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Monitoring Abiotic Stressors in Rainfed Vineyards Involves Combining UAV and Field Monitoring Techniques to Enhance Precision Management

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Abstract: Future climate conditions may jeopardize the suitability of traditional grape-growing areas in the Mediterranean. However, precise vineyard management is a crucial component of adaptation strategies aimed at optimizing resource efficiency, which is essential for sustainable farming practices. A fine-scale characterization, based on the spatial variability of soil's physical–chemical and hydrological traits combined with temporal variability of vine canopy temperature extracted from UAV thermal images has been adopted in a rainfed vineyard of central Italy, for better understanding the impact of soil and climate abiotic factors in the vineyard for planning precision adaptation strategies encouraging sustainable resource use. This study identifies significant soil heterogeneity within the tested vineyard, affecting water retention, nutrient availability, and vine water stress. We combined ground-based measurements with remote sensing-enhanced data spatialization and helped to advocate for site-specific management techniques as short- and long-term strategies (such as canopy management, deficit irrigation, and compost application) to counter climate emergencies, restore soil health, and preserve vine function and economic yields.

Keywords: crop water stress index; leaf removal; nutrient supply; *Vitis vinifera* L.; water retention curve; precision agriculture; soil physical and chemical traits

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1. Introduction

Globally, agriculture accounts for approximately 70% of total water withdrawals [1,2]. In the coming years, agricultural systems will increasingly rely on irrigation due to the effects of climate change, which are expected to become more intense and severe because of rising temperatures, as well as changes in precipitation patterns [3,4] and cloud cover [5]. Furthermore, Mediterranean countries are expected to face increased vulnerability regarding water availability and competition for water use across sectors such as household consumption, energy production, tourism, industrial processes, and agriculture. According to climate scenarios RCP 8.5 and RCP 4.5 [3], grape production will require, on average, 10% more water between 2035 and 2065 [6].

In Italy, grapevines (*Vitis vinifera* L.) are one of the most important crops and are highly affected by hydro-climatic conditions [7]. Soil abiotic stressors are regarded as the most significant environmental factors in viticulture [8–10]. The spatial and temporal variability of factors such as soil, topography, and vine system type (rootstock and cultivar) significantly influences vine water status, as well as grape yield and wine quality. Understanding this variability within the vineyard is essential. More localized data are needed to define site-specific management units and develop flexible management practices to achieve this, providing new opportunities for winegrowers.

Key soil properties for quantifying stressors and detecting vineyard drought indices include (i) soil matric potential, which governs critical processes like water infiltration, evaporation, plant water uptake, and microbial activity [11]; (ii) soil temperature, which is influenced by physical and chemical properties and is strongly affected by water content [12] and soil management practices [13]; (iii) soil electrical conductivity (EC), useful for assessing soil salinization and compaction [14]; (iv) soil depth, an indicator of the depth available for root growth [15]; (v) soil moisture, a measure of surface water availability and groundwater storage [16]; and (vi) plant-available water, defined as the difference between the soil water content at field capacity and the permanent wilting point [17]. Additionally, it is important to characterize the soil texture of the vineyard. According to Kramer & Boyer (1995) [18], soils with loamy to slightly loamy textures are more favorable for vine growth compared to sandy or sandy–loamy textures.

Traditional methods of soil study provide extensive knowledge about soil properties, including biological characteristics (e.g., microbial biomass, earthworms), edaphic factors (e.g., salinity, organic matter, texture), topographic features (e.g., slope, elevation), and climatic conditions (e.g., relative humidity, temperature, rainfall). However, they often lack detailed information on the spatial–temporal variability within the field. To address this limitation, proximal and remote sensing technologies are becoming increasingly important for mapping spatial–temporal variability. Spatial data analysis can integrate information from multiple independent sources to generate new insights, helping winegrowers tackle complex issues. Proximity sensors mounted on remotely piloted unmanned aerial vehicles (UAVs) can quickly assess soil moisture status in both the topsoil and the plants in vineyards. Furthermore, these technologies enable monitoring and management of the spatial variability of soil responses, which can help reduce variations in vine vigor, final berry composition, and wine chemistry [19].

This study aims to define the physical, chemical, hydraulic, and thermal properties of vineyard soils and canopy at the site-specific level and to monitor these properties to guide precision management practices. This approach combines traditional soil survey methods with ground-based surveys and unmanned aerial vehicles (UAVs) to enable precise mapping of thermal stressors in vineyards, facilitating targeted interventions to optimize grapevine health and enhance crop yields. Field surveys and ground-based measurements provide high-resolution data that can validate and calibrate remote sensing observations. This synergy improves the overall accuracy of the data collected, ensuring that remote sensing analyses reflect true ground conditions, and can help refine UAV interpretations related to crop health [20]. The specific objective is to map the abiotic condition in vineyards at a micro-scale (above 1:2500—RESOLUTION OIV-VITI 423-2012 REV1). On-site soil analysis supports the application of ‘the right treatment in the right place at the right time’, thereby promoting sustainable intensification of viticulture through precision soil management and the use of on-farm data collected in the field.

2. Materials and Methods

2.1. Study Area and Experimental Design

The experiment was conducted in 2019 in a commercial rainfed vineyard located in central Italy (42°52′09.19″N, 12°56′37.34″E, upper-left corner of the polygon; 42°51′93.96″N, 12°56′49.41″E, lower-right corner of the polygon) within the Narni Protected Geographical Indication (PGI—D.M. 18.11.1995, G.U. 284 of 05.12.1995) in the Umbria Region. The Narni area has undergone geological evolution associated with the Umbrian-Marchigian Apennines, a mountain range in which the study area is situated. This region became involved in orogenesis starting from the Middle Miocene onward [21]. The initial phases of folding were accompanied by the formation of foreland basins oriented in the Apennine direction, progressively shifting eastward at the expense of the foreland. The sedimentary successions deposited in these basins are characterized by the presence of thick turbidite layers [22]. From the Miocene to the Pliocene and Pleistocene, the Umbrian-Marchigian area underwent a transition from a predominantly marine environment to a continental one. In the region, except for its westernmost part, exclusively continental (lacustrine and marshy) Pliocene sediments are exposed. Pleistocene sedimentation is primarily associated with alluvial and deltaic plains (Tiber basin), as well as lacustrine and marshy environments [23]. They are soils with a very low rainwater retention capacity, making them highly susceptible to water erosion (very high surface runoff), a moderate depth accessible to roots, and poor aeration (https://siat.regione.umbria.it/webgisru/—Soil Map (accessed on 12 December 2024): Pedological Subsystem: Hill of Collescipoli; Pedological Subsystem: b, TER, PTR, OLM, SBI), all soil abiotic factors that combine to increase the level of stress in the vineyard and reduce the berry quality [24]. In addition, these environments can lead to a rich nutrient profile in the soil. Alluvial and deltaic deposits often bring in nutrient-rich sediments, which can enhance vine growth and grape quality. However, excessive nutrients can lead to overly vigorous growth, which might affect grape quality [24].

The study area is situated 120 m above sea level and covers an area of 3 hectares with clay–loam soil. The vineyard consists of the Ciliegiolo variety grafted onto 420A rootstock (15 years old). Ciliegiolo is planted with a spacing of 0.8 m within rows and 2.8 m between rows, resulting in a plant density of 4464 vines per hectare, with rows oriented north-south (Figure 1). The vines are trained on a vertical shoot-positioned cordon trellis with 8 to 10 nodes (bud load) per vine.

The average annual precipitation is 115 mm per year, with an average summer temperature of about 23 °C and a winter temperature of 10 °C (https://www.arpa.umbria.it/ accessed on 23 April 2023). The region has a typical warm temperate climate, characterized by mild and wet winters and fresh to warm summers (https://www.arpa.umbria.it/—accessed on 23 April 2023).

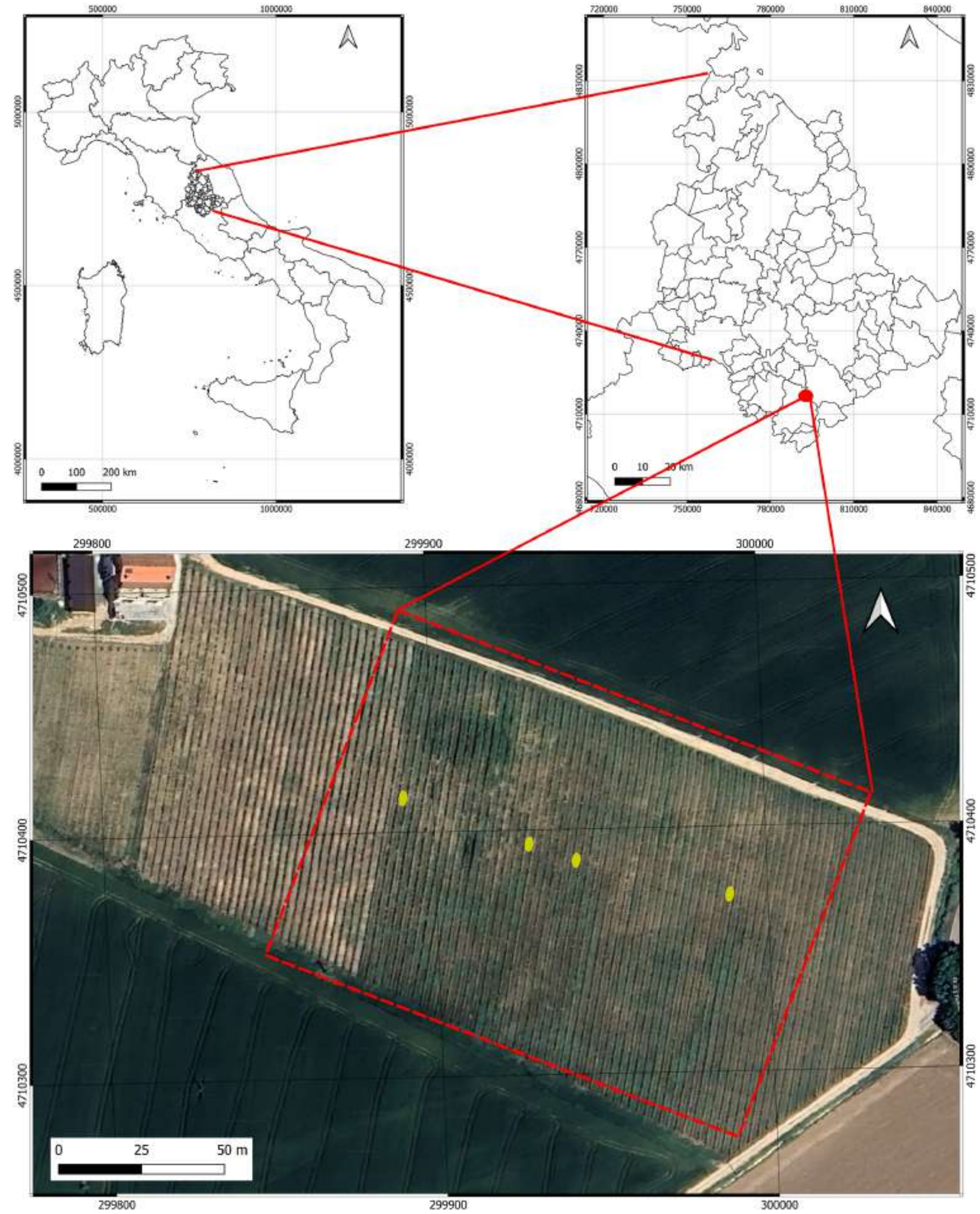

Figure 1. Umbria region (central Italy), highlighting the grape-growing study area (red circle) and the tested vineyard area (red square). The yellow circles indicate the four soil profiles made.

2.2. Traditional Ground-Based Soil Data Collection

Within the study area, four soil profiles were surveyed and characterized for their physical, chemical, and hydrological properties. Each soil profile, measuring 50 × 1.50 × 2 m, was described, photographed, and classified according to the international soil classification system of the Soil Survey Staff (1998) [25] and USDA Soil Taxonomy [26]. Within the soil profiles, soil samples were taken from three horizons (0.0–0.30 m; 0.30–0.60; 0.60–0.90) starting with the upper layer, where the main mass of fine roots [27], responsible for the majority of water uptake, is concentrated. These samples were analyzed to determine their physical, chemical, and hydrological properties. The soils are predominantly coarse-textured colluvium derived from alluvial sediment and are classified as Haplustept according to soil taxonomy [28].

The collected soil samples were sieved (removing particles less than 2 mm in size) and dried. Subsequently, the samples were analyzed to determine soil texture, following the standard methodology proposed by the Soil Survey Staff (1998) [25]. The investigated terrains can be categorized as follows:

P1: Typic Haplustept fine loamy, mixed, mesic (thermic)

P2/P3: Typic Haplustept fine, mixed, mesic (thermic)

P4: Typic Haplustept coarse loamy, mixed, mesic (thermic)

Soil pH was measured in deionized water using a glass electrode at a soil/water ratio of 1:2.5 [29]. Organic nitrogen reserves (total nitrogen—TN, g/kg) were determined using Kjeldahl's procedure. Apparent electrical conductivity (ECa, dS/m), soil available phosphorus (P, mg/kg), and soil organic matter (g/100 g) were measured according to FAO Standard Operating Procedures (SOPs). In addition, the following data were determined: effective cation exchange capacity (CEC) according to the ISO 11260:2018 standard procedure [26]; the four most abundant exchangeable cations in the soil—calcium (Ca, meq/100 g), magnesium (Mg, meq/100 g), potassium (K, meq/100 g), and sodium (Na, meq/100 g)—following the method of Pleysier and Juo (1980) [28]; total $CaCO_3$ concentration ($TCaCO_3$, g/kg) according to Demolon and Leroux (1952) [30]; and the carbon-to-nitrogen (C/N) ratio, computed considering that soil organic matter (SOM) is composed of a stoichiometric percentage of 58% carbon (C = SOM (%) $\times$ 1.72) and the ratio Mg/K. Finally, gravimetric moisture values and the water retention curve were determined using Stakman's sandbox technique [31], following the matric potentials outlined in Richards' method (1948) [32]. The gravimetric moisture percentage was determined at -33 kPa to establish the field capacity (FC). The FC technique employs pressure extractors with ceramic plates to measure water retention at -33 kPa. Soil moisture is extracted from soil samples by increasing air pressure in the extractor until the desired pressure is reached. The porous ceramic plate serves as a hydraulic link, allowing water to move from the soil to the exterior of the extractor. The time required to reach equilibrium ranges from 14 to 20 days [33].

The permanent wilting point (PWP) (pF 4.2, -1500 kPa) utilizes a similar approach to FC but employs a membrane instead of a ceramic plate, allowing for quicker equilibrium. Equilibrium is reached when the flow of water from the exterior ceases [34]. The available water capacity (AWC) was calculated using the following equation:

$$AWC = FC - PWP \tag{1}$$

2.3. Proximal Soil Sensing

Soil temperature, electrical conductivity (EC), and volumetric water content (VWC) were determined using time domain reflectometry (TDR) (FieldScout® TDR 250, Aurora, IL, USA). TDR is an electronic, rapid, and non-invasive tool that operates on radar principles, transmitting signals into the medium and collecting reflected signals. Additionally, the TDR 250 features a temperature sensor at the base of the anchoring points of the sampling tips, allowing for the determination of soil temperature.

Within the study area, 40 sampling points were selected for soil moisture measurement using portable TDR with 18-cm-long probes. These sampling points were georeferenced and measured periodically throughout the 2019 season to assess spatial–temporal patterns under various atmospheric conditions and during critical growth stages of grapevines: BBCH 065—flowering; BBCH 079—berries touching; BBCH 089—ripening of berries [35]. A real-time kinematic (RTK) global navigation satellite system (GNSS) Leica CS10 model (Leica Geosystems, Switzerland), with an accuracy of 1 mm, was used to georeference all soil samples. The TDR data were mapped through spatial interpolation using the Kriging technique, which estimates data values at unknown points based on values at known points [36]. Spatial distribution maps were created using QGIS (3.28.2). Advanced geostatistical methods, specifically Kriging, were employed for all spatial interpolation to predict variability. In the vineyard study area, thermal images were acquired using unmanned aerial vehicles (UAVs). The DJI MATRICE 600 RTK UAV, equipped with an integrated high-performance RTK module, was utilized to capture thermal images, providing high-precision positioning without the need for a ground-based base station. The DJI MATRICE 600 is a hexacopter with a maximum transmission distance of 4 km and a maximum flight time of 38 min, with a load capacity of approximately 8 kg. The camera used was the Zenmuse XT (DJI, Shenzhen, China, powered by FLIR), which is compatible with the M600 RTK (DJI, Shenzhen, China) (Figure 2).

Figure 2. Images of (**a**) the unmanned aerial vehicle (UAV) (DJI M600), and (**b**) the thermal infrared sensor (Zenmuse XT).

The camera was set to capture images at a 90° tilt with a shooting interval of 3 s during the image collection phases. UAV campaigns were conducted on clear-sky days from berry set to harvest, in accordance with BBCH stages. Flight missions were planned using the Ground Station Pro app (DJI GS Pro, Nanshan District, Shenzhen, China). Each flight lasted approximately 7 min, covering an area of 1.5 hectares at a nominal speed of 4 m/s and an altitude of 30 m, during which the camera acquired nadiral images with 90% frontal and side overlap.

For calibration of the thermal images, four ground reference panels (GRPs) measuring 0.60 × 0.60 m were positioned along the rows. These panels consisted of two plastic panels covered with black vinyl tape and two white Teflon® panels. The Leica CS10 model GNSS (Leica Geosystems, Heerbrugg, Switzerland) was used to capture the coordinates of the GRPs.

2.4. Analysis of Thermal Images

The thermal images have been processed for obtaining a digital (thermal) orthophoto map [37–39]. The acquired thermal images were calibrated using FLIR Thermal Studio Pro 4.5.6 pix (Pak Shek Kok, Shatin, N.T. Hong Kong). The processed radiometric (RJPG) images were then imported into Pix4DMapper, a drone photogrammetry software (Prilly, Switzerland). Pix4D Mapper 2.083 software utilizes radiometric metadata from RJPGs to identify key points and tie points, enabling the creation of thermal orthomosaics. The result of this procedure is a thermal orthophoto that can be imported into QGIS for further analysis. To verify the accuracy of the temperatures measured by the UAV camera against actual soil temperatures, ground reference panels (GRPs) measuring 60 × 60 cm were positioned, with emissivity values recorded: two white Teflon panels (emissivity 0.94) and two black panels (emissivity 0.96). For each GRP, three temperature measurements were taken using an RS PRO RS-9862S Infrared Thermometer, Cardiff, Wales (±0.5 °C, emissivity 0.10–1.00). Image calibration was conducted by generating a linear correlation [40] between the temperature data collected from the GRPs and the corresponding temperatures on the thermal images from the drone.

2.5. Vegetation Index Calculation

The Crop Water Stress Index (CWSI) was calculated among the indices derived from thermal data. The CWSI is the most widely used [41–43] and has been found to correlate with irrigation volumes around midday [44,45].

In general, the CWSI is computed using the following equation:

$$CWSI = \frac{Tc - Twet}{Tdry - Twet} \quad (2)$$

T_c (°C) represents the measured canopy temperature, while T_{wet} and T_{dry} denote the lower and upper boundary temperatures, respectively. T_{wet} corresponds to a fully transpiring leaf with open stomata, and T_{dry} represents a non-transpiring leaf with closed stomata. Both T_{wet} and T_{dry} were measured directly in the field. To determine T_{dry}, the leaves of two vines were coated on both sides with Vaseline to prevent transpiration and eliminate cooling caused by water loss, thereby simulating the physiological response of a leaf under water stress. T_{wet}, on the other hand, was obtained by thoroughly wetting both sides of the leaves of another two vines. Measurements were taken 30 min after applying Vaseline for T_{dry} and 20 s after wetting the leaves for T_{wet}.

2.6. Statistical Analysis

Statistical comparisons among soil abiotic factors were evaluated using one-way Analysis of Variance (ANOVA) and Tukey's multiple comparisons at a 0.05 significance level. To further explore the relationship among soil characteristics, a regression model was employed to assess correlations between available water content (AWC) at field capacity (FC) and electrical conductivity (EC). Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were used to identify which soil abiotic factors contributed to the characterization of soil profile differences and to group the soil abiotic stressors for all horizons. Statistical analysis was conducted using XLSTAT software Version 2016.02.28451 package.

3. Results

3.1. Soil Chemical, Physical, and Water Traits

The four exploratory shafts revealed variations in depth and development of horizons (per slopes and surface erosion): a shallow horizon with development influenced by agronomic management (e.g., soil tillage), and two deeper horizons extending from 1.00 to 1.20 m.

The greatest differences are evident from the horizon AB/B (0.3–0.6 m). P1 presented a similar texture between the horizons (clay–silt), P2 and P3 increased the clay content in the deeper horizon, while P4 presented a shallow soil (like P1) but increased the sand content in the deeper horizon (0.3–0.6 m). The soil pH values ranged from 8.3 to 8.9 and were classified as moderately alkaline (ranging from 7.9 to 8.4) and strongly alkaline (ranging from 8.5 to 9.0) (Table 1) [46]. When the soil pH varies from 6 to 7 it is the most suitable soil pH in terms of vine cultivation for plant growth, and nutrients are readily available [47]. The SOM contents in the tested vineyard showed very low values.

TN showed from medium–high value in the first horizon (0–0.3 m) to medium in the following horizons. $CaCO_3$ content exceeded in all horizons 200 ppm and characterized them as calcareous soils, which are frequently characterized by the low bioavailability of plant nutrients due also to the alkaline pH. The available phosphorus contents of soils showed a wide variation across soil horizons, where values ranged between 2 and 23 mg·kg^{-1}. CEC showed limited variation across the soil horizon, with the lower value in P4 horizon AB, according to EC, that also showed lower value in P4 horizon AB, where sand content reached 81% (Table 1). Based on the results obtained, the soil samples analysed can be defined as non-saline [14,48,49]. In addition, EC showed a linear relationship with water content at FC, due to the high sensitivity of EC to water content.

Table 1. Chemical and physical properties for four soil pits (P1 ÷ P4).

Chemical and Physical Properties	P1			P2			P3		P4	
	A1	AB/B	B/C	A	B/C	C/R	A1/B	B/C	A1	AB
	0–0.30 m	0.30–0.60 m	0.60–0.80 m	0–0.30 m	0.30–0.60 m	0.60–1.00 m	0–0.30 m	0.30–0.60 m	0–0.30 m	0.30–0.60 m
Sand [%]	29.6	29.8	43.1	28.6	30.5	23.5	19.2	13.4	21.6	81
Silt [%]	33	36.6	25.9	30.5	31.3	30.4	36.9	30.5	34.2	3.7
Clay [%]	37.4	33.6	31	40.9	38.2	46.1	43.9	56.1	44.2	15.3
pH	8.3	8.4	8.5	8.5	8.5	8.4	8.4	8.3	8.3	8.9
EC [dS·m^{-1}]	0.11	0.09	0.08	0.11	0.1	0.12	0.12	0.14	0.12	0.06
Organic matter [SOM] [g·100 g^{-1}]	0.67	<0.34	<0.34	<0.34	<0.34	<0.34	0.78	<0.34	1.14	<0.34
Total nitrogen (TN) [g·kg^{-1}]	0.76	0.41	0.38	0.51	0.43	0.51	0.8	0.62	1.07	0.32
Total $CaCO_3$ ($TCaCO_3$) [g·Kg^{-1}]	309.4	392.9	379.8	292.4	305.3	241.9	227.9	35.6	320.4	308.2
Available phosphorous (P) [mg·Kg^{-1} o ppm]	23	11	10	5	3	9	3	8	22	2
Cation exchange capacity (CEC) [meq·100 g^{-1}]	24.4	20.4	22.8	27.3	27	27.8	29.9	32.2	25.1	9.2
Calcium (Ca) [meq·100 g^{-1}]	22.98	19.71	21.39	26.61	24.65	26.11	33.56	35.71	26.26	8
Magnesium (Mg) [meq·100 g^{-1}]	0.9	0.4	0.34	0.53	0.54	0.58	1	0.81	1.09	0.13
Potassium (K) [meq·100 g^{-1}]	0.47	0.24	0.28	0.21	0.21	0.25	0.37	0.07	0.04	0.05
Sodium (Na) [meq·100 g^{-1}]	0.09	0.08	0.08	0.1	0.1	0.1	0.11	0.13	0.09	0.07
Ratio Mg·K^{-1}	1.9	1.7	1.2	2.5	2.6	2.3	2.7	11.6	27.3	2.6
Ratio C·N^{-1}	5.1	2.7	2.9	3.3	2.1	2.9	5.6	2.7	6.2	2.5

The plant available water content was calculated and reported in Table 2, in conjunction with the soil air capacity (SAC) (defined as the difference between water content at saturation and water content at field capacity (pF 2.5). It corresponds to the amount of air that the soil can provide at the time of maximum moisture (i.e., at field capacity)) and bulk density (bulk density was calculated by measuring the water content at the wilting point by drying the sample in an oven at 105 °C for 24 h. The weight obtained, related to the volume of the undisturbed sample, is the bulk density). Moreover, soil moisture retention curves for the four soil profiles are reported in Figure 3.

SAC values showed all soil horizons to be poorly aerated especially in the upper horizons of P2 and P3. Ferreyra et al. [50] classified the soil air capacity as limited for values of 15% or less. AWC and the relative water retention curves (Figure 3) differ on whether samples came from a superficial or sub-superficial horizon (Table 1). Higher soil moisture (%) at FC was found in subsurface horizon P2 > P3 > P4 > P1 (44.4, 35.3, 27.4, and 24.5—Figure 4). The P1 surface horizon showed a lower AWC (5.6%) than all other surface horizons. Therefore, the P2 and P3 showed higher moisture content compared to the P4 and P1 due to higher contents of fine material (silt, clay).

Table 2. Bulk density, soil air content—SAC(%) and available water capacity—AWC (%) of soil horizons (shallow and deep horizons).

Soil Horizon	Bulk Density (g cm^{-3})	SAC (%)	AWC (%)
P1 A1	1.0	29.4	5.6
P1 AB/B	1.2	24.7	7.9
P2 A	1.6	9.4	14.0
P2 B/C	1.2	20.9	14.5
P3 A1/B	1.3	20.7	9.1
P3 B/C	1.5	14.1	13.7
P4 A1	1.3	18.9	11.5
P4 AB	1.4	35.0	4.7

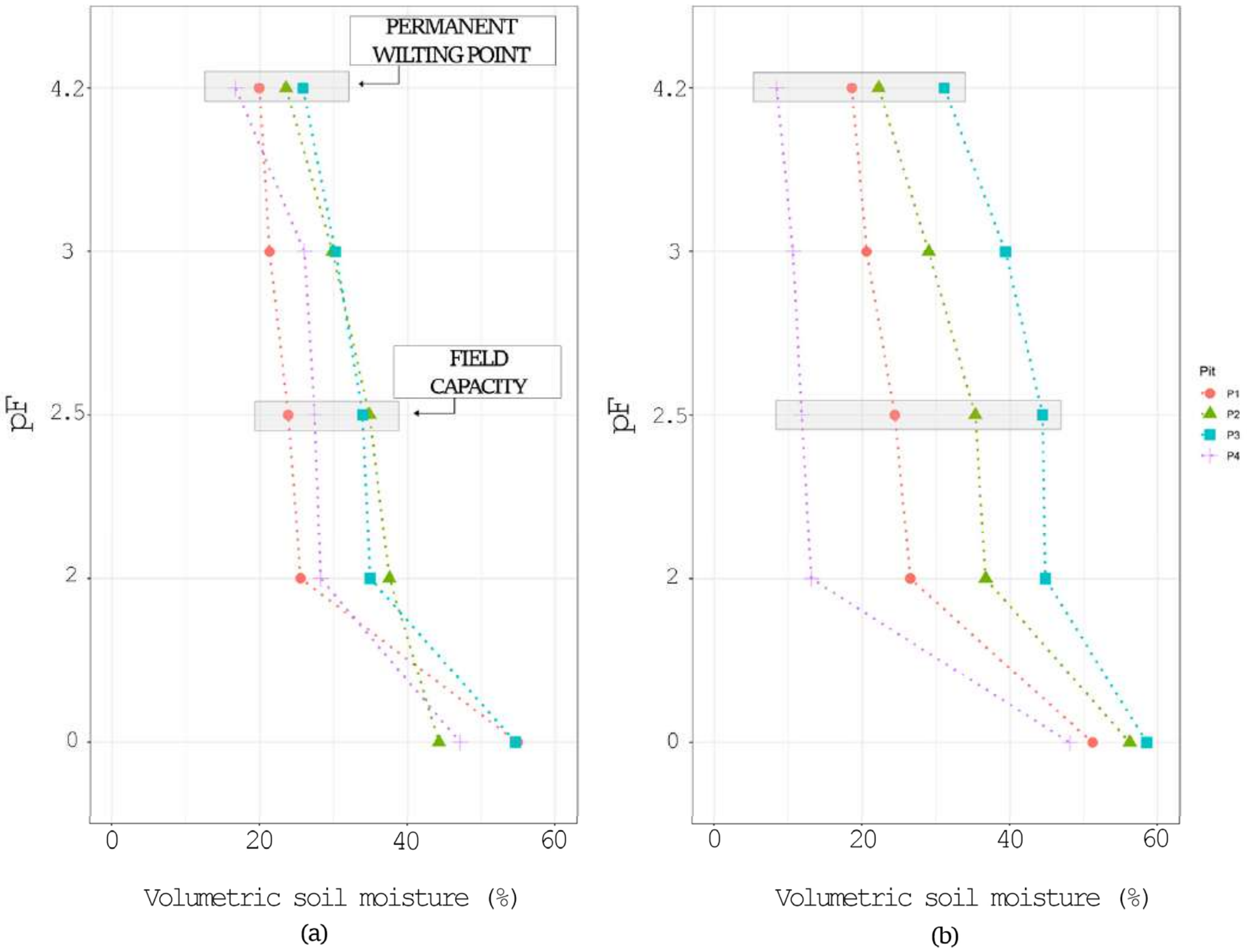

Figure 3. Soil moisture retention curves for four soil profiles (P1–P4) and for the surface (**a**) (0–0.3 m) and deepest (**b**) (0.3–0.6 m) horizons.

For deep horizons, soil moisture at PWP (Figure 3) showed higher values in P3 > P2 > P1 > P4 (31.1%, 22.2%, 18.6%, and 8.4%). P1 and P4 showed the lowest moisture content plant-available (7.9 and 4.7, respectively) and the P4 deep horizon stood out for being the only one with a sandy texture (Table 1).

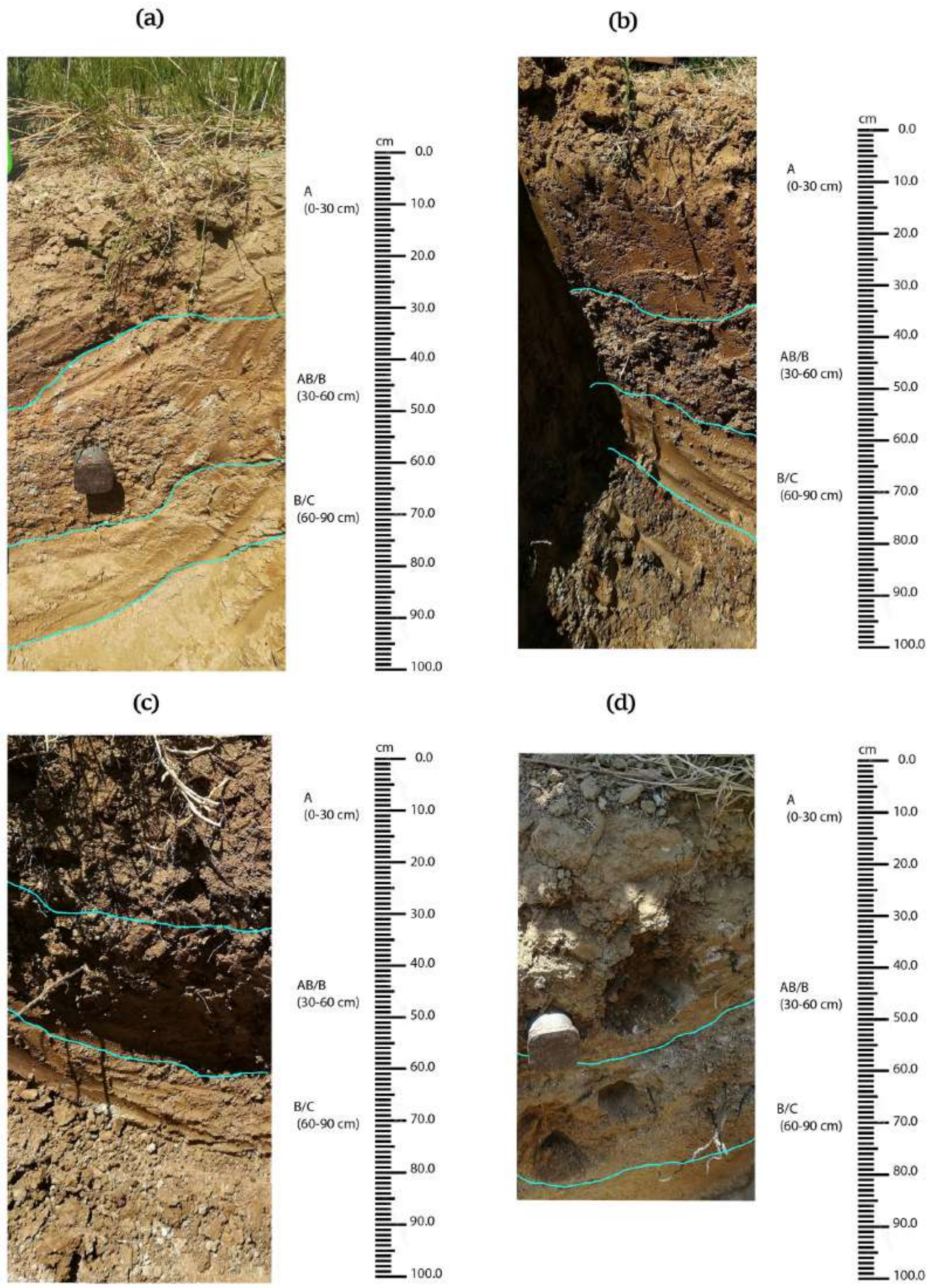

Figure 4. Four soil pits ((**a**) P1, (**b**) P2, (**c**) P3, and (**d**) P4), horizons individuation (line in figures) and soil texture classification.

3.2. Soil Thermal Characterization

Among the indices of abiotic soil stress, soil temperature was also determined using the TDR probe and the UAV's thermal imaging camera and showed a linear regression (R^2 = 0.6). The quantitative data of statistical significance are shown in Figure 5.

Soil temperature showed significant differences among soil profiles during the season. P4 exhibited the highest values in August during the berry ripening (BBCH 089) and the lowest one in July after a rainy period (BBCH 079).

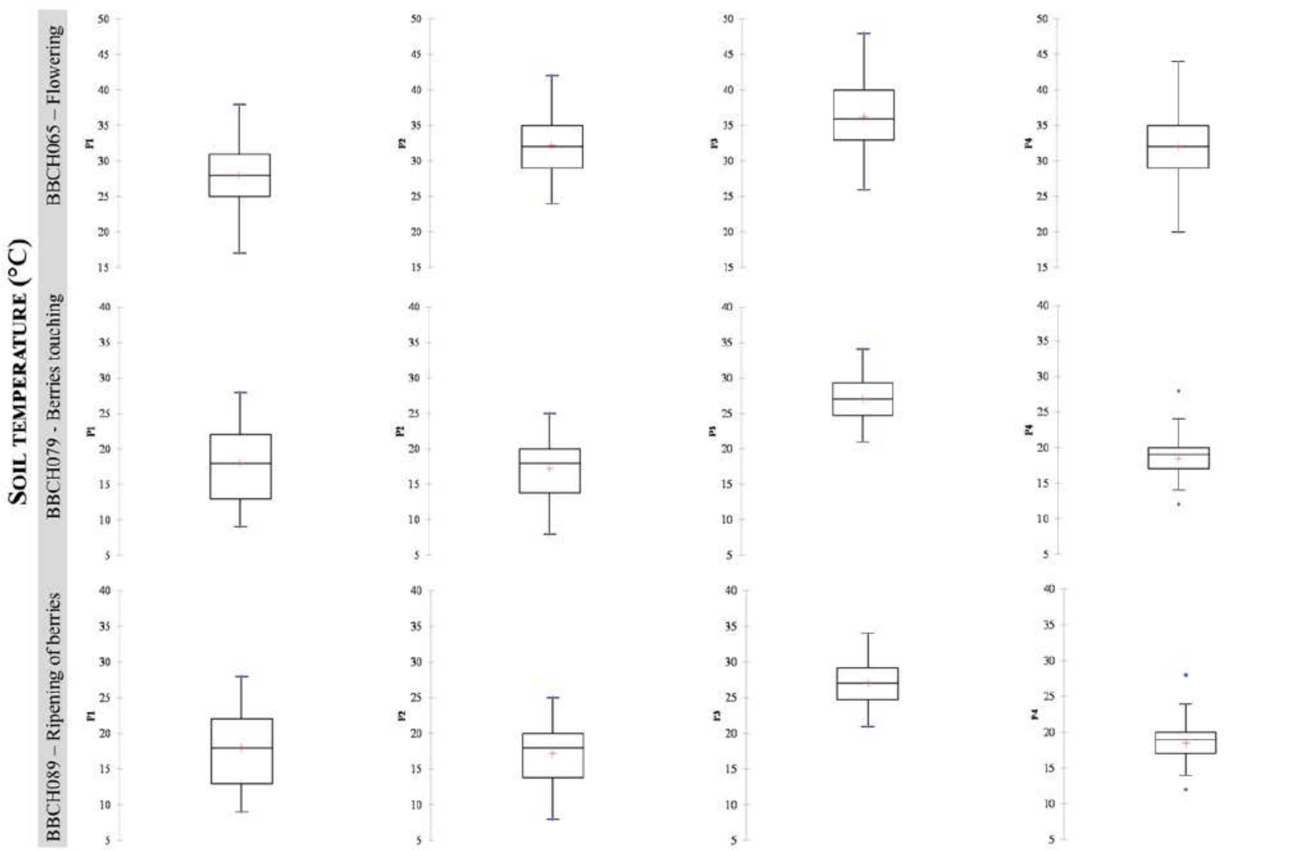

Figure 5. Box plot graphs show soil temperature (°C) spread for soil profiles (P1–P4) during the phenological stages (BBCH 065, BBCH 079, and BBCH 089).

Extreme thermal events are crucial stressor factors during berry ripening, as shown by CWSI measurements (Figure 6). Vines cultivated in P4 are subjected to extreme canopy temperatures combined with higher soil temperature and lower soil AWC at FC and PWP. The CWSI values varied in amplitude over the three dates (June—BBCH 065; July—BBCH 079; August—BBCH 089) and were related to the soil profile, as also shown by PCA analysis (Figure 7a,b).

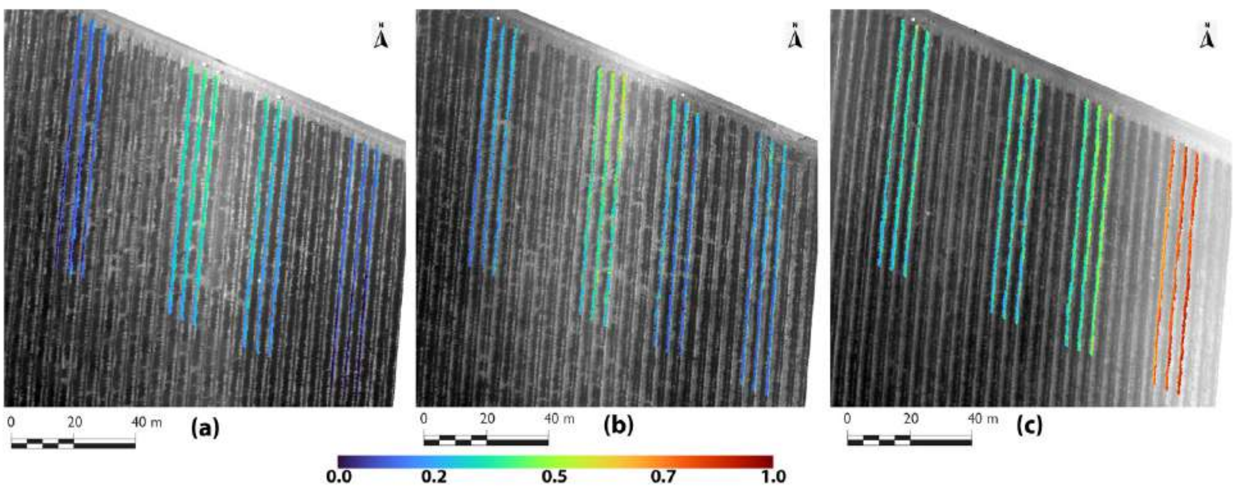

Figure 6. CWSI for the tested area of the vineyard, (**a**) June; (**b**) July and (**c**) August.

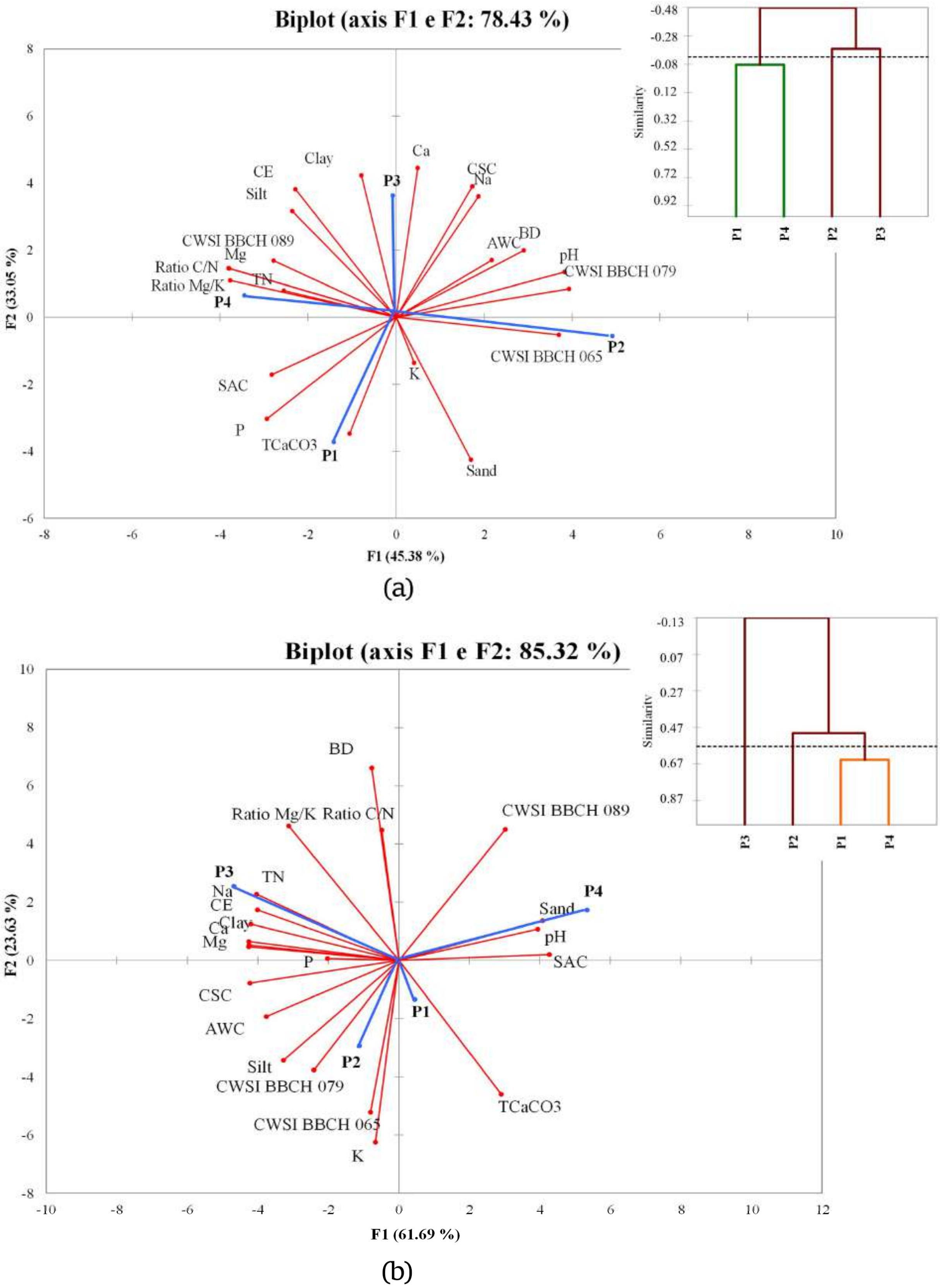

Figure 7. Factoring loadings and cores along principal components F1 and F2 with similarity dendrograms (small square) of the investigated soil profile (P1–P4) obtained performing PCA and HCA using plant water stress (CWSI) and soil surface (**a**) and subsurface (**b**) metrics.

3.3. Multivariate Statistical Analysis of Abiotic Edaphic Factors

PCA was performed using all measured soil traits for both surface and subsurface layers (Figure 7), as well as the Crop Water Stress Index (CWSI) for the tested vines located near the soil profiles. The analysis was conducted at three phenological stages of the vines: BBCH 065 (flowering), BBCH 079 (berry development), and BBCH 089 (berry ripening). The PCA results revealed that the first two principal components accounted for 78.4% and 85.3% of the total variance for surface and subsurface soil indicators, respectively, and the plant water stress analysis. For the soil surface, the PCA highlighted a clear gradient along the first axis (F1) that was strongly associated with the CWSI values. Negative F1 values corresponded to higher vine water stress, reflecting the relationship between soil conditions and plant physiological responses. In particular, P4 was positively correlated with the factors driving F1 and negatively correlated with available water content (AWC), particularly noticeable in quadrant I (CWSI—BBCH 089). This finding underscores the strong influence of soil water-holding capacity on vine water status during critical phenological stages. The second axis (F2) was associated with a gradient of sand content in the soil surface layer, suggesting that soil texture significantly influenced water availability and stress patterns. For the subsurface soil, the PCA scores for soil metrics and vine water stress (CWSI) along the first and second principal components revealed a distinct gradient. The first axis (F1) was predominantly related to Soil Organic Carbon (SAC) and sand content, indicating their combined influence on subsurface water dynamics. P1 and P4 profiles exhibited similar loading factor patterns across all depths, while P2 and P3 formed a distinct group in the cluster analysis conducted after PCA. Interestingly, while P2 subsurface horizons demonstrated similarities to P1 and P4, they were more divergent from P3. This grouping reflects variations in soil properties, such as organic carbon content and texture, which may drive differences in water stress responses among vines. These findings emphasize the complex interactions between soil physical and chemical properties and vine water stress across phenological stages. The PCA not only clarified the relationships among variables but also provided practical insights into how specific soil traits, such as water retention capacity and sand content, influence vine performance under different stress conditions. These results can inform site-specific management strategies aimed at optimizing vineyard water use efficiency and improving resilience to environmental stressors.

4. Discussion

Global environmental and agricultural policies place healthy soils at the core of efforts to achieve climate neutrality, foster a resilient environment, and ensure sustainable food systems. A healthy soil is soil that performs and optimizes soil functions [51] by promoting high yields and quality crops, facilitating effective water infiltration and storage capacity, efficiently retaining and recycling nutrients while meeting crop nutrient demands, sequestering carbon and minimizing greenhouse gas emissions, and fostering diverse microorganisms and robust biological activity [51]. The capacity of the soil to perform these functions can be assessed using a range of chemical, physical, and biological indicators of soil health, which could also be useful in directing technical practices towards multi-functional agroecosystems [52].

Although soil and its health are considered crucial factors in sustaining ecosystems, food security, and climate regulation [53], many agronomic techniques adopted in agriculture and viticulture as concrete solutions that support agroecosystems in transitioning towards sustainable intensification (SI), aligning with the objectives of the Sustainable Development Goals [54], do not include a detailed understanding of soil properties, particularly their spatial heterogeneity. SI can only be realized by adopting suitable agricultural and eco-friendly practices that rely on precise information regarding soil's physical and chemical characteristics [55], along with their spatial distribution (maps). In the absence of this information, the principles of precision agriculture cannot be effectively implemented [56].

Vitis vinifera L. is not particularly sensitive to soil sickness, but some soil characteristics can result in limited abiotic conditions which affect vine growth and grape ripening through temperature, water, and minerals [57–59]. Soil temperature significantly impacts vine phenology, while limited water supply restricts shoot and berry growth, essential for high-quality red wine production. Available water content significantly affects soil nutrient availability, microbial activity [60–62], and vine water status, which influences secondary metabolites like polyphenols and aroma compounds [57].

When abiotic soil conditions and climatic limitations work together, they lead to increased negative effects on the eco-physiological responses of the vine [63] increasing heterogeneity in canopy traits, grape quality, ripening, and yield.

This study aimed to underline the need to increase the knowledge of within-vineyard soil health status and its heterogeneity in the vineyard, starting from some soil abiotic traits that, combined, could be considered to identify within-vineyard management zones useful to address specific management practices helping to restore soil quality and health and to improve the sustainability of viticultural sectors.

The results confirmed the critical conditions of vineyard soils concerning fertility, water available to the vine, and summer abiotic stress factors, which determine the decrease in soil capacity for *Vitis vinifera* L. under Mediterranean conditions.

The soil profiles of the tested vineyard were classified as having very low soil organic matter (SOM) content. Optimal SOM levels for vine-growing soils are typically between 2% and 3% [21,64,65], highlighting that most European vineyards are characterized by soils with low fertility. Soils with compromised quality and health indicators do not fulfil all their ecological functions [66], compromising the sustainability of agroecosystems, also in terms of plant balance, yield, and berry quality [67]. SOM plays a crucial role in water retention [68,69], largely determined by soil texture [65]. The tested vineyard exhibited high heterogeneity in soil texture, particularly across different soil depths and horizons. Notably, soil sand content emerged as a key factor influencing water retention properties, as it significantly affects permanent wilting point (PWP) and available water content (AWC) [64]. All soil profiles, probably as a result of conventional soil management combined with the geo-pedological nature of the soil, showed a reduction of porosity, aeration and organic matter that directly and indirectly damaged the soil's biological community, resulting in a decrease in the availability of water, oxygen, nutrients, and mutualistic organisms for vine roots [66].

AWC and SAC are also sensitive to soil temperature [65], which influences the grapevine cooling process (transpiration) and canopy growth. As soil moisture and AWC decrease in the rhizosphere, transpiration is reduced, leading to an increase in the vine's canopy temperature [42–44]. Soil horizons with low water retention capacity predominantly, as seen in profile P4, have a coarse-sand texture. This type of soil is not ideal for vineyards in semi-arid climates [64], and specific adaptation strategies must be implemented to mitigate the multiple summer stresses on both soil and vine. A widely adopted method to improve the health of soils poor in organic matter and under limiting conditions due to abiotic soil and climate factors is the application of compost (intra-row and inter-row). It could be considered an adaptation and mitigation technique [] to counteract the effect of climate change because it works in the short and in the long term to improve SOM [68,69]; increase total N, absolute amounts of organic N, and inorganic N from mineralization [51,69]; influence P dynamics by providing a source of mineral and organic P [51,69]; improve soil aggregation, infiltration, and water holding capacity; reduce bulk density [51,70]; and, although not always, increase the size of microbial biomass [71], resulting as a potential C sequestration practice [69].

In this grape-growing area, with its semi-arid climate [67], low soil water content will exacerbate heat anomalies and extreme thermal events [72–74]. Mapping the spatial distribution of some soil traits, such as sand content, has become crucial to adopt strategies in the short term to preserve the vine sector's AWC, soil temperature, and CWSI in both surface and subsurface horizons which are recommended as important tools for soil management [64]. In particular, EC shows a linear relationship with water content at field capacity (FC), and according to some authors [75,76], it could serve as a proxy for water content only at FC. EC is influenced by a combination of physical and chemical soil properties, including clay content, soil water content, and soil temperature, and is also affected by farm soil management practices [14]. Evaluating soil spatial heterogeneity, such as through soil profiles, texture, and electrical conductivity maps, is essential for optimizing fertilization and irrigation practices. Findings showed clay to clay—loam texture had a significant influence on water retention properties [77], while on the other hand, silt content also impacted soil water retention at field capacity (FC), as it helps regulate pore distribution and improve AWC. This demonstrates that the soil surface horizons in the vineyard varied widely and were strongly influenced by both soil physical–chemical traits and abiotic factors. Together with best management practices, irrigation demands have been increasing to mitigate effects of environmental stress in Mediterranean grape growing areas. Here, improved knowledge not only on the ecophysiology and genetics of the vine [63], but also on the abiotic factors of the soil and canopy, is crucial for precise water resource management aimed at reducing water consumption in the vineyard. The data collected can then be used for the development of irrigation below evapotranspiration losses (deficit irrigation) to contribute to water-saving and efficient use of water by the plant [78].

PCA and clustering analysis revealed high heterogeneity in soil abiotic indices across the studied vineyard, reflecting the varying and limited water conditions for the vines in the field, and highlighting the need for different strategic management practices.

Taken together, the findings highlight the importance of site-specific information on vineyard soils and the mapping of abiotic stressors at both the vineyard and vine scales. Aerial and portable devices can serve as effective soil management tools in this context.

5. Conclusions

The transition to environmentally sustainable agroecosystems must begin with site-specific knowledge of abiotic edaphic traits. This knowledge must then be used to implement the most appropriate climate change adaptation and mitigation strategies, both in the short and long term. Findings demonstrate how fine-scale mapping of soil traits enables the identification of heterogeneous conditions in the physical, chemical, and hydraulic properties of the soil. These maps could also be used for site-specific hydrologic model parameterization, taking into account small-scale spatial variability in soil properties, and can help reproduce micro-zonation at the farm and vineyard level, leading to more realistic predictions of spatially and temporally distributed water flows. Precise and spatial information on soil multifunctional data would be highly useful for growers in predicting soil abiotic factors. Considering that soil and abiotic data are dynamic over time, an approach based on them can be used for the purposes of differential management, identification of homogeneous areas, and sampling, while the use of proximity sensing can help determine the presence and levels of abiotic stresses during the season and guide prompt intervention with the most suitable agronomic technique. UAV techniques can significantly reduce the time and costs associated with data collection, but the main aim of this study focused on targeted zones in a vineyard (within-vineyard management zones) for detailed study while leveraging remote sensing to gather broader context. This approach can streamline research processes, allowing for quicker responses to emerging issues, such as environmental changes or resource management challenges. Taken together, data showed that this integrated approach enhances the robustness, relevance, and efficiency of research and practical applications across various domains.

This could aid in adapting short- and long-term strategies to address climate emergencies, identifying optimal environmental conditions, selecting suitable varieties and rootstocks, differentiating soil management practices, and improving canopy management. It would also help restore soil health, preserve natural resources, and enhance economic outcomes. Further research is needed to explore the spatial variability of soil abiotic properties and assess their impact on vine performance.

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References

1. European Environment Agency (EEA). Improvement of Irrigation Efficiency. Climate-ADAPT. Available online: https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/improvement-of-irrigation-efficiency (accessed on 12 November 2022).
2. World Bank. Water in Agriculture. Available online: https://www.worldbank.org/en/news/infographic/2023/07/26/water-in-agriculture (accessed on 18 October 2022).
3. Pachauri, R.K.; Allen, M.R.; Barros, V.R.; Broome, J.; Cramer, W.; Christ, R.; van Ypserle, J.P. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2014; p. 151.
4. Sulser, T.; Wiebe, K.D.; Dunston, S.; Cenacchi, N.; Nin-Pratt, A.; Mason-D'Croz, D.; Robertson, R.D.; Willenbockel, D.; Rosegrant, M.W. *Climate Change and Hunger: Estimating Costs of Adaptation in the Agrifood System*; International Food Policy Research Institute (IFPRI): Washington, DC, USA, 2021.
5. Sanchez-Lorenzo, A.; Enriquez-Alonso, A.; Calbó, J.; González, J.-A.; Wild, M.; Folini, D.; Norris, J.R.; Vicente-Serrano, S.M. Fewer Clouds in the Mediterranean: Consistency of Observations and Climate Simulations. *Sci. Rep.* **2017**, *7*, 41475. [CrossRef] [PubMed]
6. Jones, G.V.; Edwards, E.J.; Bonada, M.; Sadras, V.O.; Krstic, M.P.; Herderich, M.J. Climate Change and Its Consequences for Viticulture. In *Managing Wine Quality*, 2nd ed.; Reynolds, A.G., Ed.; Woodhead Publishing: Woodhead, UK, 2022; pp. 727–778.
7. Levantesi, S. Italy Must Prepare for a Future of Chronic Drought. *Nat. Italy* **2022**. [CrossRef]
8. Masia, S.; Trabucco, A.; Spano, D.; Snyder, R.L.; Sušnik, J.; Marras, S. A Modelling Platform for Climate Change Impact on Local and Regional Crop Water Requirements. *Agric. Water Manag.* **2021**, *255*, 107005. [CrossRef]
9. Koundouras, S.; Marinos, V.; Gkoulioti, A.; Kotseridis, Y.; van Leeuwen, C. Influence of Vineyard Location and Vine Water Status on Fruit Maturation of Nonirrigated Cv. *Agiorgitiko (Vitis vinifera L.). Effects on Wine Phenolic and Aroma Components. J. Agric. Food Chem.* **2006**, *54*, 5077–5086.
10. Guix-Hébrard, N.; Voltz, M.; Trambouze, W.; Garnier, F.; Gaudillère, J.P.; Lagacherie, P. Influence of Watertable Depths on the Variation of Grapevine Water Status at the Landscape Scale. *Eur. J. Agron.* **2007**, *27*, 187–196. [CrossRef]
11. Campbell, G.S. *Soil Physics with BASIC: Transport Models for Soil-Plant Systems*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 1985.

12. Tesic, D.; Woolley, D.J.; Hewett, E.W.; Martin, D.J. Environmental Effects on Cv. Cabernet Sauvignon (*Vitis vinifera* L.) Grown in Hawke's Bay, New Zealand: 1. Phenology and Characterisation of Viticultural Environments. *Aust. J. Grape Wine Res.* **2002**, *8*, 15–26. [CrossRef]
13. Steenwerth, K.; Belina, K.M. Cover Crops and Cultivation: Impacts on Soil N Dynamics and Microbiological Function in a Mediterranean Vineyard Agroecosystem. *Appl. Soil Ecol.* **2008**, *40*, 370–380. [CrossRef]
14. Corwin, D.L.; Lesch, S.M. Apparent Soil Electrical Conductivity Measurements in Agriculture. *Comput. Electron. Agric.* **2005**, *46*, 11–43. [CrossRef]
15. Mullins, M.G.; Bouquet, A.; Williams, L.E. *Biology of the Grapevine*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2016; pp. 137–145.
16. Pandey, D.K.; Putrevu, D.; Misra, A. Large-Scale Soil Moisture Mapping Using Earth Observation Data and Its Validation at Selected Agricultural Sites over Indian Region. In *Agricultural Water Management*; Srivastava, P.K., Gupta, M., Tsakiris, G., Quinn, N.W., Eds.; Academic Press: London, UK, 2021; pp. 185–207.
17. Hillel, D. *Environmental Soil Physics*, 1st ed.; Academic Press: Waltham, MA, USA, 1998.
18. Kramer, P.J.; Boyer, J.S. *Water Relations of Plants and Soils*, 1st ed.; Academic Press: San Diego, CA, USA, 1995.
19. Brillante, L.; Mathieu, O.; Lévêque, J.; van Leeuwen, C.; Bois, B. Water Status and Must Composition in Grapevine Cv. Chardonnay with Different Soils and Topography and a Mini Meta-Analysis of the Δ13C/Water Potentials Correlation. *J. Sci. Food Agric.* **2018**, *98*, 691–697. [CrossRef]
20. Gatti, M.; Garavani, A.; Squeri, C.; Diti, I.; De Monte, A.; Scotti, C.; Poni, S. Effects of Intra-Vineyard Variability and Soil Heterogeneity on Vine Performance, Dry Matter and Nutrient Partitioning. *Precis. Agric.* **2022**, *23*, 150–177. [CrossRef]
21. Cipriani, A. Geology of the Mt. Cosce sector (Narni Ridge, Central Apennines, Italy). *J. Maps* **2016**, *12* (Suppl. S1), 328–340. [CrossRef]
22. Storti, F.; Salvini, F. The evolution of a model trap in the central Apennines, Italy: Fracture patterns, fault reactivation and development of cataclastic rocks in carbonates at the Narni Anticline. *J. Pet. Geol.* **2001**, *24*, 171–190. [CrossRef]
23. Stendardi, F.; Capotorti, F.; Fabbi, S.; Ricci, V.; Silvestri, S.; Bigi, S. Geological map of the Mt. Vettoretto–Capodacqua area (Central Apennines, Italy) and cross-cutting relationships between Mts. Sibillini Thrust and Mt. Vettore normal faults system. *GFT&M* **2020**, *12*, 1–22.
24. Poni, S.; Gatti, M.; Palliotti, A.; Dai, Z.; Duchêne, E.; Truong, T.T.; Tombesi, S. Grapevine quality: A multiple choice issue. *Sci. Hortic.* **2018**, *234*, 445–462. [CrossRef]
25. USDA. *Sunn Hemp: A Cover Crop for Southern and Tropical Farming Systems*; USDA: Washington, DC, USA, 1999.
26. *ISO 11260:2018*; Soil Quality—Determination of Effective Cation Exchange Capacity and Base Saturation Level Using Barium Chloride Solution. International Organization for Standardization: Geneva, Switzerland, 1994.
27. Pleysier, J.L.; Juo, A.S.R. A Single-Extraction Method Using Silver-Thiourea for Measuring Exchangeable Cations and Effective CEC in Soils with Variable Charges. *Soil Sci.* **1980**, *129*, 205–211. [CrossRef]
28. Kissel, D.E.; Sonon, L.; Vendrell, P.F.; Isaac, R.A. Salt concentration and measurement of soil pH. *Commun. Soil Sci. Plant Anal.* **2009**, *40*, 179–187. [CrossRef]
29. Demolon, A.; Leroux, D. *Guide Pour l'Etude Expérimentale du Sol*, 2nd ed.; Gauthier-Villars: Paris, France, 1952; Volume 74.
30. Stakman, W.P.; Walk, G.A.; van der Harst, G.G. Determination of Soil Moisture Retention Curves I. Sand Box Apparatus. In *Range PF 0 to 2.7*; Instituut voor Cultuurtechniek en Waterhuishouding: Wageningen, The Netherlands, 1969.
31. Richards, L.A. Porous Plate Apparatus for Measuring Moisture Retention and Transmission by Soil. *Soil Sci.* **1948**, *66*, 105–110. [CrossRef]
32. Reynolds, W.D. An analytic description of field capacity and its application in crop production. *Geoderma* **2018**, *326*, 56–67. [CrossRef]
33. Ghanbarian-Alavijeh, B.; Millán, H. The relationship between surface fractal dimension and soil water content at permanent wilting point. *Geoderma* **2009**, *151*, 224–232. [CrossRef]
34. Lorenz, D.H.; Eichhorn, K.W.; Bleiholder, H.; Klose, R.; Meier, U.; Weber, E. Growth Stages of the Grapevine: Phenological Growth Stages of the Grapevine (*Vitis vinifera* L. ssp. *vinifera*)—Codes and Descriptions According to the Extended BBCH Scale. *Aust. J. Grape Wine Res.* **1995**, *1*, 100–103. [CrossRef]
35. Li, J.; Wan, H.; Shang, S. Comparison of Interpolation Methods for Mapping Layered Soil Particle-Size Fractions and Texture in an Arid Oasis. *CATENA* **2020**, *190*, 104508. [CrossRef]
36. Sapirstein, P. Accurate Measurement with Photogrammetry at Large Sites. *J. Archaeol. Sci.* **2016**, *66*, 137–145. [CrossRef]
37. Zheng, H.; Zhong, X.; Yan, J.; Zhao, L.; Wang, X. A Thermal Performance Detection Method for Building Envelope Based on 3D Model Generated by UAV Thermal Imagery. *Energies* **2020**, *13*, 6677. [CrossRef]
38. Waagen, J.; Sánchez, J.G.; van der Heiden, M.; Kuiters, A.; Lulof, P. In the Heat of the Night: Comparative Assessment of Drone Thermography at the Archaeological Sites of Acquarossa, Italy, and Siegerswoude, The Netherlands. *Drones* **2022**, *6*, 165. [CrossRef]

39. Xu, R.; Li, C.; Bernardes, S. Development and Testing of a UAV-Based Multi-Sensor System for Plant Phenotyping and Precision Agriculture. *Remote Sens.* **2021**, *13*, 3517. [CrossRef]
40. Idso, S.B.; Jackson, R.D.; Pinter, P.J.; Reginato, R.J.; Hatfield, J.L. Normalizing the Stress-Degree-Day Parameter for Environmental Variability. *J. Agric. Meteorol.* **1981**, *24*, 45–55. [CrossRef]
41. Jackson, R.D.; Idso, S.B.; Reginato, R.J.; Pinter, P.J. Canopy Temperature as a Crop Water Stress Indicator. *Water Resour. Res.* **1981**, *17*, 1133–1138. [CrossRef]
42. Jackson, R.D.; Kustas, W.P.; Choudhury, B.J. A Reexamination of the Crop Water Stress Index. *Irrig. Sci.* **1988**, *9*, 309–317. [CrossRef]
43. Katimbo, A.; Rudnick, D.R.; DeJonge, K.C.; Lo, T.H.; Qiao, X.; Franz, T.E.; Nakabuye, H.N.; Duan, J. Crop Water Stress Index Computation Approaches and Their Sensitivity to Soil Water Dynamics. *Agric. Water Manag.* **2022**, *266*, 107611. [CrossRef]
44. Taghvaeian, S.; Comas, L.; DeJonge, K.C.; Trout, T.J. Conventional and Simplified Canopy Temperature Indices Predict Water Stress in Sunflower. *Agric. Water Manag.* **2014**, *144*, 69–80. [CrossRef]
45. Sadovski, A. Study on pH in Water and Potassium Chloride for Bulgarian Soils. *Eurasian J. Soil Sci. (EJSS)* **2019**, *8*, 11–16. [CrossRef]
46. Jakšić, S.; Ninkov, J.; Milić, S.; Vasin, J.; Banjac, D.; Jakšić, D.; Živanov, M. The State of Soil Organic Carbon in Vineyards as Affected by Soil Types and Fertilization Strategies (Tri Morave Region, Serbia). *Agronomy* **2021**, *11*, 9. [CrossRef]
47. Landon, J.R. *Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Sub Tropics*; Longman Scientific & Technical Publ.: Harlow, UK, 1991.
48. Hirst, J.M. *Agricultural Compendium for Rural Development in the Tropics and Subtropics*; EUROCONSULT, Ed.; Elsevier: Amsterdam, The Netherlands; Oxford, UK, 1989.
49. Ferreyra, R.; Selles, G.; Pinto, M.; Morales, M.; Seguel, O. Effect of Soil Air Capacity on Water Relations and Vegetative Growth of 'Thompson Seedless' Grafted on Different Rootstocks: Preliminary Results. *Acta Hortic.* **2009**, *889*, 145–150. [CrossRef]
50. Lampkin, N.H.; Pearce, B.D.; Leake, A.R.; Creissen, H.; Gerrard, C.L.; Girling, R.; Lloyd, S.; Padel, S.; Smith, J.; Smith, L.G.; et al. *The Role of Agroecology in Sustainable Intensification*; Report for the Land Use Policy Group; Organic Research Centre, Elm Farm and Game & Wildlife Conservation Trust: Reading, UK, 2015.
51. Lazcano, C.; Decock, C.; Wilson, S.G. Defining and Managing for Healthy Vineyard Soils, Intersections With the Concept of Terroir. *Front. Environ. Sci.* **2020**, *8*, 68. [CrossRef]
52. Pennock, D.; McKenzie, N.; Montanarella, L. *Status of the World's Soil Resources: Technical Summary*; FAO: Rome, Italy, 2015.
53. Biasi, R.; Farina, R.; Brunori, E. Family Farming Plays an Essential Role in Preserving Soil Functionality: A Study on Active Managed and Abandoned Traditional Tree Crop-Based Systems. *Sustainability* **2021**, *13*, 3967. [CrossRef]
54. Cambardella, C.A.; Karlen, D.L. Spatial Analysis of Soil Fertility Parameters. *Precision Agric.* **1999**, *1*, 5–14. [CrossRef]
55. Vavoulidou, E.; Charoulis, A.; Soulis, K.; Karyotis, T.; Kavvadias, V. Soil Survey for Improvement of Farming Practices in Malia Municipality, Greece. *Commun. Soil Sci. Plant Anal.* **2009**, *40*, 1020–1033. [CrossRef]
56. Pereyra, G.; Pellegrino, A.; Gaudin, R.; Ferrer, M. Evaluation of Site-Specific Management to Optimize *Vitis vinifera* L. (Cv. Tannat) Production in a Vineyard with High Heterogeneity. *OENO One* **2022**, *56*, 397–412. [CrossRef]
57. Van Leeuwen, C.; Roby, J.P.; De Rességuier, L. Soil-Related Terroir Factors: A Review. *OENO One* **2018**, *52*, 173–188. [CrossRef]
58. De Santis, D.; Frangipane, M.T.; Brunori, E.; Cirigliano, P.; Biasi, R. Biochemical Markers for Enological Potentiality in a Grapevine Aromatic Variety under Different Soil Types. *Am. J. Enol. Vitic.* **2016**, *68*, 208–217. [CrossRef]
59. Jiménez-Ballesta, R.; Bravo, S.; Amorós, J.A.; Pérez-de-los-Reyes, C.; García-Pradas, J.; Sánchez, M.; García-Navarro, F.J. An Environmental Approach to Understanding the Expansion of Future Vineyards: Case Study of Soil Developed on Alluvial Sediments. *Environments* **2021**, *8*, 96. [CrossRef]
60. Lanyon, D.; Cass, A.; Hansen, D. *The Effect of Soil Properties on Vine Performance*; CSIRO Land and Water Technical Report; CSIRO: Adelaide, Australia, 2004.
61. Clark, J.S.; Campbell, J.H.; Grizzle, H.; Acosta-Martínez, V.; Zak, J.C. Soil Microbial Community Response to Drought and Precipitation Variability in the Chihuahuan Desert. *Microb. Ecol.* **2009**, *57*, 248–260. [CrossRef] [PubMed]
62. Pérez-de-los-Reyes, C.; Sánchez-Ormeño, M.; Martín-Consuegra, S.B.; García-Pradas, J.; Pérez-de-los-Reyes, M.L.; Ramírez, A.; Ortíz-Villajos, J.A.A.; García Navarro, F.J.; Ballesta, R.J. The Influence of Depth on the Water Retention Properties of Vineyard Soils. *Agric. Water Manag.* **2022**, *261*, 107507. [CrossRef]
63. Brunori, E.; Bernardini, A.; Moresi, F.V.; Attorre, F.; Biasi, R. Ecophysiological Response of *Vitis vinifera* L. in an Urban Agrosystem: Preliminary Assessment of Genetic Variability. *Plants* **2022**, *11*, 3026. [CrossRef] [PubMed]
64. Costa, J.M.; Egipto, R.; Aguiar, F.C.; Marques, P.; Nogales, A.; Madeira, M. The Role of Soil Temperature in Mediterranean Vineyards in a Climate Change Context. *Front. Plant Sci.* **2023**, *14*, 725. [CrossRef]
65. Biasi, R.; Brunori, E.; Ferrara, C.; Salvati, L. Assessing Impacts of Climate Change on Phenology and Quality Traits of *Vitis vinifera* L.: The Contribution of Local Knowledge. *Plants* **2019**, *8*, 121. [CrossRef]

66. Visconti, F.; López, R.; Olego, M.Á. The Health of Vineyard Soils: Towards a Sustainable Viticulture. *Horticulturae* **2024**, *10*, 154. [CrossRef]
67. Santos, J.A.; Yang, C.; Fraga, H.; Malheiro, A.C.; Moutinho-Pereira, J.; Dinis, L.T.; Schultz, H.R. Long-Term Adaptation of European Viticulture to Climate Change: An Overview from the H2020 Clim4Vitis Action. *IVES Tech. Rev. Vine Wine* **2021**. [CrossRef]
68. Rubio, R.; Pérez-Murcia, M.D.; Agulló, E.; Bustamante, M.A.; Sánchez, C.; Paredes, C.; Moral, R. Recycling of Agro-Food Wastes into Vineyards by Composting: Agronomic Validation in Field Conditions. *Commun. Soil Sci. Plant Anal.* **2013**, *44*, 502–516. [CrossRef]
69. Calleja-Cervantes, M.E.; Fernández-González, A.J.; Irigoyen, I.; Fernández-López, M.; Aparicio-Tejo, P.M.; Menéndez, S. Thirteen Years of Continued Application of Composted Organic Wastes in a Vineyard Modify Soil Quality Characteristics. *Soil Biol. Biochem.* **2015**, *90*, 241–254. [CrossRef]
70. Ramos, M.C. Effects of Compost Amendment on the Available Soil Water and Grape Yield in Vineyards Planted after Land Levelling. *Agric. Water Manag.* **2017**, *191*, 67–76. [CrossRef]
71. Gaiotti, F.; Marcuzzo, P.; Belfiore, N.; Lovat, L.; Fornasier, F.; Tomasi, D. Influence of Compost Addition on Soil Properties, Root Growth and Vine Performances of *Vitis vinifera* cv Cabernet sauvignon. *Sci. Hortic.* **2017**, *225*, 88–95. [CrossRef]
72. Rawls, W.J.; Pachepsky, Y.A.; Ritchie, J.C.; Sobecki, T.M.; Bloodworth, H. Effect of Soil Organic Carbon on Soil Water Retention. *Geoderma* **2003**, *116*, 61–76. [CrossRef]
73. Olness, A.; Archer, D. Effect of Organic Carbon on Available Water in Soil. *Soil Sci.* **2005**, *170*, 90–101. [CrossRef]
74. Vogel, J.; Paton, E.; Aich, V. Seasonal Ecosystem Vulnerability to Climatic Anomalies in the Mediterranean. *Biogeosciences* **2021**, *18*, 3137–3149. [CrossRef]
75. Feng, X.; Qian, C.; Materia, S. Amplification of the Temperature Seasonality in the Mediterranean Region Under Anthropogenic Climate Change. *Geophys. Res. Lett.* **2022**, *49*, e2022GL100570. [CrossRef]
76. Kachanoski, R.G.; Wesenbeeck, I.J.V.; Jong, E.D. Field Scale Patterns of Soil Water Storage from Non-Contacting Measurements of Bulk Electrical Conductivity. *Can. J. Soil Sci.* **1990**, *70*, 537–542. [CrossRef]
77. Besson, A.; Cousin, I.; Bourennane, H.; Nicoullaud, B.; Pasquier, C.; Richard, G.; Dorigny, A.; King, D. The Spatial and Temporal Organization of Soil Water at the Field Scale as Described by Electrical Resistivity Measurements. *Eur. J. Soil Sci.* **2010**, *61*, 120–132. [CrossRef]
78. Costa, J.M.F.; Vaz, M.; Escalona, J.M.; Egipto, R.; Lopes, C.M.; Medrano, H.; Chaves, M.M. Water as a Critical Issue for Viticulture in Southern Europe: Sustainability vs Competitiveness. *IVES Tech. Rev. Vine Wine* **2020**. [CrossRef]