Geoderma Regional 33 (2023) e00631

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Role of cultivars and grass in the stability of soil moisture and temperature in an organic vineyard

Manuel López-Vicente [a,*], Laura Pereira-Rodríguez [a], Rosane da Silva-Dias [a], Xiana Raposo-Díaz [a], Gao-Lin Wu [b], Antonio Paz-González [a]

[a] Group Aquaterra, CICA – Interdisciplinary Centre of Chemistry and Biology, Universidade da Coruña, As Carballeiras s/n, Campus de Elviña, 15071 A Coruña, Spain
[b] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A & F University, Yangling, Shaanxi 712100, China

A R T I C L E I N F O

Keywords:
Vineyard
Soil moisture
Soil temperature
Spatial pattern
Index of temporal stability
Ground cover

A B S T R A C T

Soil water content (SWC) and temperature (ST) are main parameters in agriculture, but are difficult to predict due to the numerous processes involved. To find stability patterns, this study evaluated the soil hydro-thermic response in a rainfed organic vineyard with humid climate, a permanent grass cover and under no-tillage and homogeneous soil and topographic conditions. The differences between the rows (R) and inter-row areas (IR) and two cultivars (Agudelo –Ag– and Blanco Legítimo –BL–) were assessed. SWC and ST were measured with 12 probes every 15 min at 5, 15 and 25 cm depth over the crop cycle (242 days). On average, wetter (+2.2%) and cooler (−1.4%) values appeared in Ag than in BL that may be associated with differences in vine water demand. IR had wetter (+5.9%) and cooler (−0.7%) conditions than R due to higher water consumption by vines. Significant differences appeared when time-series analysis was split into three periods: drying and warming (spring), dry and warm (summer), and wetting and cooling (autumn). SWC and ST correlated well in R, but moderate correlations appeared in IR, showing a more complex pattern in this zone. In general, the most stable conditions appeared at 15 cm depth, with drier and warmer conditions in the deepest layer in spring and autumn. This vertical pattern did not vary over time for ST, but IR had the most stable and moistest conditions in summer at 25 cm. The relative differences among zones and cultivars revealed that Ag had moister, but less representative, conditions than BL at the three soil layers in spring, and this pattern kept in summer at 15 and 25 cm, but only in autumn at 15 cm. Regarding ST, the pattern was very stable, and cooler and representative conditions prevailed in Ag. BL has been rarely cited in the literature, and these results contributed with new insights about the SWC and ST dynamic on this cultivar. Cooler conditions always appeared in IR, compared with R; and R always had more representative values of SWC than IR. The pattern of ST was more variable and R only had more representative values than IR at 15 cm in summer and at 25 cm in spring and summer. This article represents the first study that calculated the index of temporal stability (ITS) for SWC and ST in any type of woody crop. Our findings allowed to identify the most representative areas of the hydro-thermic response of the soil in the vineyard, which is of interest to save time and resources during long-term monitoring tasks in commercial vineyards.

1. Introduction

Soil water content (SWC) and soil temperature (ST) are two key parameters to explain plant growth (Jarvis et al., 2022; Liu et al., 2022), crop yield (Rahman et al., 2020), runoff coefficient (Wei et al., 2007) and the biological activity of soil (Wang et al., 2021). In particular, SWC is a limiting factor for crop production and quality due to water deficit (Villalobos and Fereres, 2016), water excess (Irmak and Rathje, 2008), poor synchronisation between the crop growing and rainy season (Van Leeuwen and Darriet, 2016), duration of the plant water stress (Reynolds et al., 2005), and water supply conditions during grape ripening (Zufferey et al., 2018). Soil salinization and sodification is another relevant issue in soil water management in irrigated vineyards with saline water (Aragüés et al., 2014). Soil temperature (ST) in farmland is

* Corresponding author.
E-mail address: manuel.lopez.vicente@udc.es (M. López-Vicente).

https://doi.org/10.1016/j.geodrs.2023.e00631
Received 20 February 2023; Received in revised form 4 March 2023; Accepted 8 March 2023
Available online 12 March 2023

influenced by different aspects like the presence of crop residues (McCalla and Duley, 1946), tillage practices (Shen et al., 2018), the soil moisture status (Luo et al., 1992), and soil mineralogy, colour and stoniness. In vineyards, previous studies have proven that mulches and groundcovers affect ST (cooling or warming) both in the inter-row and intra-row areas owing to changes in soil water consumption and transpiration, and soil water evaporation, as well as due to shading the soil surface from solar radiation, increasing field floor reflectance, and isolation of topsoil. Compared with bare soil conditions, these changes are especially marked during the day-night cycles and seasonal changes. In a two-acre vineyard planted in 2007, Bavougian and Read (2018) found that average daily ST was mostly higher under mulches than under bare soil. In other cases, bare ST was higher than with a partial grass cover, and the difference between the two treatments was greater in the middle of the inter-row, just under the grass layer (Pradel and Pieri, 2000). Therefore, results reported in the literature are not consistent and show discrepancies. This study aims to shed light on this topic by analysing SWC and ST at high spatial and temporal resolution in the rows and inter-row areas of an organic vineyard.

Climate change is altering rainfall patterns, increasing air temperature and modifying/ exacerbating climate regimes; all these endangering the agronomic, environmental and economic sustainability of farmland (Shayanmehr et al., 2020; Bonetti et al., 2022). In vineyards, higher temperatures and frequent drought episodes are affecting grape production, moving the ripening phase to warmer periods in the summer (Van Leeuwen and Darriet, 2016). In a long-term study in German vineyards, Koch and Oehl (2018) found significant increments of sugar concentration, but lower yields due to increases of air temperature without changes in the total annual precipitation. Recent model predictions of SWC suggest that changes in precipitation and air temperature based on future climatic scenarios will increase the number of days per year when SWC is below the wilting point, being vineyards seriously affected due to their physiographic conditions (Horel et al., 2022). Therefore, a better comprehension of the SWC and ST dynamics results necessary to face the current challenges of viticulture under the major threats of climate change.

After vine plantation, when earthworks favour spatial heterogeneity, farmers try to achieve homogeneous soil conditions by using the same tillage practices and crop management throughout the field. However, the intrinsic soil heterogeneity is high even if soil type does not change (Gasch et al., 2015) and the topographic conditions are the same (Goenster-Jordan et al., 2018). Both SWC and ST are difficult to predict because they tend to vary across the field –see López-Vicente et al. (2015) for SWC and Tian et al. (2022) for ST–, along the soil profile in the different layers –see Wu et al. (2020) for SWC and Pradel and Pieri (2000) for ST–, and over the course of the year –see López-Vicente and Álvarez (2018) and Wilson et al. (2020) for SWC and Ramírez-Cuesta et al. (2022) for ST–. Computer-based numerical approaches –models– allow to simulate and predict SWC and ST at different soil depths –sometimes at 3D– and over a wide range of scenarios (Oliveira, 2001; Kisekka et al., 2022). However, these tools require parameterization, calibration and validation tasks that are usually time- and cost-demanding, and not always model's output are precise. Therefore, accurate mapping and characterization of the spatial and temporal dynamic of SWC and ST is a complex task that requires further research and results necessary in precision farming (Tang et al., 2020; Abdellatif et al., 2021).

In this study, we hypothesized that under homogeneous soil, topographic, crop, tillage and ground cover conditions, the hydro-thermic response of the soil in a woody crop should be explained by specific agronomic factors like cultivars and zones (rows and inter-row areas). To prove this statement, we characterized at very fine resolution the 3D patterns of SWC and ST, and for the first time in the literature their index of temporal stability, in an organic vineyard under humid and mild conditions, considering different soil layers (topsoil, main root zone and near the limit between soil and rocks). Woody crops represent an important part of arable land worldwide, and thus, this study will contribute to a better understanding of the intrinsic heterogeneity of the hydro-thermic response of the soil over a crop cycle. This knowledge will be of interest for precision farming practices.

2. Material and methods

2.1. Study area

The selected vineyard is located in the municipality of Betanzos (A Coruña province, Autonomous Community of Galicia, NW Spain), in an area called 'Brabío' (43° 15′ 56.20" N; 8° 12' 01.00" W), and it is managed by 'Pagos de Brigante' winery (Fig. 1a). The field is located near the Atlantic Ocean (at only 7 km from the cost), ranging the elevation between 35 and 48 m above sea level. Topography is hilly, with a mean slope gradient of 30%, and the hillslope is straight –neither convex nor concave–. Plantation includes two white grape varieties: 'Agudelo' and 'Blanco Legítimo' or 'Branco Lexítimo' in Galician, and vines are approximately 27 years old. Betanzos is an ancient winemaking area situated in the most northern viticole geographic area of Galicia. Despite the fact that 'Blanco Legítimo' (hereinafter BL) is less fertile than 'Agudelo' (hereinafter Ag) (BL clusters are smaller and lighter than those of Ag), both varieties have similar organoleptic characteristics, and thus, are commonly planted together (Vilanova et al., 2009).

The vineyard has 592 vines in 1919 m^2 (plantation density of 3085 vines / ha). This density is similar to others found in steep and mountainous Galician vineyards (Figueiredo-González et al., 2013), but lower than those observed in steep vineyards in northern Portugal (Figueiredo et al., 2021). In our field, the vines are trellised to a vertical shoot position (espalier system), with two branches per vine. Nine rows are devoted to Ag and ten rows to BL. All these rows are parallel to the steepest direction of the slope. An additional row appears at the bottom of the field, perpendicular to the other rows, that includes vines of the two varieties. The climate is temperate oceanic. In the last 15 years (2007–2021), the mean precipitation and temperature were of 1141 mm and 13.5 °C, respectively, with 21 days per year of frost (data source: 'Mabegondo' weather station, METEOGALICIA). Winters are mild and rainy: The average monthly values of rainfall, temperature and days with frost between November and March were 140 mm, 9.7 °C and 4 days of frost. Summers are cool and quite sunny, with mean monthly precipitation and temperature of 58, 27, 42 and 44 mm and 16.8, 18.8, 18.8 and 17.4 °C in June, July, August and September, respectively, favouring good conditions for plant growth.

The soil is classified as Cambric Umbrisol (according to the World Reference Base (WRB) of the FAO), and no difference was observed throughout the field. Homogeneous ground conditions with spontaneous/ resident vegetation covering the soil in the rows (R hereinafter) and inter-row areas (IR hereinafter) remained during the whole study period: from 26th February to 25th October 2021. Grape harvesting took place on 24th September, and on 26th October soil was ploughed to control weeds. This period corresponded to a complete crop cycle, as it began approximately 2–3 weeks before bud break (second half of March), and ended one month after harvesting. The resident vegetation included the following plant species: Cock's-foot (*Dactylis glomerata*), dandelion (*Taraxacum officinale*), red clover (*Trifolium pratense*), common mallow (*Malva sylvestris*), elmleaf blackberry (*Rubus ulmifolius*), wild strawberry (*Fragaria vesca*), apple mint (*Mentha suaveolens*), common sorrel (*Rumex acetosa*), ray grass (*Lolium perenne*), umbrella papyrus (*Cyperus alternifolius*; allochthonous plant), horseweed (*Conyza canadensis*; allochthonous plant) and meadow vetchling (*Lathyrus pratensis*). Weed control was done by mechanical mowing, using a weed cutter, without disturbing the soil, making a total of three cuts per year. Plant residues remained on the ground. No herbicide was used because the field is managed under organic farming. In spite of the seasonal changes of vine and grass growth and development (see the NDVI maps

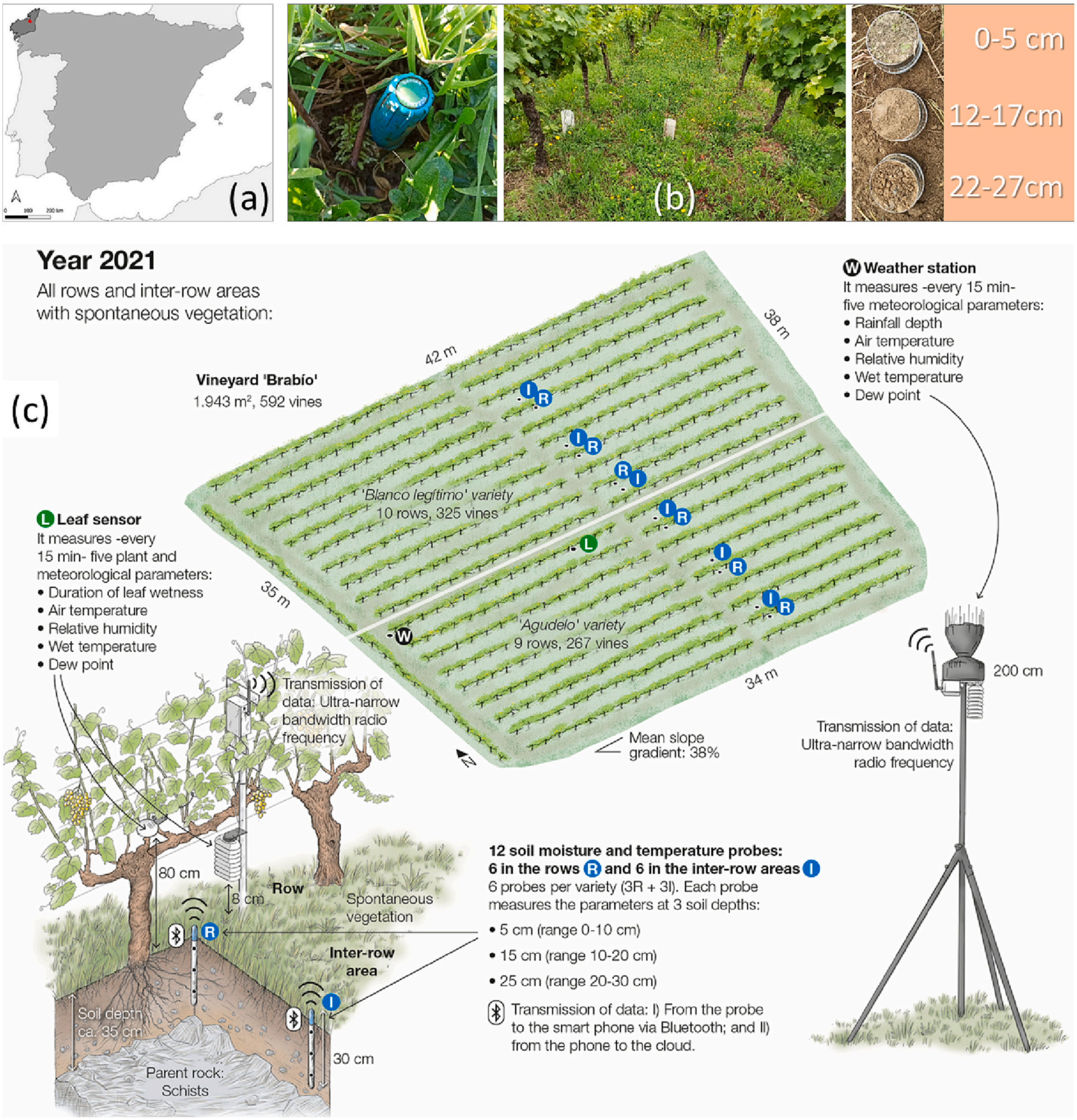

Fig. 1. Location of the study area (red point) in A Coruña province (dark grey), NW Spain (a). Pictures of the soil moisture and temperature probes as they look after their installation (b). Infographic showing the field and location of all devices (c).

in Appendix A1), the soil in R and IR was always covered by vegetation and plant debris in the area of the 12 probes (Figs. 1b and 3a) due to the favourable climatic characteristics of the study area and the environmentally friendly conditions of the tillage practices.

2.2. Field monitoring of soil and climatic parameters

Twelve capacitance-based technology Sentek Drill & Drop Bluetooth® soil moisture and temperature probes were installed on February 26th, 2021 (records started at 11:30 AM), and had been measuring volumetric SWC (θ) and temperature (Fig. 1b). Six probes were devoted for each variety (three in R and three in IR; Fig. 1c), and SWC and ST were measured every 15 min at 5, 15 and 25 cm depth (6912 values per day). This setting was chosen because soil is shallow in the places where the probes were installed, and parent rock appeared at an average depth of 35 cm when probes were installed. The soil remained undisturbed throughout the study period that lasted 242 days (until 24:00 h of the 25th October), reaching a total number of 1,669,176 measurements. The measure at each soil depth represents the average value of SWC / ST within a sphere of influence of 10 cm diameter from the location of each sensor: $\theta_5=\overline{SWC}$ and $ST_5=\overline{ST}$ between 0 and 10 cm; $\theta_{15}=\overline{SWC}$ and $ST_{15}=\overline{ST}$ between 10 and 20 cm; and $\theta_{25}=\overline{SWC}$ and $ST_{25}=\overline{ST}$ between 20 and 30 cm.

The topographic conditions in the measurement points were similar among them, being all probes located in the upper part of the field. Besides, the field is situated next to a paved trail with a drainage system (ditch) that conducts runoff out of the study area, and near the divide of the hillslope. Therefore, the contribution of runoff to the soil water recharge is not much relevant (see map in Appendix A2), and in the case of intense rainfall events, the upslope drainage areas of the probes are comparable. No piezometer was installed to monitor the water table, and subsurface flow may occur, but the contribution of this flow to the hydro-thermic dynamic in the probes should be of minor relevance. No rill or interrill soil erosion feature was observed in the field either before or during the surveys of this study. Even though, no sedimentation feature was identified. Therefore, we assumed that soil redistribution processes did not affect the hydro-thermic response of the soil, and most part of soil water recharge was explained by direct rainfall. A weather station (model Raincrop by Sencrop, France) was installed in the field on the same date when the probes were installed, and five climatic parameters have been continuously recorded every 15 min: Rainfall depth (R, in mm; double tipping bucket), air temperature (T, in °C), relative humidity (RH, in %), wet temperature (in °C) and dew point (in °C) (Fig. 1c). This equipment sent data at real time to the cloud service of Sencrop. In this study, we used the values of R, T and RH to characterize the general climatic conditions of the different hydro-thermic periods: Spring, summer and autumn.

2.3. Soil characterization

To characterize the spatial variability of the soil properties (across the field and accounting the soil profile), a field survey was done and 108 soil samples were collected using steel cylinders with an internal diameter of 8 cm and a height of 5 cm (251.33 cm^3). Three samples were collected near each probe, at a distance of approximately 50–60 cm, and at three soil depths: between 0 and 5 cm, between 12 and 17 cm, and between 22 and 27 cm, mirroring the positions of the soil moisture and temperature measurements. Soil samples were transported to the laboratory to determine soil physical and chemical parameters. With undisturbed samples, we obtained the bulk density (BD, in g / cm^3) and the saturated hydraulic conductivity (Kfs, in mm / h; using the KSAT-METER© easy-to-use automated setup). After milling the samples gently –without breaking the rocks–, the coarse fragment content (in % of weight) was estimated. By using the fine fraction (mean particle size <2 mm), we determined the clay, silt and sand content (in %; BECKMAN COULTER laser granulometer), the type of texture, and the content of organic matter (OM, in %; calcination in muffle furnace method). The mean values of these parameters were calculated for each soil layer in R and IR of the two cultivars.

2.4. Statistical analysis

Before doing the statistical analysis, non-valid numbers –due to instrumental errors– were deleted (e.g. '9999', '-1' for soil moisture, unwarranted extreme outliers). A second analysis included the identification of sharp changes such as abrupt rises or drops in the values of SWC or ST. Before removing any sharp change in the database of a specific probe, we compared the abnormal value with those values measured in the other probes in the same date. If the anomaly only appeared in one probe, that value was removed, but all values were preserved if the sudden change was recorded in all probes. Once the database was refined, we initially did a statistical analysis to find significant differences between the values of soil moisture and temperature between the two zones (R vs. IR), the two vine varieties (Ag vs. BL), and the three soil layers (5, 15 and 25 cm). Differences in the soil properties were also evaluated. The analysis of variance (one-way ANOVA for each set of data selected for the comparison) was done at $P \leq 0.05$, after testing data normality (Shapiro-Wilk Test), and checking that the F-critical value of the analysis was lower than the F-value. When data series failed normality test, the Kruskal–Wallis non-parametric test was done.

The relative differences ($\delta_{i,j,t}$) were calculated at each measurement point i considering either the vertical profile (3 points per probe; $j = V$) or the horizontal profile (12 points per soil depth; $j = H$) and time t (measurement date: 23,183 records per probe and depth of each soil parameter). Then, the mean relative difference (MRD), the standard deviation of the relative difference (SDRD), the coefficient of variation (CVRD), and the index of the temporal stability (ITS) were calculated for different time intervals (T = total period) to characterize the spatio-temporal patterns of soil moisture and temperature:

$$\overline{\theta_{i,j,t}} = \frac{1}{n_{i,j,t}} \sum_{t=1}^{n_t} \theta_{i,j,t} \quad (1)$$

$$\delta_{i,j,t} = \frac{\theta_{i,j,t} - \overline{\theta_{i,j,t}}}{\overline{\theta_{i,j,t}}} \quad (2)$$

$$MRD_{i,j,T} = \frac{1}{n_T} \sum_{t=1}^{n_T} \delta_{i,j,t} \quad (3)$$

$$SDRD_{i,j,T} = \sqrt{\frac{1}{N_T - 1} \sum_{t=1}^{N_T} \left(\delta_{i,j,t} - MRD_{i,j,T}\right)^2} \quad (4)$$

$$CVRD_{i,j,T} = \frac{SDRD_{i,j,T}}{\left|MRD_{i,j,T}\right|} \quad (5)$$

$$ITS_{i,j,T} = \sqrt{MRD_{i,j,T}{}^2 + SDRD_{i,j,T}{}^2} \quad (6)$$

The combination of the vertical (3 depths per probe) and horizontal (12 probes per depth) components allowed to obtain a pseudo-3D spatial pattern of SWC and ST at each time interval. Case studies about the usefulness of the Eqs. (1), (2), (3), (4) and (5) in the evaluation of soil moisture patterns in cropland and areas with natural vegetation can be found in many studies, such as those made by Vachaud et al. (1985) in grass, olive and wheat fields, Zhao et al. (2010) in a semi-arid steppe ecosystem with perennial grasses, López-Vicente et al. (2015) in a cereal field, Wei et al. (2017) in a headwater forest catchment, Yetbarek and Ojha (2020) in small farm-representative plots, and Zhang et al. (2022) in winter wheat and spring maize fields. In vineyards, water storage variability was analysed using these equations by Luciano et al. (2014) in Brazil, Nolz and Loiskandl (2017) in Austria, and in Spain by López-Vicente and Álvarez (2018). The ITS –Eq. (6)– provides a single metric to identify the best sampling locations that are representative of the average field conditions. More details about this method can be found in Zhao et al. (2010), Wei et al. (2017) and Zhang et al. (2022). As suggested by Jacobs et al. (2004), ITS can be used instead of the root mean square error (RMSE) in order to avoid the conflicts with the general definition of the RMSE. According to Eq. (6), the point with the highest time stability is identified as the one with the lowest ITS; and threshold values of ITS can be used to identified the most divergent zones within the study area.

3. Results

3.1. Degree of heterogeneity of the soil properties

Considering all samples, the mean and standard deviation (SD) values of the soil properties were as follows: 1.14 ± 0.15 g / cm^3 of bulk density, 36.1% weight ± 8.8% of coarse fragments (mean Ø > 2 mm), 12.0% ± 4.9% of clay, 41.5% ± 3.9% of silt, 46.5% ± 7.8% of sand –loam texture–, 7.2% ± 2.8% of organic matter (OM), and 813 ± 1437 mm / h of saturated hydraulic conductivity (Kfs) (Table 1). The SD of all properties was low, except that of Kfs due to the occurrence of two outliers. In most cases, the upper-most layer had the lowest values of bulk density (differences were significant compared with the values at 15 and 25 cm), clay (differences were only significant in IR-BL) and silt, and the highest of sand (with significant differences in IR-BL), OM (differences were significant in BL) and Kfs (differences were significant in R-Ag and IR-BL). These results may indicate past events of soil erosion

Table 1
Mean values of bulk density (BD), content of clay, silt and organic matter (OM), type of soil texture, and saturated hydraulic conductivity (Kfs), in the different zones, cultivars and soil layers. Different lower case letter indicates significant differences at 0.05 level.

Zone	Variety	Soil depth	BD	Rocks	Clay	Silt	Sand	Texture	OM	Kfs*
		(cm)	g / cm^3	% weight	%	%	%	Type	%	mm / h
R	Ag	5	0.94**a**†a‡a#	33.2%a†a‡a#	9.0%a†a‡a#	40.1%a†a‡a#	50.9%a†a‡a#	Loam	10.1%a†a‡a#	1259**a**†a‡a#
		15	1.17**b**†a‡a#	30.0%a†a‡a#	12.7%a†a‡a#	44.4%a†a‡a#	42.8%a†a‡a#	Loam	7.3%a†a‡a#	804**ab**†a‡a#
		25	1.32**b**†a‡a#	37.8%a†a‡a#	13.7%a†a‡a#	43.9%a†a‡**a**#	42.4%a†a‡a#	Loam	6.7%a†a‡a#	347**b**†a‡a#
	BL	5	0.94**a**†a‡a#	31.0%a†a‡a#	9.7%a†a‡a#	40.1%a†a‡a#	50.2%a†a‡a#	Loam	8.9%**a**†a‡a#	1006a†a‡a#
		15	1.16**b**†a‡a#	38.5%**ab**†a‡a#	12.5%a†a‡a#	42.8%a†a‡a#	44.7%a†a‡a#	Loam	5.4%**b**†a‡a#	251a†a‡a#
		25	1.25**b**†a‡a#	43.4%**b**†a‡a#	14.0%a†a‡a#	43.7%a†a‡a#	42.3%a†a‡a#	Loam	4.7%**b**†a‡a#	173a†a‡a#
IR	Ag	5	0.98**a**†a‡a#	29.3%a†**a**‡a#	7.6%a†a‡a#	37.4%a†a‡a#	55.0%a†a‡a#	Sandy loam	11.6%a†a‡a#	2813a†a‡a#
		15	1.21**b**†a‡a#	26.0%a†**a**‡a#	11.8%a†a‡a#	42.9%a†a‡a#	45.3%a†a‡a#	Loam	6.7%a†a‡a#	287a†a‡a#
		25	1.29**ab**†a‡a#	36.9%a†a‡a#	12.5%a†a‡a#	40.1%a†a‡**b**#	47.4%a†a‡a#	Loam	5.9%a†a‡a#	1215a†a‡a#
	BL	5	1.03**a**†a‡a#	40.3%a†**b**‡a#	10.4%**a**†a‡a#	37.7%a†a‡a#	51.9%**a**†a‡a#	Loam	9.2%**a**†a‡a#	1194**a**†a‡a#
		15	1.15**ab**†a‡a#	39.5%a†**b**‡a#	14.5%**b**†a‡a#	41.4%a†a‡a#	44.1%**ab**†a‡a#	Loam	5.3%**b**†a‡a#	317**ab**†a‡a#
		25	1.29**b**†a‡a#	47.3%a†a‡a#	15.7%**b**†a‡a#	43.5%a†a‡a#	40.8%**b**†a‡a#	Loam	4.1%**b**†a‡a#	173**b**†a‡a#

* Falling head normalized at 10 °C.
† Differences between the three soil depths within the same zone and cultivar.
‡ Differences between the two cultivars within the same soil depth and zone.
# Differences between the two zones within the same soil depth and cultivar.

by water that reduced fine particles on surface, but this process is not currently observed at all. In general, soil at 15 cm had lower content of rocks and lower Kfs than near the soil surface, favouring better conditions for soil water storage. At 25 cm, soil had high values of BD, the highest of rocks and clay, and the lowest of OM. Despite the fact that clear differences appeared in the measured soil physical and chemical properties between the three soil layers, no significant differences were observed within the same soil layer between the two cultivars and the two zones (R vs. IR). Therefore, our initial hypothesis of homogeneous soil conditions across the field was validated, and the different patterns of stability of SWC and ST should be explained by agronomic reasons and not associated with soil properties.

3.2. *Annual differences among zones, cultivars and soil layers*

The values obtained during the whole period (242 days) were analysed to identify the general spatial patterns, considering the different zones, cultivars and soil layers (Table 2). Including all values, the mean SWC and ST were 21.81% vol. and 16.49 °C, respectively, with slightly wetter (+2.2%) and cooler (−1.4%) values in the 'Ag' probes than in the 'BL' probes though differences were not significant, and this pattern remained when the two cultivars were analysed considering R (Ag: +1.7% SWC and − 2.0% ST) and IR (Ag: +2.6% SWC and − 0.8% ST) separately. Greater, but not significant, differences appeared when the two zones were compared between them, with wetter (+5.9%) and cooler (−0.7%) conditions in IR than in R, and this pattern remained in the two cultivars with more marked differences in Ag for SWC and in BL for ST.

Focussing on the three soil layers (0–10, 10–20 and 20–30 cm), some significant differences were observed in the SWC within each set of zone and cultivar, although no significant difference was obtained between the values of ST. In all cases, the lowest and significantly different SWC values were observed at 25 cm, while the pattern of the moistest values differed between R and IR. Below the vines, the moistest conditions appeared in the upper-most layer in R of Ag (+11.7% compared to 25 cm) and BL (+11.6%). However, in IR the highest values of SWC were found at 15 cm, both in Ag (+34.1% than at 25 cm) and BL (+21.7% than at 25 cm), with intermediate values at 5 cm (+9.5% on average). Besides, the differences between soil layers were more marked in IR than in R.

The values of ST did not define a clear pattern and no significant difference was found between the three layers, but in general warmer conditions prevailed at 15 cm and cooler conditions at 5 cm. The probes of Ag followed this pattern both in R and IR, but the probes of BL showed slight differences with the coolest values at 25 cm in R and the warmest conditions at the same depth in IR. The correlation between the values of SWC and ST was good in R ($R^2 = 0.8059$) and at 5 cm ($R^2 = 0.8166$) and 25 cm ($R^2 = 0.9368$), and moderate in IR ($R^2 = 0.4056$) and at 15 cm ($R^2 = 0.4926$). The correlations were similar in the two cultivars: Ag ($R^2 = 0.5156$) and BL ($R^2 = 0.5819$) (Fig. 2).

Table 2
Mean soil water content and temperature in the different zones and varieties: row (R), inter-row (IR), Agudelo (Ag) and Blanco Legítimo (BL).

Zone	Variety	Soil water content (% vol.)				Soil temperature (°C)			
		Soil depth (cm)				Soil depth (cm)			
		0–30	5	15	25	0–30	5	15	25
R + IR	Ag + BL	21.8	22.1**a**[€]	23.3**a**[€]	20.0**b**[€]	16.5	16.4a[€]	16.5a[€]	16.5a[€]
	Ag	22.0a[*]	21.8**ab**[€]	24.2**a**[€]	20.1**b**[€]	16.4a[*]	16.3a[€]	16.5a[€]	16.4a[€]
	BL	21.6a[*]	22.4**a**[€]	22.4**a**[€]	19.9**b**[€]	16.6a[*]	16.6a[€]	16.6a[€]	16.6a[€]
R	Ag + BL	21.2a[$]	22.3**a**[€]	21.1**ab**[€]	20.0**b**[€]	16.5a[$]	16.5a[€]	16.6a[€]	16.5a[€]
	Ag	21.4a[*]a[$]	22.5a[€]	21.5a[€]	20.1a[€]	16.4a[*]a[$]	16.2a[€]	16.5a[€]	16.4a[€]
	BL	21.0a[*]a[$]	22.2a[€]	20.7a[€]	19.9a[€]	16.7a[*]a[$]	16.7a[€]	16.7a[€]	16.6a[€]
IR	Ag + BL	22.4a[$]	21.8**a**[€]	25.5**b**[€]	20.0**a**[€]	16.4a[$]	16.4a[€]	16.5a[€]	16.5a[€]
	Ag	22.7a[*]a[$]	21.2**a**[€]	26.9**b**[€]	20.1**a**[€]	16.4a[*]a[$]	16.3a[€]	16.5a[€]	16.4a[€]
	BL	22.2a[*]a[$]	22.5**ab**[€]	24.1**a**[€]	19.8**b**[€]	16.5a[*]a[$]	16.5a[€]	16.4a[€]	16.6a[€]

Values correspond to the whole study period.
Different bold minor case letter means that differences were significant.
[*] Differences between varieties within the same zone in the whole profile (0–30 cm).
[$] Differences between zones within the same variety in the whole profile (0–30 cm).
[€] Differences between the soil depths within the same zone and variety.

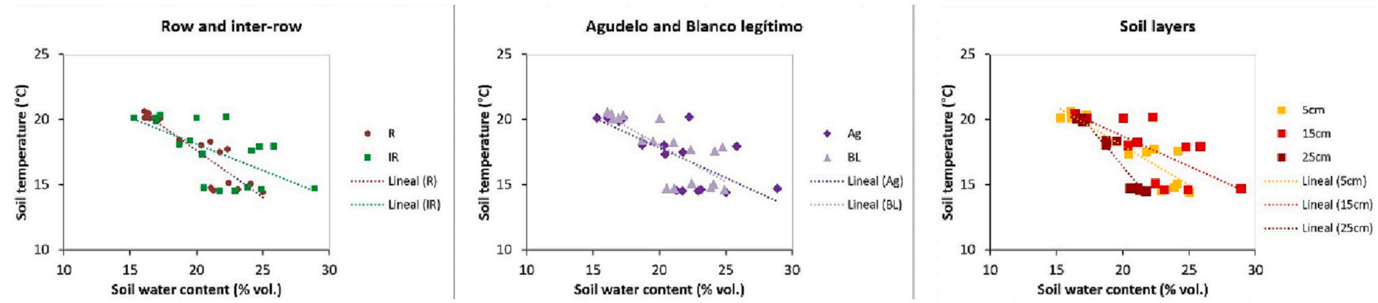

Fig. 2. Relationship between the mean values of soil water content and soil temperature in the rows (R), inter-row areas (IR), Agudelo (Ag) and Blanco Legítimo (BL) varieties, and in the three soil layers.

3.3. Temporal patterns of soil moisture and temperature: hydro-thermic periods

During the analysis of the temporal series of data of SWC and ST, we found three different periods according to the evolution of the values: I) drying-and-warming, from 26 February to 22 June (spring), II) dry-and-warm, from 23 June to 6 September (summer); and III) wetting-and-cooling, from 7 September to 25 October (autumn) (Fig. 3). Despite the fact that precipitation, air temperature and air humidity, as well as water consumption by plants, clearly influenced the values of soil moisture and temperature, this study did not consider these processes, and the statistical analysis was focused on the identification of the spatial patterns of SWC and ST across the field and their temporal evolution (stability and variability). The values of the observed climatic and soil parameters differed between the three periods. The mean daily rainfall depth, air temperature and relative humidity was 2.3, 0.5 and 1.7 mm, 13.0, 18.3 and 15.8 °C, and 79.6%, 82.3% and 86.9% in spring, summer and autumn, respectively. Regarding SWC and ST, the mean values considering the three soil layers were 23.3%, 17.3% and 21.4% vol. / 15 min, and 14.7, 20.2 and 18.0 °C / 15 min in spring, summer and autumn, respectively.

The pattern of variability of SWC and ST differed among them and over the three hydro-thermic periods (Fig. 4). In general, the range of values of SWC was higher than the range of values of ST, appearing the lowest dispersion of SWC in autumn and of ST in summer. Considering both the range of values between the percentiles 75 and 25 and the maximum and minimum values, at 5 cm and 15 cm, the highest ranges of SWC and ST appeared in the drying and warming period and the lower ranges for both parameters happened in the other two periods with minor differences between the ranges in summer and autumn. At 25 cm, the differences between the ranges of the periods were less marked, but similar to the pattern observed at 5 and 15 cm. When time-series analysis was split into the three hydro-thermic periods, significant differences appeared between the two zones (R vs. IR; Fig. 4A) and two vine varieties (Ag vs. BL; Fig. 4B). In general, the differences between the values of SWC were more marked (lower *p*-values) than the differences between the values of ST (higher p-values). The differences among zones were more emphasized for SWC, and the differences among varieties were slightly more marked for ST. The lowest differences appeared in spring, but more distinct values were recorded in summer and autumn.

3.4. Relative differences: vertical component

The relative differences (MRD_V) of SWC and ST between the three soil layers showed important changes in the patterns over the three hydro-thermic periods, appearing drier and warmer conditions in the deepest layer during the drying and warming (26Fb - 22Jn) and wetting and cooling (7Sp – 25Oc) periods, but, conversely, during the dry and warm (23Jn – 6Sp) period, the driest and warmest conditions were found in the upper-most layer (Table 3). This pattern was not affected by the vine varieties, but a different behaviour was found between the two zones regarding the values of the wettest and warmest values. In particular, the location of the wettest conditions did not vary over time in IR and they always appeared at 15 cm, whereas the pattern in R showed clear temporal changes, with the wettest conditions at 5 cm during the drying and warming and wetting and cooling periods, and at 25 cm during the dry and warm period. In general, and as it was expected, negative MRD_V-SWC were associated with positive MRD_V-ST, and positive MRD_V-SWC with negative MRD_V-ST, although the relationship between these metrics showed different degree of correlation: Good in R ($R^2 = 0.6054$) and BL ($R^2 = 0.5185$), and very poor in IR ($R^2 = 0.0056$) and Ag ($R^2 = 0.0012$) (Appendix B1a).

The standard deviation of the relative differences ($SDRD_V$) of SWC and ST showed a very homogeneous pattern between the two vine varieties, the two field zones and the three hydro-thermic periods (Appendix C1). In almost all cases of $SDRD_V$-SWC and in all cases of $SDRD_V$-ST, the highest range of values appeared in the upper-most layer, and the lowest range at 15 cm. Only the rows of BL showed a different pattern of $SDRD_V$-SWC during the drying and warming and wetting and cooling periods, with the highest range of values at 25 cm, but the lowest range of values kept at 15 cm. Although the linear relationships between $SDRD_V$-SWC and $SDRD_V$-ST did not provide high correlations: BL ($R^2 = 0.2122$) > IR ($R^2 = 0.1824$) > Ag ($R^2 = 0.1707$) > R ($R^2 = 0.1185$), the general trend indicated that higher $SDRD_V$-SWC concurred with higher $SDRD_V$-ST (Appendix B1b). The coefficient of variation of the relative differences ($CVRD_V$) gave a first approximation of the stability of the values over the study period (Appendix C2). The combined analysis of MRD_V and $SDRD_V$ allowed the identification of well-defined patterns: The dry conditions observed in R and IR at 5 cm, and the warm conditions in R, had moderate or low variability over the three hydro-thermic periods, and thus, could be considered as dry, warm and stable; although warm conditions in IR showed higher variability. Wet and cool conditions also had moderate or low variability. The highest variability appeared in those areas with intermediate values of soil moisture and temperature, namely: I) high values of $CVRD_V$-SWC were found at 15 cm in R during the three periods, in the upper-most layer during the first and third periods, and in the deepest soil layer during the second period in IR. II) high values of $CVRD_V$-ST prevailed at 15 and 25 cm in spring and autumn and at 5 cm in summer. No clear difference was found between the behaviour of the two cultivars regarding $CVRD_V$. Due to the wide range of possible values, the correlation between $CVRD_V$-SWC and $CVRD_V$-ST was very low (Appendix B1c).

The lowest values of the index of temporal stability (ITS_V) appeared at 15 cm in all cases for ST ($\overline{ITS_V}$=0.029 ± 0.009), regardless the hydro-thermic periods, vine varieties and field zones, and also at 15 cm for SWC ($\overline{ITS_V}$=0.117 ± 0.064), especially in R over the three periods, and during spring and autumn in IR (Table 4). Therefore, the prevailing conditions previously described with MRD_V, $SDRD_V$ and $CVRD_V$ at this soil layer were the representative conditions of the field over the course of the crop cycle. Conversely, the less representative conditions of the hydro-thermic status of the soil were those obtained in the upper-most layer in all cases of ST ($\overline{ITS_V}$=0.079 ± 0.023) and almost all cases of

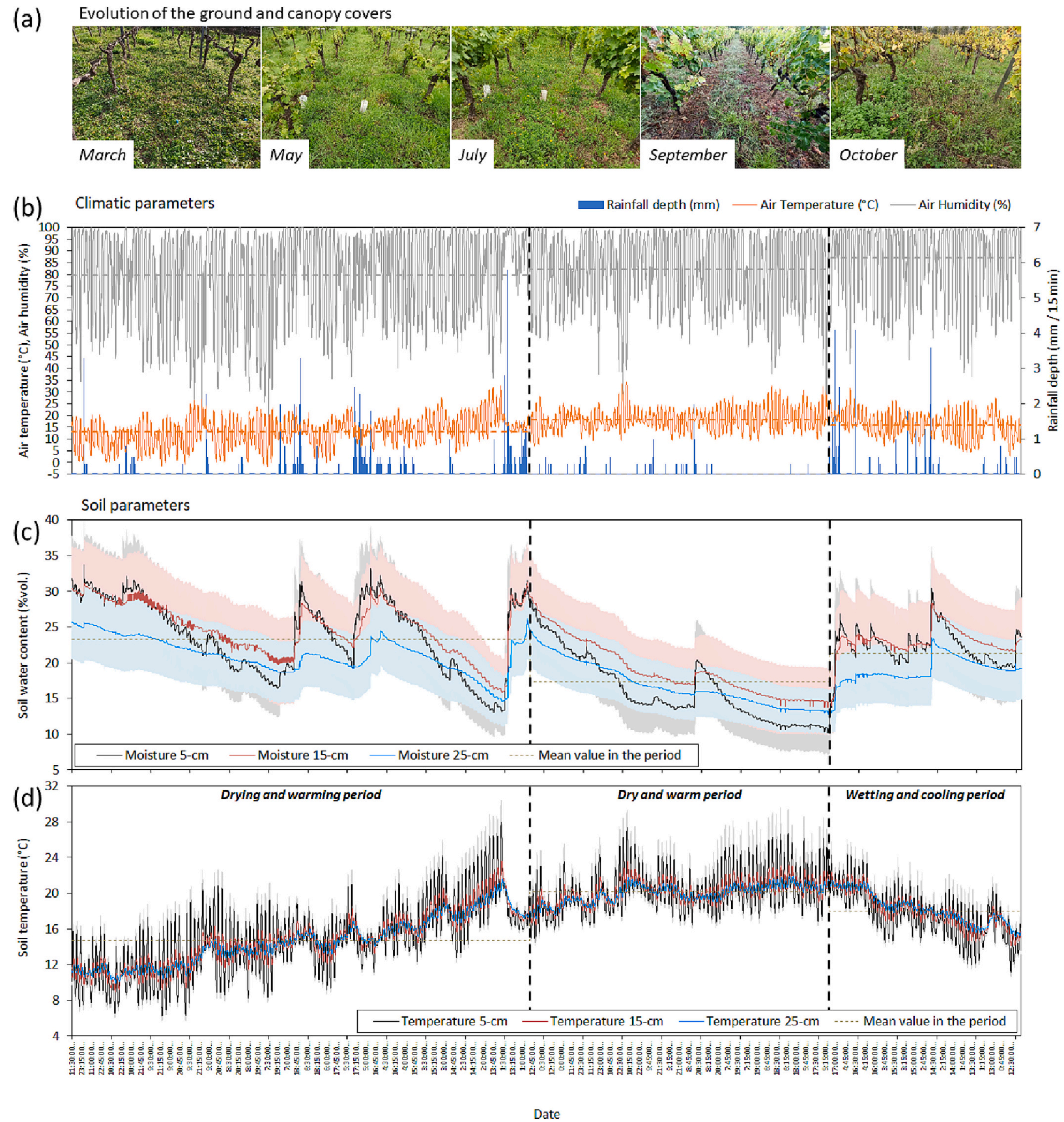

Fig. 3. Sequence of pictures showing the evolution of the ground cover and vine canopy cover over the study period (a). Evolution in the values of rainfall depth, air temperature and humidity (b), and in the mean values of soil moisture (c) and temperature (d) –observed in the 12 probes– at 5-, 15- and 25-cm depth over the study period. The mean values during the three hydrothermal periods are drawn with dotted lines. Shadow colours correspond to the standard deviation.

SWC ($\overline{ITS_V}$=0.173 ± 0.079). At 25 cm, the representativeness of SWC ($\overline{ITS_V}$=0.153 ± 0.060) and ST ($\overline{ITS_V}$=0.056 ± 0.016) was intermediate, except in summer, when the most representative conditions of SWC appeared at this depth. Mirroring the pattern of the previous metric, the highest ITS_V appeared in different soil layers in BL and Ag, indicating that the probes installed in the two cultivars captured slight differences in the hydro-thermic response of the soil. The limited range of values of ITS_V explained the poor correlation between the values of ITS_V-SWC and ITS_V-ST, although value distribution showed that low ITS_V-SWC was generally associated with low ITS_V-ST (Appendix B1d).

3.5. Relative differences: horizontal component

Focusing on the changes between the different zones and cultivars at the same soil depth, the horizontal analysis of the relative differences (MRD_H) revealed different spatial patterns when the three soil layers were compared (Table 5). During the first hydro-thermic period (spring), Ag had moister conditions than BL at the three soil layers, and

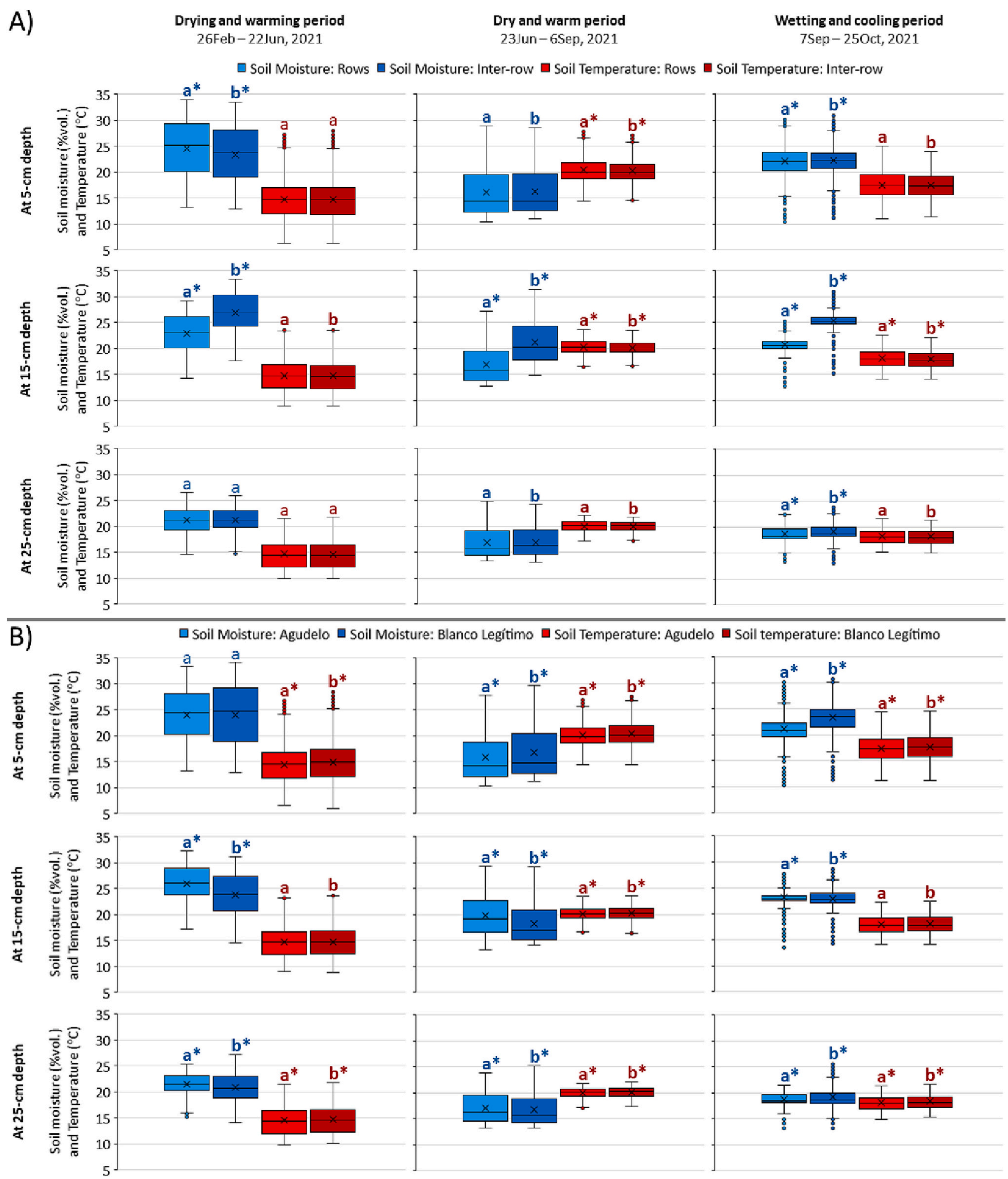

Fig. 4. Boxplots of distributions of the mean values (from the 12 probes) of soil moisture and temperature during the three hydro-thermic periods at 5-, 15- and 25-cm depth, and considering: A) the two zones (R and IR); and B) the two varieties (Ag and BL). Different lower case letter indicates significant differences at 0.05 level, and asterisk significant differences at 0.01 level (Kruskal–Wallis one-way analysis of variance).

this pattern kept in summer at 15 and 25 cm, but only in autumn at 15 cm. In autumn, BL had moister conditions than Ag at 5 and 25 cm. Regarding ST, the pattern was very stable and cooler conditions prevailed in Ag during the three periods and in the three soil layers. With regard to the two field zones, IR presented moister conditions than R during the three periods at 15 cm, and at 5 and 25 cm in summer and autumn. R only had moister conditions than IR in spring at 5 and 25 cm. Cooler conditions always appeared in IR, compared with R, during the three hydro-thermic periods and at the three soil layers. The values of MRD_H-SWC showed a negative relationship with those of MRD_H-ST, with moderate correlation at 15 and 25 cm, and very low correlation at 5 cm (Appendix B2a).

Table 3
Mean values of MRD_V of soil moisture and temperature calculated for each variety and field zone during the three hydrothermal periods, and considering the vertical component of the analysis (soil depth – SD; j = V in Eqs. (1) to (6)). Background colour: Blue indicates wet and cool conditions; green indicates intermediate conditions; and orange indicates dry and warm conditions.

Zone	SD	Soil moisture									Soil temperature								
		Drying & warming (26Fb - 22Jn)			Dry & warm (23Jn – 6Sp)			Wetting & cooling (7Sp – 25Oc)			Drying & warming (26Fb - 22Jn)			Dry & warm (23Jn – 6Sp)			Wetting & cooling (7Sp – 25Oc)		
	(cm)	Ag+BL	Ag	BL	Ag+BL	Ag	BL	Ag+BL	Ag	BL	Ag+BL	Ag	BL	Ag+BL	Ag	BL	Ag+BL	Ag	BL
R+IR	5	0.026	0.010	0.043	-0.072	-0.106	-0.038	0.040	0.017	0.063	-0.009	-0.014	-0.004	0.003	0.000	0.007	-0.026	-0.027	-0.025
	15	0.062	0.090	0.032	0.089	0.127	0.051	0.070	0.096	0.044	0.004	0.009	0.000	0.003	0.005	0.000	0.006	0.008	0.003
	25	-0.088	-0.101	-0.075	-0.016	-0.021	-0.012	-0.110	-0.113	-0.107	0.005	0.005	0.004	-0.006	-0.005	-0.007	0.020	0.019	0.022
R	5	0.073	0.074	0.072	-0.036	-0.054	-0.018	0.074	0.073	0.075	-0.010	-0.017	-0.003	0.004	-0.001	0.008	-0.027	-0.027	-0.027
	15	-0.007	0.000	-0.016	0.011	0.024	-0.001	0.005	0.002	0.008	0.006	0.008	0.005	0.004	0.004	0.004	0.007	0.007	0.008
	25	-0.066	-0.074	-0.056	0.025	0.031	0.019	-0.079	-0.075	-0.084	0.004	0.009	-0.002	-0.007	-0.003	-0.012	0.019	0.020	0.019
IR	5	-0.018	-0.053	0.017	-0.108	-0.158	-0.058	0.006	-0.039	0.050	-0.008	-0.012	-0.005	0.003	0.001	0.005	-0.025	-0.028	-0.023
	15	0.127	0.180	0.075	0.166	0.231	0.102	0.136	0.191	0.081	0.003	0.010	-0.005	0.002	0.007	-0.003	0.004	0.010	-0.002
	25	-0.109	-0.127	-0.092	-0.058	-0.072	-0.044	-0.141	-0.152	-0.131	0.005	0.002	0.009	-0.005	-0.008	-0.002	0.021	0.018	0.025

Table 4
Mean ITS_V calculated for each variety and field zone, and considering the vertical component of the analysis (soil depth – SD; j = V in Eqs. (1) to (6)). Background colour: Light blue indicates the highest temporal stability; light purple indicates intermediate conditions; and purple indicates the lowest temporal stability.

Zone	SD	Soil moisture									Soil temperature								
		Drying & Warming			Dry & Warm			Wetting & Cooling			Drying & Warming			Dry & Warm			Wetting & Cooling		
	(cm)	Ag+BL	Ag	BL	Ag+BL	Ag	BL	Ag+BL	Ag	BL	Ag+BL	Ag	BL	Ag+BL	Ag	BL	Ag+BL	Ag	BL
R+IR	5	0.183	0.228	0.118	0.210	0.272	0.119	0.172	0.202	0.137	0.110	0.104	0.115	0.061	0.057	0.064	0.067	0.066	0.069
	15	0.123	0.152	0.081	0.152	0.194	0.095	0.120	0.151	0.077	0.041	0.039	0.043	0.022	0.022	0.023	0.023	0.023	0.023
	25	0.160	0.187	0.125	0.151	0.192	0.096	0.180	0.194	0.164	0.077	0.071	0.082	0.044	0.040	0.047	0.049	0.046	0.052
R	5	0.140	0.162	0.109	0.131	0.163	0.089	0.122	0.128	0.116	0.113	0.110	0.117	0.065	0.060	0.069	0.072	0.070	0.073
	15	0.079	0.088	0.068	0.092	0.121	0.048	0.064	0.074	0.053	0.043	0.041	0.044	0.024	0.023	0.024	0.025	0.025	0.025
	25	0.110	0.107	0.112	0.101	0.124	0.072	0.131	0.120	0.142	0.079	0.073	0.084	0.046	0.041	0.051	0.051	0.049	0.054
IR	5	0.216	0.279	0.125	0.266	0.348	0.143	0.211	0.256	0.155	0.106	0.098	0.113	0.057	0.054	0.059	0.063	0.061	0.064
	15	0.153	0.196	0.092	0.195	0.246	0.125	0.157	0.201	0.096	0.040	0.037	0.042	0.021	0.021	0.022	0.021	0.022	0.021
	25	0.196	0.241	0.136	0.189	0.241	0.114	0.218	0.248	0.183	0.075	0.069	0.080	0.041	0.039	0.042	0.047	0.043	0.050

Table 5

Average MRD_H at each cultivar and zone, considering the soil depth (SD) as the reference of the analysis (j = H in Eqs. (1) to (6)). * When all values of the two zones and two cultivars of the same soil depth are combined, MRD_H is zero because there is no difference. Background colour: Blue indicates wet and cool conditions; green indicates intermediate conditions; and orange indicates dry and warm conditions.

		Soil moisture									Soil temperature								
		Drying & Warming			Dry & Warm			Wetting & Cooling			Drying & Warming			Dry & Warm			Wetting & Cooling		
SD	Variety	Zone			Zone			Zone			Zone			Zone			Zone		
(cm)		R	IR	R+IR	R	IR	R+IR	R	IR	R+IR	R	IR	R+IR	R	IR	R+IR	R	IR	R+IR
5	Ag+BL	0.025	-0.025	Zero*	-0.008	0.008	Zero*	-0.006	0.006	Zero*	0.002	-0.002	Zero*	0.003	-0.003	Zero*	0.003	-0.003	Zero*
	Ag	0.049	-0.041	0.004	-0.007	-0.050	-0.028	-0.018	-0.077	-0.047	-0.017	-0.008	-0.013	-0.010	-0.008	-0.009	-0.004	-0.010	-0.007
	BL	0.001	-0.009	-0.004	-0.008	0.065	0.028	0.006	0.089	0.047	0.021	0.005	0.013	0.015	0.003	0.009	0.010	0.004	0.007
15	Ag+BL	-0.089	0.089	Zero*	-0.116	0.116	Zero*	-0.100	0.100	Zero*	0.003	-0.003	Zero*	0.003	-0.003	Zero*	0.006	-0.006	Zero*
	Ag	-0.065	0.167	0.051	-0.091	0.176	0.043	-0.115	0.124	0.005	-0.008	-0.001	-0.005	-0.005	-0.002	-0.003	-0.002	-0.005	-0.003
	BL	-0.114	0.011	-0.051	-0.142	0.057	-0.043	-0.086	0.076	-0.005	0.015	-0.006	0.005	0.011	-0.005	0.003	0.013	-0.007	0.003
25	Ag+BL	0.000	-0.000	Zero*	-0.004	0.004	Zero*	-0.100	0.100	Zero*	0.001	-0.001	Zero*	0.001	-0.001	Zero*	0.006	-0.006	Zero*
	Ag	0.007	0.029	0.018	0.019	0.004	0.012	-0.115	0.124	-0.009	-0.004	-0.009	-0.007	-0.002	-0.007	-0.004	-0.002	-0.005	-0.007
	BL	-0.007	-0.029	-0.018	-0.028	0.004	-0.012	-0.086	0.076	0.009	0.007	0.007	0.007	0.004	0.005	0.004	0.013	-0.007	0.007

$SDRD_H$ showed that IR always had higher ranges of SWC than R in the three soil layers and during the three periods (Appendix C3). Conversely, lower ranges of ST prevailed in IR during the three periods at 5 cm, but this pattern progressively change in the deeper layers, and IR had lower ranges than R at 15 cm during two periods (spring and autumn), and only in one period (autumn) at 25 cm. Regarding cultivars, lower ranges of SWC predominated in BL in summer at the three soil layer and in the three periods at 25 cm. Considering R and IR as a whole, BL always had higher ranges of ST than Ag in the three soil layers and during the whole study period. However, a more complex pattern appeared when $SDRD_H$ was analysed in detail (e.g. R-BL in summer), explaining the low correlation between $SDRD_H$-SWC and $SDRD_H$-ST at 5 and 25 cm (Appendix B2b).

The combined analysis of the values of $CVRD_H$ and MRD_H allowed the identification of the following patterns (Appendix C4): I) R had lower variability of SWC and ST than IR in the three periods and at the three soil layers, except for ST than had lower variability of ST in spring at 15 cm, in summer at 5 cm, and at the three soil layers in autumn. II) In general, lower variability of SWC appeared in BL, but higher variability of ST. III) for the whole period (242 days), the mean values of $CVRD_H$ of SWC and ST at 5, 15 and 25 cm were of 1.12 and 4.22, 0.42 and 3.61, and 2.09 and 9.76, respectively, indicating that the lowest variability in the values of the two soil parameters happened at 15 cm, and the highest at the deepest soil layer. However, the variability of the magnitude of the response of the two variables over the three periods in the two varieties and the two zones explained the low correlation between the values of $CVRD_H$-SWC and $CVRD_H$-ST (Appendix B2c).

The values of ITS_H showed a homogeneous pattern of soil moisture: R ($\overline{ITS_H}$=0.168 ± 0.058) always had more representative values of SWC than IR ($\overline{ITS_H}$=0.271 ± 0.063) in the three soil layers and during the three hydro-thermic periods (Table 6). Regarding ST, the pattern was more variable and R ($\overline{ITS_H}$=0.028 ± 0.015) only had more representative values than IR ($\overline{ITS_H}$=0.026 ± 0.012) at 15 cm in summer and at 25 cm in spring and summer. Therefore, the behaviour of SWC and ST differed in terms of temporal stability and spatial representativeness. When the two varieties were analysed, BL ($\overline{ITS_H}$=0.217 ± 0.049) had more representative values of SWC than Ag ($\overline{ITS_H}$=0.222 ± 0.103), but Ag ($\overline{ITS_H}$=0.019 ± 0.010) always had more representative values of ST than BL ($\overline{ITS_H}$=0.035 ± 0.012). These findings reflected the different response of the soil in terms of SWC and ST, and explain the low correlation between ITS_H-SWC and ITS_H-ST (Appendix B2d).

4. Discussion

4.1. Influence of climatic parameters, soil properties and cultivars

Summer conditions –lower precipitation, and higher air temperature and water demand by plants– explained the low values of SWC and high of ST observed in this season. During the whole crop cycle –excluding winter–, the mean value of ST ($\bar{x}$ = 16.49 ± 3.42 °C) was 8.1% higher than the mean value of air temperature ($\bar{x}$ = 15.26 ± 5.94 °C), with 65% of all measurements with higher values of ST than air temperature (during the nights and in the coldest months) and 35% with colder values of ST than of air temperature (during the hottest hours of the day and in the summer). The mean ST was 12.8%, 10.2% and 13.4% higher than the air temperature in spring, summer and autumn, respectively. This is the first study that compares the evolution of ST and air temperature in a vineyard included in the 'Viño da Terra de Betanzos' protected geographical indication (IGP), presenting useful information for local viticulturists that may be concerned about high air temperatures during summer and their negative influence on grape growth and maturity (Clemente et al., 2022). Plant cover and litter below the vines

Table 6
Mean ITS_H calculated for each variety and field zone, considering the soil depth (SD) as the basis of the analysis (j = H in Eqs. (1) to (6)). Background colour: Light blue indicates the highest temporal stability; light purple indicates intermediate conditions; and purple indicates the lowest temporal stability.

		Soil moisture									Soil temperature								
		Drying & Warming			Dry & Warm			Wetting & Cooling			Drying & Warming			Dry & Warm			Wetting & Cooling		
SD	Variety	Zone			Zone			Zone			Zone			Zone			Zone		
(cm)		R	IR	R+IR	R	IR	R+IR	R	IR	R+IR	R	IR	R+IR	R	IR	R+IR	R	IR	R+IR
5	Ag+BL	0.153	0.251	----	0.142	0.329	----	0.187	0.278	----	0.044	0.044	----	0.046	0.040	----	0.041	0.025	----
	Ag	0.152	0.274	0.221	0.132	0.400	0.298	0.077	0.279	0.205	0.042	0.038	0.040	0.029	0.026	0.027	0.031	0.025	0.028
	BL	0.155	0.225	0.193	0.152	0.239	0.200	0.254	0.276	0.265	0.047	0.049	0.048	0.059	0.050	0.055	0.049	0.025	0.039
15	Ag+BL	0.185	0.261	----	0.204	0.312	----	0.214	0.266	----	0.027	0.026	----	0.031	0.032	----	0.022	0.018	----
	Ag	0.130	0.284	0.221	0.163	0.348	0.272	0.139	0.286	0.225	0.017	0.013	0.015	0.015	0.015	0.015	0.009	0.015	0.012
	BL	0.227	0.235	0.231	0.238	0.271	0.255	0.269	0.245	0.257	0.035	0.035	0.035	0.041	0.043	0.042	0.030	0.021	0.025
25	Ag+BL	0.124	0.265	----	0.145	0.264	----	0.214	0.266	----	0.013	0.022	----	0.020	0.024	----	0.022	0.018	----
	Ag	0.112	0.339	0.252	0.107	0.343	0.254	0.139	0.286	0.245	0.011	0.017	0.014	0.011	0.014	0.012	0.009	0.015	0.015
	BL	0.135	0.160	0.148	0.175	0.146	0.161	0.269	0.245	0.167	0.015	0.026	0.021	0.026	0.032	0.029	0.030	0.021	0.015

and in IR acted as an insulating layer, preventing exchanges (heat flux) between topsoil and atmosphere, such as Pradel and Pieri (2000) observed in a French vineyard with and without grass cover. Our results agreed with those obtained by Darouich et al. (2022) for SWC in Italian and Portuguese rainfed vine-growing areas under different climatic conditions, and by Mekki et al. (2018) in north-eastern Tunisia under Mediterranean semiarid to sub-humid conditions. It is worth noting that the magnitude of the changes of SWC and ST in vineyards located near the Atlantic coast has been rarely evaluated (e.g. Pradel and Pieri, 2000). For the first time in a Galician or Portuguese vineyard with temperate oceanic climate, the dynamic of SWC and ST has been studied at high-resolution. This study also proves the relevance of splitting the time-series analysis into different hydro-thermic periods: When the analysis of differences was done considering the whole period, only significant differences appeared in the values of SWC and ST between the different layers (Table 2), but significant differences appeared among zones and cultivars when the analysis was done separately for each hydro-thermic period (Fig. 4).

Vine water consumption has received a great deal of attention, especially in semi-arid areas and irrigated fields where water use efficiency is a relevant issue (Deloire et al., 2004). In humid areas with mild temperature, like the site of this study, water stress is less frequent and of low intensity when it occurs (Martínez et al., 2016). The technical staff of the vinery of this study confirmed the minor occurrence of water stress in the vines. Therefore, the focus on vine water consumption, and the subsequent soil water balance, is on the different water requirements of the distinct vine varieties, e.g. some varieties consume more water than others (Bravdo et al., 1971; Cancela et al., 2015). In our case, IR had moister values than R in the two cultivars: +6.41% in Ag and +5.43% in BL, although ST was the same in Ag and slightly cooler (−1.2%) in BL, indicating higher water consumption by the plants in R (vines and resident vegetation) than in IR (only resident vegetation). These differences may indicate that vines did not uptake much more water than the plant species of the ground cover, suggesting that SWC was a non-limiting factor of plant growth. Besides, the observed differences of SWC between soil layers were more marked in IR than in R, and this fact could be explained by differences in the development of the root system in R, where vine roots and those of the resident vegetation are overlapped and probably occupying the whole soil profile, and in IR, where the root system of the resident vegetation would not occupy the whole space. Focusing on this topic, a parallel research is currently studying the relationship between plant vigour metrics (e.g. NDVI, content of chlorophyll) and the dynamic of SWC and ST over the crop cycle.

In non-irrigated vineyards with permanent plant cover, very few studies have done focussed on the effect of the cover on SWC and/or ST, such as the study of Monteiro and Lopes (2007) in Portugal, of Ruiz-Colmenero et al. (2011) in central Spain, of Vršič et al. (2021) in Slovenia, and of Celette et al. (2008) in the south of France. Therefore, our study provides new insights about the effect of a permanent spontaneous cover in the dynamic of SWC and ST over the crop cycle. Regarding the differences among cultivars, the soil in Ag remained moister than the soil in BL in R (+1.67%) and IR (+2.62%), and cooler in R (−1.97%) and IR (−0.79%). These results may be an indirect evidence that vines of BL consumed more water than those of Ag. As we did not find any study in the literature about soil water consumption by Agudelo (also known as Chenin blanc) and Blanco Legítimo (also known as Albarín Blanco) vines, this study is a first approximation to know the water necessities of the two varieties. To strengthen the findings of this study, inter-annual climatic variability will be considered by means of extending the observation period, under the same or different tillage practices.

4.2. Representative areas

Mapping soil properties in vineyards is usually a complicated task due to the high spatial heterogeneity (Signorini et al., 2021), and monitoring the seasonal and inter-annual differences is a time- and resources-demanding mission (Pereyra et al., 2022). In our case of study, physiographic conditions were very homogeneous, and thus, we could firstly assess the spatial and temporal patterns at the field scale and for each cultivar and zone, and then, the location of the most representative areas of the prevalent conditions with the ITS. Regarding the vertical pattern of stability, ITS_V clearly indicated that the observed values at 15 cm were always the most stable for ST during the three hydro-thermic periods regardless the zone and cultivar, and for SWC the values at 15 cm were also the most stable and representative of the average conditions during the three periods in R, and in spring and autumn in IR. During the summer and in IR, the most stable values of SWC appeared at 25 cm. Therefore, cultivars did not modify the vertical pattern of SWC and ST, but the two zones (R and IR) showed some relevant differences in the two soil parameters. These changes may be explained by: I) the shallow conditions of the soil (maximum depth of approximately 35 cm) –a different pattern might be found in areas with deeper soils–; and II) the extension of the root system in R, which occupies the whole soil profile, and IR, where the roots of the plants are more concentrated in the upper-most layers. Our hypothesis of the different extension of the root systems is based on the study of Celette et al. (2008) in a French vineyard with permanent and non-permanent covers. These authors found that the values of the root length density (RLD; length of the roots in cm per unit of soil volume in cm^3) in R were higher and with a homogeneous pattern along the soil profile than in IR, especially in the topsoil and the deeper soil layers, describing a more heterogeneous pattern.

A novel aspect of this study is that for the first time in the literature, ITS has been calculated in a vineyard. Even though, this is the first application of ITS in a permanent/ woody crop, identifying the locations that are representative of the average field conditions of SWC and ST. These findings are relevant to reduce the time and cost of long-term monitoring tasks by means of reducing the number of measuring points. Zhang et al. (2022) found in a multiple cropping systems (winter-wheat, spring-maize, rotation of winter-wheat and spring-maize) with three tillage practices (no tillage, subsoiling tillage, conventional tillage) that the topsoil layer showed a higher ITS value for all cropping systems, but the ITS increased with soil depth in the deep soil profile (below 3.0 m). We found lower stability at the upper-most layer than at 15 cm, and this different result may be associated with the differences among the root systems and plan growth of the annual and permanent crops. The observed differences in the hydro-thermic response of the soil over the crop cycle support the necessity of implementing precision farming practices in order to provide the best management practices regarding soil moisture and temperature, and crop water stress (Bellvert et al., 2014).

4.3. Differences and relationships between soil moisture and temperature dynamics

The relationship between ST and SWC in cultivated soils has been studied for decades and in different crops, describing distinct patterns. In maize fields and under tropical conditions, Lal (1974) observed that mulching caused a decrease in the maximum ST measured at different soil depths together with an increase in SWC. Schonbeck and Evanylo (1998) evaluated the effects of hay, compost, plastic and paper mulches on ST and SWC on tomato fields, finding a general tendency of decreasing soil moisture levels when soil temperature increased. At larger scales, Lakshmi et al. (2003) reported that surface temperature increases corresponded to a decrease in the soil moisture in different American crops and land uses (forest, rangeland, pasture, grassland, wheat, corn, alfalfa, peanuts, cotton and fallow). In Australian semiarid vineyards, Kerridge et al. (2013) observed higher ST in R and lower in IR, higher soil water evaporation in IR than in R, and more interesting, R had less spatial variability compared to IR. All these previous studies agree among them and also with the results of this study (Fig. 2), but any of them calculated the inherent spatio-temporal variability of SWC and ST due to different cultivars and zones that we have assessed under homogeneous physiographic conditions (Fig. 4). To advance in the comprehension of the relationships between SWC and ST in vineyards, the study of the effect of bare soil patches below the vines (Pradel and Pieri, 2000), the presence of mulches in R and IR (Bavougian and Read, 2018), and of seeded cover crops (Steenwerth and Belina, 2008) will be considered in further research activities.

5. Conclusions

The spatial and temporal patterns of the hydro-thermic response of the soil were calculated in a rainfed vineyard under humid and homogeneous soil conditions, highlighting the role played by the two cultivars and two zones. For the first time in the literature of woody crops, the index of temporal stability was used to identify the most representative areas to measure SWC and ST. These findings are relevant to reduce the time and cost of long-term monitoring by reducing the number of measuring points. Significant differences appeared between the drying and warming, dry and warm, and wetting and cooling seasons. SWC and ST correlated well in the rows (R), but moderate correlations appeared in the inter-row areas (IR), showing a more complex response in this zone. Both cultivars, Agudelo –Ag– and Blanco legítimo –BL–, had drier and warmer conditions in the deepest layer in spring and autumn, and in the upper-most layer in summer, with the most stable conditions at 15 cm depth. This vertical pattern remained for ST, but it changed for SWC in IR, with the most stable and moistest conditions in summer at 25 cm.

Ag had moister, but less representative conditions than BL at the three soil layers in spring, and this pattern kept in summer at 15 and 25 cm, but only at 15 cm in autumn. ST pattern was very stable, and cooler and representative conditions prevailed in Ag. These results may be an indirect evidence of different water demand by the two varieties. BL has been rarely cited in the literature, and this study contributes with new insights about the SWC and ST dynamic on this cultivar. In general, IR had wetter and cooler conditions than R, suggesting higher water consumption by the plants in R (vines and resident vegetation). Within each soil layer, R always had more representative values of SWC than IR, and the pattern of ST were more variable, and R only had more representative values than IR at 15 cm in summer and at 25 cm in spring and summer. These changes may be explained by the extension of the root zone in R (higher density and length) and IR (more concentrated in the upper soil layers). The existence of a total cover with resident plant species did not prevent the occurrence of spatial and temporal changes that suggest the implementation of precision farming practices. This study has estimated the inherent heterogeneity of the hydro-thermic response of the cultivated soil –despite homogeneous soil conditions– that is of relevance to refine the assessment of the actual role played by tillage practices, plant species or treatments. Further researches should be conducted on the response time among climatic and soil parameters, the correlation between plant vigour metrics and the dynamic of SWC and ST, and the effect of mulches and bare soil patches on the hydro-thermic response.

Declaration of Competing Interest

None.

Data availability

Both pre-processed (raw) and processed data will be made available on reasoned request.

Acknowledgements

This study has been funded by 'Xunta de Galicia' through the project "Optimización de los beneficios de las cubiertas vegetales en viñedos: Sostenibilidad ambiental y económica, y comunicación en tiempo real (5G) de parámetros (GalVin-5G) (Ref. ED431H 2020/18)". We specially thank "Pagos de Brigante SL" winery for facilitating the vineyard where this study was done. We also thank Mr. Jorge Prieto Sevilla for helping us with the classification of the plant species of the resident vegetation. Funding for open access charge: Universidade da Coruña / CISUG.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2023.e00631.

References

Abdellatif, M.A., El Baroudy, A.A., Arshad, M., Mahmoud, E.K., Saleh, A.M., Moghanm, F.S., Shaltout, K.H., Eid, E.M., Shokr, M.S., 2021. A GIS-based approach for the quantitative assessment of soil quality and sustainable agriculture. Sustainability 13 (23), 13438.

Aragüés, R., Medina, E.T., Clavería, I., Martínez-Cob, A., Faci, J., 2014. Regulated deficit irrigation, soil salinization and soil sodification in a table grape vineyard drip-irrigated with moderately saline waters. Agric. Water Manag. 134, 84–93.

Bavougian, C.M., Read, P.E., 2018. Mulch and groundcover effects on soil temperature and moisture, surface reflectance, grapevine water potential, and vineyard weed management. PeerJ 6, e5082.

Bellvert, J., Zarco-Tejada, P.J., Girona, J., Fereres, E., 2014. Mapping crop water stress index in a 'pinot-noir' vineyard: comparing ground measurements with thermal remote sensing imagery from an unmanned aerial vehicle. Precis. Agric. 15, 361–376.

Bonetti, S., Sutanudjaja, E.H., Mabhaudhi, T., Slotow, R., Dalin, C., 2022. Climate change impacts on water sustainability of South African crop production. Environ. Res. Lett. 17 (8), 084017.

Bravdo, B., Lavee, S., Samish, R.M., 1971. Analysis of water consumption of various grapevine cultivars. Vitis – J. Grapevine Res. 10 (4), 279–291.

Cancela, J.J., Fandiño, M., Rey, B.J., Martínez, E.M., 2015. Automatic irrigation system based on dual crop coefficient, soil and plant water status for *Vitis vinifera* (cv Godello and cv Mencía). Agric. Water Manag. 151, 52–63.

Celette, F., Gaudin, R., Gary, C., 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. Eur. J. Agron. 29 (4), 153–162.

Clemente, N., Santos, J.A., Fontes, N., Graça, A., Gonçalves, I., Fraga, H., 2022. Grapevine sugar concentration model (GSCM): a decision support tool for the Douro superior winemaking region. Agronomy 12 (6), 1404.

Darouich, H., Ramos, T.B., Pereira, L.S., Rabino, D., Bagagiolo, G., Capello, G., Simionesei, L., Cavallo, E., Biddoccu, M., 2022. Water use and soil water balance of Mediterranean vineyards under rainfed and drip irrigation management: evapotranspiration partition and soil management modelling for resource conservation. Water 14 (4), 554.

Deloire, A., Carbonneau, A., Wang, Z., Ojeda, H., 2004. Vine and water: a short review. Oeno One 38 (1), 1–13.

Figueiredo, T., Poesen, J., Fonseca, F., Hernández, Z., 2021. Long term erosion rates in Douro vineyards, Portugal: effects of rainfall characteristics and plant density. In: Vieira, A.A.B., Bento-Gonçalves, A.J. (Eds.), Soil Conservation: Strategies, Management and Challenges. Nova Science Publishers, New York, pp. 67–105. ISBN 978–1–53619-600-9.

Figueiredo-González, M., Cancho-Grande, B., Boso, S., Santiago, J.L., Martínez, M.C., Simal-Gándara, J., 2013. Evolution of flavonoids in Mouratón berries taken from both bunch halves. Food Chem. 138 (2–3), 1868–1877.

Gasch, C.K., Huzurbazar, S.V., Stahl, P.D., 2015. Small-scale spatial heterogeneity of soil properties in undisturbed and reclaimed sagebrush steppe. Soil Tillage Res. 153, 42–47.

Goenster-Jordan, S., Jannoura, R., Jordan, G., Buerkert, A., Joergensen, R.G., 2018. Spatial variability of soil properties in the floodplain of a river oasis in the Mongolian Altay Mountains. Geoderma 330, 99–106.

Horel, Á., Zsigmond, T., Farkas, C., Gelybó, G., Tóth, E., Kern, A., Bakacsi, Z., 2022. Climate change alters soil water dynamics under different land use types. Sustainability 14 (7), 3908.

Irmak, S., Rathje, W.R., 2008. Plant Growth and Yield as Affected by Wet Soil Conditions Due to Flooding or Over-Irrigation. Ed. University of Nebraska–Lincoln, Index: Irrigation Engineering – Irrigation Operations & Management, p. G1904.

Jacobs, J.M., Mohanty, B.P., Hsu, En-Ching, Miller, D., 2004. SMEX02: field scale variability, time stability and similarity of soil moisture. Remote Sens. Environ. 92 (4), 436–446.

Jarvis, N., Groh, J., Lewan, E., Meurer, K.H.E., Durka, W., Baessler, C., Pütz, T., Rufullayev, E., Vereecken, H., 2022. Coupled modelling of hydrological processes and grassland production in two contrasting climates. Hydrol. Earth Syst. Sci. 26, 2277–2299.

Kerridge, B.L., Hornbuckle, J.W., Christen, E.W., Faulkner, R.D., 2013. Using soil surface temperature to assess soil evaporation in a drip irrigated vineyard. Agric. Water Manag. 116, 128–141.

Kisekka, I., Peddinti, S.R., Kustas, W.P., McElrone, A.J., Bambach-Ortiz, N., McKee, L., Bastiaanssen, W., 2022. Spatial–temporal modeling of root zone soil moisture dynamics in a vineyard using machine learning and remote sensing. Irrig. Sci. 40, 761–777.

Koch, B., Oehl, F., 2018. Climate change favors grapevine production in temperate zones. Agric. Sci. 9, 247–263.

Lakshmi, V., Jackson, T.J., Zehrfuhs, D., 2003. Soil moisture–temperature relationships: results from two field experiments. Hydrol. Process. 17 (15), 3041–3057.

Lal, R., 1974. Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. Plant Soil 40, 129–143.

Liu, S., Li, J., Zhang, X., 2022. Simulations of soil water and heat processes for no tillage and conventional tillage systems in mollisols of China. Land 11 (3), 417.

López-Vicente, M., Álvarez, S., 2018. Stability and patterns of topsoil water content in rainfed vineyards, olive groves, and cereal fields under different soil and tillage conditions. Agric. Water Manag. 201, 167–176.

López-Vicente, M., Quijano, L., Navas, A., 2015. Spatial patterns and stability of topsoil water content in a rainfed fallow cereal field and Calcisol-type soil. Agric. Water Manag. 161, 41–52.

Luciano, R.V., Albuquerque, J.A., Mafra, Á.L., da Costa, A., Grah, J., 2014. Water storage variability in a vineyard soil in the southern highlands of Santa Catarina state. Rev Bras Ciênc Solo 38 (1), 82–93.

Luo, Y., Loomis, R.S., Hsiao, T.C., 1992. Simulation of soil temperature in crops. Agric. For. Meteorol. 61 (1–2), 23–38.

Martínez, E.M., Rey, B.J., Fandiño, M., Cancela, J.J., 2016. Impact of water stress and nutrition on *Vitis vinifera* cv. 'Albariño': soil-plant water relationships, cumulative effects and productivity. Span. J. Agric. Res. 14 (1), e1202.

McCalla, T.M., Duley, F.L., 1946. Effect of crop residues on soil temperature. Agron. J. 38 (1), 75–89.

Mekki, I., Zitouna, R., Jacob, F., Ben-Mechlia, N., Prevot, L., Albergel, J., Voltz, M., 2018. Impact of land use on soil water content in a hilly rainfed agrosystem: a case study in the cap bon peninsula in Tunisia. Agrofor. Int. J. 3 (1), 64–74.

Monteiro, A., Lopes, C.M., 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agric. Ecosyst. Environ. 121 (4), 336–342.

Nolz, R., Loiskandl, W., 2017. Evaluating soil water content data monitored at different locations in a vineyard with regard to irrigation control. Soil Water Res. 12 (3), 152–160.

Oliveira, M.T., 2001. Modeling water content of a vineyard soil in the Douro region, Portugal. Plant Soil 233, 213–221.

Pereyra, G., Pellegrino, A., Gaudin, R., Ferrer, M., 2022. Evaluation of site-specific management to optimise *Vitis vinifera* L. (cv. Tannat) production in a vineyard with high heterogeneity. Oeno One 56 (3), 397–412.

Pradel, E., Pieri, P., 2000. Influence of a grass layer on vineyard soil temperature. Aust. J. Grape Wine Res. 6, 59–67.

Rahman, M.N., Hangs, R., Schoenau, J., 2020. Influence of soil temperature and moisture on micronutrient supply, plant uptake, and biomass yield of wheat, pea, and canola. J. Plant Nutr. 43 (6), 823–833.

Ramírez-Cuesta, J.M., Consoli, S., Longo, D., Longo-Minnolo, G., Intrigliolo, D.S., Vanella, D., 2022. Influence of short-term surface temperature dynamics on tree orchards energy balance fluxes. Precis. Agric. 23, 1394–1412.

Reynolds, A.G., Parchomchuk, P., Berard, R., Naylor, A.P., Hogue, E., 2005. Gewurztraminer grapevines respond to length of water stress duration. Int. J. Fruit Sci. 5 (4), 75–94.

Ruiz-Colmenero, M., Bienes, R., Marques, M.J., 2011. Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. Soil Tillage Res. 117, 211–223.

Schonbeck, M.W., Evanylo, G.K., 1998. Effects of mulches on soil properties and tomato production I. soil temperature, soil moisture and marketable yield. J. Sustain. Agric. 13 (1), 55–81.

Shayanmehr, S., Henneberry, S.R., Sabouni, M.S., Foroushani, N.S., 2020. Climate change and sustainability of crop yield in dry regions food insecurity. Sustainability 12 (23), 9890.

Shen, Y., McLaughlin, N., Zhang, X., Xu, M., Liang, A., 2018. Effect of tillage and crop residue on soil temperature following planting for a black soil in Northeast China. Sci. Rep. 8, 4500.

Signorini, M., Borruso, L., Randall, K.C., Dumbrell, A.J., Pii, Y., Mimmo, T., Cesco, S., 2021. Soil heterogeneity within a vineyard impacts the beta but not the alpha microbial agro-diversity. Appl. Soil Ecol. 166, 104088.

Steenwerth, K., Belina, K.M., 2008. Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem. Appl. Soil Ecol. 40, 359–369.

Tang, T., Radomski, M., Stefan, M., Perrelli, M., Fan, H., 2020. UAV-based high spatial and temporal resolution monitoring and mapping of surface moisture status in a vineyard. Pap. Appl. Geogr. 6 (4), 402–415.

Tian, M., Gao, W.-D., Ren, T.-S., Li, B.-G., 2022. Spatio-temporal variation of soil water and temperature between maize rows as affected by no-tillage and strip crop straw

mulching in southern Jilin Province | 条带覆盖免耕下吉林南部玉米行间土壤水分和温度的时空动态. J. Plant Nutr. Fertil. 28 (7), 1297–1307.
Vachaud, G., Passerat De Silans, A., Balabanis, P., Vauclin, M., 1985. Temporal stability of spatially measured soil water probability density function. Soil Sci. Soc. Am. J. 49, 822–828.
Van Leeuwen, C., Darriet, P., 2016. The impact of climate change on viticulture and wine quality. J. Wine Econ. 11 (1), 150–167.
Vilanova, M., Genisheva, Z., Bescansa, L., Masa, A., Oliveira, J.M., 2009. Volatile composition of wines from cvs. Blanco lexítimo, Agudelo and Serradelo (*Vitis vinifera*) grown in Betanzos (NW Spain). J. Inst. Brew. 115 (1), 35–40.
Villalobos, F.J., Fereres, E. (Eds.), 2016. Principles of Agronomy for Sustainable Agriculture. Springer International Publishing, Cham, Switzerland. https://doi.org/10.1007/978-3-319-46116-8.
Vršič, S., Breznik, M., Pulko, B., Rodrigo-Comino, J., 2021. Earthworm abundance changes depending on soil management practices in Slovenian vineyards. Agronomy 11 (6), 1241.
Wang, G., Li, W., Wang, K., Huang, W., 2021. Uncertainty quantification of the soil moisture response functions for microbial dormancy and resuscitation. Soil Biol. Biochem. 160, 108337.
Wei, L., Zhang, B., Wang, M., 2007. Effects of antecedent soil moisture on runoff and soil erosion in alley cropping systems. Agric. Water Manag. 94 (1–3), 54–62.
Wei, L., Dong, J., Gao, M., Chen, X., 2017. Factors controlling temporal stability of surface soil moisture: a watershed-scale modelling study. Vadose Zone J. 16 (10) https://doi.org/10.2136/vzj2016.12.0132.
Wilson, T.G., Kustas, W.P., Alfieri, J.G., Anderson, M.C., Gao, F., Prueger, J.H., McKee, L. G., Alsina, M.M., Sanchez, L.A., Alstad, K.P., 2020. Relationships between soil water content, evapotranspiration, and irrigation measurements in a California drip-irrigated pinot noir vineyard. Agric. Water Manag. 237, 106186.
Wu, G.-L., Dang, Z.-Q., Huang, Z., Liu, Y., Tian, F.-P., López-Vicente, M., 2020. Five-year soil moisture response of typical cultivated grasslands in a semi-arid area: implications for vegetation restoration. Land Degrad. Dev. 31 (9), 1078–1085.
Yetbarek, E., Ojha, R., 2020. Spatio-temporal variability of soil moisture in a cropped agricultural plot within the Ganga Basin, India. Agric. Water Manag. 234, 106108.
Zhang, Y., Li, H., Sun, Y., Zhang, Q., Liu, P., Wang, R., Li, J., 2022. Temporal stability analysis evaluates soil water sustainability of different cropping systems in a dryland agricultural ecosystem. Agric. Water Manag. 272, 107834.
Zhao, Y., Peth, S., Wang, X.Y., Lin, H., Horn, R., 2010. Controls of surface soil moisture spatial patterns and their temporal stability in a semi-arid steppe. Hydrol. Process. 24, 2507–2519.
Zufferey, V., Verdenal, T., Dienes, A., Belcher, S., Lorenzini, F., Koestel, C., Gindro, K., Spangenberg, J.E., Viret, O., Spring, J.-L., 2018. The impact of plant water status on the gas exchange, berry composition and wine quality of Chasselas grapes in Switzerland. Oeno One 52 (4). https://oeno-one.eu/article/view/2181.