

A DATA-DRIVEN TOOL FOR SITE-SPECIFIC IRRIGATION OPTIMIZATION IN VINEYARDS

UN OUTIL PILOTÉ PAR LES DONNÉES POUR L'OPTIMISATION DE L'IRRIGATION PROPRE À CHAQUE SITE DANS LES VIGNOBLES

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ABSTRACT

Operational Group PRERIVID is focused on the development of an advanced decision-support tool for irrigation management aimed at estimating vineyard water requirements with a prediction horizon of up to seven days (Bellvert *et al.*, 2021). The main objective was to integrate continuous field monitoring with short-term predictive modelling in order to improve the accuracy of irrigation scheduling under variable soil and climatic conditions, particularly in scenarios characterized by increasing water scarcity and climatic uncertainty (Kang *et al.*, 2023).

To achieve this, commercial vineyard plots were instrumented with a network of soil moisture and electrical conductivity sensors installed at multiple depths within the soil profile.

A central methodological component of the project was the systematic comparison between continuous sensor-based measurements and soil water content values obtained using Time Domain Reflectometry (TDR) techniques. TDR measurements were performed periodically as a reference method to validate and calibrate the permanently installed sensors. This comparative approach enabled the identification of sensor bias, potential signal drift, and site-specific calibration factors related to soil texture, bulk density, salinity, and electrical conductivity. By refining the relationship between sensor outputs and actual volumetric water content, the overall accuracy, consistency, and robustness of the monitoring system were significantly enhanced across different vineyard sites and soil conditions.

The results demonstrated a strong agreement between TDR measurements and the calibrated sensor network, confirming the reliability of the monitoring framework for operational use in vineyard management. The application of the PRERIVID methodology led to measurable improvements in water use efficiency and provided greater control over vine water status throughout the growing season. Furthermore, the optimized irrigation regimes contributed to maintaining grape yield and quality under conditions of increasing climatic variability, while also supporting the long-term sustainability of water resources at the farm and regional scales.

Keywords: Water scarcity; Climatic uncertainty; Commercial vineyard plots; Soil texture; Monitoring framework.

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RÉSUMÉ

Le groupe opérationnel PRERIVID se consacre au développement d'un outil avancé d'aide à la décision pour la gestion de l'irrigation, destiné à estimer les besoins en eau des vignobles avec un horizon prévisionnel allant jusqu'à sept jours (Bellvert et al., 2021). L'objectif principal était d'intégrer le suivi continu sur le terrain et la modélisation prédictive à court terme afin d'améliorer la précision de la programmation de l'irrigation dans des conditions pédologiques et climatiques variables, en particulier dans les situations caractérisées par une pénurie d'eau croissante et une incertitude climatique accrue (Kang et al., 2023).

À cette fin, des parcelles viticoles commerciales ont été équipées d'un réseau de capteurs d'humidité du sol et de conductivité électrique installés à plusieurs profondeurs dans le profil pédologique.

Une composante méthodologique centrale du projet consistait à comparer systématiquement les mesures continues fournies par les capteurs aux valeurs de teneur en eau du sol obtenues par réflectométrie dans le domaine temporel (TDR). Des mesures TDR ont été réalisées périodiquement comme méthode de référence afin de valider et d'étalonner les capteurs installés en permanence. Cette démarche comparative a permis de détecter les biais des capteurs et une éventuelle dérive du signal, ainsi que de déterminer des facteurs d'étalonnage propres au site liés à la texture du sol, à la densité apparente, à la salinité et à la conductivité électrique. L'affinement de la relation entre les signaux des capteurs et la teneur volumique réelle en eau a sensiblement amélioré la précision, la cohérence et la robustesse globales du système de suivi dans les différents vignobles et sous diverses conditions pédologiques.

Les résultats ont montré une forte concordance entre les mesures TDR et le réseau de capteurs étalonné, confirmant la fiabilité du dispositif de suivi pour une utilisation opérationnelle dans la gestion des vignobles. L'application de la méthodologie PRERIVID a entraîné des améliorations mesurables de l'efficacité de l'utilisation de l'eau et permis un meilleur contrôle de l'état hydrique de la vigne tout au long de la saison de croissance. En outre, les régimes d'irrigation optimisés ont contribué à maintenir le rendement et la qualité des raisins dans un contexte de variabilité climatique croissante, tout en favorisant la durabilité à long terme des ressources en eau à l'échelle de l'exploitation et de la région.

Mots clés : Pénurie d'eau croissante; Incertitude climatique; Parcelles viticoles commerciales; Texture du sol; Dispositif de suivi.

INTRODUCTION

In recent decades, viticulture has been increasingly challenged by the impacts of climate change, variability in water availability, and the growing need to enhance the sustainability of agricultural systems. Rising temperatures, irregular precipitation patterns, and more frequent drought events are significantly affecting vineyard water balance, compromising both grape yield and quality. In this context, efficient irrigation management has become a critical factor in ensuring the economic and environmental viability of the wine sector (Finco et al., 2020).

Traditionally, irrigation decisions have often relied on grower's experience or on limited field observations, which can lead to suboptimal water application. However, advances in monitoring technologies and modelling approaches have created new opportunities to implement more precise and adaptive irrigation strategies (Pero et al., 2023). Precision viticulture has emerged as an innovative framework that integrates sensors, real-time data, and predictive models to optimize water use and improve agronomic decision-making.

Within this framework, the development of decision-support tools, such as those proposed in the PRERIVID Operational Group, represents a significant advancement. These tools enable the estimation of vineyard water requirements several days in advance by combining data from soil sensors, weather stations, and plant water status measurements. This integration allows for a more

comprehensive understanding of the soil-plant-atmosphere continuum, facilitating irrigation strategies that are better aligned with both current and anticipated conditions (Sun *et al.*, 2023).

Furthermore, the incorporation of validation and calibration techniques, such as Time Domain Reflectometry (TDR), enhances the reliability of monitoring systems, ensuring that irrigation decisions are based on accurate and representative data. This is particularly important in heterogeneous environments, where soil properties and microclimatic conditions may vary significantly within the same vineyard (Santesteban *et al.*, 2013).

The use of short-term predictive models makes it possible to anticipate crop water needs, optimizing both the timing and volume of irrigation applications. This approach not only contributes to reducing water consumption and associated costs but also minimizes agronomic risks such as excessive water stress or nutrient leaching, which can negatively affect vine development and grape composition.

Overall, the integration of monitoring, validation, and predictive technologies provides a robust foundation for advancing efficient, sustainable, and resilient irrigation systems in viticulture. In a context defined by climatic uncertainty and increasing pressure on water resources, these tools play a key role in modernizing vineyard management and supporting the long-term adaptation of viticultural systems (Silvestri *et al.*, 2025).

MATERIAL AND METHODS

The analysis focused on three commercial vineyard plots located in different wine-producing regions: Quinta de Couselo, Quinta Sardonia and Bodegas Engera, selected to represent diverse soil, climatic and management conditions.

- Quinta de Couselo plot:

The study is a commercial vineyard belonging to Quinta de Couselo winery, located within the Rías Baixas Denomination of Origin (41°56'09.4"N, 8°49'10.3"W, O Rosal, Pontevedra). The vineyard covers approximately 2 ha, is trained on pergola systems and planted with the white grape variety cv.'Caiño Blanco'.

Within the experimental vineyard, three different treatments were established (Quinta de Couselo irrigation – moderate cover crop, PRERIVID irrigation – intensive cover crop and PRERIVID irrigation – moderate cover crop). These treatments covered four rows of pergola-trained vines, with two replicates. Each replicate included two blocks (A and B), arranged perpendicular to the vineyard rows.

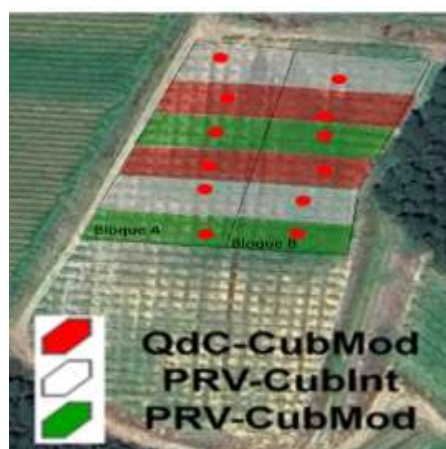


Figure 1. Experimental design of treatment blocks in the Quinta de Couselo plot.

The plot is equipped with a localized irrigation system using 8 L/h emitters connected to distributors, from which four irrigation tubes extend towards the base of each plant. In this way, each tube delivers an approximate flow rate of 2.3 L/h per plant, ensuring a uniform and controlled water supply directly to the root zone.

A total of six Teros 12 sensors were installed in the vineyard, distributed across three locations corresponding to the defined treatments. Two sensors were installed at each location, at two different depths (20 and 50 cm), allowing the measurement of volumetric soil water content, apparent soil electrical conductivity and temperature (Figure 1).

- Quinta Sardonía plot:

The study was conducted in a commercial vineyard belonging to Quinta Sardonía winery, located in Sardón del Duero (Valladolid) (41°62'N, 4°46'W), within a plot of approximately 1.3 ha. The vineyard is planted with the red grape variety cv. 'Tempranillo', trained on a vertical trellis system, with a planting spacing of 2.5 × 1.2 m.

In the experimental vineyard, four different treatments were applied (rainfed tillage – SL, rainfed alternate cover crop – SA, irrigated tillage – RL, and irrigated alternate cover crop – RA), with four replicates for each treatment. Each experimental unit consisted of four rows with ten vines per row, resulting in a block design arranged in a north–south direction, coinciding with the trellis rows. This design was based on a prior soil study of the vineyard, as shown in the Figure 2.

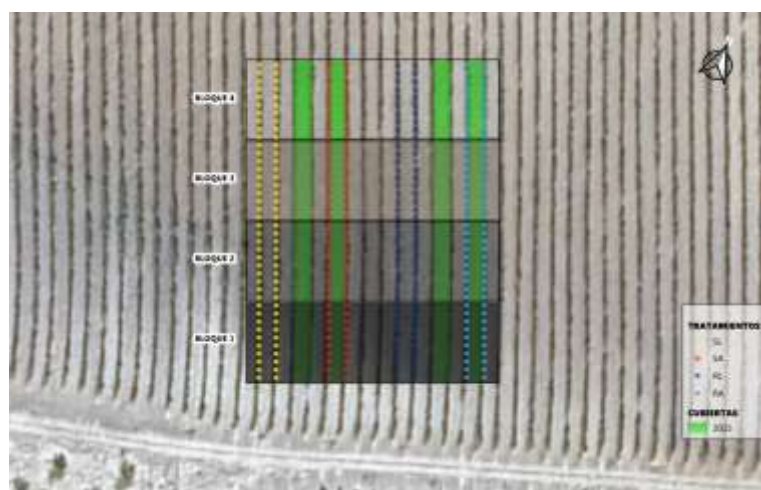


Figure 2. Experimental design of treatment blocks in the Quinta Sardonía plot.

The plot is equipped with a localized irrigation system with emitters of 2.5 L/h, spaced 75 cm apart along the vine rows. Each plant receives approximately 4 L/h, corresponding to an irrigation rate of 1.33 mm/h. The irrigation dose, applied weekly, corresponds to 30% of the weekly reference evapotranspiration (ET_o). Two types of soil water content sensors were implemented. On one hand, a TDR sensor (installed at 60 cm depth) was placed in each replicate of each treatment. On the other hand, a Weenat device (with sensors at multiple depths) was installed in three out of the four replicates of each treatment in the vineyard.

- Bodegas Enguera plot:

The study area in the Valencian Community is located in a vineyard belonging to Bodegas Enguera (39.009481 N, -0.723085 W, Enguera, Valencia). The plot has a total surface area of 4.5 ha, with a 1 ha sub-plot where the experiment is conducted. The vineyard is planted with the Marsanne variety, 12

years old, grafted onto Fercal rootstock, and trained using a double cordon Royat system, with a planting density of 2.60 * 1.55 m.

The irrigation system is subsurface, installed in the center of the inter-rows, with emitters spaced 0.75 m apart and a flow rate of 2 L/h. A total of four Sentek Drill and Drop soil moisture probes were installed, providing precise monitoring of soil temperature and moisture at different depths within the soil profile. As shown in the images, the probes were installed underground to monitor subsurface irrigation in the plot (Figure 3).

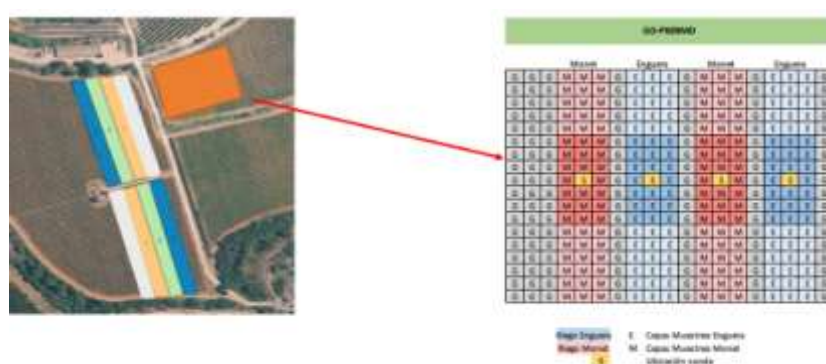


Figure 3. Experimental design of treatment blocks in Bodegas Enguera plot.

Experimental design and field instrumentation

Each vineyard plot was instrumented with a network of soil sensors installed at multiple depths within the soil profile to monitor volumetric water content and electrical conductivity. This configuration allowed the characterization of soil water dynamics across the active root zone. In addition, on-site weather stations were deployed in each location to record key meteorological variables, including air temperature, relative humidity, solar evapotranspiration and to support the calculation of crop water requirements.

Reference measurements and sensor calibration

Time Domain Reflectometry (TDR) measurements were periodically performed in each plot to obtain reference values of soil volumetric water content. These measurements were used to validate and calibrate the continuous sensor data. The comparison between sensor readings and TDR measurements enabled the identification of systematic deviations, sensor drift and site-specific calibration factors related to soil properties such as texture, bulk density and salinity.

Estimation of crop water requirements

Crop water requirements were estimated using a predictive modelling approach that integrates soil moisture data, meteorological inputs and crop-specific parameters. The model generated short-term forecasts of vineyard water demand with a prediction horizon of up to seven days. The modelling framework accounted for both soil water availability and atmospheric demand, enabling a dynamic representation of the soil-plant-atmosphere continuum.

Data analysis and model evaluation

Model performance was evaluated by comparing predicted water requirements with reference values derived from weather station data and standard evapotranspiration calculations. The comparison was carried out on a weekly basis for each vineyard plot. Total and mean deviations between predicted and reference values were calculated to quantify model accuracy. In addition, graphical analyses were performed to assess the temporal evolution of predicted and measured water requirements and to

identify periods of higher discrepancy. The evaluation considered differences in irrigation period length among the three sites, allowing for a comparative assessment of model performance under varying climatic and agronomic conditions.

RESULTS AND DISCUSSION

The analysis of soil water content in the experimental vineyards allowed the evaluation of soil water dynamics and the performance of continuous monitoring systems in relation to reference measurements obtained using TDR.

In Quinta de Couselo, the temporal evolution of soil moisture measured by TDR shows a pattern consistent with crop dynamics and environmental conditions, characterized by gradual depletion of soil water content between irrigation or rainfall events, followed by increases after water inputs. The relationship between TDR measurements and data recorded by Teros 12 sensors shows a well-defined linear trend (Figure 4), indicating that these sensors are capable of accurately representing soil water content. However, slight deviations are observed in certain moisture ranges, particularly at higher values, which may be related to soil-specific characteristics or sensor response (Figure 5).

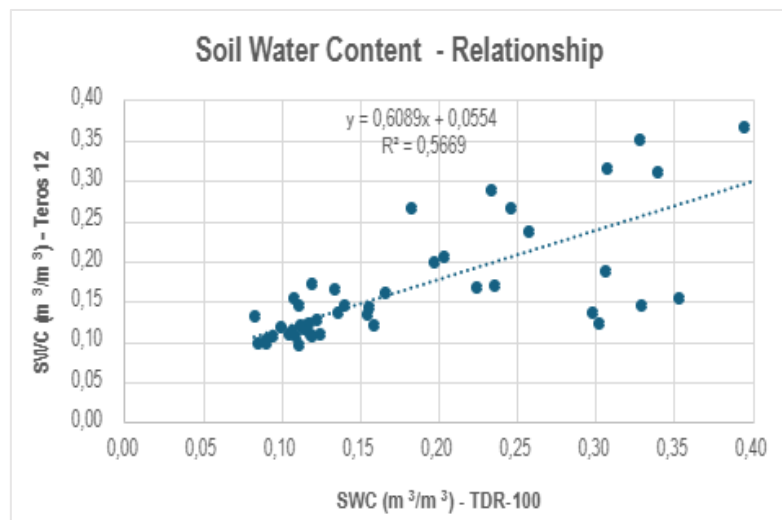


Figure 4. Soil water content relationship between Teros 12 and TDR-100 (Quinta de Couselo).

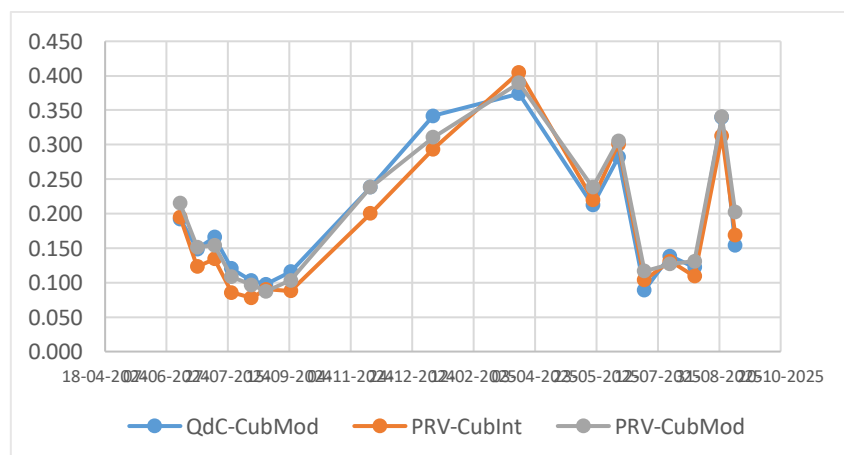


Figure 5. Evolution of soil water content in the 2025 season (Quinta de Couselo).

In Quinta Sardonía, TDR measurements also reflect a dynamic variation of soil water content throughout the study period, influenced by irrigation management and climatic conditions. The relationship between TDR values and those obtained from Weenat sensors shows a positive correlation, demonstrating the ability of these devices to track temporal changes in soil moisture. Nevertheless, some data dispersion is observed in specific moisture ranges (Figures 6-7).

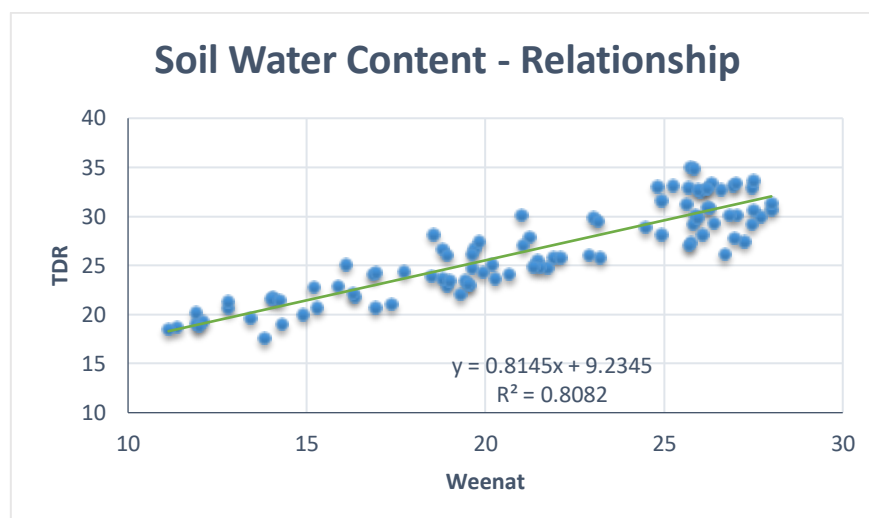


Figure 6. Soil water content relationship between Teros 12 and TDR-100 (Quinta Sardonía).

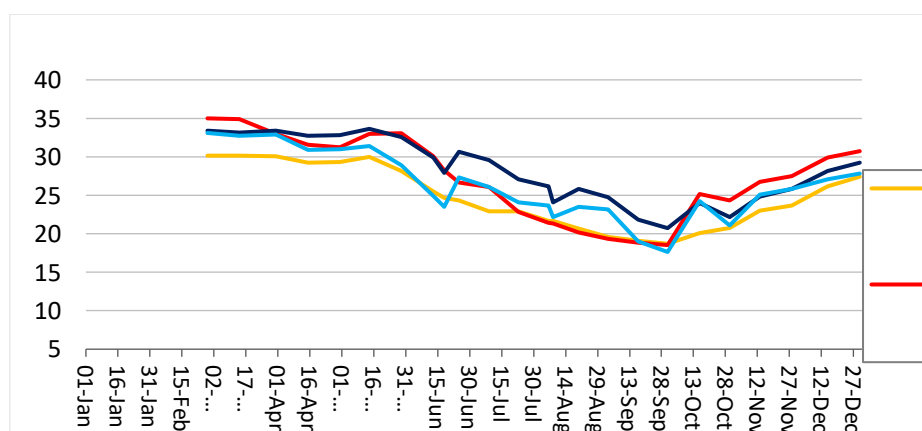


Figure 7. Evolution of soil water content in the 2025 season (Quint Sardonía).

The analysis of irrigation water requirement predictions across the three experimental vineyard plots (Quinta de Couselo, Quinta Sardonía and Bodegas Enguera) shows a generally strong agreement between model estimations and measured values derived from weather station data, although differences in accuracy are observed depending on site-specific conditions.

In Quinta de Couselo plot, a high level of agreement is observed between predicted and measured crop water requirements throughout the analysed period. Both curves follow a similar trend, with a gradual increase during mid-season followed by a decline towards the end of the summer period. Weekly deviations remain relatively low, with a total deviation of approximately 4.12mm and a daily mean deviation of 0.06mm, indicating high model accuracy under a shorter irrigation period (10 weeks). Observed discrepancies are limited to specific weeks and may be associated with localized meteorological variability not fully captured by the model (Figure 8).



Figure 8. Predicted vs. measured vineyard water requirements and weekly deviations in Quinta de Couselo.

In Quinta Sardonía, where the irrigation period extends over 12 weeks, the model maintains strong predictive performance, although a slight increase is observed (6.52mm total deviation and 0.54mm weekly mean deviation). The predicted and measured curves show close alignment, particularly during peak water demand periods, where both reach similar maximum values. However, larger discrepancies appear during the early stages of the season, linked to variability in soil moisture conditions or vine physiological responses during early growth stages (Figure 9).



Figure 9. Predicted vs. measured vineyard water requirements and weekly deviations in Quinta Sardonía.

In contrast, Bodegas Enguera plot, characterized by a shorter irrigation period (6 weeks), exhibits greater relative variability in prediction accuracy. While the general trend is well captured, deviations are proportionally higher (total deviation of 5.68mm and daily mean deviation of 0.14mm). A notable trend is observed in one of the central weeks, where the model significantly over underestimates water demand. This behaviour may be related to more extreme soil and climatic conditions or less stable soil water dynamics (Figure 10).

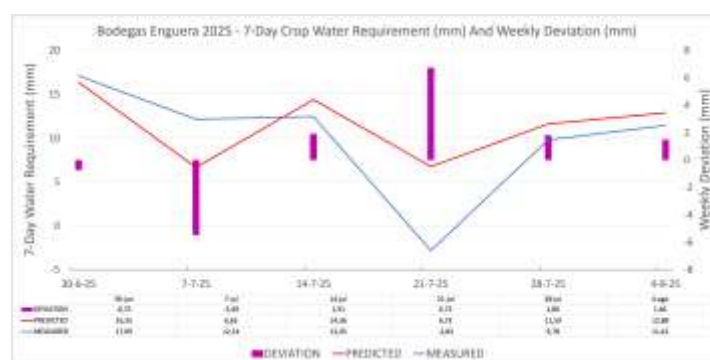


Figure 10. Predicted vs. measured vineyard water requirements and weekly deviations in Bodegas Enguera.

The comparative analysis of weekly graphs indicates that the model successfully reproduces the temporal evolution of crop water requirements across all three sites, capturing both peak demand periods and subsequent declines. Weekly deviations bars remain within acceptable ranges in most cases, although occasional deviations highlight the complexity of the soil-plant-atmosphere system.

CONCLUSIONS

Continuous monitoring systems are effective tools for tracking soil water status in vineyards. The general agreement with TDR reference measurements highlights their suitability for irrigation management applications, although calibration and validation processes are necessary to ensure optimal accuracy under specific field conditions.

Overall, the results confirm the robustness of the predictive framework developed within the PRERIVID project, demonstrating high reliability under diverse vineyard conditions. However, they also emphasize the importance of site-specific calibration and the integration of local data to further improve model accuracy, particularly under highly variable climatic conditions or shorter irrigation periods.

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