). This approach relies on the inverse correlation between neutrons generated by cosmic-ray fluxes and the existence of hydrogen, primarily present in the soil as in the water molecule. Consequently, in soils with low water content, more neutrons are reflected, signifying lower soil water levels. Conversely, moist soil decelerates and absorbs neutrons, resulting in a reduction in the intensity of detected neutrons (Zreda et al., 2008). CRNS probes are installed above the soil surface allowing non-invasive moisture measurements, with a penetration depth ranging from 10 cm to 40 cm and a radius of influence ranging from 100 m to 200 m (Schrön et al., 2017).
Recent advancements in sensor implementation have enabled the utilization of CRNS probes to monitor SM fluctuations in agricultural fields, particularly in response to irrigation interventions (Brogi et al., 2023; Gianessi et al., 2024). However, the ongoing debate surrounding the use of CRNS for precision irrigation continues to captivate attention, with studies on the topic remaining limited (Li et al., 2019).
Given the circumstances, this study endeavors to investigate the potential of CRNS in monitoring SM dynamics in response to precipitation and irrigation events across a large vineyard area. The distinctive feature of the irrigation system in the vineyard involves the utilization of a subsurface drip irrigation system (SDI), representing a novel application within the realm of CRNS. Additionally, other SM sensors were assessed for comparative analysis and for delineating spatial variability within the designated area. Ultimately, the physiological responses of the vines were assessed to ascertain whether SM could indeed impact vine water status and berry composition.

Materials and methods

Site overview and instruments

The vineyard (*Vitis vinifera* L. cv Trebbiano romagnolo and cv Pignoletto) is located in the Emilia-Romagna region, in the northeast of Italy, covering an approximate area of 12 hectares (Fig 1). The vines were oriented northeast to southwest, trained to a vertical shoot positioned spur-pruned cordon, and spaced at 1 m within the row and 2.5 m between rows. Soil samples were collected to analyze the Particle Size Distribution (PSD) and determine the soil texture using a PARIO instrument from METER Group (Pullman, WA, USA). Accordingly, the site is classified as silty clay.

A private company named Società Agricola CACI, based at Imola, Bologna, oversees the vineyard irrigation strategy employing a subsurface drip irrigation (SDI) system across four irrigation sectors (Fig 1.a).

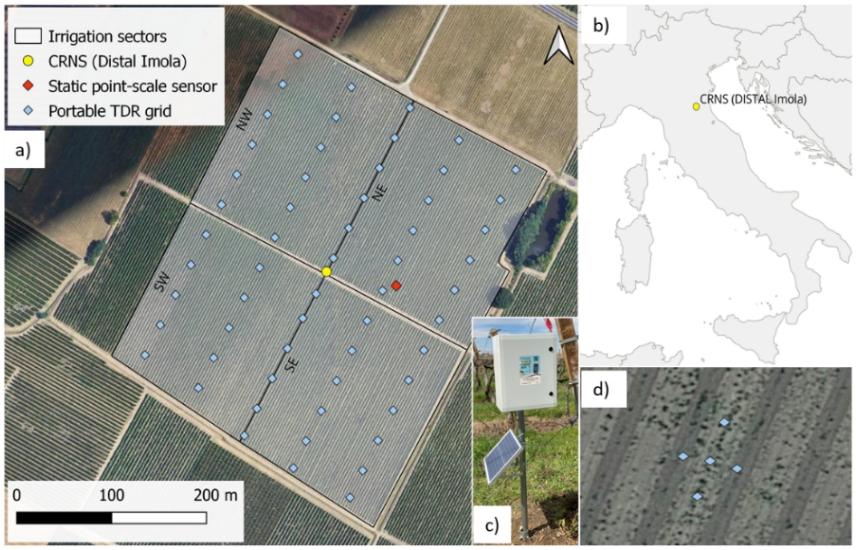

Fig 1. a) The experimental vineyard of approx. 12 ha, features a CRNS sensor from Finapp; denoted by red diamond, the static point-scale sensor from METER Group; in light blue diamonds the portable TDR grid taken into account for mobile SWC data acquisition; irrigation sectors boundaries are highlighted in black, named following the geographical coordinates as NW, NE, SW and SE, respectively. b) Map view of Italy and location of the CRNS sensor marked in yellow. c) A close-up view showcases the installation of the Finapp CRNS sensor within the vineyard. d) Detail of the scheme for mobile SWC acquisition at each location depicted at a).

The SDI system is installed at a depth of 25 cm along two lines parallel to each row of plants, approximately 50 cm away from the vines, and drip system has a water capacity of 8 l/h. Irrigation events and total volume distributed (mm d^{-1}) during the season, together with grape phenological phase (BBCH) are resumed in Table 1.

Table 1. Day of the year (DOY) of the irrigation events and respective phenological phase (BBCH) for the 2023 season.

Irrigation event (DOY)	Total volume distributed (mm d^{-1})	Grapes phenological phase (BBCH)
205	20.00	77
212	18.00	79
222	16.00	83
229	18.00	85
240	16.00	89
259	16.00	89

Precipitation data, as well as average daily temperature and relative humidity data for vapour pressure deficit VPDs calculation, were taken from the network of the Emilia-Romagna region environmental agency ARPAe (https://dati.arpae.it/dataset/erg5-interpolazione-su-griglia-di-dati-meteo). The data is obtained through spatial interpolation on a regular grid starting from the values detected by the network of meteorological stations, according to Antolini et al. (2016). The closest grid to the site was selected for the study.

Field capacity (FC) and wilting point (WP) of the site were determined using prediction algorithms (pedotransfer function PTFs) elaborated through the Web interface for European hydraulic pedotransfer functions (https://doi.org/10.34977/euptfv2.01), according to Szabó et al. (2021).

Point-scale SM sensors: static and mobile measurements

Point-scale soil moisture sensors from METER Group (Pullman, WA, USA) have been positioned below ground at two different depths (5 and 30 cm), being positioned above and below the irrigation tube for monitoring and compare the SWC_v dynamics to the CRNS sensor (Fig 1.a). Additionally, three campaigns were conducted using a portable TDR sensor from Spectrum Technologies, Inc. (Aurora, IL, USA). Measurements were conducted in DOY 128 and 158 (BBCH 53 and 57 respectively) to enhance understanding of the spatial variability of soil volumetric water content (SWC_v) across the vineyard. An additional acquisition was performed at the conclusion of the harvest season (DOY 296) to verify the consistency of observed trends. The sensor enabled mobile, point-scale, repetitive acquisitions of SWC_v (%), with a vertical spatial resolution of 15 cm depth. The acquisition scheme using the portable TDR device is depicted in Fig 1.a) and 1.d). The data were subsequently processed using QGIS software and interpolated through the Inverse Distance Weighting (IDW) method (distance coefficient P = 2.00) for visual representation.

CRNS sensor installation and calibration

The CRNS probe, manufactured by the Italian company Finapp S.r.l (Montegrotto Terme, Padova, Italy), was installed in April 2023 (Fig 1.c). Neutrons measured by the CRNS sensor were corrected to account for changing in air pressure, air humidity and incoming neutron variability following common approaches suggested in literature (Bogena et al., 2022a; Zreda et al., 2012). Calibration took place on DOY 128, which allowed to convert neutron counts into SWC based on the following equation (Desilets et al., 2010):

$$SWC_v(Nc) = \left(\frac{0.0808}{\frac{Nc}{N_0}-0.372} - 0.115 - SWC_{offset}\right) \cdot \frac{\rho_{bd}}{\rho_w} \quad \text{Eq.1}$$

where ρ_{bd} and ρ_w are respectively the soil bulk density and water density (kg m^{-3}), SWC_{offset} is the contribution of static hydrogen pools (e.g., lattice water, soil organic carbon), SWC_v (Nc) is the volumetric soil water content average during the calibration day, N_0 is the calibration parameter. Following Schrön et al. (2017), a set of 18 sample locations was established to quantify the average soil moisture content in the footprint area associated with the sensor. The laboratory analyses to determine gravimetric SWC (g g^{-1}), ρ_{bd} (g m^{-3}) and SWC_{offset} followed the procedure of Gianessi et al. (2024).

Vine water status and berry composition

Trial setup and vines selection

Based on the signal contribution and spatial sensitivity of the CRNS sensor (Schrön et al., 2017, 2023), vines were selected accordingly within the trial rows (Fig. 2). Specifically, 20 plants in each sector were chosen for further evaluation throughout the season, resulting in 40 plants per grapevine variety and 80 in total. The vine water status was assessed on three dates (DOY 201, 215, and 222) at solar midday by measuring the stem water potential (ψ_{stem}) with a Scholander pressure chamber (Soilmoisture Corp., Santa Barbara, CA, USA).

For each date, a total of 24 leaves were randomly sampled from 20 vines in each sector. The leaves were covered with aluminum foil and placed in a plastic bag for 90 minutes prior to measurement.

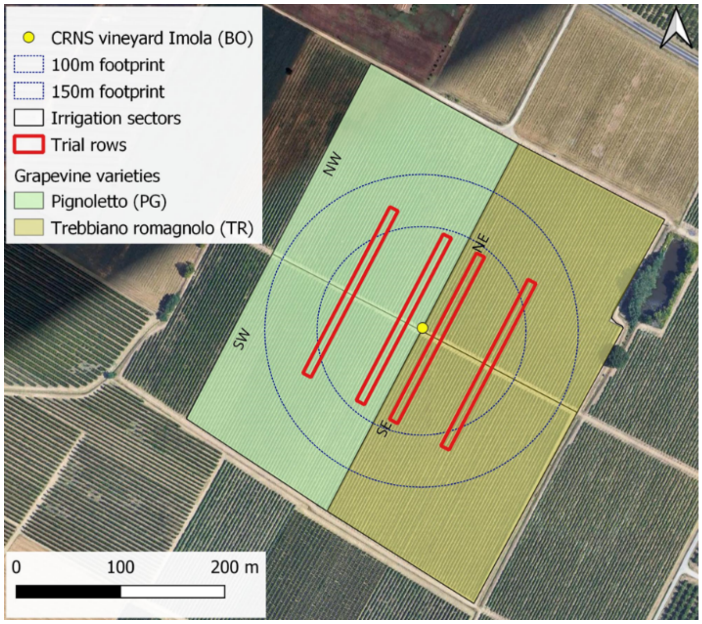

Fig 2. Overview of the theoretical horizontal footprint of the CRNS sensor's sensitivity to soil moisture variations (100 m and 150 m radius from the sensor) and the selection of trial rows, where vines were chosen for physiological assessment throughout the season. The figure also illustrates the vineyard's distribution of grapevine varieties and irrigation sectors.

From each of the 20 selected vines per sector, 50 berries were harvested on three dates before harvest (DOY 222, 234, and 243) and at harvest (DOY 249) for analysis of the following parameters: total soluble solids (°Brix), determined using a self-compensating refractometer (Misure Maselli, Parma, Italy); must pH and titratable acidity (g/l), analysed with a titrator (Crison Instruments, Barcelona, Spain).
A one-way analysis of variance (ANOVA) was conducted to assess vine water status and berry composition, considering the two grape varieties with respect to the irrigation sectors within the vineyard.

Results and discussion

Portable TDR acquisitions

The results of the measurements with the portable TDR are shown in Figure 2. Results from measurements on DOY 128 and 151 exhibited a trend in soil moisture variability, showing a moister gradient to the eastern part of the vineyard, particularly in the SE sector. The average values of SWC_v on these dates are 48,3 % and 42,1 %, respectively. These high values are attributed to the intense rainfall events that characterized the beginning of May in the Emilia-Romagna region (Fig. 3).
Further investigations, particularly concerning the physiological response of the vines, were conducted taking into account the SWC_v spatial variability observed with these measurements. The acquisition on DOY 296 confirmed the observed trend, though with a lower average SWC_v value as expected.

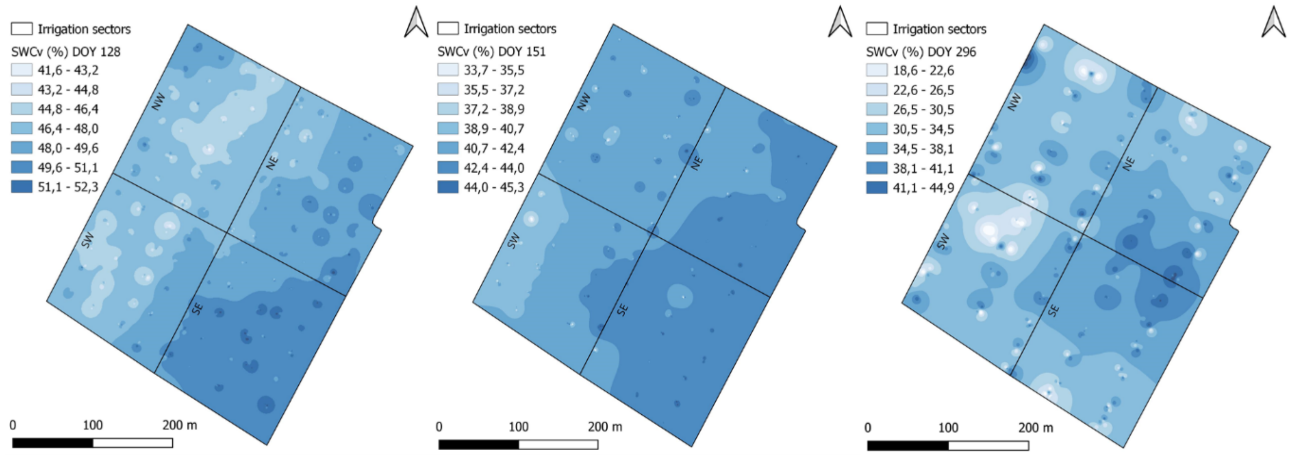

Fig. 2 Maps of the soil volumetric water content (SWC_v %) in three different dates, from left to right (DOY 128, 151, 296). Data from the portable TDR were processed on Qgis software and interpolated through Inverse Distance Weighting (IDW)

CRNS sensor calibration and season overview

Results from the calibration campaign of the CRNS sensor, occurred on DOY 128, are shown in Table 2. These results were used then to implement the Eq. 1 (Desilets et al., 2010) and consequently to transform the neutron data into SWC_v ($m^3\ m^{-3}$).

Table 2. Results of the laboratory analyses for the calibration of the CRNS sensor, following the procedure of Gianessi et al. (2024). SOC and LW, indicating soil organic carbon and lattice water respectively, contributed to the SWC_{offset}; the gravimetric soil water content (SWCg) and weighted gravimetric soil water content (SWCg_wt) were determined based on Schrön et al. (2017); ρ_{bd} is the soil bulk density; the incoming neutron correction factor (Nc) was applied according to Bogena et al. (2022b) and Zreda et al. (2012); the calibration parameter (N_0) was used in Eq. 1 (Desilets et al., 2010).

Calibration date (DOY)	SOC ($g\ g^{-1}$)	LW ($g\ g^{-1}$)	SWCg ($g\ g^{-1}$)	SWCg_wt ($g\ g^{-1}$)	ρ_{bd} ($g\ cm^{-3}$)	Nc (cph)	N_0 (cph)
128	0.028	0.019	0.259	0.256	1.446	673	1240

The seasonal dynamics of SWC_v from the CRNS sensor, as well as daily rainfall and irrigation events, are shown in Fig 3. The SWC_v trends detected with the CRNS sensor were recorded regularly throughout the season. The observed dynamics consistently responded to rainfall events and irrigations. Noteworthy are the substantial rainfall events recorded in May, with total cumulative precipitation amounting to approximately 300 mm, considering that 470 mm of precipitation was registered from March to October. Conversely, during the summer months from June to September, only 60 mm of precipitation was recorded.

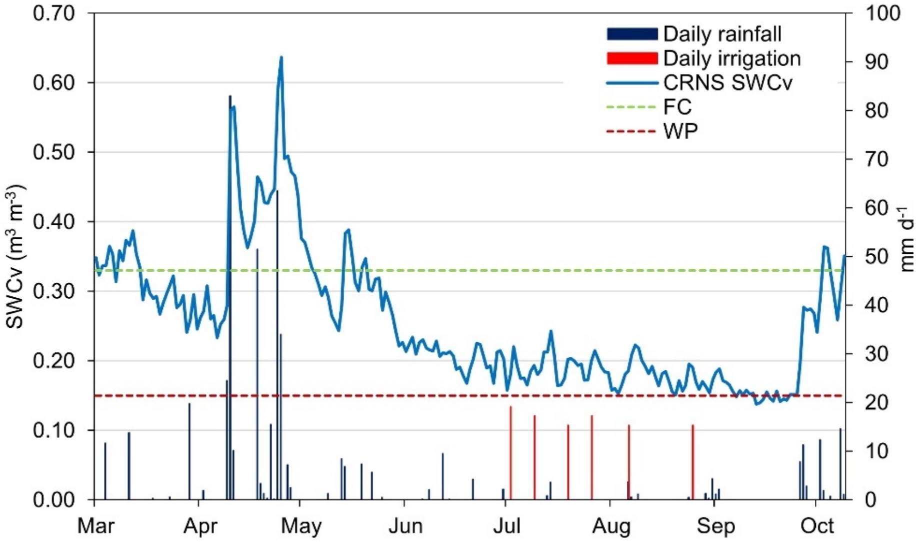

Fig 3. SWC dynamics (CRNS SWCv) throughout the 2023 season (March - October) obtained after the calibration of the CRNS sensor. Daily rainfall and irrigation events are also visible, as well as field capacity (FC) and wilting point (WP).

It is well documented in the literature that the sensitivity of the CRNS can be significantly influenced by soil and moisture heterogeneity, particularly when the footprint under investigation exceeds the field boundaries of interest (Schrön et al., 2023). In such cases, the CRNS readings may be affected by nearby irrigation practices or agronomic features, such as different crops (Baroni et al., 2018). However, under our conditions, the consistency of SWC_v dynamics throughout the season is likely attributable to the theoretical footprint being adequately suited to the area under investigation.

SWC dynamics under irrigation events

Fig 4 highlights the irrigation events, showing the SWC_v from the CRNS sensor (Fig 4.a) and point-scale sensor signals (Fig 4.b). Additionally, VPDs were considered (Fig 4.c) to provide a better understanding of atmospheric conditions.

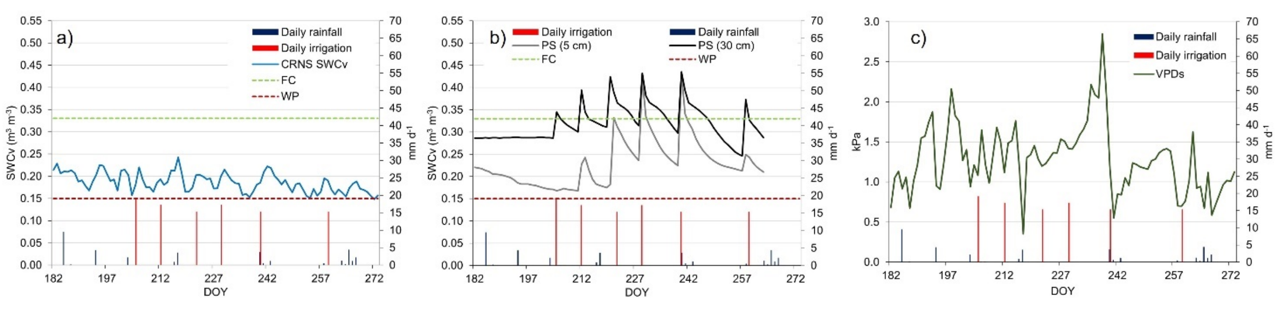

Fig 4. a) SWC_v registered with the CRNS sensor; b) SWC_v registered with the static point-scale sensor at two different depths (PS 5cm) and (PS 30cm); c) daily VPDs evolution throughout the irrigation season. All data pertain to the months between July and September in the 2023 season, from DOY 182 to DOY 272.

The SWC_v dynamics recorded by the CRNS sensor demonstrated promising results in detecting irrigation events (Fig. 4.a). The sensor accurately identified each irrigation occurrence, showing an increase in SWC_v following irrigated days. These initial findings contrast with previous literature (Brogi et al., 2023; Li et al., 2019), indicating that under these conditions, the CRNS sensor is a reliable tool for monitoring and capturing the magnitude of irrigation events even when small amount of water is distributed.

Notably, regarding the peculiarity of the SDI system, these results highlight the CRNS sensor's empirical evidence of vertical spatial sensitivity, effectively detecting SWC_v variations in depth, given that the irrigation tubes are situated 25 cm below ground. These evidences are further confirmed from the point-scale SWC_v dynamics (Fig 4.b). In this case is also visible how for most of the irrigations the SWC_v registered increased accordingly at both depths of 5 and 30 cm, respectively above and below the irrigation tube. However, it is noticeable how the responses of both point-scale sensors (5 cm and 30 cm) were hindered at the beginning of July (from DOY 182 to DOY 205), where the SWC_v dynamics appear unchanging. Moreover, the point-scale (5 cm) sensor showed inconsistent responses for the first two irrigations (DOY 205 and 212). This represents a limitation of the point-scale sensors, as they poorly reproduce the spatial and temporal behavior of SWC_v compared to the CRNS probe. This discrepancy is due to the average water content in the sampling volume and the small-scale structure of soil electrical properties, as discussed in previous literature (Evett et al., 2009). Despite this initial situation, the comparative analysis between point-scale SM sensors and the CRNS sensor revealed consistent dynamics most of the time but different SWC_v values. Specifically, the SWC_v values registered by the point-scale sensors were higher than those from the CRNS probe. This trend is further observable considering the limits of field capacity (FC) and wilting point (WP) (Fig 4.a and 4.b). In the case of point-scale measurements, the SWC_v frequently exceeded the FC, while for the CRNS probe, it is more evident that the irrigation interventions were effective in preventing the SWC_v from reaching the WP. This difference is expected due to the inherent differences in the measurement scales and methodologies of the two sensor types.

This overall situation is further confirmed by the quantitative comparison between the SWC_v registered with the CRNS sensor and with point-scale sensor (5 cm and 30 cm) shown in Table 3. The data were analyzed on a monthly basis, focusing on the months during which irrigation events occurred. Table 3 shows that the correlation between the variables was inconsistent in July and partially in August. However, a noticeable improvement in correlation is observed in September. These first results underscored the importance of integrating different types of sensors to obtain a comprehensive understanding of SWC_v dynamics.

Table 3. Correlation analyses between the SWCv registered with the CRNS sensor and the point-scale sensors (PS 5 cm and 30 cm) are presented. The analyses include the Pearson correlation coefficient (cor) and the unbiased root mean square error (ubRMSE) separated by the three months under investigation.

Variable	July		August		September	
	cor	ubRMSE	cor	ubRMSE	cor	ubRMSE
CRNS/PS (5 cm)	0.354	0.021	0.157	0.065	0.803	0.013
CRNS/PS (30 cm)	-0.204	0.031	0.169	0.147	0.812	0.118

The calculation of VPDs aligned well with the observed SWC_v, particularly on days when irrigation was applied (Fig 4.c). This is especially evident during irrigation events, where a significant decrease in VPDs values was recorded. This observation underscores the effectiveness of irrigation interventions in reducing critical VPDs thresholds. A notable instance of this effect was observed on irrigation event on DOY 240 (Table 1). Prior to irrigation on this day, VPDs values had risen significantly above the critical threshold, indicating potential stress conditions for the plants (Prieto et al., 2010). These findings suggest that timely irrigation can play a crucial role in managing VPDs and, consequently, plant health. These preliminary observations take into account that the VPD calculation was based on weather data interpolated to a larger area than the one under investigation within the vineyard. To obtain a clearer impression of the effectiveness of irrigation, further improvements might be considered.

Vine water status and berry composition

The midday stem water potential (ψ_{stem}) was measured on three different dates to evaluate the water status of the vines (Table 4). The results showed no statistically significant differences between the eastern and western sectors. Throughout the season, irrigation interventions were frequently planned and uniformly applied across the entire vineyard, preventing the vines from experiencing significant water stress. However, on DOY 215, which was three days after the second irrigation (Table 1), the water potential of vines in the SW sector indicated a higher level of initial water stress compared to the NW vines. This observation aligns with the SM maps obtained using the portable point-scale sensor (Fig. 2), which revealed that the SW zone of the vineyard was less moist than other areas. On the other hand, SE vines generally exhibited less stress in all dates in comparison with western sectors.

Another consideration is that the observed trends may also be attributed to the different grape varieties planted in the eastern and western sectors. Therefore, further investigations are required to better assess the physiological responses of the two varieties to changing SWC_v dynamics, particularly in light of the observed SM spatial heterogeneity.

Table 4. Midday stem water potential (ψ_{stem}) taken in three different dates (DOY) in vines of each sector of the vineyard, according also to grape varieties. ANOVA for water potential values within each grapevine variety in eastern and western parts was conducted. Letters indicate significant difference after Tukey's honestly significant difference test.

Grapevine variety	cv Pignoletto		cv Trebbiano romagnolo	
Irrigation sector	NW	SW	NE	SE
(DOY)	(MPa)	(MPa)	(MPa)	(MPa)
201	-0.78a	-0.82a	-0.72a	-0.66a
215	-0.88a	-1.06a	-0.82a	-0.80a
222	-0.74a	-0.80a	-0.72a	-0.66a

Throughout the ripening, evolutions of total soluble solids (°Brix), pH and titratable acidity (g/l) were evaluated, taking into account different varieties in different sectors (Fig 5).

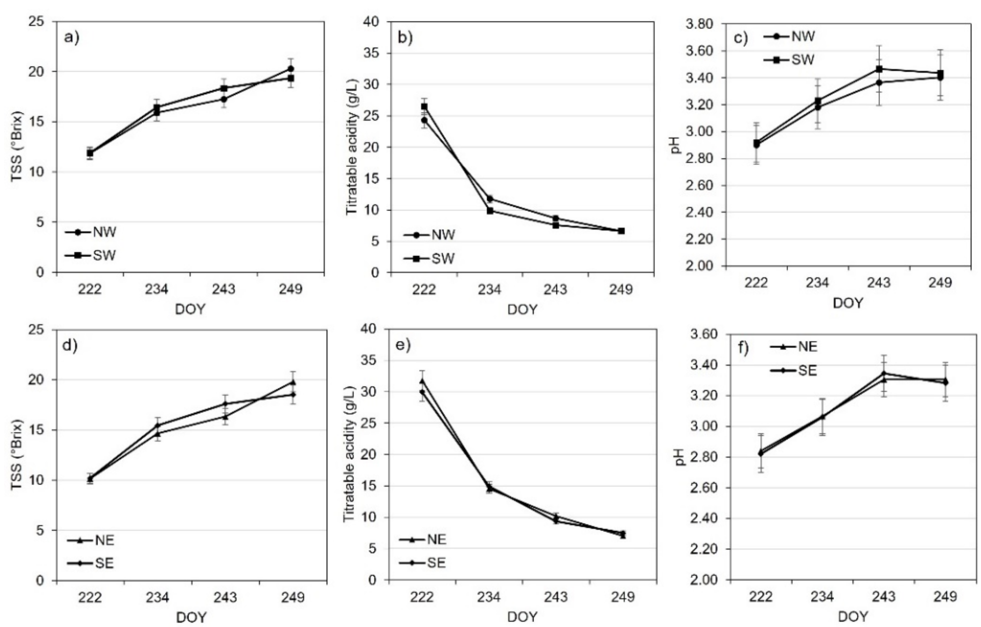

Fig 5. Grape berries evaluation of total soluble solids (°Brix), pH and titratable acidiy (g/l), respectively for Pignoletto (PG) in a), b) and c) and for Trebbiano Romagnolo (TR) in d), e), f), considering the respective irrigation sectors (NW, SW, NE, SE). In the 2023 season, harvest occurred in DOY 249 for both grapevine varieties. Error bars indicate the mean SE.

The results obtained from the analyses of berry composition during ripening indicate no significant differences between the two-irrigation sector of each variety. However, a slight difference in total soluble solids (TSS) was observed at harvest, where the data showed some variability. In contrast, the measurements of titratable acidity (TA) and pH remained consistent across all phases of analysis, including at harvest.
These findings suggest that despite the observed heterogeneous SM dynamics across the vineyard, both grapevine varieties did not exhibit substantial sensitivity to the variations in SWC_v. This outcome can likely be attributed to the frequent irrigation management, which effectively prevented significant water stress in the vines and contributed to a uniform ripening process across the vineyard. Additionally, at harvest (DOY 249), conducted with mechanical harvesting across the entire area, the yield data indicated that Pignoletto vines produced approximately 2.7 t/ha, while Trebbiano Romagnolo ones yielded around 3.4 t/ha.
These yield differences underline the intrinsic productivity variations between the two varieties. However, the effective water management practices ensured that both varieties reached their optimal yield potential without experiencing significant water stress, indicating that irrigation in vineyards is usually applied uniformly without accounting for the vineyards' heterogeneity, making water management decisions challenging (Yu et al., 2020).

Conclusion

In this study innovative and integrated environmental monitoring for precision monitoring for irrigation has been presented. The use of the CRNS technology for continuous monitoring of SWC_v in an extensive vineyard has been addressed, focusing on precipitations and irrigation events. This study also addressed the novel application of CRNS technology with a subsurface drip irrigation (SDI) system. For a more comprehensive understanding of SWCv, point-scale sensors were assessed in both mobile and static applications to evaluate soil moisture spatial variability within the vineyard and to compare with the CRNS signal. Initial results indicated a consistent dynamic of SWCv recorded by the CRNS sensor throughout the season, responsive to both rainfall and irrigation events. Empirical evidence demonstrated the reliability of the CRNS signal in capturing SWCv variations in depth during irrigation events. The static point-scale sensors further confirmed this trend; however, the SWC_v registered was not consistent all along the period investigated. In this regard, the correlation between point scale sensors and CRNS confirmed this trend, and highlighted some limitations of the point-scale measurements. This study also emphasized that the continuous monitoring of VPDs and SWC_v can lead to a better comprehension of the relation between these two variables. The observed variability in SM obtained with the mobile TDR measurements served to distinguish different zones within the vineyard, corresponding to the irrigation sectors and the two grape varieties. Despite this initial variability, we did not observe significant differences in grape maturation or vine water status. This lack of significant differences is likely due to the frequent irrigation interventions during the critical period of grape ripening after veraison. While many of the initial results are encouraging, further investigation into the potential of CRNS for SWC_v monitoring is necessary. Additionally, continued research is needed to establish the best approach for integrating sensors that evaluate the physiological response of plants and that are representative of the area under study. Optimizing irrigation practices requires a comprehensive approach that integrates long-term data collection, advanced monitoring technologies, and decision support systems. By addressing these aspects, future research can significantly contribute to sustainable viticulture practices that maximize water use efficiency while ensuring grape production. Based on these preliminary results, an important question for future research is how to optimize the management of available water resources without incurring excessive water. This raises the need for evaluating the efficiency and effectiveness of current irrigation practices and considering potential improvements.

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