agronomy

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Agronomic Responses of Grapevines to an Irrigation Scheduling Approach Based on Continuous Monitoring of Soil Water Content

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Abstract: The efficient management of irrigation water can affect crop profitability quite significantly. The application of precision irrigation based on soil monitoring can help manage water resources. In viticulture, the irrigation technique is thought to strongly influence grape ripening and the final grape composition. In this study, an irrigation decision support system was compared to a surface drip irrigation system in a commercial vineyard located in Andrea (Southern Italy) planted with *Vitis vinifera* cv. Montepulciano. We aimed to investigate the ability of the DSS to save water while maintaining an acceptable yield and quality of the grapes. To allow for the comparison, eco-physiological as well as yield parameters were measured during the irrigation periods in both irrigation systems over two years (2019 and 2020). The results indicate that the vines grown using the DSS treatment were less stressed compared to the plants grown using farm irrigation in both years. The yield attributes showed slight or no significant differences between the treatments. The quality results showed no significant differences between the treatments in both years. Our results indicate that with savings of 10% and 17% of the irrigation water in the first and second year, respectively, the DSS was able to maintain good yield and quality levels as compared to the farm irrigation system. These two-year results provide a promising implementation of its use in precision irrigation.

Keywords: cv. Montepulciano; irrigation; sensors; vineyard; precision management

Citation: Garofalo, S.P.; Intrigliolo, D.S.; Camposeo, S.; Alhajj Ali, S.; Tedone, L.; Lopriore, G.; De Mastro, G.; Vivaldi, G.A. Agronomic Responses of Grapevines to an Irrigation Scheduling Approach Based on Continuous Monitoring of Soil Water Content. *Agronomy* **2023**, *13*, 2821. https://doi.org/10.3390/agronomy13112821

Academic Editor: Ivan Francisco Garcia Tejero

Received: 10 October 2023
Revised: 6 November 2023
Accepted: 13 November 2023
Published: 15 November 2023

1. Introduction

The world population is expected to increase to 9.1 billion by 2050, resulting in a 35% food demand increase [1]. This projected increase along with the variability in the rainfall amount and timing, climate change events, and competition for water among users are putting pressure on agricultural water demands [2], especially in arid and semi-arid areas where water is scarce. Several studies indicated that the projected change in climate events will lead to an increase in crop water requirements, resulting in more severe drought periods [3]. Furthermore, climate change forecasts indicate that some scenarios for 2050 predict a 30–50% decrease in freshwater availability, while its demand in eastern and southern areas could be doubled [4]. To cope with these challenges, it is necessary to utilize the best advanced technologies to make it possible to improve irrigation efficiency and safeguard water resources [5].

Precision agriculture, in this regard, is believed to be a sustainable solution, with the possibility to enhance crop yield and quality, to some extent, by increasing water use efficiency [6]. Navarro-Hellín et al. [7] indicated that the application of a proper irrigation strategy to improve the watering process is thought to affect crop profitability quite significantly. In addition, the concept of the MAD (management allowed deficiency), developed by Merriam [8], relates the maximum soil moisture deficiency, through the soil moisture tension, to crop production and the economic value of water and crop value. Nevertheless, the trade-off between the efficient management of water resources and improving crop yield is a tough challenge and has been highly discussed in the present and future agendas regarding food security [9]. In fact, water resources are increasingly being scrutinized due to the changing surface water or groundwater availability at both the regional and global levels. Even though there is a relative abundance of water resources in Italy, the southern part of the country is suffering from seasonal water scarcity phenomena due to inefficiency in water governance and management [10]. In fact, agriculture is by far the largest consumer (70%) of water resources in the world [11]. In Italy, it is estimated that nearly two thirds of the available water resources are used for irrigation [12]. In the Apulia region (Southern Italy), as in the other southern regions, water supply is becoming a social and economic emergency primarily because of increasing water demand and a lack of management practices [13]. Further associated decreases in the mean precipitation could aggravate this situation and threaten the regional and, therefore, the national economy. In this regard, the efficient use of water is becoming an increasingly important consideration, sometimes at the expense of crop quality [7].

In viticulture, several literature studies indicate that proper irrigation management can optimize grape ripening and the overall vine performance [14,15] including the quality of the berries [16]. Furthermore, canopy management (for example apical or basal defoliation and shoot trimming) could affect the grape quality and berry composition at harvesting time [17]. However, irrigation effects need to be interpreted regarding soil water status, crop eco-physiological parameters and the studied cultivar [18]. Moreover, sustainable viticulture is directly linked to a low input in terms of water [19]. It is widely accepted that soil moisture content affects, directly and indirectly, several important soil biological processes important for plant growth, and, therefore, productivity [20]. Therefore, understanding the patterns of soil moisture distribution is useful for efficient irrigation water management in agriculture. Several studies have indicated that the accurate estimation of soil water content is important for improving crop yield, the efficient application of irrigation water, and reducing the potential environmental impacts of farming [21]. The authors also indicated that when the soil water content is well-characterized across the field, nutrients can be applied more efficiently. Such findings have led to a growing interest in the development of real-time soil moisture monitoring tools. Therefore, to play a major role in addressing the current and future global food security problems, more innovative and sustainable irrigation management approaches are required.

Today, the importance of the rationalization of water use in tackling sustainability challenges in agriculture within a multidisciplinary approach has called for the development of a decision support tool for confronting these challenges. The adaptation of sensor information and communication technology can help farmers improve water use efficiency and, therefore, crop yields. Soil moisture sensors can provide important information on plant-available water as a function of the soil volumetric water content. The timing of irrigation can, therefore, be determined by monitoring the soil moisture and starting irrigation when the soil moisture reaches a predetermined level. There are different types of available soil moisture sensors that have been used in precision irrigation. Among the main goals of precision irrigation are the increase in water efficiency, reduction in energy consumption, and improvement in crop yield by using technology such as wireless sensor networks, mobile devices, remote sensing, real-time control, and information systems [22]. However, a good understanding of soil texture, which defines important parameters, is important for effective irrigation water management [23]. Different sensors have been used in conjunction with instrumentation systems to control the irrigation process. In recent years, the quick development of wireless sensor networks has led to the use of sensor equipment with no or very little wiring, and great improvements in their installation and maintenance [24,25]. In the Mediterranean environment, the limited availability of water implies the need to search for agronomical strategies that can mitigate the consequences of water deficits and increase the efficiency of the irrigation supply [26].

Therefore, in this study, we proposed an easy-to-apply irrigation decision support system (DSS) based on a software system that can support effective and efficient decisions on the amount and the timing of irrigation interventions for water irrigation management in agriculture. However, our tested DSS lacks the degree of autonomy that activates or deactivates the irrigation system compared to several DSSs (i.e., [27,28]).

The main objective was to validate an irrigation scheduling procedure based on the use of a newly improved engineering soil moisture sensor, which allows for the adjustment of the irrigation inputs according to the soil moisture, which varies across the different development stages of the crop. For that, we tested the viability of the DSS against the traditional farm irrigation system in terms of the crop productivity and quality in a vineyard located in Southern Italy. The aim is to introduce a decision support tool to enhance the trade-off between crop productivity and water resource use from a sustainable water management point of view.

2. Material and Methods

2.1. Site Description and Meteorological Data

The experiment was conducted on an area of about 1.45 ha within a commercial vineyard located near Andria (41°14′11.05″ N, 16°11′33.01″ E) (Apulia region, Southern Italy) over two irrigation seasons (2019 and 2020). The study site was planted, in 2004, with *Vitis vinifera* L. 'Montepulciano', grafted on Paulsen 1103 rootstock. The grapevines were trained to a vertical trellis system on a cordon oriented north–south and were planted with a spacing of 2.30 × 1.0 m (4348 vines/ha). The site is 142 m elevated above sea level. The soil is sandy clay loam according to the USDA classification (soil depth 0.60 m), and the climate in the area is Mediterranean, with mild winters and hot and dry summers. The average annual rainfall is 597 mm, the average maximum temperature is 21.7 °C, and the average minimum temperature is 11 °C (from a thirty-year time series of climatic data).

In addition, meteorological data were recorded at the station located in the experimental field and were used to estimate reference evapotranspiration (ET_o) and saturated vapor pressure deficit (VPsat; saturation minus actual water vapor pressure) of the studied vineyard during the 2019 and 2020 growing seasons. The VPsat is believed to be used as an accurate measure for predicting plant transpiration and water loss [29], and it was calculated as the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated according to the Murray equation based on the Clausius–Clapeyron approximation [30], while ET_o was calculated using Penman–Monteith equation, as an important variable for the development of a rational irrigation management plan in arid/semi-arid environments such as the Mediterranean region [26]. Figure 1 shows the seasonal and inter-seasonal variation in reference evapotranspiration (ET_o, mm month^{-1}), the amount of rainfall (R, mm month^{-1}), and saturated vapor pressure deficit (VPsat, kPa) during the two years of the experiment.

2.2. Irrigation Treatments and the Experimental Design

In this study, an innovative decision support system (DSS) for crop irrigation was tested and compared with the traditional irrigation practice (hereinafter called farm irrigation) used to irrigate the vineyard at the study site. The comparison considered the sustainability of the irrigation system in terms of water saving while maintaining or enhancing (if possible) crop yield and quality. The farm irrigation system, on the one hand, was managed by specialised personnel at the study farm. The water amount supplied during both irrigation seasons in the vineyard field following the farm irrigation system can be seen in Table 1. On the other hand, the DSS, developed by Robert Bosch GmbH Company, Stuttgart, Germany, is based on the use of the sensor (TEROS10, by METER GRroup, Inc., Pullman, WA, USA) that measures the daily soil moisture (w%) for continuous monitoring of soil water status supporting farmers in water irrigation management.

The DSS consists of three main parts: hardware (sensors, device-to-web-data logger and thermo-hygrometer), algorithm, and graphic user interface (app) [31]. Within the monitoring of soil moisture via the DSS, the TEROS10 sensor is connected directly to the internet via a communication box which sends the data securely to a web platform (DeepField IoT Cloud '(c) 2022 Deepfield Connect GmbH, Ludwigsburg, Germany') on a regular basis, which in turn sends information and alerts to the farmer on the app, which is compatible with smartphones, tablets, or computers [32]. Once the soil moisture sensor is installed in one location, it will start sending weather (i.e., temperature and humidity) as well as soil moisture information periodically. Farmers, in this case, can monitor through the app, so that unnecessary journeys to the field to check on frost, heat, or dryness can be avoided [33]. Such information can allow the farmer to keep track of field water status at any given time, and can provide assistance with the proper timing for irrigation intervention and the quality of water to be used for irrigation thanks to an algorithm which considers the soil texture characteristics. TEROS10 sensors were used to monitor soil moisture values in both treatments.

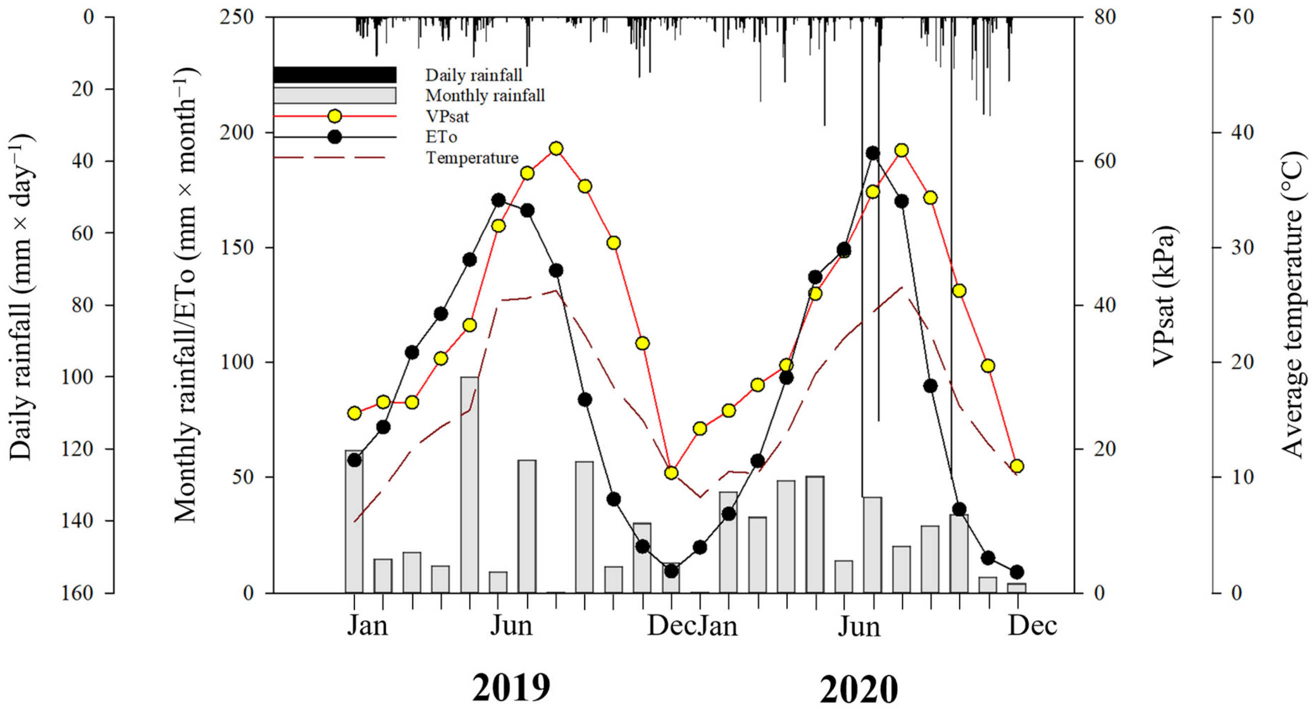

Figure 1. The amount of rainfall, saturated vapor pressure deficit, and ET_o values per month, monthly trend of the average temperature, and daily trend of rainfall during both study years.

Table 1. The amount of irrigation water supply during the two irrigation seasons (2019 and 2020) under both irrigation systems (DSS and farm irrigation). Saving indicates the water percentage saved by using the DSS.

Year	Treatment	Seasonal Irrigation Volume (m^3 ha^{-1})	Saving (%)
2019	DSS farm irrigation	1400 1551	10
2020	DSS farm irrigation	1347 1625	17

The DSS irrigation system was proposed with the aim of saving a significant amount of irrigation water; the irrigation interventions in both compared systems (DSS and farm irrigation) were performed based on the climate condition and crop development stage. Therefore, the irrigation season for the studied vineyard started on DOY 158 and ended with the fruit harvest on DOY 283 in the 2019 season, whereas, in 2020, the irrigation season started on DOY 172 and ended with the fruit harvest on DOY 280.

In this study, the soil moisture values for the grapevine during each irrigation season were set in accordance with the water requirement across the different phenological phases. Therefore, irrigation interventions in the proposed DSS were performed to keep the soil water content (SWC) of the first 30 cm (active root zone) of the soil at an optimum level (set as a recharge point (RP), where water can be easily taken up by the plant). This was made possible by identifying the field capacity and the RP according to the specific physical soil characteristics of the study site. Each year, irrigation interventions within the DSS were applied in full irrigation (FI) and deficit irrigation (DI) regime scheduling, considering the differences in water needs as the crop grows, according to the phenological stages. In both regimes, soil moisture was kept at 30% θ while RP was set to be 15% for FI and between 30% and 35% for DI during fruit setting and post-veraison phases, respectively.

Within each irrigation management, sensors were organised in a complete randomized block design with 3 replicates. TEROS10 sensors were installed at 30 and 60 cm of soil depth to allow the soil moisture comparison at the considered soil layers. The DSS continuously monitored the soil volume water content at 30 cm and 60 cm of soil depth. Within the DSS, the treatments were assigned as B1, B2, and B3; Z1, Z2, and Z3 were the treatments within the farm irrigation system. In each treatment, 6 vines, placed close to the sensor and within its range of detecting soil moisture, were signed and considered representative of the production and quality determination. All the replicates (3 DSS and 3 farm irrigation) were equipped with water flow meters to accurately measure the amount of water supply during every irrigation event.

All treatments, both for the vines irrigated by DSS and for the vines irrigated by traditional farm irrigation, received the same amount of fertilizers according to the regional guidelines for sustainable agronomic crop management. Other agronomic practices applied in the vineyard followed the common practices used in the area including shoot trimming applied after fruit set.

2.3. Plant and Soil Parameters

2.3.1. Plant and Soil Water Status

The installation of the TEROS10 sensors allows for the measurement of soil water content on a daily basis, in both irrigation seasons (2019 and 2020). Sensor readings were obtained as soil moisture content values which were then reported as the volume of the water content of the soil (VWC; %). In addition, in both irrigation systems, important parameters such as plant water status and soil water content were estimated in each year. Plant water status was determined by measuring stem water potential (SWP; mPa) using a pressure chamber (Plant Water Status Console 3000F01, SOILMOISTURE CORP., Santa Barbara, CA, USA). Each year, SWP was measured during the different phenological phases expressed as days of the year (DOY). The SWP was measured every 10 days during the 2019 season and every 15 days during the 2020 season due to differences in irrigation season length between the two years; however, this was believed to cover the whole irrigation season (from first irrigation to crop harvest) to evaluate plant water status. In both seasons, each time, SWP measurements were taken at midday (11.30 to 12.30 h solar) and at light saturation (PAR $\geq$ 1800 mol photons m^{-2} s^{-1}) from 2 leaves per plant of the six representative vines in each treatment. The leaves were placed in hermetic aluminum foil bags for at least 1 h prior to the measurement. Additionally, to describe the accumulated effect of the irrigation treatments [34], data on the seasonal variations in midday SWP

(MmPa) were used to calculate water stress integral (WSI) using the equation defined by Myers [35] as follows:

$$\mathrm{WSI} = \left| \sum_{i=0}^{i=t} (I - c)n \right|$$

where $\Psi_{i,i+1}$ is the average midday stem water potential for any time interval i, i + 1 (mPa); c is the value of the maximum midday stem water potential measured during a season; and n is the number of days in each interval.

2.3.2. Leaf Gas Exchange Determination

In this study, in both years and for each irrigation system, leaf gas exchange in terms of stomatal conductance (g_s; mM H_2O m^{-2} s^{-1}) and net assimilation (P_n; µm CO_2 m^{-2} s^{-1}) were measured using a gas exchange system (LI-6400, LI-COR Inc., Lincoln, NE, USA) on healthy and well light-exposed leaves of 6 vines, located close to the sensor and believed to be representative of the replicate (as shown in Figure 1). Readings were taken on three leaves per plant and the average of the three readings was used for the analysis. In addition, as important parameters to ensure sustainable water management in viticulture [36], the P_n/g_s ratio was used as an estimation of the intrinsic water use efficiency and the P_n/leaf transpiration was used to estimate the instantaneous water use efficiency (WUEi).

2.4. Berry Sampling, Yield Components, and Quality Determination

At the harvesting time, 10 clusters per treatment and per replicate were randomly taken to determine yield and its components and technological, biometric, and chemical parameters. Grapes were harvested by hand at full ripening on DOY 277 in the 2019 season and on DOY 280 in the 2020 season, from each treatment and replicate. The measured biometric parameters measured from 10 bunches per plot were length (cm), weight (g), and number of berries per bunch. After crushing, the juice of 100 berries per treatment and per replicate the total soluble solids (TSS; °Brix), pH, and titratable acidity (TA; g L^{-1}) were determined. The pH and the titratable acidity were measured using a pH meter (Crison 507; Crison Instruments, S.A., Barcelona, Spain). The titratable acidity (TA) was determined by titrating 10 mL of juice with 0.1 N NaOH until pH 8.3 and the results were expressed as g L^{-1} of tartaric acid. The TSS was determined using a hand-held refractometer (Atago, Tokyo, Japan). With 10 berries per treatment and per replicate, the skin color (ScieLab coordinates), berry weight (g), skin weight (g), and seed weight (g) were measured. The color of the skin was determined on two opposite faces (equatorial zone) for each berry using a tristimulus colorimeter (mod. CR300, Minolta Co., Ltd., Osaka, Japan) with an 8 mm measuring aperture, diffused illumination, and a viewing angle of 0°.

2.5. Statistical Analysis

The statistical analysis was carried out using Rstudio (Rstudio, PBC, Boston, MA, USA) for Windows, version 1.3.1093.0 [37]. Within each season, a comparison of means was performed using the Welch two sample t-test at a 95% probability level ($p < 0.05$). Year × treatment interaction was calculated using the two-way analysis of variance (ANOVA) at a 95% probability level ($p < 0.05$). Probability levels used were $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). Graphs were made by using SigmaPlot (Systat Software, Inc., San José, CA, USA), for Windows, version 14.0 [38].

3. Results and Discussion

3.1. Agrometeorological Data and Soil Water Balance

3.1.1. Agrometeorological Data

The meteorological data were collected from the agrometeorological station located near the experimental field and the data are shown in Figure 1. In particular, the amount of rainfall was 374 mm during the 2019 season, higher than the rainfall amount reported in the 2020 season (321 mm). The first season (2019) showed non-uniformity of the rainfall water spells, in which more than 70% of the total seasonal rainfall amount occurred during the months of January, May, July, and September, with more than 50 mm in each month (Figure 1). In the season, a larger amount of rainfall over the deficit irrigation period was reported. In 2020, the rainfall events experienced some uniformity during this season, however, with less than 50 mm monthly. In 2019, the irrigation began on the DOY 158. During this year, there was rainfall during the flowering phase (May and June) and during the fruit setting phase (July) (Figure 1). Similarly, in the 2020 season, there were spells of rainfall during the flowering and fruit setting phases; however, to a lesser extent. The cumulated annual value of the reference evapotranspiration (ET_o) for the two experimental seasons was 1130 mm and 1001 mm during the 2019 and 2020 seasons, respectively (Figure 1). In both seasons, the ET_o was higher during the fruit setting phase (July, with the highest rate being reported in the 2020 season) and lower during winter (November–January). Considering that the vapor pressure deficit (VPD) can influence water stress in grapevines depending on the crop's phenology [39], the saturated VPD was estimated in this study throughout both irrigation seasons. The VPD data (Figure 1) tends to follow the same trend of the ET_o in both seasons. The highest VPD value was reported during August, while the lowest value was reported in January in both seasons.

3.1.2. Soil Water Balance

The application of deficit irrigation (DI) in the vineyard was performed at later plant growth stages as a common practice in the area in order to save water without affecting the crop yield. In fact, several studies found that deficit irrigation in vineyards during specific phenological phases such as fruit setting [40,41] and pre- and post-veraison [42] can maintain yield and improve crop quality. In this study, the DI regime consisted of two different irrigation interventions which were applied to keep the soil moisture at 30% with an RP between 30–40%. The first deficit irrigation was applied during the fruit setting phase, in which every time the sensors detected a reduction in the humidity up to 21.00% θ (RP 30%), the vineyard was irrigated to bring the soil moisture back to 30% θ. The second deficit irrigation was instead applied during the post-veraison phase, in which every time the sensors detected a reduction in the humidity up to 19.50% θ (RP 35%), the vineyard was irrigated to bring the soil moisture back to 30% θ.

In both the 2019 and 2020 irrigation seasons, the soil water content in the root zone (0–60 cm) fluctuated greatly during both full irrigation and deficit irrigation periods (Figure 2) due to the fluctuation in rainfall events; however, the VWC values were within the range previously set by the calibration of the probe. There were statistically significant differences between the global mean of the VWC of each treatment at both depths; the interaction between year × treatment was significant per each depth too.

We believe that the VWC values out of the identified soil moisture range was due to heavy spells of rainfall, as in the case of July 2019 during the fruit setting period (Figure 1). Similarly, the VWC values out of the range of the threshold used for DI applied during the fruit setting and the post-veraison phase were due to the lack of water from rainfall; moreover, a wide temporal variability in the soil water content during the irrigation season might be due to soil structural changes, for example as a result of shrinkage cracks [43]. As mentioned above, the rainfall data (Figure 1) experienced a non-uniform distribution throughout the seasons, which was more evident during the 2019 season, and especially during the DI period (Figure 2). During the 2020 seasons, the relatively heavy, however, homogeneous distribution of rainfall throughout the season during the fruit setting phase allowed for the maintenance of the VWC within the defined range, especially during the DI period. During the FI period, however, the VWC reported higher values (out of the range) due to heavy rainfall events.

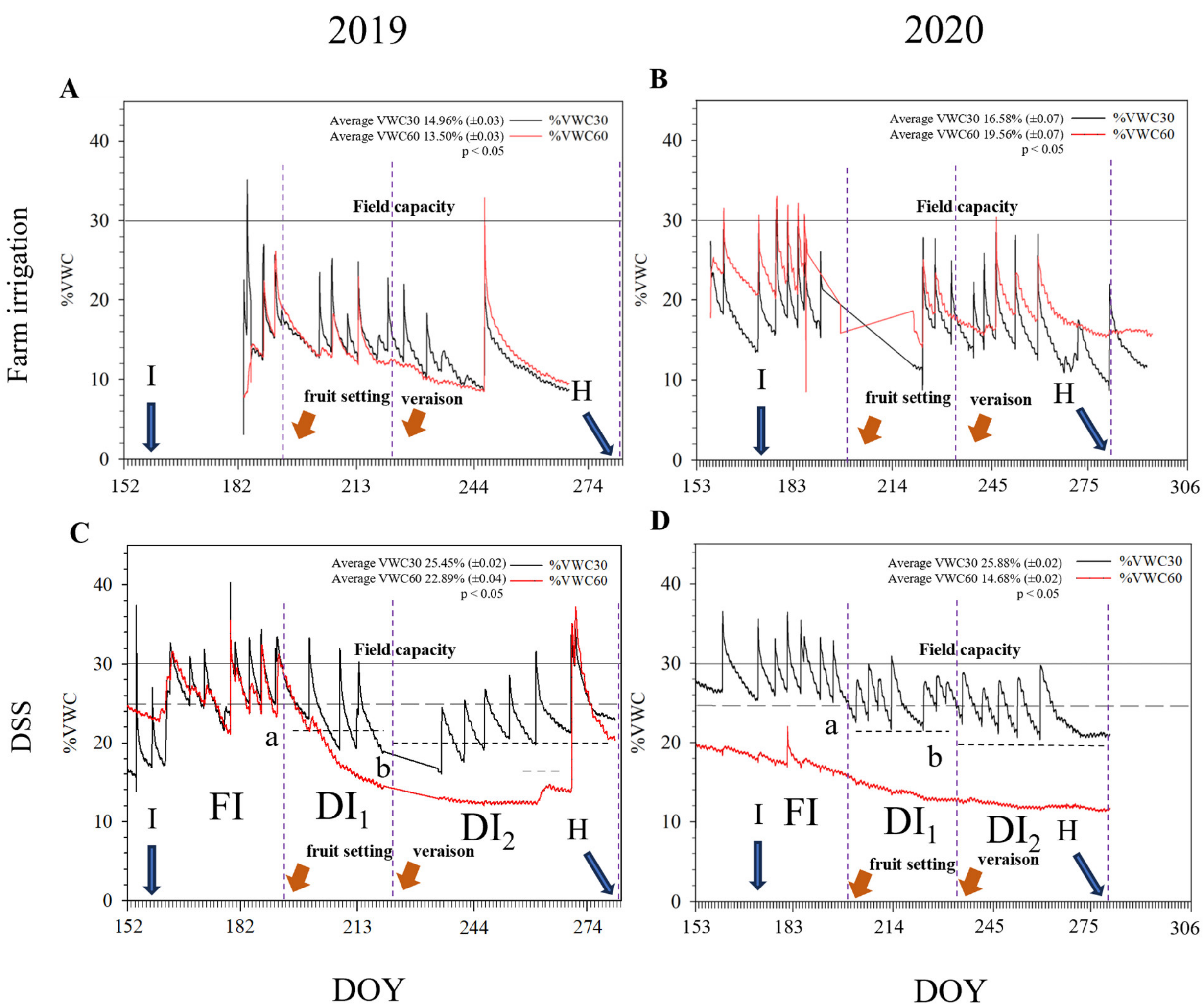

Figure 2. Variation in the volume water content (VWC) during both seasons (2019 and 2020) as affected by soil depths (30 cm (black line) and 60 cm (red line)) in the farm irrigation system (**A**, 2019; **B**, 2020) and DSS irrigation system (**C**, 2019; **D**, 2020). The thresholds indicate the limit values during full irrigation (FI) (corresponding to the field capacity of the soil) and deficit irrigation (DI) across the irrigation season; (a) is the threshold used for deficit applied during the fruit setting phase (DI_1) and (b) is the threshold used for deficit applied during the post-veraison phase (D_2). In each graph the global mean and the standard error of the volume water content are also reported.

3.1.3. Plant Water Status

In this study, we measured the SWP throughout the development stages of the vines. The measurement time was expressed as days of the year (DOY) and SWP measurements were taken 12 times throughout the 2019 irrigation season, while, in 2020, the SWP measurements were taken 11 times due to differences in the irrigation season length between the two seasons (in 2020, the irrigation season started later and ended a bit earlier compared to the 2019 season (see Section 2.2. *Irrigation Treatments and the Experimental Design*)). In particular, in the 2019 season, the SWP was measured on the 163rd, 171st, 178th, 185th, 192nd, 199th, 204th, 213th, 217th, 233rd, 239th, 246th, 254th, 260th, 268th, and 277th DOY in each irrigation treatment and replicate. In the 2020 season, instead, the SWP was measured on the 178th, 185th, 196th, 204th, 220th, 237th, 244th, 246th, 260th, 290th, and 300th DOY in each irrigation treatment and replicate.

The vine water status is believed to be an important factor that determines crop quality in viticulture [44]. The analysis of the SWP results indicates that vines under the DSS treatments showed lower water stress levels compared with farm irrigation in both years. The seasonal and inter-seasonal variations in the midday SWP (mPa) in both irrigation seasons are reported in Figure 3. In the 2019 season, the plants in both irrigation treatments did not show a high level of water stress compared to the stress threshold value (SWP > −1.2 mPa). Nevertheless, the plants irrigated with the DSS were less stressed and in some growth stages (DOY), the differences were significantly in favor of the DSS when compared to the farm irrigation system. In particular, on DOY 178, the vines irrigated by DSS were significantly less stressed than the vines irrigated using the farm irrigation system (SWP-DSS = −0.77 mPa vs. SWP-farm irrigation = −0.96 mPa). Similarly, in DOY 213, the SWP of the plants irrigated using the DSS was significantly higher than those irrigated using the farm irrigation system (SWP-DSS = −0.95 mPa vs. SWP-farm irrigation = −1.03 mPa) (Figure 3). On DOY 192, the plant stress levels were much lower in both treatments (SWP-DSS = −0.33 mPa vs. SWP-farm irrigation = −0.31 mPa) mainly due to heavy rainfall events. On the contrary, during the veraison phase, the lack of rainfall events (Figure 1) led to a significant decrease in the SWP values (below the threshold level) under both irrigation systems, particularly on the 239th, 254th, 260th, and 268th DOY. In particular, on DOY 239, the SWP values were lowered far beyond the stress threshold value (SWP < −1.2 mPa) in both treatments; however, the SWP value was higher for the plants irrigated using the DSS, but the difference was not significant as compared to the SWP for the plants irrigated using a farm irrigation system. In September (260th and 268th DOY), during the pre-ripening phase, the SWP values were significantly lower in the plants irrigated using the DSS as compared to the plants irrigated using the farm irrigation system (Figure 3).

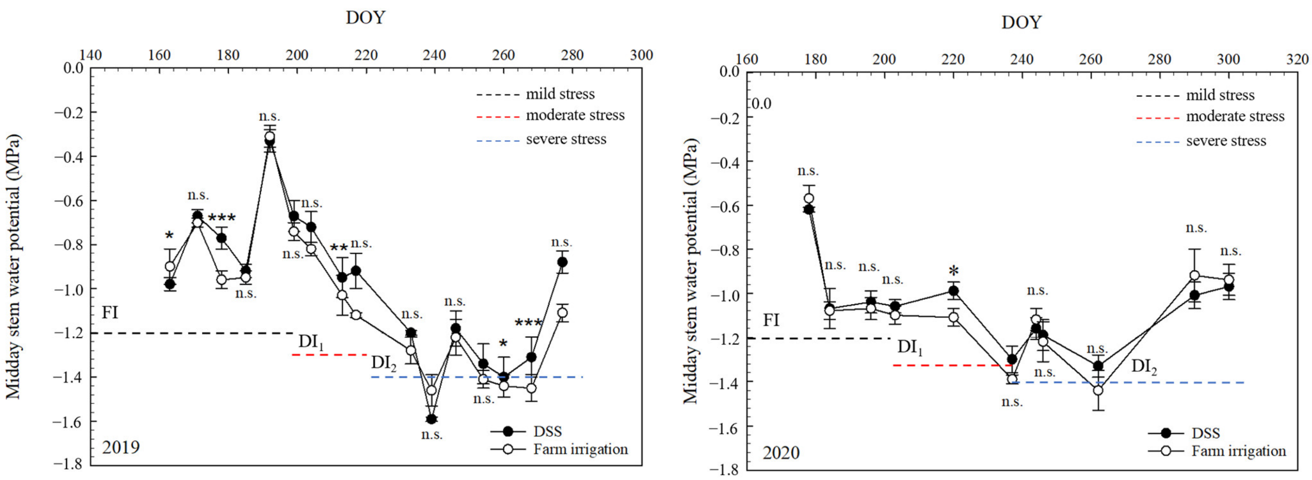

Figure 3. Seasonal/inter-seasonal variations in midday SWP (mPa) in a Montepulciano vineyard during the 2019 and 2020 irrigation seasons under both irrigation treatments (DSS and farm irrigation). Water stress thresholds are indicated for each period corresponding to the different irrigation treatments (full irrigation, FI; deficit irrigation applied during the fruit setting phase, DI_1; deficit irrigation applied during the post-veraison phase, DI_2) [45]. DOY = days of the year. Error bars indicate the standard errors; *, ** and *** are significantly different at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$ significant level, respectively while n.s. = not significant.

In 2020, irrigation began on DOY 172. During this year, the rainfall was distributed more homogenously compared to the 2019 season, with good rainfall amounts reported in August (during the veraison phase) (Figure 1). We believe that the rainfall distribution in the 2020 season directly and/or indirectly influenced the SWP values, in which the values dropped under the stress threshold value on just two occasions (in four occasions, the SWP values were reported under the stress threshold values in the 2019 season), specifically, on the 237th and 260th DOY, and the plants irrigated using the DSS were less stressed (Figure 3). In general, there were no significant differences in the SWP values between the two irrigation treatments except for the 220th DOY, on which the plants under the DSS were significantly less stressed (SWP-DSS = −0.99 mPa vs. SWP-farm irrigation = −1.11 mPa).

In addition, the water stress integral (WSI) values can be used as a quality indicator [46]; therefore, it was calculated using the data on the seasonal variations in the midday SWP (mPa) in both irrigation seasons and under both irrigation treatments. In both years of the experiment, no significant differences were found between the DSS and farm irrigation treatments; despite this, the WSI values tended to be higher for the farm irrigation vines in both years than the DSS vines (Table 2).

Table 2. Calculated WSI (mPa per day) in a Montepulciano vineyard during the 2019 and 2020 irrigation seasons and for both irrigation treatments (DSS and farm irrigation).

Year	Treatment	WSI		Year × Treatment
2019	DSS	72.80 ± 2.40	*	n.s.
	farm irrigation	82.87 ± 0.49		
2020	DSS	61.06 ± 3.56	n.s.	
	farm irrigation	68.33 ± 4.18		

* $p \leq 0.05$ significant level, while n.s. = not significant.

Concerning the leaf gas exchange results, it is widely accepted that the optimum stomatal behavior should occur when the opening of the stomata during the day allows for minimum transpiration and maximum photosynthesis, and their ratio remains constant [47]. In this study, stomatal conductance tended to be higher for the plants subjected to the DSS irrigation treatment. Figure 4 shows that a statistically significant difference was observed on DOY 217 in 2019, during the pre-veraison phase (DSS: 0.14 mmol m^{-2} s^{-1}; farm irrigation: 0.09 mmol m^{-2} s^{-1}). On the same DOY, the SWP values indicate that the vines irrigated according to the DSS were less stressed (SWP-DSS = −0.92 mPa vs. SWP-farm irrigation = −1.12 mPa). In fact, the 2020 season was drier than the 2019 season (in the irrigation season, the amount of rainfall was 216.3 mm in 2019 and was 153.2 mm in 2020); therefore, the stomatal conductance was lower in response to drier soil conditions (Figure 4) as was found by Beis and Patakas [48]. Similarly, net assimilation followed the trend of stomatal conductance. As shown in Figure 4, net assimilation tended to be higher for plants subjected to DSS treatment in the 2019 season; however, there were no statistically significant differences between the two seasons, despite the deficit irrigation that was applied during the post-veraison phase in vines under the DSS irrigation treatment. Zufferey et al. [49] reported that water stress influences the net assimilation. In this study, the net assimilation was higher during the fruit set phase in the 2020 season than in the 2019 season for both irrigation treatments (Figure 4).

In the 2019 season, on DOY 182, there were statistically significant differences between the two treatments, with a greater intrinsic water use efficiency (P_n/g_s) for the vines irrigated using the DSS probably due to improved irrigation management, with an optimal evaluation of the soil water status by the probes. On the contrary, on DOY 217, there were significant differences in the (P_n/g_s) value, with a higher intrinsic water use efficiency reported for the vines irrigated using the farm irrigation system. The significantly lower intrinsic water use efficiency value on the 217 DOY for the vines irrigated using the DSS was probably due to a significantly higher stomatal conductance (Figure 4) (in August 2019, there was no rain and irrigation using the DSS probably allowed the plants to maintain a higher stomatal conductance). In the 2020 season, there were no statistically significant differences between the two irrigation treatments regarding the intrinsic water use efficiency, probably thanks to a better distribution of meteoric inputs throughout the summer under the DSS. In 2019, the WUEi followed the trend of the intrinsic water use efficiency for both treatments; however, different from the intrinsic water use efficiency, the WUEi showed no statistically significant differences only in the last measurement of the irrigation season; in 2020, the WUEi decreased less markedly than the intrinsic water use efficiency in the first part of the irrigation season. No statistically significant differences were detected between the treatments in 2020 (Figure 4).

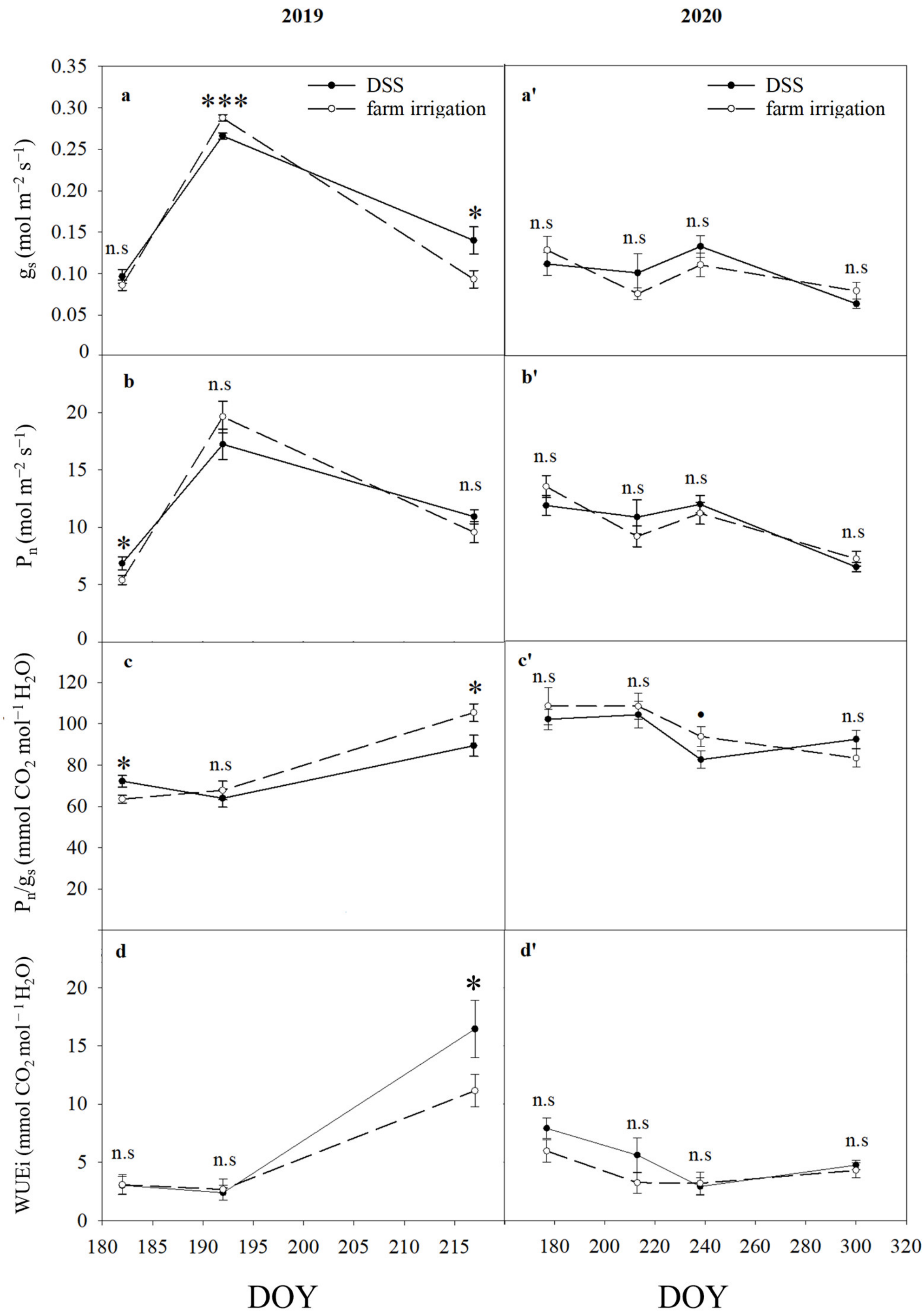

Figure 4. Seasonal/inter-seasonal variations in stomatal conductance (g_s, mol m^{-2} s^{-1}; **a**, 2019, **a′**, 2020), net assimilation (P_n, µmol m^{-2} s^{-1}; **b**, 2019, **b′**, 2020), intrinsic water use efficiency (P_n/g_s, (mmol m^{-2} s^{-1} mol m^{-2} s^{-1}); **c**, 2019, **c′**, 2020), and instantaneous water use efficiency (WUEi, P_n/transpiration (mmol m^{-2} s^{-1} mol m^{-2} s^{-1}); **d**, 2019, **d′**, 2020) in a Montepulciano vineyard during the 2019 and 2020 irrigation seasons under both irrigation treatments (DSS and farm irrigation). DOY = days of the year. Error bars indicate the standard errors; * and *** are significantly different at $p \leq 0.05$ and $p \leq 0.001$ significant level, respectively while n.s. = not significant.

3.2. Yield and Yield Components

Vine productivity can be limited by water availability and preceding rainfall during the season [50]. In agreement with the results reported by Acevedo-Opazo et al. [51], we did not find a significant difference in the average cluster weight between the two treatments in the 2019 season (Table 3); however, in the 2020 season, there was a significant difference between the treatments in favor of the farm irrigation system. Similarly, the number of berries and cluster length in the 2020 season was significantly higher for the vines irrigated using the farm irrigation systems (Table 3). Salón et al. [52], evaluated small irrigation contributions along with seasonal rainfall and found that irrigation increases the yield by increasing the berry weight; in our study, although we were not comparing with rainfed conditions, we found that water reduction due to the deficit irrigation did not result in statistically significant differences in the weight of 10 berries in both seasons (Table 3).

Table 3. Characteristics of berries and clusters of grapes from a Montepulciano vineyard during the 2019 and 2020 seasons as affected by irrigation treatment (DSS vs. farm irrigation).

Year	Treatment	Cluster Length (cm)		Year × Treatment	Cluster Weight (g)		Year × Treatment
2019	DSS farm irrigation	16.6 ± 0.4 16.1 ± 0.3	n.s.	*	274 ± 12.7 253 ± 11.9	n.s.	**
2020	DSS farm irrigation	16.1 ± 0.4 17.2 ± 0.3	*		251 ± 14.1 304 ± 11.6	**	
		Berries per Cluster		**Year × Treatment**	**Weight of Berries per Cluster (g)**		**Year × Treatment**
2019	DSS farm irrigation	156.3 ± 7.6 146.1 ± 7	n.s.	*	263.1 ± 12.4 243.3 ± 11.3	n.s.	**
2020	DSS farm irrigation	131.9 ± 6.8 154.6 ± 6.5	*		244.2 ± 12.8 291.1 ± 11.1	**	
		10 Berries Weight (g)		**Year × Treatment**	**Weight of 10 Skins (g)**		**Year × Treatment**
2019	DSS farm irrigation	17.4 ± 0.7 18 ± 0.3	n. s.	n.s.	1.5 ± 0.05 1.6 ± 0.005	n.s.	n.s.
2020	DSS farm irrigation	26.9 ± 1.7 26 ± 1	n.s.		2.3 ± 0.3 2.3 ± 0.1	n.s.	
		Seed No. of 10 Berries		**Year × Treatment**	**Seed Weight of 10 Berries (g)**		**Year × Treatment**
2019	DSS farm irrigation	12.3 ± 0.5 13.3 ± 0.8	n.s.	n.s.	0.42 ± 0.01 0.41 ± 0.01	n.s.	n.s.
2020	DSS farm irrigation	19.3 ± 0.9 17.6 ± 0.4	n.s.		0.63 ± 0.03 0.52 ± 0.02	*	

* and ** are significantly different at $p \leq 0.05$ and $p \leq 0.01$ significant levels, respectively while n.s. = not significant.

In 2019, there were no statistically significant differences in other clusters' components; on the contrary, in 2020, there was a statistically significant difference in the cluster length in favor of the farm irrigation treatment (Table 3). High temperatures near the budburst can reduce the number of flowers [53]. In this case, the number of berries per cluster was not affected by both treatments in 2019; however, in 2020, there was a statistically significant difference in fertility, with a reduction in the number of berries per cluster with the DSS, probably due to the combined effect of high temperature and deficit irrigation (Table 3). Despite the values of the cluster weight, cluster length, number of berries per cluster, and weight of berries being significantly greater for plants irrigated by farm irrigation in 2020, there were no statistically significant differences in yield parameters between both treatments; in particular, the number of clusters per vines and the production per vines on a hectare base were similar for both treatments (Table 4). These results indicate that the application of the DSS for irrigation made it possible to maintain crop production in both seasons, allowing for water savings of 10% in the 2019 and 17% in the 2020 seasons (Table 1).

Table 4. Number of clusters, production per vine, and total soluble solids (TTS) in a Montepulciano vineyard during 2019 and 2020 seasons as affected by irrigation treatment (DSS vs. farm irrigation).

Year	Treatment	No. Clusters per Vine		Year × Treatment	Yield (kg ha^{-1})		Year × Treatment	Water Productivity (Yield/Irrigation)
2019	DSS farm irrigation	20.75 ± 1.87 22.55 ± 2.19	n.s.	n.s.	23,400 ± 2210 22,800 ± 3100	n.s.	n.s.	16.71 14.70
2020	DSS farm irrigation	17.22 ± 2.11 17.66 ± 2.77	n.s.		14,700 ± 1500 16,500 ± 1750	n.s.		10.91 10.15

n.s. = not significant.

3.3. Technological Maturity

The biochemical composition of the grapes from the pre-veraison phase to the post-veraison phase could be influenced by cultivation practices, light, and temperature [54,55]. The total soluble solids, pH, and titratable acidity are the most important parameters to evaluate the ripeness of grapes, which were reported in this study for both treatments and study years (Table 5).

Table 5. Effects of two different irrigation treatments (DSS vs. farm irrigation) on pH, total soluble solids TSS (°Brix), and titratable acidity of grape juice at the time of harvesting in both years of the experiment.

Year	DOY	Treatment	pH		Year × Treatment	TSS (° Brix)		Year × Treatment	Titratable Acidity (g L^{-1})		Year × Treatment
2019	282	DSS farm irrigation	4.05 ± 0.05 3.94 ± 0.10	n.s.	n.s.	21.5 ± 0.30 21.2 ± 0.60	n.s	n.s.	5.05 ± 0.20 5.01 ± 0.30	n.s.	n.s.
2020	280	DSS farm irrigation	2.81 ± 0.07 2.81 ± 0.09	n.s.		23.7 ± 0.34 23.1 ± 0.55	n.s		3.62 ± 0.18 3.65 ± 0.25	n.s.	

n.s. = not significant.

In this study, we found no differences in the content of the TSS between the irrigation treatments in both seasons, in agreement with the findings of Barbagallo et al. [56]. For the titratable acidity, we did not find differences between the irrigation treatments, unlike Barbagallo et al. [56], who found differences in the TA concentrations depending on the irrigation treatment. The data related to the pH (Table 5) indicate that the irrigation treatments had no influence on the pH in both seasons. This was in line with the results of Chaves et al. [57]; however, in contrast to what was reported by Esteban et al. [58], who found differences in the pH based on the availability of water in the soil. According to Hrazdina et al. [59], a different pH could be due to the metabolism of major acids and the accumulation of cations, which lead to salification.

The maturity index, calculated as the TSS/TA ratio, as indicated by Du Plessis and Van Rooyen [60], was similar for both treatments in 2019 (DSS: 4.25; farm irrigation: 4.23) and 2020 (DSS: 3.75; farm irrigation: 3.65). Pinillos et al. [61] reported that the application of deficit irrigation caused changes in the colorimetric index values; in this experiment, there were no statistically significant differences in the colorimetric index values (Table 6).

Table 6. Effect of irrigation treatments (DSS vs. farm irrigation) on colorimetric attributes (L—lightness, bright to dark; A—redness, green to red; B—yellowness, blue to yellow) of the berry skin measured on the side exposed towards the outside of the bunch in both seasons (2019 and 2020).

Year	Treatment	L		Year × Treatment	A		Year × Treatment	B		Year × Treatment
2019	DSS farm irrigation	44.71 ± 0.22 45.07 ± 0.31	n.s.	n.s.	0.45 ± 0.04 0.51 ± 0.06	n.s.	n.s.	1.56 ± 0.16 1.33 ± 0.25	n.s.	n.s.
2020	DSS farm irrigation	29.81 ± 0.51 30.28 ± 0.53	n.s.		−0.08 ± 0.12 −0.04 ± 0.10	n.s.		−3.23 ± 0.30 −2.64 ± 0.23	n.s.	

n.s. = not significant.

4. Conclusions

In arid and semi-arid regions, drought conditions call for the efficient usage of available water. In arid areas like the Puglia region, the continuous monitoring of the soil water status is crucial for an efficient agricultural irrigation system due to the scarcity of irrigation water. Wireless sensors can enhance data availability and be used in decision support systems to facilitate farm irrigation and enable more sustainable water usage (avoiding stress or over-irrigation). In this study, we tested whether the proposed DSS irrigation system, which used 10% and 17% less water than traditional farm irrigation during two consecutive years (2019 and 2020, respectively), could maintain or even improve the productivity and quality of grapes in the studied vineyard. Our tested DSS's important feature was its ability to detect water shortage within the active root zone throughout the irrigation seasons, where irrigation interventions were applied accordingly. Additionally, the farmer was able to receive an alarming notification not only recommending him to start irrigation (when water was not available due to a stress period or when winter precipitation was not adequate) but also to stop irrigation whenever the crop had received enough water to avoid over-irrigation (filling soil pores beyond soil water holding capacity).

The analysis of the SWP data indicated that, despite the overall lower irrigation volumes applied, the vines irrigated following the DSS treatments were generally comparable to the vines irrigated with the farm system in terms of the plant water stress. In addition, most quality and yield parameters obtained under the DSS were comparable to those obtained under the farm irrigation system, with some exceptions. These results indicate the viability of the DSS in maintaining the good production and quality of grapes, with a significant reduction in the irrigation water, despite the limitation of irrigation management of using only the soil moisture parameter. The overall results of this study can provide useful information to growers for the constant monitoring of soil moisture, therefore, applying water only when needed or at strategic times. This two-year study indicates that the DSS for water irrigation management in vineyards can participate in the sustainability effort for managing irrigation water, especially under the arid and semi-arid conditions of the Mediterranean region. However, further studies should be conducted to evaluate the long-term efficiency of the DSS in different agronomic and varietal conditions. Our results can also open the door for further research for a further reduction in irrigation water in the frame of the sustainable use of water resources.

Author Contributions: Conceptualization, G.A.V. and D.S.I.; methodology, G.A.V. and D.S.I.; software, S.P.G.; validation, G.A.V.; formal analysis, S.P.G.; investigation, L.T., G.L., and S.P.G.; data curation, S.A.A., G.D.M., L.T., G.L., and S.P.G.; writing—original draft preparation, S.P.G.; writing—review and editing, S.C., G.L., S.A.A., L.T., G.D.M., D.S.I., and G.A.V.; visualization, S.P.G.; supervision, G.A.V.; project administration, G.A.V.; funding acquisition, G.D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Società Centro Studi Componenti per veicoli SPA CVIT—BOSCH. Upgrade e validazione del sistema di monitoraggio Deepfield—Basic Soil per la gestione di precisione dell'irrigazione.

Data Availability Statement: Data are available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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