



Effect of multifunctional irrigation on grape quality: a case study in Northern Italy

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Abstract

In recent decades, worldwide wine-growing regions have been affected by increasingly more frequent effects of climate change, such as long period of droughts during the growing season, summer heat waves, and late spring frost events, thus causing concern for the grape quality and production. In this context, it is necessary to develop innovative agronomic practices to counter the various negative effects from those extreme weather events, by equipping the vineyards with effective and reliable multifunctional systems, which are also economically sustainable. Particularly, a multifunctional irrigation system can be used to reduce the risk of extreme weather events and, at the same time, to improve quality and quantity of grape production, reducing their inter-annual variability as well, by providing an optimized plant water nutrition. In a vineyard situated south of Lake Garda (Northern Italy), a multifunctional irrigation system equipped with drippers and mini-sprinklers (the latter to protect from both late spring frost and summer high-temperature event) was assessed. The results obtained for the growing season 2020–21 showed that the optimized drip irrigation reduced water consumption without affecting the grape yield, both in quantity and quality. The frost protection operated by mini-sprinklers increased the air temperature at bud's level of about 1 °C, suggesting a positive effect on plant production. Finally, in 2020, must quality was positively affected by summer sprinkler irrigation, increasing the levels of malic acid and titratable acidity of over 0.7 g L⁻¹ while lowered total soluble solids. Further activities in the 2022 season intend to better assess the water use efficiency of this promising multifunctional system.

Introduction

Due to climate change, extreme weather events such as heat waves, long periods of drought during the growing season, and increasingly hot and dry springs are increasingly occurring. Many studies show that in recent decades, there has been a trend toward increasing temperatures in wine-growing regions worldwide, including the Mediterranean area (Jones 2012; Duchene and Schneider 2005; Fraga et al. 2012; Palliotti et al. 2014). Furthermore, recent projections assess that the frequency of heat waves will increase by 2100 (Cowan et al. 2014; Schoetter et al. 2014). The warming conditions determine increasing crop water requirements, while the water scarcity due to decreasing rainfall during

spring and summer exposes the crops to water stress; moreover, the increasingly frequent heat waves expose crops to thermic stress as well. Critical issues related to droughts and increasing temperature were highlighted also in the study area (Crespi et al. 2020; Bartolini et al. 2008; Brunetti et al. 2004).

The effects of climate change on grapevine are multiple. The temperature increase can accelerate the ripening of the vine, causing an excessive sugar accumulation and a high alcohol in the wine, as well as a reduction in total acidity (De Orduna 2010; Keller 2010; Caffarra and Eccel 2011; Sadras and Moran 2012). Furthermore, the increasing temperatures affect the synthesis and accumulation of polyphenols, vitamins, and aromatic compounds in berries (Keller 2010; Palliotti et al. 2014). Depending on the phenological phase, water stress affects quantity and quality of grape yield (Mendez-Costabel et al. 2014a, b; Shellie et al. 2014a, b; Koundouras et al. 2009); the effect of water stress on sugar accumulation and total acidity is still controversial (Mirás-Avalos and Intrigliolo 2017). To counter the

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effects of climate change, adaptation strategies are adopted in viticulture (Naulleau et al. 2021). Long-term strategies, such as changes in vineyard locations, consider the selection of cooler sites for planting vineyards (Hannah et al. 2013; Delay et al. 2015; Moriondo et al. 2013; Fraga et al. 2016). Short-term adaptation strategies are numerous: selection of tolerant varieties and drought-resistant rootstocks (Romero et al. 2018; Serra et al. 2014; Zhang et al. 2016), reduction in planting density (Pieri et al. 2012), and use of smart irrigation strategies (deficit irrigation, partial root-zone drying, water re-use, as reviewed in Medrano et al. 2015) are measures adopted to limit the effects of water stress and to optimize the water use efficiency; measures such as changes in row orientation (Hunter et al. 2016) and use of shading systems (Greer and Weston 2010; Caravia et al. 2015, 2016) are adopted to reduce thermic stress. Irrigation is the adaptation measure mainly used worldwide (Sacchelli et al. 2016; Lereboullet et al. 2013; Neethling et al. 2017; Galbreath 2014). In particular, the Italian DOC and DOCG disciplinary introduces in viticulture the practice of emergency irrigation. Irrigation demand in viticulture will increase, due to the combined effect of decreased rainfall and increased temperature during the growing season (Fraga et al. 2018; Bonada et al. 2018); Naulleau et al. (2021) estimate that irrigation needs in Europe will double compared to the current one, increasing much more than in other regions where the demand for water is already high, such as in Australia.

Irrigation can be used to counter not only the water stress, through water nutrition, but also the thermic stress induced by extreme heat waves. The evaporative cooling effect on canopy and berries has been well studied since the 1970s (Kliewer and Schultz 1973; Aljibury et al. 1975). Aljibury et al. (1975) and more recently Greer and Weedon (2014) studied the impact of the canopy cooling also on growth processes, in particular on the increase in shoot growth rate. The first studies on cooling irrigation considered overhead sprinkler systems, which only partially irrigate the bunch zone (Aljibury et al. 1975; Greer and Weedon 2014). More recently (Caravia et al. 2017; Cogato et al. 2021) cooling irrigation has been investigated as tool to counter the extreme heat waves in Australian vineyards. Particularly, Caravia et al. (2017) studied a sprinkler cooling system inside the canopy at the bunch level.

Moreover, the temperature increase can anticipate the sprouting phases of the vine, thus increasing the risks of late spring frosts which can induce damages on buds and shoots (Poling 2008), and finally reduced grape production. Poni et al. (2022), Zohner et al. (2020), and Dinu et al. (2021) confirmed this tendency specifically at the scale of the study area. Wind machines, sprinkler irrigation or delayed pruning are some measures adopted to face the risks from low temperature. During frost events, water application by sprinklers produces a layer of ice on buds and shoots, aimed at keeping

their temperature slightly above the critical values (Poling 2008). Since a constant application of water is required during the frost events, this measure can require high water amounts.

As climate change causes varied effects on grape growing, it is necessary to explore and develop innovative agronomic practices to counter them, equipping the vineyards with automated multifunctional systems. The assessment of these systems must not only consider their effectiveness and reliability in facing the extreme weather events, but also the economic and managerial sustainability to make the innovative practices operative. The ability of automated multifunctional irrigation, using either drip or sprinkler method, to counter heat summer events on vineyard and other crops has been investigated in previous studies (see, e.g., Cogato et al. 2021; Deligios et al. 2019; Greer and Weedon 2014). Numerous studies have also explored the effects of irrigation on crop protection from late spring frost (see, e.g., Praticelli et al. 2008; Ghaemi et al. 2009; Yongguang et al. 2016). The objective of our study is to explore the potential of a unique automated multifunctional irrigation system to contrast both types of unfavorable extreme temperature events and to maintain suitable soil water conditions during the crop season in the vineyard. We focused both on the selection of the most suitable emitters and on the identification of efficient and effective irrigation management protocols to minimize water and energy use.

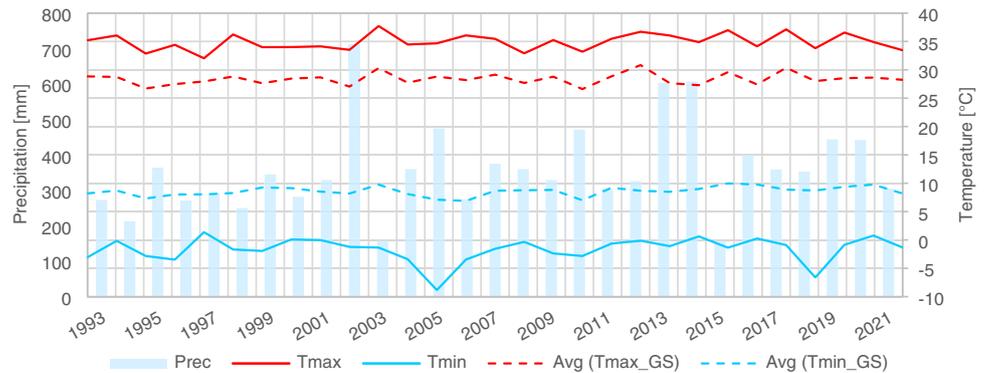
Materials and methods

Experimental site

The study was conducted during the 2020 and 2021 agricultural seasons, in a commercial vineyard located in Cavriana, Lombardy, Italy (45°21'33.5" N 10°36'19.3" E) at 135 m a.s.l., in the viticultural area of Garda Colli Mantovani DOC. The vineyard is almost level course and rows are oriented along the East–West axis. The grapevine variety is Chardonnay, grafted on rootstock 420A; the vines are trained using Guyot system, with distance on the row of 0.8 m and distance between rows of 2.5 m. Soil between rows are grass covered with periodic mowing.

The site agro-meteorological conditions are described in Fig. 1, showing the behavior from 1993 to 2021 of the minimum and maximum daily temperature and of the cumulated precipitation during the vine growing season from mid-March to end-August. Moreover, the average minimum and maximum temperature in the vine growing season are reported. Those historical data of precipitation and temperature are extracted from a global dataset of estimated atmospheric, land surface, and ocean quantities, which was developed by the European Centre for Medium-Range

Fig. 1 Temperature and precipitation extracted from the ERA5 dataset, evaluated for the vine growing season, from 1993 to 2021: minimum and maximum daily temperature (light blue and red solid lines), average of the minimum and maximum daily temperature (light blue and red dashed lines), and cumulated precipitation (light blue bars)



Weather Forecasts (ECMWF), based on the fifth generation of European ReAnalysis (ERA5), considering a combination of forecast model data and worldwide observations (hourly values, with 9 km horizontal resolution).

The ERA5 data show that the 2020 growing season had a 23% higher precipitation with respect to the average value in the period 1993–2021. On the other hand, the 2021 season was 15% drier. The maximum temperature in July and August 2020, and in June 2021 were, respectively, 1.1 °C and 1.6 °C hotter, and 0.5 °C hotter than the average value in the period 1993–2021 of the July and August, and of the June maximum temperature. Moreover, the minimum temperature in April 2021 was 2.5 °C cooler than the average value in the period 1993–2021 of the April minimum temperature.

Experimental design

Eight plots were designed within the experimental vineyard to compare four different irrigation strategies, specifically two plots for each irrigation management (labeled with the letters a and b). The following strategies were considered:

- Drip irrigation (DI), providing automatically water supply by drippers, mainly for water plant nutrition when the soil water content was below a water stress threshold (condition monitored with sensors installed along the rooted soil profile), and secondarily to protect the vine from excessively high summer temperatures.
- Drip and sprinkler irrigation (DSI), providing automatically water supply by drippers for water plant nutrition and by sprinklers for protection of the vine from temperature-related stresses, due to late spring frosts or excessively high summer temperatures.
- Traditional irrigation (TI), operated by the farmer with drippers, based on farmer’s usual practices without a monitoring system supporting the irrigation scheduling.
- No irrigation (NI), providing no water supply at all; the consequent soil–crop system conditions were compared with those induced by the different irrigation strategies.

Each plot includes 5 rows, with about 14 vines on each row, except for the DSI plots (see “[Experimental plots with different irrigation treatments](#)”). The two plots for the same irrigation strategy are separated by 5 vines (about 4 m), while the plots with different irrigation strategies are separated by 10 vines (about 8 m).

As the soil–crop system conditions in the experimental plots should be affected only by the different irrigation managements, the plots were located in areas within the vineyard with no significant differences in soil properties. To detect these areas, the soil variability was investigated through a geophysical survey, with a multi-frequency electromagnetic induction (EMI) sensor (GeM2, Geophex USA).

The EMI survey was carried out in February 2019, after a rainfall period, to investigate soil conditions nearly at field capacity. Soil electrical conductivity (EC), which is correlated to physical and hydrological soil properties, such as soil texture and soil water retention, was measured at three depths (0–20 cm, 0–35 cm and 0–80 cm), operating with three different frequencies. Hence, three EC maps were obtained, by interpolating the measurements recorded at the different soil depths. Overall, the soil profile characteristics appear less variable for depths greater than 35 cm, rather than at shallow depths.

The Fig. 2 shows the EC map referring to the 0–80 cm depth; the area where soil variability is less emphasized, both laterally and in depth, with EC values from 75 to 110 mS/m, is highlighted through a red box. The experimental plots were located within that area. In each plot, instruments to measure soil water status, plant and air conditions were installed (see following “[Continuous monitoring through a Wireless Sensor Network](#)”).

Since EMI survey indirectly measures the soil properties and does not describe in detail the vertical variability of the soil profile, the soil textural properties and the skeleton contents were preliminarily investigated within that experimental area by collecting in soil samples at 12 distributed points at increasing depths up to 70 cm. Laboratory analysis showed that most of the soils belong to loam (L) and sandy-loam (SL) texture classes, and that

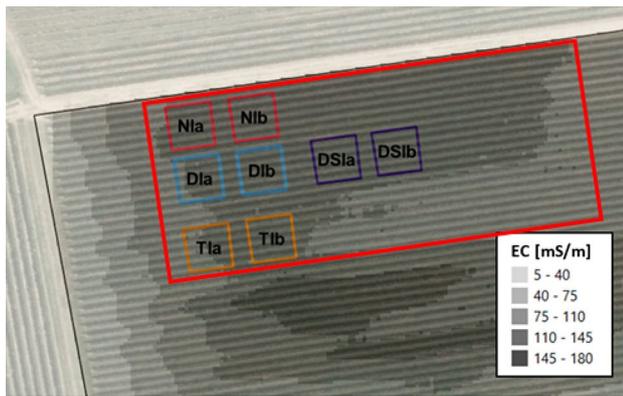


Fig. 2 The experimental site, a vineyard situated in Cavriana (south Lake Garda, in northern Italy): EC map referring to soil depth 0–80 cm, red box with EC values from 75 to 110 mS/m (experimental plots were located within this area), and position of plots with different irrigation management (DI, drip irrigation; DSI, drip and sprinkler irrigation; TI, traditional irrigation; NI, no irrigation). In transparency the orthophoto with the vineyard rows (color figure online)

the skeleton content is relevant (even higher than 25%) and progressively increasing with depth.

Consequently, the experimental plots were located where the skeleton content was less than 25% in the 0–70 cm soil profile, to avoid problems with the reliability of soil water content (SWC) measurements through capacitance-based technology probes (Fig. 2). Moreover, the soil profile of each plot was characterized by measuring texture, skeleton content, and SWC at field capacity (FC) and wilting point (WP) on disturbed and undisturbed soil samples collected at 30 and 60 cm depths (Table 1) in one point within the plot. The available water contents (AWC) between WP and FC characterizing the soil profile of each plot are reported in Table 2.

Table 1 Physical soil characterization of soil samples collected at 30 and 60 cm depths for each irrigated plot: texture, skeleton content, and USDA texture class are reported

Plot	Management	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	USDA texture class	Skeleton (%)
T1b	TI	30	46	36	18	L	6.55
T1b	TI	60	43	37	20	L	12.07
T1a	TI	30	51	34	15	L	15.81
T1a	TI	60	49	34	17	L	23.76
D1b	DI	30	41	41	18	L	12.09
D1b	DI	60	37	40	23	L	0.71
D1a	DI	30	45	38	17	L	7.53
D1a	DI	60	46	35	20	L	19.48
DS1b	DSI	30	56	33	12	SL	11.18
DS1b	DSI	60	52	31	17	L	17.06
DS1a	DSI	30	63	29	7	SL	24.85

Table 2 Hydrological soil characterization of soil samples collected at 30 and 60 cm depths for each irrigated plot, the SWC at FC and WP and the AWC are reported

Plot	Management	Depth (cm)	FC	WP	AWC
T1b	TI	30	0.20	0.13	0.07
T1b	TI	60	0.23	0.14	0.09
T1a	TI	30	0.17	0.10	0.07
T1a	TI	60	0.17	0.11	0.06
D1b	DI	30	0.18	0.13	0.05
D1b	DI	60	0.33	0.19	0.14
D1a	DI	30	0.17	0.13	0.04
D1a	DI	60	0.19	0.12	0.06
DS1b	DSI	30	0.14	0.10	0.04
DS1b	DSI	60	0.14	0.10	0.04
DS1a	DSI	30	0.09	0.05	0.04

Experimental plots with different irrigation treatments

The experimental vineyard was already equipped with a drip irrigation system, characterized by driplines with DN 20 mm, 1 m distance between drippers, and drip flow rate of 4 l/h (irrigation rate 1.6 mm/h) at 1 bar operating pressure. To realize the experimental set up, the existing irrigation system was modified creating a bypass to control drip irrigation in the DI and DSI plots, separately from drip irrigation in the TI plots. Moreover, the DSI plots were equipped with an additional irrigation line (DN 32 mm), to supply a sprinkler irrigation system. Sprinklers with drop size suitable for both cooling and late spring-frost irrigation were chosen. In the latter case, sprinkler irrigation aims at protecting the buds through a thin ice layer that maintains the plant organs at temperature around 0 °C (ARPAE Emilia Romagna 2004): for this reason, the drop size has to be sufficiently big to reduce the evaporative process. On the other

hand, in case of heat events, the drop size has to be small enough to easily evaporate, to reduce air and grape temperature (Anconelli et al. 2018).

In 2020, an over-vine 360° sprayer system (Series 700 dynamic sprayer—nozzle diameter 0.9 mm, Tavlit) was set up in both DSI plots (Fig. 3a): 9 sprinklers per row were installed at 4 m distance, at about 2.5 m above the ground (45 sprinklers altogether). Each sprinkler is characterized by wetted diameter of about 4 m, operating pressure of 3.5 bar, flow rate of 40 l/h (irrigation rate 4 mm/h), and drops diameter from 60 to 100 µm. These sprinklers requested a lot of manpower for maintenance (frequent pruning to avoid the branches of the vine prevent the sprinkler functioning, and frequent replacement of the nozzles); therefore, in 2021, they were substituted with two types of alternative emitters. In the DSIa plot, an over-vine strip pattern sprinkler system (ProSpray—PROS02 body spray and ES-515 nozzles, Hunter), with 5 cm pop-up nozzles, was installed (Fig. 3b): 5 sprinklers per row were installed at 4 m distance, at about 2.5 m above the ground (20 sprinklers altogether). Each sprinkler is characterized by a wetted strip with extent 4 m × 1.5 m, 2 bar operating pressure, and flow rate of 150 l/h (irrigation rate 15 mm/h). In the DSIb plot, an under-vine 180° micro-sprayer system (MFG Ivory micro-sprayer base and 180° nozzles—Irritec) was installed (Fig. 3c). The nozzles were directly nested in the dripline, at about 0.50 m above the ground. Nine sprinklers per row were installed at 2 m distance (forty-five sprinklers altogether). Each sprinkler is characterized by a water stream directed upward and a wetted area of 2 m × 1 m, 2 bar operating pressure, and flow rate of 53 l/h (irrigation rate 10.6 mm/h). The two sprinklers

nearest the air–soil–plant monitoring station were installed at 3.5 m distance to avoid direct spraying on the thermo-hygrometers installed in the plot (see the following “[Continuous monitoring through a Wireless Sensor Network](#)”), reducing the irrigation rate to 6.1 mm/h.

Continuous monitoring through a wireless sensor network

A wireless sensor network (WSN) was setup to measure continuously the agro-meteorological conditions outside and inside plots, as well as the soil water status within each plot. Particularly, the WSN consisted of six monitoring points:

1. Agro-meteorological station (AG) (MaxiMet GMX541, Gill Instruments): it was installed just outside the field, nearby the vine rows of the experimental plots. It is composed by an optical rain gauge, a radiometer, an anemometer, and a thermo-hygrometer placed about 3 m above the ground. From June 2020, a traditional rain gauge (Digital Tipping Bucket Rain Collector 3665, Spectrum Technology) was added to overcome some failures of the optical one. Any lack of data was solved integrating the dataset with the agro-meteorological data recorded at the monitoring station situated in Olfino (about 8 km far), installed next to an experimental vineyard studied in another research project.
2. Air–soil–plant monitoring stations: they were installed within the vineyard, in one plot for each of the irrigation treatments DI, TI, and NI (i.e., the DIa, TIb, and NIa plots), and in both the DSI plots to check the dif-



Fig. 3 Over-vine sprinkler system for 2020 (a). Sprinkler system for 2021: over-vine (b) and under-vine (c). Drip irrigation are managed jointly in DI and DSI plots, while drip and sprinkler irrigation in DSI plots are managed separately. In DSI plots, the drip and sprinkler irri-

gation lines belong to independent sectors, each one equipped with pressure and volumetric gauges, to respectively control the operating pressure and monitor the water consumption; moreover, a solenoid valve was installed in each sector to automatically activate irrigation

ferent performances of the pop-up over-vine and under-vine sprinkler irrigation systems. The stations in DIa, DSib, TIb, and NIa plots consist of the following sensors installed during 2020 season: two thermo-hygrometers (HC2A-S3, Rotronic), one installed over-vine (about 2 m above the ground) and the other one installed in the lower canopy (about 1 m above the ground); one leaf wetness sensor (LEM-WT), installed inside the canopy on the grapes line; two thermocouples (LEM-T), to measure berry temperature; one SWC probe (Drill&Drop, Sentek), with sensors every 10 cm from 5 to 85 cm depth (setup in May 2020 in DIa, TIb and DSib plots, in July 2020 in NIa). The station in DSIA was installed during 2021 season, with the following sensors: two thermo-hygrometers (HC2A-S3, Rotronic) (setup in June 2021), installed at 1 and 2 m above the ground, and one SWC probe (Drill&Drop, Sentek) with sensors every 10 cm from 5 to 85 cm depth (setup in March 2021).

Moreover, all the plots were equipped with one SWC probe (Drill&Drop, Sentek) with sensors every 10 cm from 5 cm to 85 cm depth from March 2021.

In each monitoring point, a datalogger CR1000X (Campbell) was installed to collect and store the data measured by the sensors, except for the DSIA plot, where a datalogger CR200 (Campbell) was installed. Each datalogger is powered by a 30 W solar panel charging a 12 V battery. Particularly, CR1000X in the agro-meteorological station stores every 15 min the average values of wind speed and direction, solar radiation, air temperature and humidity, and cumulated rain. CR1000X in the air–soil–plant monitoring stations store every 15 min the average values of air temperature and humidity at two heights, temperatures in two berries, leaf wetness, and of SWC recorded at nine depths in both the plots for DI, TI, and NI treatments and in DSib plot; CR200 in the air–soil–plant monitoring station in DSIA plot stores every 15 min the average and instantaneous values of air temperature and humidity at two heights and of SWC recorded at nine depths.

Moreover, the solenoid valves and the volumetric gauges were connected to the agro-meteorological station's datalogger, to automatically activate irrigation, and store the data on irrigation volume recorded every 10 min.

The five CR1000X dataloggers communicate through a radio connection system (Fig. 4), with each other and with a PC installed in the farm, in which the recorded data are stored to be remotely accessed. The data recorded in DIa and DSib plots and transmitted to the agro-meteorological station's datalogger are used to activate drip and sprinkler irrigation. The CR200 datalogger was not included in the communication network, then the data recorded in

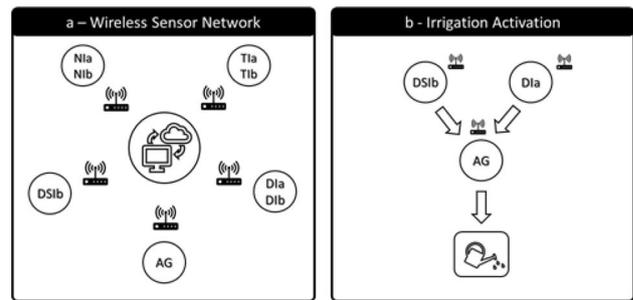


Fig. 4 Communication system among dataloggers. **a** All the dataloggers (except for that one in DSIA) communicate through a radio connection system with each other and with a PC installed in the farm to store and remotely access the data recorded. The data stored in the PC can be accessed remotely. **b** Dataloggers in DSib and DIa plots transfer data on temperature and SWC to AG datalogger, to activate drip and sprinkler irrigation

the DSIA plot cannot be remotely accessed nor considered to activate irrigation.

Periodic measurements

Measurements of vine water status

To monitor the evolution of the vine water status during the season, the water potential in pre-dawn (Ψ_{pd}), from 3:00 am to 5:30 am, was measured four times during the vegetative season. In 2020, measurements of Ψ_{pd} were carried out on 25 June, 9 July, 28 July, and 12 August for all the treatments; in 2021, Ψ_{PD} was measured on 22 June, 29 June, 26 July, and 18 August only in NI plots. For each experimental plots, three plants were selected and the Ψ_{pd} measurement was performed on one median leaf per plant chosen from a primary shoot; a Scholander pressure chamber (Scholander et al. 1965), produced by PMS Instrument Company, Corvallis, Oregon (USA) was used. Moreover, in the same days during the timeframe 0.00–2.00 pm, vapor pressure deficit in the sub-stomatal chamber (VPD) was measured on one sunny leaf per plant, using a leaf portable photosynthesis system (CIRAS-3, PP Systems, Amesbury, MA, USA) equipped with PLC6 (U) cuvette 18 mm circular (2.5 cm² head plate). VPD measurements were performed under conditions to guarantee a vapor pressure deficit inside the leaf chamber of about 1.5 kPa: constant saturating PPFD of 1500 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$, CO₂ concentration of 300 $\mu\text{mol mol}^{-1}$, block temperature of 25 °C, and relative humidity between 60 and 70%. Both Ψ_{pd} and VPD were measured on three leaves per plot, for a total of six biological repetitions per irrigation treatment.

Production-related traits

To monitor the grape ripening, four samplings were performed at the phenological stages of pre-véraison, véraison, ripening, and harvesting, during 2020 and 2021 seasons. At each sampling, three representative bulks of about 50 berries for each plot were randomly collected from both sides of the vine rows. Furthermore, at harvest, the numbers of buds, shoots, and bunches of three plants per plot were counted and the total grape production per vine was weighted. From the same plants, a number of 50 berries per vine were weighed to determine berry fresh weight. Must was obtained from the collected berries, which were pressed and added with 0.2% sodium azide (NaN_3) to prevent fermentation. On the vines whose production was assessed, the pruning weight was measured during dormancy as index of plant vigor. Ravaz index, calculated as the ratio between grape production per plant and relative pruning weight, was considered as an index of the vegetative-productive balance.

Must quality determination

The quality of must was analyzed considering the measurements of total soluble solids (TSS), pH, titratable acidity (TA), and organic acids. TSS were determined on grapevine must by refractometry, using a digital refractometer (DBR 35 SALT). Results were expressed as Brix ($^{\circ}\text{Bx}$). Must pH and TA were detected by an automatic titrator. Briefly, 7, 5 mL of juice for each sample were diluted to 50 mL with ultrapure water (resistivity $> 18.2 \text{ M}\Omega\cdot\text{cm}$ at 25°C) for TA analysis. The samples were titrated with 0.1 M NaOH to a pH of 8.3 using an automatic titrator (FLASH Automatic titrator, Steroglass). Acidity was expressed as g titratable acid/L. Malic acid content in must was determined by high-performance liquid chromatography (HPLC) according to Baccichet et al. (2020). Briefly, 2 ml of must added with 0.5% (w/v) EDTA were centrifuged at 14,000 rpm for 15 min and filtered (0.45 μm nylon membrane) before HPLC analysis (injection volume was 5 μL). Sample were injected into a Perkin Elmer series LC200 pump (Perkin Elmer, Norwalk, CT), using an Aminex HPX-87H cation exchange column (Bio-Rad Laboratories, Inc.). The analyses were performed at 65°C with a flow rate of 0.6 mL/min using 4 mM H_2SO_4 as eluent under isocratic conditions.

Statistical analysis

To assess the effect of the different irrigation managements on water and physiological vine status, and on must quality, all the measurements described in sections from “[Measurements of vine water status](#)” to “[Must quality determination](#)” were processed using Microsoft Office Excel Professional Plus 2016 and SPSS statistical environment (IBM SPSS

Statistics 26). Single effects of factors and their interactions were tested by univariate ANOVA, after accounting for normality of distribution and homogeneity of variance. For ANOVA models, the levels of significance were considered for $p \leq 0.001$ (***), $0.001 \leq p \leq 0.01$ (**), and $0.01 \leq p \leq 0.05$ (*). Post hoc comparison of means was performed using Duncan test, considering the significant level of $p \leq 0.05$.

The effect of irrigation managements was assessed also on data about the soil water availability over WP in the rooted soil profile (SWA). The SWA values were evaluated as difference between the average value of the SWC measured from 25 to 65 cm depths, and the average WP calculated from the values measured at 30 and 60 cm depths; SWA values were calculated for DS1b, DIa, T1b, and NIa plots, in the irrigation season, from mid-May to end-August. Particularly, the variability of SWA due to irrigation strategies for each year, and that one due to experimental year for each irrigation strategy were analyzed; moreover, for each year, the irrigation strategies were compared two by two. As the variability of SWA was not homogeneous for the different irrigation managements, the analysis was carried out by the Welch test instead of ANOVA test. Levels of significance were considered for $p \leq 0.001$ (***), $0.001 \leq p \leq 0.01$ (**), and $0.01 \leq p \leq 0.05$ (*).

Irrigation management protocols

The irrigation in DI and DSI plots was managed according to specific protocols.

Drip irrigation (in both DI and DSI plots) was managed to achieve primarily the optimization of water supply according to the vine phenological stage (i.e., irrigation is activated only when SWC is below a water stress threshold), maintaining quality and productivity standards while minimizing water consumption; secondarily, to contrast the effects of summer high-temperature events, by providing water during the night before the day on which the event is forecasted, to increase the SWC easily available for plants (Webb et al. 2009; Hayman et al. 2012).

The water stress threshold refers to the SWC throughout the rooted soil profile; hence, it was evaluated taking into account the hydrological soil properties measured on the soil samples collected at 30 and 60 cm depths, particularly in DIa and DS1b plots (Table 2). Also, the vine phenological stage was considered to properly assess the water stress threshold values (Deloire et al. 2004), accounting for the greater susceptibility of the vine to water stress during the flowering and véraison stages rather than during the ripening stage. Finally, the SWC threshold was evaluated as half of the AWC value for the soil profile (Allen et al. 1998; Doorenbos and Kassam 1979), during the stages from flowering to véraison, and as 60% of AWC for the stages from véraison to ripening. The AWC value for the

soil profile was calculated as the average of the values assessed at 30 and 60 cm depths for DIa and DS1b plots (Table 2). When SWC was below the threshold value, the water amount supplied by irrigation increased the SWC up to FC (calculated for the rooted soil profile, as the average of the FC values measured at 30 and 60 cm in DIa and DS1b plots).

Sprinkler irrigation in DSI plots was managed to face both late frosts in spring and extreme high temperatures in summer. In case of spring frost, water was continuously supplied to maintain a thin liquid layer around the buds, avoiding them to freeze and damage; in case of summer high temperatures, water was supplied with evaporative cooling function.

Specifically, the sprinkler irrigation countering late spring frosts was activated when the air wet bulb temperature was below a proper air temperature threshold, sufficiently cautionary to avoid sprinkler damaging because of the water freezing into pipes. The continuous water application was stopped when the air temperature after sunrise was stably above 0° (Jorgensen et al. 1996). During extreme high-temperature summer events, sprinkler irrigation was activated when the air temperature rose above a threshold temperature for heat stress insurgence. In the scientific literature, the temperature value above which severe stress may occur is of about 35 °C (Greer and Weedon 2012, 2014); therefore, a slightly lower threshold value (33 °C) was considered in our experiment; this also allowed to explore a greater number of irrigation events and gather a wider dataset. Moreover, during the summer high-temperature events, continuous and pulsed water applications were tested and compared to verify their efficacy in protection from thermal stress and their efficiency in terms of water consumption.

Results

Meteorological data

In Fig. 5, the daily values of precipitation and of minimum and maximum temperature registered at the meteorological station in the experimental site during the 2020 and 2021 growing seasons (from mid-March to end-August) are reported.

The measured precipitation cumulated over 2020 and 2021 growing seasons fits well with the ERA5 values, even if some difference in the temporal distribution of monthly precipitation was found. Also the behavior of the measured daily maximum and minimum temperature fits quite well with the ERA5 dataset, even if sometimes a weak correspondence was detected during the extreme events in the season, mainly for minimum temperature. Consequently, comparing the measured values of cumulated precipitation with the ERA5 values for the year 2020 and 2021, their difference (in absolute value) resulted less than the difference (in absolute value) between the latter and the ERA5 average values in the period 1993–2021; thus, the recorded site-specific data confirmed the assessment on 2020 and 2021 years based on ERA5 data: the 2020 growing season was wetter and the 2021 one was drier than the average season in the period 1993–2021. Moreover, the measured monthly maximum and minimum temperatures, respectively, for July and August 2020 (35.0 and 35.8 °C) and June 2021 (33.1 °C), and for April 2020 and 2021 (− 1.7 and − 1.6 °C) were higher and lower than the ERA5 values; hence, measurements confirmed that the maximum and minimum temperatures, respectively, in July and August 2020 and June 2021, and in April 2020

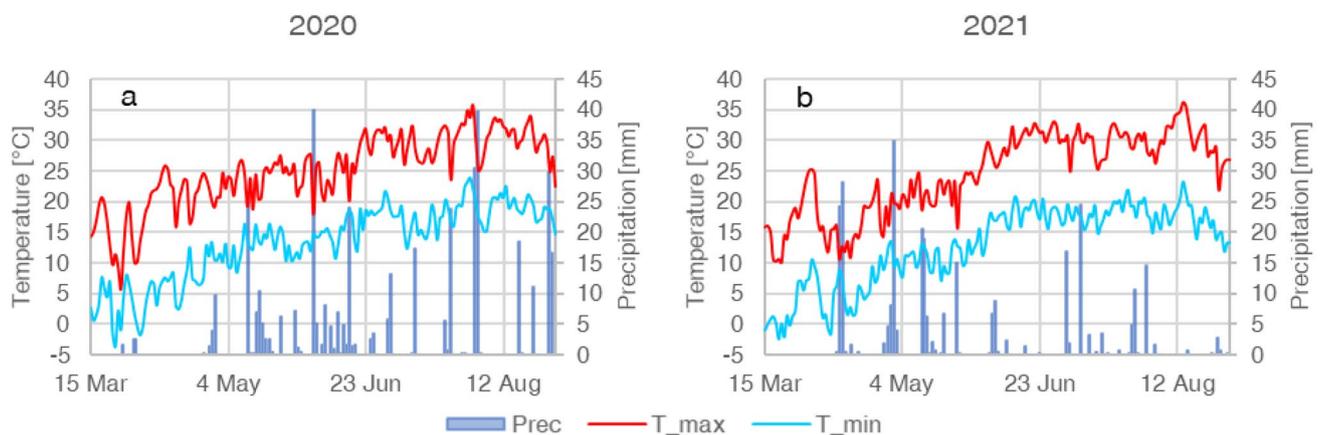


Fig. 5 Daily minimum (light blue lines) and maximum (red lines) temperature [°C] and daily precipitation (blue bars) [mm] registered at the meteorological station in the experimental site in Cavriana,

during the 2020 (a) and 2021 (b) growing season, from mid-March to end-August (color figure online)

and 2021 were, respectively, hotter and cooler than the average value in the period 1993–2021 for those months.

Particularly, the 2 years show a different behavior in terms of precipitation, with 415 mm cumulated during the growing season in 2020, and 286 mm in 2021. Moreover, in 2020, precipitation was quite evenly distributed all over the growing season, with greater amounts in June (107 mm) and August (151 mm). Conversely, in 2021, drier months (March, June, and August) alternated with wetter ones (April, May, and July). Finally, during July 2021, precipitation events were frequent but low.

Regarding temperature behavior, spring-frost and summer high-temperature events occurred in both 2020 and 2021 seasons. In 2020, three events of spring frosts were recorded, during the nights of 23/24 March, 25/26 March, and of 1/2 April 2020, with minimum temperature within the vineyard rows equal to -6° , -2° , and -4° °C, respectively. In 2021, two episodes were recorded, during the nights of 6/7 and 7/8 April, with minimum temperature within the rows equal to -1° °C and -3° °C, respectively.

Temperature recorded within the vineyard rows was higher than 33° °C for 41 h distributed over 10 days, between mid-July and end-August, during summer 2020, and for 43 h distributed over 11 days, between end-June and mid-August, during summer 2021. Precisely, the temperature reached the maximum value of 36.7° °C on 1 August 2020, and of 36.2° °C on 15 August 2021.

The average temperature during those high-temperature events was 34° °C in both the years, but a larger number of hours with temperature higher than 35° °C was recorded during 2021. Indeed, the box plot in Fig. 6 shows that the temperature distribution for the events in 2021 is strongly not symmetric, with the 75th percentile higher than that one for the events in 2020. The average daily duration with

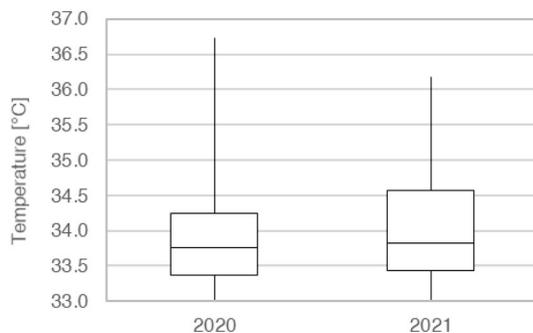


Fig. 6 Temperature distribution during summer high-temperature events (temperature above 33° °C), for 2020 and 2021 growing seasons. The ends of the *whiskers* extending from the box indicate minimum and maximum temperature recorded during the events. The lower part of the box shows the temperature distribution between 25th and 50th percentile, while the upper part of the box shows the distribution between 50th and 75th percentile

temperature higher than 33° °C was 4 h in 2020 and 3.5 h in 2021, while the number of consecutive days for which those events occurred was 3 in 2020 (from 30 July to 1 August) and 6 in 2021 (from 11 to 16 August).

Irrigation management protocols

Drip irrigation

Drip irrigation for water plant nutrition was automatically activated when SWC along the rooted soil profile (i.e., profile SWC) was below a water stress threshold (see “[Irrigation management protocols](#)”). Particularly, the profile SWC was calculated as the average value of the SWC measured in DS1b and DIa plots at different depths. Preliminarily, the SWC profiles measured in DS1b and DIa plots on 31 May 2020 (Fig. 7), a day far enough from rainy events, were analyzed to decide the depths at which to consider the SWC measurements for evaluating the profile SWC. The shallow depths from 5 to 15 cm were excluded as the majority of grapevine absorbing roots are generally concentrated from 20 to 80 cm soil depths (Swanepoel and Southey 1989). The greatest depths from 75 to 85 cm were excluded, for which SWC values were maximum along the DIa profile, resulting in a higher value for the profile SWC; in that case, the actual SWC at depth between 45 and 65 cm would have been lower than the profile SWC, thus causing delayed irrigation. Finally, as a precaution, the profile SWC was assessed as the average value of SWC measured at depths from 25 to 65 cm, in both DIa and DS1b plots.

For 2020 season, the water stress threshold was set at 14% from flowering to véraison, and at 13% from véraison to ripening. The irrigation depth per application was about 18 mm (11 h).

The analysis of data acquired during the 2020 season, particularly of the SWC and Ψ_{pd} measurements (see

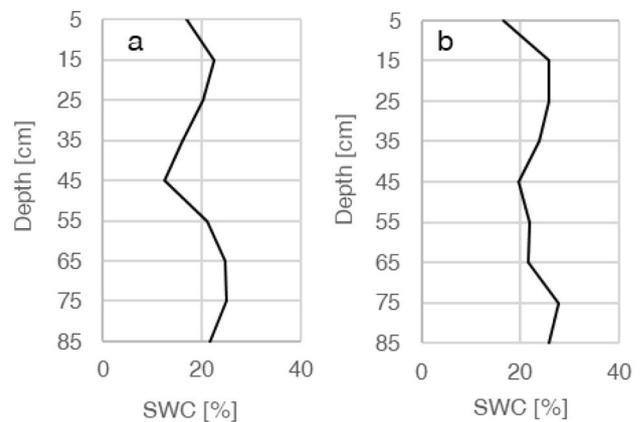


Fig. 7 Daily average SWC profiles measured in DS1b plot (a) and DIa plot (b), on 31 May 2020

following “Effect of irrigation managements on grapevine water status”), suggested that the SWC threshold values set for 2020, assessed from the analytical measurements of soil hydrological properties, were likely overestimated. Hence, to manage irrigation in 2021, both the water stress threshold and the irrigation depth considered in the 2020 season were lowered; specifically, the threshold was set at 13% from flowering to véraison, and at 12% from véraison to ripening, while the irrigation depth per application was reduced to 10 mm (6 h).

Nightly drip irrigation countering heat stress onset was automatically activated if temperature higher than 35 °C and no precipitation were forecasted for the following day. To reduce the water consumption, irrigation started only when the SWC condition was below a proper threshold higher than the water stress one. Particularly, irrigation was activated when the profile SWC was less than 17%. An irrigation depth of 8 mm distributed over 5 h (between 1 and 6 am) was applied in 2020; this value was reduced to 6.5 mm over 4 h (between 2 and 6 am) in 2021, because of the results obtained in 2020 (see following “Effect of irrigation managements on grapevine water status”).

Sprinkler irrigation

Sprinkler irrigation countering late spring frosts was automatically activated when the wet bulb temperature dropped below 1 °C; it was calculated according to Stull (2011), as function of the air temperature and relative humidity in lower-canopy, considering their values measured in DSIB plot. The water application was continuous and was stopped when the lower-canopy air temperature measured in NIa plot rose above 2 °C and have increased in the previous hour of 1 °C at least (ARPAE Emilia Romagna 2004).

During the 2020 season, sprinklers were activated for evaporative cooling irrigation when the average value of the air temperature recorded in DSIB plot at different heights (over-vine and in lower canopy) exceeded 33 °C. Differently, during the 2021 season, after the first sprinkler activation at 33 °C, the following ones occurred at 34 °C, to reduce water consumption.

Particularly, the protocol used in 2020 checked every 10 min the average air temperature measured in DSIB plot, and the sprinklers were continuously activated for 1 h only when the average temperature was higher than 33 °C. After this 1-h activation, the temperature was newly checked every 10 min until exceeding the threshold value. In 2021, a pulsed application was tested, aimed at reducing irrigation water consumption. In this case, the lower canopy air temperature measured in DSIB plot was checked every minute: when it exceeded the threshold, 1-min sprinkler activation was followed by 2-min break. After the break, the air temperature was newly checked every minute until exceeding the

threshold value. Differently from 2020, in 2021, only the temperature of the lower canopy, close to the bunches, was exploited, considering that the thermal stress affects mainly the bunch growing and its quality.

Water consumption under different irrigation managements

The cumulative water amounts consumed for the different irrigation strategies, in the 2020 and 2021 seasons, are reported in Fig. 8 and Table 3.

Drip irrigation

In 2020, two nightly drip irrigations were provided in DI and DSI plots, respectively, on July 22 and July 31. The overall water consumption was 14 mm. During 2021 season, no drip irrigation was provided in DI and DSI plots. Drip irrigation operated by the farmer in TI plots consisted of two 12-h and one 13-h irrigations in 2020, and of three irrigations of 18, 12, and 24 h, respectively, in 2021. The overall water used was 59 mm and 86 mm, in 2020 and 2021, respectively.

Sprinkler irrigation

Sprinkler irrigation for spring frosts was activated two times both in 2020 and 2021. It was continuously provided, on nights of 24–25 and 25–26 March 2020 and on nights of 6–7

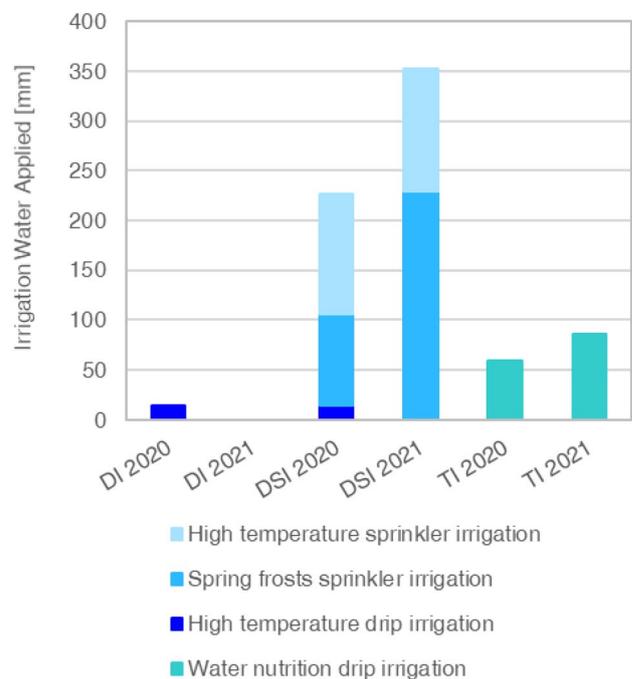


Fig. 8 Yearly irrigation water applied [mm] for DI, DSI, and TI treatments in 2020 and 2021

Table 3 Yearly irrigation water applied [mm] for DI, DSI, and TI treatments in 2020 and 2021

	DI		DSI		TI	
	2020	2021	2020	2021	2020	2021
Water nutrition drip irrigation	–	–	–	–	59	86
High-temperature drip irrigation	14	–	14	–	–	–
Spring frosts sprinkler irrigation	–	–	91	229	–	–
High-temperature sprinkler irrigation	–	–	121	125	–	–

and of 7–8 April 2021, for 10.5 and 11 h in 2020, and for 3.2 and 11.5 h in 2021. The water consumption was 91 mm in 2020 and 229 mm in 2021.

Sprinkler irrigation for summer high-temperature events was activated in 2020 for about 23 h distributed in 10 days from mid-July to end-August, with a total water consumption of 121 mm; in 2021, it was activated for 7.5 h distributed in 11 days from end-June to mid-August, with a total water consumption of 125 mm.

Effects of sprinkler irrigation on air temperature

Late spring frosts

Figure 9A shows the temperature trajectories recorded in DSIB (dark blue line) and NIA (red line) plots, during the night of 25–26 March 2020, when a late spring frost occurred. The irrigation was automatically activated at 20:30, when the temperature measured in NIA plot was about 4 °C, while it was 3.5 °C in DSIB plot; this gap in

temperature was kept until the temperature measured in NIA plot fell below 0 °C and when the temperature in DSIB plot was up to 1 °C higher than in NIA plot. The irrigation was automatically stopped at 07:30 (Fig. 9a).

When the late frost occurred on the night of 7–8 April 2021, sprinklers were automatically activated at 20.00 and continuously worked until 07:30 (Fig. 9b). When the temperature measured in TIB plot (even lower than those measured in NIA plot) fell below 0 °C (yellow line in Fig. 9b), the temperature measured in DSIB plot (dark blue line in Fig. 9b) was up to 2.5 °C higher than that in TIB plot, with an average gap between the temperature measured in the two plots of about 0.5 °C.

Summer high-temperature events

The highest temperature in 2020 was reached on 1 August, when the daily maximum temperature measured in lower canopy in DSIB plot was 36.7 °C. Five 1-h sprinkler irrigation were provided, mostly during midday hours, as

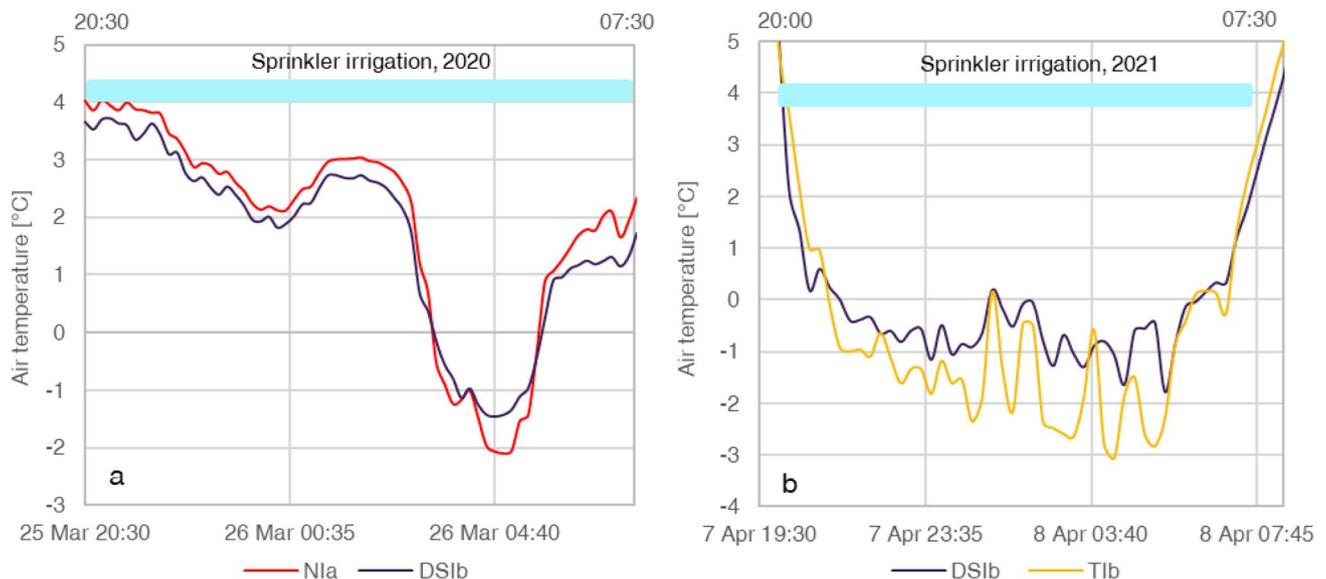


Fig. 9 Sprinkler irrigation facing late spring frost, effect on air temperature: **a** temperature recorded during the night of 25–26 March 2020, in DSIB (dark blue line) and NIA (red line) plots. The irrigation was continuously activated for 11 h, from 20:30 to 07:30. **b** Tempera-

ture recorded during the night of 7–8 April 2021, in DSIB (dark blue line) and TIB (yellow line) plots. The irrigation was continuously activated for 11.5 h, from 20:00 to 07:30 (color figure online)

shown in Fig. 10a (light blue squares). The sprinkler irrigation determined a decreasing trend in the lower-canopy air temperature (dark blue line in Fig. 10a), with values on average 3 °C lower than those ones measured in NIa plot (red line in Fig. 10a). Particularly, the lower-canopy temperature in DSIB plot did not exceed 34 °C.

In 2021, significant high-temperature events were recorded from 11 to 16 August, with daily maximum temperature higher than 34 °C and up to 36 °C on 14 and 15 August. Particularly, on 15 August, sprinkler irrigation was activated 76 times, as shown by the light blue dots in Fig. 10b. During the first sparse activations, the cooling effect assessed with respect to the lower-canopy temperature recorded in NIa plot (red line in Fig. 10b) was comparable in DSIB plot (solid dark blue line in Fig. 10b) and in DSIA plot (dashed dark blue line in Fig. 10b). The lower-canopy temperature in DSIA and DSIB plots was on average, respectively, 3 and 1.5 °C lower than that in NIa plot. On the other hand, as irrigations became more frequent, the above-canopy irrigation in DSIA plot resulted in an increasing temperature gap from the temperature in NIa plot, with a more intense cooling effect than in DSIB. This behavior in DSIA plot was probably due to the thermo-hygrometers wetting, because of the irrigation applied over-vine and with higher flowrate than that of the under-vine 180° micro-sprayers in DSIB plot (see “[Sprinkler irrigation](#)”).

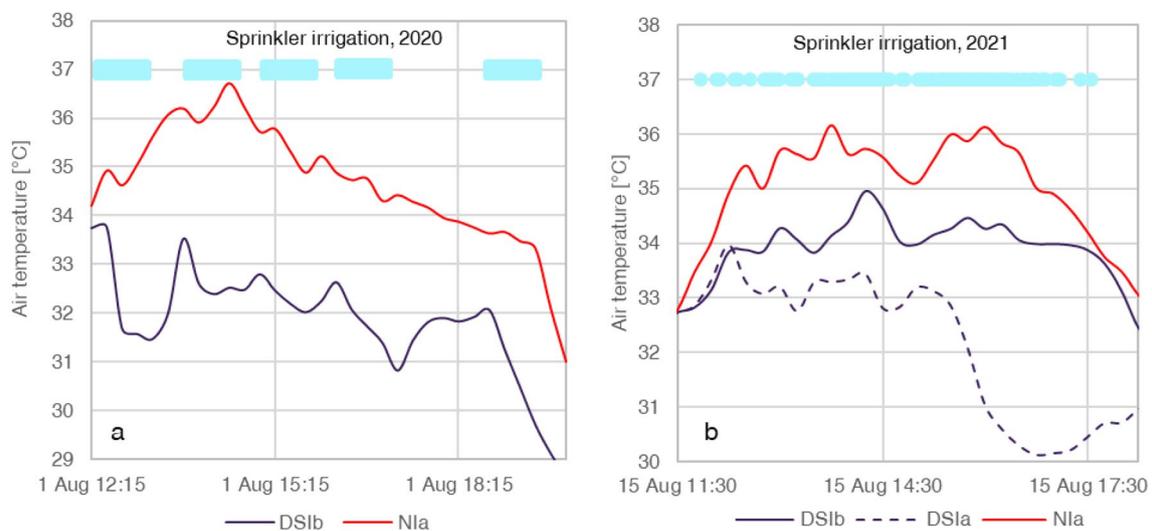


Fig. 10 Sprinkler irrigation facing summer high-temperature events, effect on temperature in the lower canopy: **a** temperature recorded on 1 August 2020 in DSIB (dark blue line) and NIa (red line) plots. Five 1-h sprinkler irrigations were applied, at 12:15, 13:45, 15:00, 16:15,

Effect of irrigation managements on soil water availability for vine

The effects of irrigation management were evaluated also in terms of different SWA values in the growing season from mid-May to end-August (data were available from 11 July to 31 August 2020 and from 25 May to 31 August 2021). The analysis of variability through Welch test show that the SWA values were significantly different for all the irrigation treatments in both 2020 and 2021^(b), with the lowest value for DI, while the highest value occurred for DSI in 2020 and for TI in 2021^(b) (Table 4). Moreover, all the treatments except for NI had different SWA in 2020 and 2021^(a) with values always higher in 2020 (Table 4). Particularly, Table 4 shows that the DSI treatment had the highest SWA in 2020, while it decreased of about 40% in 2021^(a), and the DI treatment had the lowest SWA both in 2020 and 2021^(a).

Effect of irrigation managements on grapevine water status

In 2020, the Ψ_{PD} values were measured in NI and DI plots (Fig. 12a) and in DSI plots; particularly, in the latter case, they did not detect water stress conditions (measured values always above -0.2 MPa), even though the profile SWC, ranging during the vegetative period, from 12 to 28%, and from 13 to 30% in DSIB and DIa plots, respectively, exceeded the water stress threshold of 14% (Fig. 11). That fact highlighted how this threshold was overestimated, then a lower value (12–13%, according to the different stages) was chosen for the irrigation protocol adopted in 2021 (see “[Drip irrigation](#)”).

18:45. **b** Temperature recorded on 15 August 2021 in DSIB (solid dark blue line), DSIA (dashed dark blue line), and NIa (red line) plots. Seventy-six 1-min sprinkler irrigations were applied, from 11:51 to 17:34 (color figure online)

Table 4 SWA (soil water availability over wilting point in the rooted soil profile from 25 to 65 cm depths, calculated as difference between profile SWC and WP) measured in NIa, TIb, DIa, and DSIb plots. Analysis of variability through Welch test, on SWA measured in NIa, TIb, DIa, and DSIb plots in 2020 and 2021. The effect of the different irrigation managements on SWA was assessed separately for

the years 2020^(a) and 2021^(b); moreover, for each year, the irrigation strategies were compared two by two. Analysis of variability through Welch test, on SWA measured in NIa, TIb, DIa, and DSIb plots, during the same period in 2020 and 2021 due to the experimental year for each irrigation management

Management	SWA [mm], 2020 ^(a)		SWA [mm], 2021 ^(a)		SWA [mm], 2021 ^(b)	
	M	SD	M	SD	M	SD
NI	30.67	10.05	30.39	9.84	40.11	16.56
TI	38.17	14.81	34.22	22.46	45.03	20.97
DI	24.73	17.91	17.86	9.74	33.36	21.27
DSI	41.99	11.49	25.16	14.24	34.37	17.49
Welch test on SWA in 2020 ^(a)					Welch test on SWA in 2021 ^(b)	
DSI–DI***					DSI–DI***	
DSI–NI***					DSI–NI***	
DSI–TI*					DSI–TI***	
DI–NI***					DI–NI***	
DI–TI***					DI–TI***	
NI–TI***					NI–TI***	
Management					Welch test on SWA between 2020 ^(a) –2021 ^(a)	
NI					–	
TI					**	
DI					***	
DSI					***	

Mean values (M) and standard deviation (SD) were reported

^(a) from 11 July to 31 August and ^(b) from 25 May to 31 August

Significant differences were reported for $p \leq 0.001$ (***), $0.001 \leq p \leq 0.01$ (**), and $0.01 \leq p \leq 0.05$ (*)

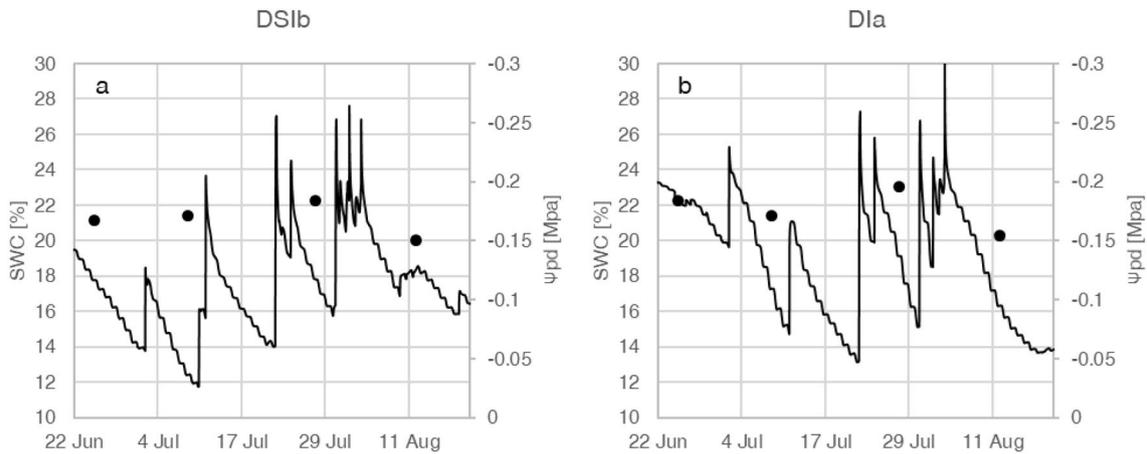


Fig. 11 Profile SWC (black line on left y-axes) and pre-dawn water potential (Ψ_{PD}) (black dots on right y-axes) measured in 2020, in DSIb (a) and DIa (b) plots. According to Deloire et al. (2004),

threshold between no-stress and mild water stress was considered for $\Psi_{PD} = -0.2$. According to experimental protocol, SWC water stress threshold was set to SWC = 14%

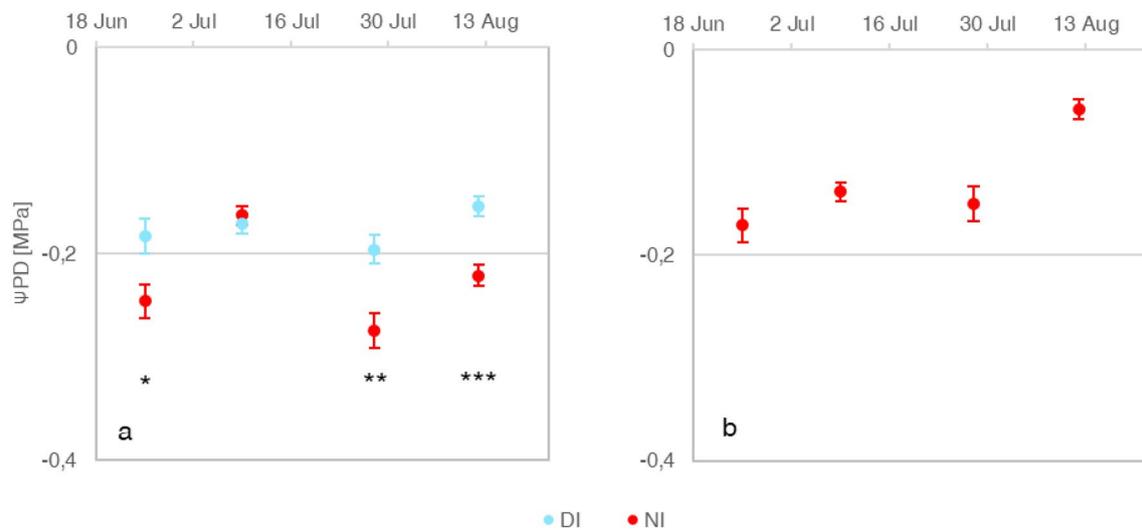


Fig. 12 Measurements of the pre-dawn water potential (Ψ_{PD}), performed in NI and DI plots in 2020 (A), and in NI plots in 2021 (B). Dots correspond to the mean levels, whereas bars represent the standard error of means. According to Deloire et al. (2004),

threshold between no-stress and mild water stress was considered for $\Psi_{PD} = -0.2$. Significant differences between irrigation treatments at each measurement day were reported for $p \leq 0.001$ (***), $0.001 \leq p \leq 0.01$ (**), and $0.01 \leq p \leq 0.05$ (*)

Moreover, irrigation management affected the grapevine water status in 2020, showing significant differences of Ψ_{PD} between irrigated (DI) and non-irrigated (NI) vines on 25 June ($p = 0.023$), 28 July ($p = 0.005$), and 12 August ($p = 0.001$). Under NI management, Ψ_{PD} amounted to -0.25 ± 0.02 , -0.28 ± 0.02 , and -0.22 ± 0.01 MPa for 25 June, 28 July, and 12 August, respectively, showing a mild water stress. In the same days, higher levels of Ψ_{PD} (always above -0.2 MPa) were recorded in the DI plots. No significant differences occurred between the measurements in the NI and DI plots, on 9 July.

In 2021, the Ψ_{PD} values were measured only in NI plots (Fig. 12b) since no irrigation was applied in 2021 in DI plots. Those measurements assessed the absence of water stress.

Significant correlations between Ψ_{PD} and the mean profile SWC were not identified. Nevertheless, a positive correlation was found between the SWC measured at 65 cm depth and Ψ_{PD} , reporting a Pearson index of $r = 0.26$ ($p = 0.03$). Higher correlation was found between the profile SWC and VPD in the sub-stomatal chamber of leaves ($r = -0.66$; $p = 0.00$). The relationship between SWC and VPD was reported in Fig. 13: in particular, VPD increased at decreasing levels of SWC.

Effect of irrigation managements on grape production

The main factor affecting the production of grape was the experimental year, explaining the 76% of the total variance. Differences between years were significant ($p = 0.005$), with

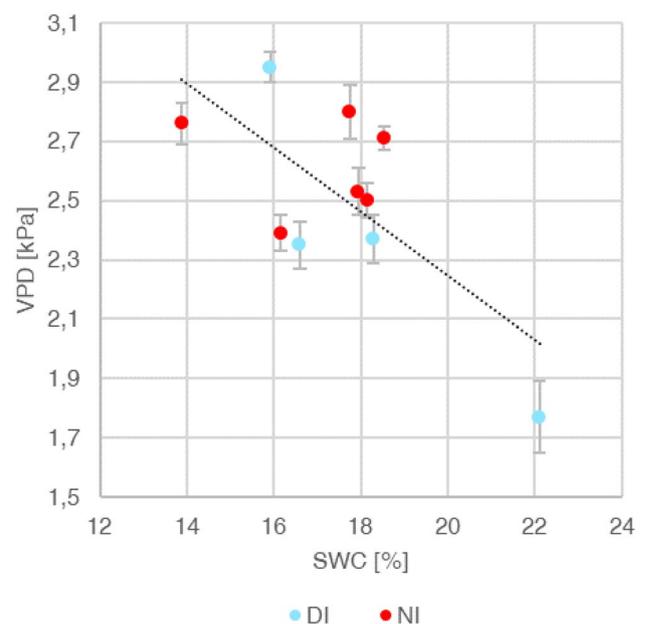


Fig. 13 Relation between the profile SWC and VPD values measured in 2020 and 2021, in NI and DI plots ($r = -0.66$; $p = 0.00$). Dots correspond to the mean levels, whereas bars represent the standard error of means

higher average production per plant reported in 2020. The water management and its interaction with the year collectively explained the 15% of variance, whereas other factors represented the remaining 9%. A significant effect of irrigation management was not identified. Nevertheless, in 2020, the production of NI was reduced of 16%, 21%, and 22%

with respect to TI, DI and DSI, respectively. In 2021, the production of grape was similar for DI, TI, and NI, which was reduced of 18% with respect to DSI. Average levels of production are reported in Table 5.

Vegetative–productive balance, estimated by Ravaz index, was also strongly affected by the year ($p=0.003$), which explained the 75% of total variance. Irrigation management explained the 13% of variance while its interaction with the experimental year explained the 5%. No significant effect was found for the irrigation management. In 2020, average values ranged between 4.18 ± 0.47 for NI and 5.52 for DI (± 0.72) and DSI (± 0.53). Whereas in 2021, average values ranged between 3.15 ± 0.33 for NI and 4.14 ± 0.53 for DSI (Table 5).

The fertility of shoots (clusters/shoots ratio) and the fertility of buds (clusters/buds ratio) were affected by the interaction between irrigation management and the experimental year, explaining the 31% of variability for the ratio clusters/shoots and the 26% for the ratio clusters/buds. Significant effect of fertility was not found for any of the experimental years. In 2020, the average number of clusters per bud ranged between 0.86 ± 0.07 for DSI and 1.08 ± 0.14 for NI, whereas in 2021 ranged between 0.81 ± 0.10 for DI and 0.99 ± 0.16 for DSI (Table 5).

Effect of irrigation managements on grape quality

In the first experimental year, at véraison (on 28 July 2020), the average value of berry weight was 1.07 ± 0.05 , reporting no significant differences among irrigation managements. Average berry weight gradually increased during ripening, with higher rate for DSI than DI and NI. Significant effect of the irrigation management was shown on 12 July and 25 August. At harvest (25 August), the average weight of berry was about 1.67 ± 0.10 , 1.56 ± 0.08 , and 1.53 ± 0.06 for DSI, DI, and NI, respectively (Fig. 14a). In 2021, differences between irrigation managements were significant ($p < 0.015$) only in the first stage of ripening (29 July). In particular, on 29 July, the average weight of berry for DSI, DI, and NI was around 1.73 ± 0.10 , 1.71 ± 0.10 ,

and 1.81 ± 0.10 , respectively. At harvest, on 25 August, no significant differences among irrigation management were found, with an average weight of the berry around 1.75 ± 0.11 (Fig. 14b).

In Fig. 14c and Fig. 14d were shown the soluble solids contents of grape, expressed as brix ($^{\circ}\text{Bx}$), evaluated during ripening for both years. In 2020, must obtained from DSI reported a significant lower sugar concentration on 18 and 25 August compared to NI and DI. At harvest (25 August), average sugar contents for DSI, DI, and NI were around 16.82 ± 0.45 , 18.38 ± 0.82 , and $19.40 \pm 1.02^{\circ}\text{Bx}$ respectively. No significant differences between treatments were found for soluble solids in 2021, with an average content amounting to 19.2°Bx at harvest.

Concerning pH, a significant effect of irrigation management was not found in 2020. Average values were about 2.57 ± 0.04 during véraison and they reached 3.47 ± 0.06 at harvest (Fig. 15a). Mean values of pH were lower during ripening in 2021, reaching a maximum of about 3.08 ± 0.06 at harvest. Significant differences between water managements were observed in the first stages of ripening on 29 July and 5 August, when DSI showed lower pH than other treatments (Fig. 15b).

The total acidity of grapes at véraison was about 25 g L^{-1} in both experimental years, but different dynamics occurred during ripening. In 2020, acidity levels rapidly decreased in the first stage of ripening. Higher acidity was maintained until harvest by DSI with respect to DI and NI, reaching the mean levels of 7.22 ± 0.42 , 6.34 ± 0.64 , and $5.82 \pm 0.41 \text{ g L}^{-1}$, respectively (Fig. 15c). In 2021, total acidity gradually reduced from véraison to the harvest, maintaining higher levels with respect to 2020. Significant effect of irrigation management occurred on 19 August, reporting higher acidity for DSI than DI and NI, with average values of 14.38 ± 1.89 , 12.74 ± 1.48 , and $11.53 \pm 0.91 \text{ g L}^{-1}$, respectively (Fig. 15d).

The content of malic acid in grapevine has been evaluated in musts in both years. In 2020, a significant effect of irrigation management was found ($p < 0.000$). DSI resulted in higher malic content during the whole ripening compared to the other treatments (Fig. 15e). At harvest, average malic

Table 5 Mean values \pm standard error of total production of grape per plant, Ravaz index, average weight of clusters, fertility of shoots (clusters/shoots), and fertility of buds (clusters/buds) for each irrigation management in 2020 and 2021

Year	Treatment	Production per plant (kg)	Ravaz index	Average clusters weight (kg)	Clusters/shoots	Clusters/buds
2020	NI	2.56 ± 0.24	4.18 ± 0.47	0.13 ± 0.00	1.11 ± 0.08	1.08 ± 0.14
	TI	2.98 ± 0.29	4.52 ± 0.34	0.13 ± 0.01	1.13 ± 0.09	1.06 ± 0.09
	DI	3.09 ± 0.40	5.25 ± 0.72	0.13 ± 0.01	1.04 ± 0.10	1.03 ± 0.09
	DSI	3.13 ± 0.38	5.52 ± 0.53	0.14 ± 0.01	1.03 ± 0.09	0.86 ± 0.07
2021	NI	2.28 ± 0.25	3.15 ± 0.33	0.15 ± 0.01	0.91 ± 0.09	0.84 ± 0.13
	TI	2.36 ± 0.13	4.12 ± 0.54	0.14 ± 0.01	1.31 ± 0.14	0.92 ± 0.08
	DI	2.04 ± 0.14	3.41 ± 0.54	0.16 ± 0.02	1.19 ± 0.05	0.81 ± 0.1
	DSI	2.70 ± 0.31	4.14 ± 0.53	0.15 ± 0.01	1.23 ± 0.19	0.99 ± 0.16

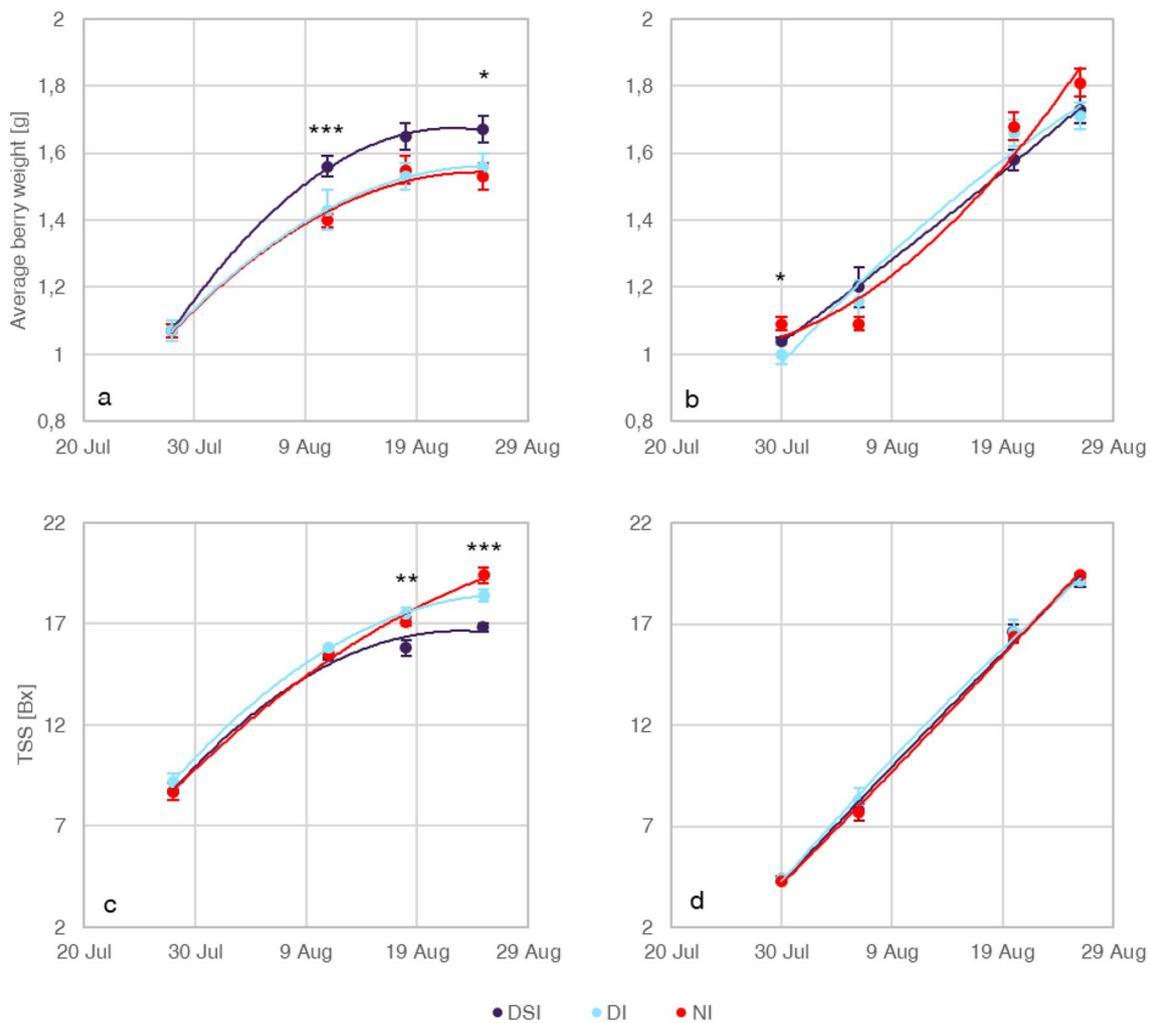


Fig. 14 Grape quality parameters for each irrigation management in 2020 and 2021: average weight of berry in 2020 (**a**) and 2021 (**b**); solid soluble content [$^{\circ}\text{Bx}$] in 2020 (**c**) and 2021 (**d**). Dots correspond to the mean levels, whereas bars represent the standard error

of means. Significant differences between treatments at each day were reported for $p \leq 0.001$ (***), $0.001 \leq p \leq 0.01$ (**), and $0.01 \leq p \leq 0.05$ (*)

acid in DSI, DI, and NI was 2.36, 1.55, and 1.63 mg mL^{-1} , respectively.

In 2021, the effect of the irrigation management on malic acid level was significant only on 29 July. In particular, higher level of malic acid was found in DSI with respect to other treatments. During ripening, differences among water managements gradually attenuated (Fig. 15f).

Discussion

Water consumption and water stress levels

The overall water consumptions for drip irrigation in DI and TI plots were compared: a water saving greater than 75% was achieved in DI plots with respect to TI plots; particularly,

it was 76% in 2020 when only two nightly water applications were provided (14 mm and 59 mm delivered, respectively, in DI and TI), and 100% in 2021 when no irrigation occurred (0 mm and 86 mm delivered, respectively, in DI and TI plots). Consequently, the average SWA values in the irrigation period in 2020 and 2021 were the lowest among the different irrigation managements (Table 4); nevertheless, the reduced water consumption in DI plots did not reflect in a production decline (Table 5). The activation time of sprinkler irrigation in DSIIb plot during summer high-temperature events was much larger in 2020 (23 h) than in 2021 (7 h); consequently, the water volume applied onto the 230 m^2 area of the plot was also larger in 2020 (30 m^3 compared to 24 m^3 in 2021), although the values of the 2 years are closer due to the higher irrigation rate provided by the emitters used in 2021 (14.9 mm/h) with respect to 2020 (5.7 mm/h).

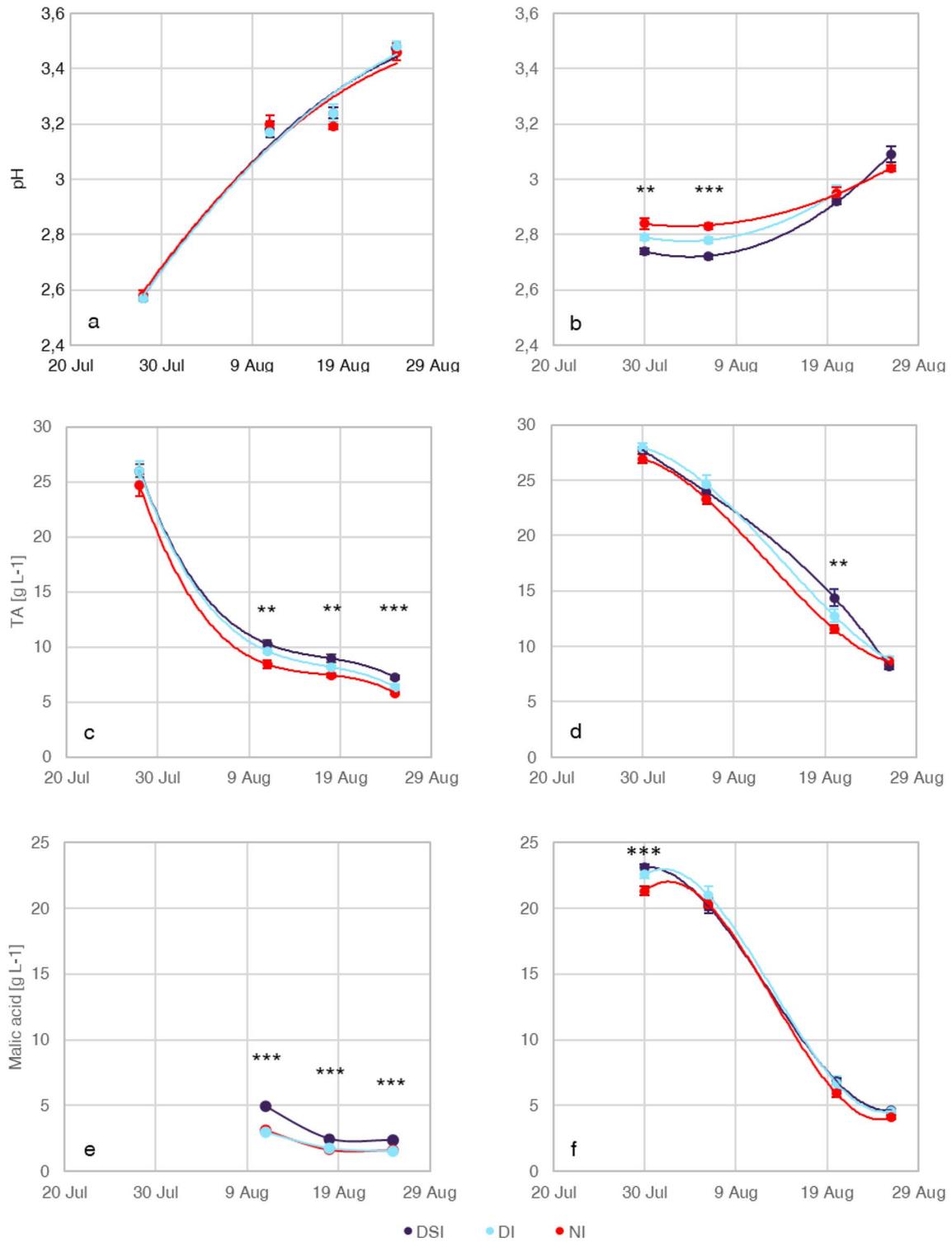


Fig. 15 Grape quality parameters for each irrigation management in 2020 and 2021: pH content in 2020 (a) and 2021 (b); titratable acidity [g L⁻¹] in 2020 (c) and 2021 (d); malic acid concentration [mg mL⁻¹] in 2020 (e) and 2021 (f). Dots correspond to the mean levels,

whereas bars represent the standard error of means. Significant differences between treatments at each day were reported for $p \leq 0.001$ (***), $0.001 \leq p \leq 0.01$ (**), and $0.01 \leq p \leq 0.05$ (*)

Consequently, SWA in DSIIb resulted significantly different between 2020 and 2021 and higher in 2020 (Table 4).

Moreover, the water volume used in 2020 in DI and DSI plots reduced the vine water stress, as highlighted by the Ψ_{PD} values measured during the season. Indeed, the Ψ_{PD} measured in NI plots (Fig. 12a) exceeded the threshold of -0.2 MPa (Deloire et al. 2004), showing a mild-to-moderate water deficit, whereas the Ψ_{PD} measured in DI and DSI plots (Fig. 11 and Fig. 12a) was always higher than that threshold, resulting in no water stress. In 2021, that threshold was never reached even for NI (Fig. 12b); actually, despite precipitation in 2021 was lower than in 2020, it was well distributed during the growing season to meet the crop water requirements.

Moreover, Table 4 shows that SWA in NI resulted not significantly different between years 2020 and 2021. This fact seemed not consistent with the detection of mild water stress conditions in 2020 and no water stress occurred in 2021. On the other hand, this result highlights the relevant role of precipitation distribution in influencing the water stress condition. Moreover, SWA was evaluated along the soil profile from 25 to 65 cm, while the vine water stress conditions appeared mainly influenced by the SWC measured at 65 cm depth (Fig. 13).

Grape production

Even if ANOVA results did not show a significant effect of the irrigation treatments in terms of grape production, the trend of production per vine was lower in NI than in DI and DSI plots, with a reduction of about 20% in 2020 and 4% in 2021. The loss of production could be related to the lowest Ψ_{PD} values reached in NI, although only mild water stress occurred (Fig. 12). In literature, a loss of production of about 10% has been found under mild-to-moderate water deficit, even though the effect of the water condition was not significant (Mendez-Costabel et al. 2014a; Acevedo-Opazo et al. 2010). Nevertheless, under severe water deficit, the production of grape per vine can be significantly reduced over the 30% respect to well-watered conditions (Shellie et al. 2014b; Herrera et al. 2015; Koundouras et al. 2009). Moreover, Mirás-Avalos and Intrigliolo (2017) showed that the loss of production caused by water deficit depends on the grapevine variety, because of the different strategies adopted to face the stress. The response of the variety Chardonnay to water stress involves a rapid stomatal closure, to reduce the water loss through the transpiration process (Vandeleur et al. 2009; Rogiers et al. 2009), which is driven by the VPD in the sub-stomatal chamber. Despite only mild levels of water stress were reached, in the present study, the measurements of VPD in the sub-stomatal chamber resulted to be significantly correlated to the soil water content in the rooted profile (Fig. 13). In a recent experiment under controlled condition on Tempranillo grapes, a significant

interaction was found between the water condition (irrigated and non-irrigated) and the air temperature on the cluster weight (Kizildeniz et al. 2015). In particular, under well-watered conditions, the weight of cluster was not affected by the temperature, whereas under water deficit, it was reduced by a temperature increase of 4 °C. Thus, the use of sprinkler irrigation to reduce air temperature during summer high-temperature events could affect the production of grape, but in this study, it was not possible to discern the effect of water or temperature on production. Nevertheless, in 2020, when mild-to-moderate water deficit occurred in NI plots, the average berry weight measured in DSI plots was significantly higher than those measured in DI and NI plots for the whole ripening (Fig. 14a, b), and the SWA in DSI was significantly higher with respect to the other treatments (Table 4). Moreover, the average cluster weight measured in 2020 was higher in DSI plots (0.14 kg) than in DI and NI plots (0.13 kg), although differences among treatments were not significant (Table 5).

In 2021, the average grape production in DSI was about 18% higher than in the other plots, and about 8% higher with respect to the 2020. Whereas SWA in DSI was significantly lower in 2021 (Table 4). Consequently, the increment of grape production recorded in 2021, could not be ascribed to the additional water provided with sprinkler irrigation, but it could be related to the frost protection provided through sprinkler irrigation. In particular, the sprinkler irrigation activated for the frost event of April 7, during bud swelling phenological stage, maintained the temperature slightly higher than the critical threshold, generating a positive effect on buds' fertility. In fact, DSI reported the highest number of clusters per each bud left during pruning, with respect to the other plots (Table 5). This effect could have contributed to the highest production of grape in DSI plots during 2021. In 2020, the sprinkler irrigation activated for frost protection had a positive effect on air temperature (Fig. 9a) but no significant effects were detected in terms of bud's fertility (Table 5), since the late frost probably occurred before the budburst. A positive effect on yield of sprinkler irrigation countering late frost has been reported in literature for other horticultural crops (Tsipouridis et al. 2006).

Grape quality

Quality of grape is strictly related to the water status of vines. In general, no differences in the quality parameters measured in DSIIa plots (over-vine sprinkler irrigation) and in DSIIb plots (under-vine sprinkler irrigation) were recorded. Several studies showed an increment in sugar content of berries under different levels of water stress compared to control conditions. For example, Herrera et al. (2015) reported in Merlot an increment above 5% of TSS under mild and severe water deficit. Similar

trends were obtained on Cabernet Sauvignon under both mild-to-moderate water deficit, with an increment of about 3%, and under moderate-to-severe stress levels, reporting increments of 2.6%, 5.3%, and 0.8% in three different experimental years (Shellie et al. 2014b). In our study, no significant differences of TSS between the irrigation managements DI and NI were found (Fig. 14c, d), probably due to the mild level of water stress reached in 2020 and the absence of water stress detected in 2021. In 2020, a delay in ripening was observed for DSI, resulting in lower TSS and higher TA of musts. A significant increment in TA was reported for DI and DSI with respect to NI during the whole ripening in 2020 (Fig. 15c). In 2021, DSI reported lower pH than NI at véraison and post-véraison, as well as higher TA during ripening, but the acidity levels of the two treatments matched at harvest (Fig. 15b–d). Controversial results about the effect of water stress on the acidity of grape and must are reported in literature. Indeed, Talaverano et al. (2017) reported both a decrement and increment in TA under mild-to-moderate conditions compared to well-watered control on Tempranillo across two experimental seasons. An increment in TA of about 2% was observed on Tempranillo under moderate-to-severe water deficit with respect to the irrigated control, but a decrement was found under mild-to-moderate deficit (Intrigliolo et al. 2012).

Due to climate change, a trend of decreasing acidity level in wines has been observed in the last decades (Van Leeuwen et al. 2019; De Orduna 2010). This issue becomes critical when high acidity levels are required, such as in sparkling wine production (Jones et al. 2014), widespread in the study area. Specific acids in must are differently affected by water stress of vine. In particular, among major acids, the most influenced by environmental conditions is the malic acid (De Orduña 2010; Carbonell-Bejerano et al. 2013). Controversial effects are reported in literature, suggesting that water deficit affects both positively and negatively the concentration of malic acid, depending on several environmental factors, such as the level and the period of stress (Lopèz et al. 2007; Salazar-Parra et al. 2010; Kizildeniz et al. 2015). In our work, the effect of irrigation management on malic acid content reflected the trends observed for TA, with significant differences between plots during the whole ripening in 2020 and only during véraison in 2021 (Fig. 15e, f). In particular, the level of malic acid was higher for DSI, especially in 2020. This effect could be related to the higher volume of water supplied to DSI and partially to the lower temperatures during summer high-temperature events (Fig. 10). Sadras et al. (2013) reported a negative effect of high temperature to the acidity of grape for the varieties Cabernet Franc and Chardonnay, but both traits were unresponsive for Shiraz. Nevertheless, a significant effect of sprinkler

irrigation on TA was not observed on Cabernet Sauvignon in Caravia et al. (2017).

Conclusion

The results obtained through the multifunctional irrigation systems adopted to improve the resilience of vineyard to climate change, facing the water stress conditions as well as the late spring frosts and the summer high-temperature events, showed that water consumption for irrigation can be considerably reduced without affecting the grape yield, both in quantity and quality, through an optimized management, achieved by equipping the vineyard with a monitoring system to assess the crop–soil water status. Moreover, in cooling sprinkler irrigation, mainly the management strategy used to distribute the water amounts over time rather than the flow rate of sprinklers affected the system's ability to lower temperature; hence, reduction in water consumption can be achieved through the optimization of water amount distribution over time.

Due to the mild water deficit that occurred in the experimental seasons, a significant effect of plant water nutrition by irrigation on grape production was not detected. Nevertheless, a trend of higher production was noticed across the 2 years due to the evaporative cooling irrigation, which could be explained by the higher water amount distributed by sprinklers during the events with thermal stresses high temperature in summer and late spring.

Concerning the frost protection, the sprinkler irrigation positively influenced buds' fertility (even though not significantly).

Finally, the grape quality, evaluated through measurements of total soluble solids, pH, titratable acidity, and organic acids, was mainly affected by sprinkler irrigation. In particular, the higher water supplied and the lower temperatures during summer high-temperature events increased the level of malic acid and hence titratable acidity. Moreover, no differences in the grape quality were recorded due to the specific irrigation system, equipped with over-vine or under-vine sprinklers, while a significant increment in titratable acidity during ripening was observed for the plots with drip irrigation and combined drip-sprinkler irrigation, compared to the plots with no irrigation.

Moreover, the sprinkler system setup in the 2021 season showed promising results in terms of both efficacy in cooling air and reduction in water applied; nevertheless, the results obtained refer to a single season. Because of these issues, further experiments are needed to consolidate the promising outcomes.

This study will continue in the 2022 growing season, and depending on the weather conditions, it may be possible to investigate the response of the vine in conditions of water scarcity, according to the different irrigation managements.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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