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Interannual climatic variability effects on yield, berry and wine quality indices in long-term deficit irrigated grapevines, determined by multivariate analysis

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Abstract: The effects of climatic factors on yield and berry and wine quality for long-term (7 years) deficit-irrigated (DI) Monastrell wine grapes under the semiarid conditions of south-east Spain were analyzed. The relationships between climatic variables and the yield, and novel technological berry quality ($QI_{technologicalberry}$), phenolic berry quality ($QI_{phenolicberry}$), overall berry quality ($QI_{overallberry}$), and wine quality (QI_{wine}) indices confirmed that the most important climatic factors were rainfall, temperature, and radiation. Climate was more influential in determining yield, berry, and wine composition in some important physiological periods such as early season (budburst–fruit set) and ripening (véraison–harvest). In general, climate had more influence on berry quality than on wine quality indices and greater $QI_{overallberry}$ was also reflected in greater QI_{wine}. According to the stepwise multiple regression, the best fitted models for the partial root-zone drying irrigation (PRI) system were less complex (with a lower number of climatic variables) than for the regulated deficit irrigation (RDI) system, suggesting that PRI is less influenced by climatic factors than RDI. For PRI, the models for yield, berry and wine quality were explained by three climatic factors (rainfall, T^a, and radiation), whereas for RDI, more climatic factors came into play (number of hours of sunshine, evapotranspiration, and vapor pressure deficit). According to these models, in RDI, a sunny and drier pre-véraison period followed by higher soil water availability and associated greater crop evapotranspiration during ripening favored final berry and wine quality. In contrast, in PRI, greater rainfall during the growing season and greater solar radiation during ripening were the main climatic factors that positively influenced the yield response, berry and wine quality. Besides, berry quality in PRI was more affected (negatively) by high temperatures (high T^{a}max and T^{a}min) during the growing season than in RDI and SDI, indicating that cooler and humid years may favor the PRI response more. These results suggest that years with a cool, wet winter followed by a mild, wet spring and early summer (April–June) and a mild fruit set–véraison period (June–July), and then greater solar radiation during ripening (August–mid-September) provide adequate growth potential and increase the likelihood of higher berry and wine quality in PRI. Besides, more irrigated SDI vines were less sensitive to high temperatures and low soil water content during ripening than RDI and PRI vines.

Keywords: berry quality indices, climatic factors, multivariate analysis, deficit irrigation techniques, wine quality index, yield

Introduction

Partial root-zone drying irrigation (PRI) is an irrigation technique used for many crops worldwide, including wine grapes, which has been developed to impose soil moisture

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heterogeneity in the root zone, using irrigation to alternately wet and dry the two parts of the plant root system. In theory, drying of the roots triggers chemical signals (increase in abscisic acid [ABA] and/or changes in other hormones, xylem sap pH, and/or the different hormones interaction) that are transported to the shoots through the xylem, altering shoot physiology.[1,2] The effect generally associated with PRI is an increased xylem ABA concentration, which in turn reduces vegetative growth and plant water use more than fruit growth, thereby maintaining the yield and increasing water use efficiency.[1] In addition, the irrigated roots supply sufficient water to the shoots to prevent plant water deficit, maintaining the water status in the shoots.[3,4] However, there is still considerable controversy regarding the effects of PRI in wine grapes and other crops because PRI experiments have not always detected differences in crop water use, crop yield, or fruit quality when compared to more conventional deficit irrigation (DI) practices with the same amount of water, especially in field conditions with different experimental, soil, and climatic conditions.[5–17]

Multiple reasons have been suggested for the varied and inconsistent effects of PRI, including differences in soil type,[18,19] intensity and modulation of chemical signals,[20] distribution of soil water content,[21,22] adaptation of species to soil moisture heterogeneity or homogeneity,[23] root hydraulic redistribution,[24] methodological problems in applying PRI and/or unsuitable irrigation management,[25] and differences in the varieties, rootstocks, and environmental conditions.[26,27] We reported that the effects of PRI on vegetative and reproductive development were more pronounced in some years than in others,[25,28] suggesting that environmental factors and climatic conditions (such as prevalent rainfall, solar radiation, temperature, and vapor pressure deficit [VPD]) during the growing season can influence root–shoot physiological processes and hydraulic and chemical signaling under PRI, determining the final nature and intensity of chemical signaling.[26,27] These differences in climatic conditions among years can explain the interannual variability in the response of the yield, berry and wine quality to PRI, when compared to more conventional DI practices (regulated deficit irrigation [RDI] or sustained deficit irrigation [SDI]), and can help explain why, in some years, the response to PRI is more positive – from a quality point of view – than in other years.[7,28–31] This was also suggested by the significant interactive effects of year, irrigation volume, and irrigation placement reported in long-term DI Monastrell wine grapes.[32] In this regard, it has been suggested that, in years with lower spring rainfall, PRI could provide better fruit quality than DI, especially in red wine varieties.[7] Thus, it is necessary to identify the climatic factors during the growing season that have the maximum impact on the different DI treatments and to find under what environmental conditions PRI delivers an improvement in vine performance and is more suitable than more conventional DI strategies (RDI).

In this study, we focused on the effects of interannual climatic variability on yield response and berry and wine quality attributes in long-term DI Monastrell grapevines under semiarid conditions, using multivariate analysis. Specifically, we employed multiple regression procedures to relate viticulture (dependent) variables (yield, berry and wine quality) to the climate (independent) variables. We determined the climatic factors that had the maximum impact on the yield and quality of Monastrell grapes and wines for the different irrigation treatments, irrigation systems, and phenological periods. Thus, using climatic factors, significant multiple linear regression models for yield, berry and wine quality indices (QIs) were established. We also analyzed whether compositional changes in grapes due to the irrigation treatments were reflected in the wine composition, and which agronomic and grape parameters correlated the best and were better predictors of wine quality.

Materials and methods

Field conditions, plant materials, and irrigation treatments

This research was carried out in a 1 ha vineyard at the Centro Integrado de Formación y Experiencias Agrarias (CIFEA) experimental station in Jumilla, Murcia (southeast Spain, latitude: 38° 2′ N; longitude: 1° 58′ W, 395 m above the sea level). The soil was fine clay of 60 cm depth (48% clay, 30% silt, and 22% sand; field capacity 35%). The irrigation water, from a well, had an electrical conductivity of 1.6 dS m^{-1}. The grapevines were 13-year-old Monastrell (syn. Mourvèdre), a red wine variety, grafted onto 1103 Paulsen rootstock. The training system was bilateral cordon trellised to a three-wire vertical system. The vine rows ran from N–NW to S–SE, and the planting density was 2.5 m between rows and 1.25 m between vines (3,200 vines ha^{-1}). Six two-bud spurs (12 nodes) were left after pruning, while in May, green nonproductive shoots were removed from each vine in the same manner for all treatments, according to the grower's practice in the area.

During seven consecutive years (2006–2012), a moderate RDI strategy was applied under conventional drip irrigation (RDI-1) and under PRI (PRI-1). A more severe RDI strategy was also applied under conventional drip irrigation (RDI-2) and under PRI (PRI-2). These DI treatments were also compared with an SDI treatment involving irrigation at 40%–60% of crop evapotranspiration (ETc) throughout the season, a treatment which allowed us to minimize vine water stress and served as a control.[32,33] The experimental design consisted of four replicates per treatment in a completely randomized block. Each replicate contained 164 vines. Border vines in each row were excluded from the study to eliminate potential edge effects. The crop coefficients (Kc) used, fertilizers and water applied, and the methodology used to calculate ETc have been described in detail previously.[28,32–35]

Irrigation was applied three to five times per week, depending on the phenological period, and was controlled automatically. Water was applied using one pressure-compensated emitter per plant (4 L h^{-1}) with one drip irrigation line per row for the conventional drip irrigation in RDI and a double line per row for the PRI. In the PRI layout, the two pipelines were joined on both sides of the trunk and placed underneath each vine row. In each pipeline in the PRI treatments, there were alternate zones with and without emitters to create dry and wet root zones within each vine row. In the PRI treatments, water was supplied to only one side of the root system at a time, alternating every 14–16 days. In the RDI treatments, irrigation water was supplied simultaneously to the entire root system. Each year, the PRI treatments were applied throughout the growing season (from early April to end of October). To apply the same amount of water in PRI and RDI, the irrigation times were doubled in the PRI-1 and PRI-2 treatments, compared with RDI-1 and RDI-2, respectively.

Climatic factors and cluster berry microclimate

During the 7-year experimental period, the daily climatic data (rainfall, number of hours of sunshine, incident global solar radiation, daily T^amax, daily T^amin, evapotranspiration [ETo], and VPD) were collected every year in a meteorological station (Campbell mod. CR 10X; Campbell Scientific, Inc., Logan, UT, USA) located at the experimental vineyard (and belonging to the Servicio de Información Agraria de Murcia). The maximum and minimum daily air temperatures were calculated as the average of T^amax and T^amin, respectively, for a 24-hour period. The number of hours of sunshine was computed when the average of 1 hour was >1,200 W m^{-2} of solar radiation (Table S1). The climate was Mediterranean semiarid, with hot, dry summers, scarce annual rainfall (<300 mm $year^{-1}$), a mean annual atmospheric VPD of 1.12 kPa, and a total annual reference ETo of around 1,200 mm for the period 2006–2012 (Table 1).

Table 1 Monthly rainfall and atmospheric VPD at the experimental site every year and in different representative phenological stages during the experimental period (2006–2012)

	2006		2007		2008		2009		2010		2011		2012	
	Rainfall (mm)	VPD (kPa)	Rainfall (mm)	VPD (kPa)	Rainfall (mm)	VPD (kPa)	Rainfall (mm)	VPD (kPa)	Rainfall (mm)	VPD (kPa)	Rainfall (mm)	VPD (kPa)	Rainfall (mm)	VPD (kPa)
January	46.7	0.25	24.4	0.55	3.6	0.57	16.6	0.42	20.9	0.37	1.9	0.45	7.0	0.58
February	12.6	0.41	18.1	0.61	18.1	0.49	1.7	0.52	20.6	0.46	6.2	0.75	2.4	0.71
March	0.3	0.93	49	0.86	2.6	1.01	45.4	0.75	36.3	0.55	23	0.56	55.7	0.86
April	30.7	0.95	55.4	0.62	4.9	1.18	19.1	0.83	15.1	0.73	48.8	1.09	23.3	1.02
May	71	1.10	14.3	1.42	133.8	0.99	7.3	1.32	22.3	1.17	10.7	1.20	5.3	1.63
June	0.3	1.61	0.2	1.83	102.6	1.38	1.6	2.10	39.8	1.47	3.5	1.64	1.3	2.43
July	13.6	2.33	1.3	2.12	0.6	1.96	0.1	2.40	0.1	1.98	2.9	2.02	4.3	2.17
August	0.8	1.91	21.3	1.90	0	2.02	35.9	1.94	33.4	1.78	3.1	2.27	3.4	2.71
September	49.1	1.40	16.3	1.24	61.8	1.37	27.5	1.18	42	1.35	13.9	1.56	46.9	1.67
October	2.3	1.16	84.6	0.78	31.3	0.71	5.7	1.14	18.7	1.01	1.7	1.14	54.4	0.96
November	55.6	0.55	1.5	0.72	14.8	0.54	5	0.88	41.5	0.63	46.0	0.51	81.2	0.39
December	1.8	0.48	0.4	0.54	2.5	0.38	57.9	0.49	14.4	0.41	0.2	0.57	3.2	0.55
Total	284.8	1.09	286.8	1.10	376.6	1.05	224	1.17	305	0.99	167.1	1.15	288	1.31
Dormancy period (December–March)	61.4	0.52	91.9	0.64	26.8	0.61	121.6	0.55	92.2	0.45	31.3	0.58	68.3	0.68
Budburst–fruit set (April–May)	101.7	1.03	69.7	1.02	138.7	1.09	26.4	1.08	37.4	0.95	59.5	1.15	28.6	1.33
Fruit set–véraison (June–July)	13.9	1.97	1.5	1.98	103.2	1.67	1.7	2.25	39.9	1.73	6.4	1.83	5.6	2.30
Véraison–harvest (August–September)	49.9	1.66	37.6	1.57	61.8	1.70	63.4	1.56	75.4	1.57	17	1.92	50.3	2.19
Postharvest (October–November)	57.9	0.86	86.1	0.75	46.1	0.63	10.7	1.01	60.2	0.82	47.7	0.83	135.6	0.68

Abbreviation: VPD, vapor pressure deficit.

The diffuse light intensity (photosynthetic active radiation [PAR] 400–700 nm), air temperature, and relative humidity in the cluster zone were measured inside the canopy, close to fruiting positions, on sunny days, at specific periods before and after véraison in 2006, 2008, 2011, and 2012. Readings were taken in eight vines per treatment every 5 minutes, on the clusters' surface facing east–west, using HOBO relative humidity/temp/light/external sensors with four channels (Onset Computer Corporation, Cape Cod, MA, USA). Bunch exposure percentages were determined in 20 vines for each treatment in 2006, 2008, 2010, and 2012 at midday (12 noon–2.00 pm).

Berry temperature was determined on clear, sunny days in sunlight-exposed (east facing) and nonexposed bunches (inside the canopy, in the cluster zone), twice during the day: in the early morning (8.00 am–10.00 am) and afternoon (1.00 pm–3.00 pm), at véraison and after véraison in 2006, 2007, and 2008. It was measured in 20 vines per treatment (two representative bunches per vine) using a Testo 845 infrared thermometer (Testo, Germany).

Vegetative development and yield response

In 2006, 2007, and 2008, the total leaf area per vine was estimated pre- and post-véraison in 16 vines per treatment (four per plot), using a nondestructive method, by developing a polynomial equation relating the main vein length to the leaf area.[28,34] For the period 2009–2012, the total leaf area per vine was estimated every year at the end of June (maximum vegetative growth period) and post-véraison (August) using a nondestructive method, namely, a significant polynomial regression equation relating the main shoot length to the main shoot total leaf area.[32,33,35] The exposed leaf area was estimated every year (2008–2012) during the pre- and post-véraison periods in 16 vines per treatment (the same vines used for total leaf area) by measuring the external perimeter of the leaf area (the height and width of the canopy).[32] Each year at harvest, the yield components were measured for 13 vines per plot (52 vines per treatment). The yield per vine, number of clusters per vine, cluster weight, berry number per cluster, and berry weight were determined.

Berry and wine composition and QIs

At harvest, the fresh berry weight, total soluble solids (in ºBrix), solutes per berry (g), and the juice pH, titratable acidity, organic acids (malic and tartaric), and phenolic maturity of the grapes were determined as described in detail previously.[32,34,35] Twenty microvinifications were carried out during 5 years (2006–2010) (four per treatment, one per plot) as described in detail previously.[32,35] The chemical and phenolic composition of the wines were analyzed at the end of the alcoholic and malolactic fermentation. Absorbance measurements for color intensity (CI), CIElab parameters, total phenol index (TPI), and total anthocyanins were made with a Shimadzu UV-1603 spectrophotometer (Shimadzu Corp., Kyoto, Japan) using glass cells of 0.2 cm path length, according to the methodology described.[32,35]

We calculated different berry and wine QIs. We included several important technological and phenolic parameters in order to have a more global, quantitative view of the quality. To evaluate technological and phenolic ripeness and to establish these novel QIs, firstly we chose some berry and wine attributes (technological and phenolic parameters that have been used traditionally in the wine industry) important for the harvest and winemaking process and based on the literature,[36–39] the recommendations of local winemakers, and our own results of the study area, and we defined ranges and threshold values for the different quality parameters chosen. Then, every year, we classified the grapes and wines of the different irrigation treatments into four groups according to their composition (Tables 2–4). Each group was given a value

Table 2 Berry parameters and classification used to establish berry technological quality index ($QI_{Technologicalberry}$) in Monastrell grapevines

Score	ºBrix	Total acidity (g L⁻¹)	Tartaric/malic ratio	pH	Sugars (g L⁻¹)	Sugars/acidity ratio
0	<22	<2.5	<3	>4	<200	<70
1	22–23	2.5–3.0	3–4	3.9–4.0	200–225	70–75
2	23–24	3–4	4–5	3.8–3.9	225–250	75–80
3	24–25	4–5	>5	<3.8	>250	>80

Table 3 Berry parameters and classification used to establish berry phenolic quality index ($QI_{phenolicberry}$) in Monastrell grapevines

Score	Total anthocyanins (mg L⁻¹)	Extractable polyphenols	A_{520}	Berry weight (g)	Seed maturity
0	<600	<40	<2	>2 to <0.8	>60
1	600–750	40–55	2–3	1.5–2	60–50
2	750–900	60–70	3–4	1.2–1.5	50–40
3	>900	>70	>4	0.8–1.2	<40

Table 4 Wine parameters and classification used to establish wine quality index QI_{wine} in Monastrell grapevines

Score	TPI	Total anthocyanins (mg L⁻¹)	CI
0	<35	<200	<8
1	35–50	200–300	8–10
2	50–60	330–400	10–12
3	>60	>400	>14

Abbreviations: CI, color intensity; TPI, total phenol index.

between 0 and 3: group 1, with the lowest score (0), had the worst composition and lowest quality and group 3, with the highest score (3), had the best composition and highest quality of grapes and wines (Tables 2–4). According to this classification, the berry and wine QIs were calculated using the following equations:

$$QI_{technologicalberry} = {}^{o}Brix + \text{total acidity} + \text{tartaric/malic ratio} + pH + \text{sugars} + \text{sugar/acidity ratio} \quad (1)$$

$$QI_{phenolicberry} = Ant_{tot} + Polyph_{extr} + A_{520} + \text{berry weight} + SM \quad (2)$$

where $Polyph_{extr}$ are extractable polyphenols, A_{520} is the absorbance at 520 nm, and SM is the seed maturity index that measures the contribution of seeds to the total amount of polyphenols, mainly tannins from seeds.[40]

$$QI_{wine} = (1)TPI + (0.5)*Ant_{tot} + (0.5)*CI \quad (3)$$

In accordance with the recommendations of local winemakers, in the QI_{wine}, a coefficient value of 1 was given to the TPI due to the greater importance of this parameter in the stability and wine aging, and a lower coefficient value (0.5) was given to the total anthocyanins (Ant_{tot}) and CI of the wine.

Overall berry quality ($QI_{overallberry}$) was calculated as:

$$QI_{technologicalberry} + QI_{phenolic} \quad (4)$$

Statistical analysis

Significant differences among irrigation treatments for each variable were assessed by analysis of variance and means were separated by Duncan's Multiple Range Test ($P<0.05$), using Statgraphics 5.0 Plus software (Statistical Graphics Corp., Rockville, MD, USA). Multiple linear regression models for yield and berry and wine QIs (dependent variables) were established for each irrigation treatment, introducing into the models the following independent variables: the phenological periods and climatic factors, in order to see to what extent these variables predicted each of the dependent variables. Multiple regression procedures helped to relate viticulture variables (yield, berry and wine quality) to the climate variables, thereby revealing the climatic factors that had the maximum impact on the yield and quality of Monastrell grapes and wines for the different irrigation treatments. Besides, a stepwise multiple regression model was used to identify the optimum statistical model (using climate variables) for each irrigation system (PRI, RDI, and SDI). Finally, correlation coefficients between several agronomic parameters and the grape and wine variables were calculated to analyze whether compositional changes in grapes due to the irrigation treatments influenced wine composition and to show which agronomic factors and grape parameters were better correlated and were better predictors of wine quality.

Results

Influence of climate and phenological period on yield, berry and wine QIs

The regression models for yield were significant ($P<0.001$) for all irrigation treatments (Table 5) and indicate the following: 1) rainfall, ETo, and VPD had a significant ($P<0.001$) and positive impact on yield in all irrigation treatments, while solar radiation affected negatively the yield response only in PRI-1 and RDI-1, but not in the severely water-stressed PRI-2 and RDI-2 vines; 2) both $T^{a}max$ and $T^{a}min$ influenced negatively the yield response in some irrigation treatments – $T^{a}max$ in SDI, PRI-1, and PRI-2 and $T^{a}min$ in SDI, PRI-1, and RDI-1; and 3) all phenological periods (from budburst to postharvest) had a significant positive effect on the long-term yield response.

The predictive climatic models for the technological quality of the berry ($QI_{technologicalberry}$) were significant ($P<0.001$) for all irrigation treatments (Table 6) and indicate the following: 1) rainfall did not have a significant influence on technological berry quality; 2) $T^{a}min$ affected the $QI_{technologicalberry}$ negatively in all treatments; 3) in the more irrigated SDI vines, hours of sunshine and $T^{a}max$ had a positive influence on $QI_{technologicalberry}$, while global solar radiation and $T^{a}min$ had a negative influence; and 4) except postharvest, all phenological periods had a significant positive influence on $QI_{technologicalberry}$.

The predictive regression climatic models for phenolic berry QI ($QI_{phenolicberry}$) were also significant ($P<0.001$) for all irrigation treatments (Table 7) and indicate the following: 1) rainfall and solar radiation affected positively the berry phenolic content in the most water-stressed PRI-2 and RDI-2 vines and 2) $T^{a}max$ affected negatively the $QI_{phenolicberry}$ in SDI and RDI-2 vines, while $T^{a}min$ affected the phenolic quality negatively in all treatments.

The regression models for overall berry QI ($QI_{overallberry}$) were significant ($P<0.001$) for all irrigation treatments (Table 8) and indicate the following: 1) $T^{a}min$ affected the overall berry quality negatively in all treatments; 2) in addition, $T^{a}max$ also affected significantly and negatively $QI_{overallberry}$ only in RDI-2; and 3) in contrast, hours of sunshine

Table 5 Multiple linear regression models for yield for each irrigation treatment

Predictors	SDI		PRI-1		PRI-2		RDI-1		RDI-2	
	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t
Budburst–fruit set	12,283.68 (3,714.25)	3.31**	9,473.56 (3,004.51)	3.15**	8,426.91 (2,900.59)	2.91**	10,131.23 (3,307.93)	3.06**	5,664.44 (2,562)	2.21*
Fruit set–véraison	11,048.17 (4,769.14)	2.32*	10,890.57 (3,815.07)	2.85**	9,030.83 (3,675.28)	2.46*	11,800.98 (4,203.17)	2.81**	6,971.15 (3,282.19)	2.12*
Véraison–harvest	12,495.66 (4,876.09)	2.56*	11,997.72 (3,852.71)	3.11**	11,810.73 (3,688.97)	3.2**	13,620.72 (4,246.21)	3.21**	8,272.34 (3,283.19)	2.52*
Postharvest	17,161.83 (4,498.21)	3.82***	14,639.15 (3,620.21)	4.04***	16,427.68 (3,444.98)	4.77***	16,713.94 (3,988.5)	4.19***	11,081 (3,064.79)	3.62***
Rainfall	58.23 (14.62)	3.98***	93.6 (16.99)	5.51***	86.46 (17.71)	4.88***	104.45 (18.93)	5.52***	66.43 (15.69)	4.24***
Hours of sunshine	22.7 (11.99)	1.89	16.66 (9.55)	1.74	8.1 (9.34)	0.87	21.85 (10.52)	2.08*	1.2 (8.35)	0.14
Solar radiation	−22.62 (25.04)	−0.9	−46.93 (20.1)	−2.34*	−32.95 (19.4)	−1.7	−54.11 (22.15)	−2.44*	−17.29 (17.25)	−1
T^amax	−85.2 (29.27)	−2.91**	−50.28 (23.62)	−2.13*	−52.78 (22.96)	−2.3*	−45.13 (26.02)	−1.73	−39.43 (20.26)	−1.95
T^amin	−937.63 (455.58)	−2.06*	−752.9 (367.67)	−2.05*	−338.26 (351.59)	−0.96	−857.88 (404.95)	−2.12*	−298.91 (313.02)	−0.95
ETo	883.5 (290.86)	3.04**	808.17 (234.01)	3.45**	609.91 (225.02)	2.71**	756.34 (257.72)	2.93**	627.9 (202.53)	3.1**
VPD	148.62 (37.73)	3.94***	132.46 (30.36)	4.36***	151.75 (28.86)	5.26***	145.08 (33.45)	4.34***	104.88 (25.69)	4.08***
(Constant)	13,596.23 (7,896.94)	1.72	12,057.88 (6,372.42)	1.89	−1,334.57 (5,979.81)	−0.22	10,996.5 (7,027.62)	1.56	2,463.61 (5,325.35)	0.46
R_{adj}^2 (%)	34.9		44.3		39.3		43.1		36.5	
Model	F (12,127)=5.67***		F (12,127)=8.43***		F (12,127)=6.86***		F (12,127)=8.03***		F (12,127)=6.09***	

Note: Significant at *P<0.05, **P<0.01, ***P<0.001.
Abbreviations: ETo, evapotranspiration; PRI, partial root-zone drying irrigation; RDI, regulated deficit irrigation; SDI, sustained deficit irrigation; SE, standard error; VPD, vapor pressure deficit.

Table 6 Multiple linear regression models for technological berry quality index ($QI_{Technologicalberry}$) for each treatment

Predictors	SDI		PRI-1		PRI-2		RDI-1		RDI-2	
	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t
Budburst–fruit set	4.22 (1.99)	2.12*	8.59 (2.45)	3.5**	8 (2.35)	3.41**	4.15 (2.29)	1.81	7.35 (2.09)	3.51**
Fruit set–véraison	10.11 (2.55)	3.96***	18.19 (3.11)	5.84***	17.66 (2.98)	5.93***	14.62 (2.91)	5.02***	14.69 (2.68)	5.48***
Véraison-harvest	9.97 (2.61)	3.82***	16.21 (3.14)	5.16***	15.2 (2.99)	5.09***	12.14 (2.94)	4.12***	12.87 (2.68)	4.8***
Postharvest	4.24 (2.41)	1.76	4.87 (2.95)	1.65	3.35 (2.79)	1.2	0.04 (2.77)	0.01	4.21 (2.5)	1.68
Rainfall	0.02 (0.01)	1.96	−0.01 (0.01)	−0.51	−0.02 (0.01)	−1.1	−0.01 (0.01)	−0.81	0 (0.01)	−0.28
Hours of sunshine	0.01 (0.01)	2.08*	0.01 (0.01)	1.02	0.01 (0.01)	0.84	0 (0.01)	0.21	0.01 (0.01)	0.84
Solar radiation	−0.04 (0.01)	−2.85**	−0.01 (0.02)	−0.68	0.03 (0.02)	1.68	0.02 (0.02)	1.53	−0.01 (0.01)	−0.38
T^amax	0.04 (0.02)	2.8**	0.01 (0.02)	0.53	−0.02 (0.02)	−0.82	0.02 (0.02)	0.99	−0.01 (0.02)	−0.31
T^amin	−1.18 (0.24)	−4.83***	−1.37 (0.3)	−4.57***	−1.2 (0.28)	−4.23***	−1.21 (0.28)	−4.29***	−0.93 (0.26)	−3.64***
ETo	0.24 (0.16)	1.52	0.18 (0.19)	0.93	0.05 (0.18)	0.25	0.18 (0.18)	1	0.17 (0.17)	1.02
VPD	0 (0.02)	0.05	−0.01 (0.02)	−0.26	−0.02 (0.02)	−0.83	−0.05 (0.02)	−1.97	0 (0.02)	0.16
(Constant)	26.24 (4.23)	6.21***	29.32 (5.2)	5.64***	24.26 (4.84)	5.01***	27.04 (4.87)	5.55***	21.69 (4.35)	4.99***
R^2_{adj} (%)	33.9		31.0		33.6		29.3		28	
Model	F (12,127)=5.42***		F (12,127)=4.76***		F (12,127)=5.35***		F (12,127)=5.81***		F (12,127)=4.11***	

Note: Significant at *P<0.05, **P<0.01, ***P<0.001.
Abbreviations: ETo, evapotranspiration; PRI, partial root-zone drying irrigation; RDI, regulated deficit irrigation; SDI, sustained deficit irrigation; SE, standard error; VPD, vapor pressure deficit.

and solar radiation impacted positively $QI_{overallberry}$ in SDI and PRI-2, respectively. In general, the significant (P<0.05) negative relationships found between T^amax, T^amin, VPD, and $QI_{overallberry}$ and total anthocyanins indicate that in warmer years, with greater annual average T^amax, T^amin and VPD, decreased substantially the overall berry quality at this warm winegrowing region (Figure 1A–D).

The predictive climatic models for overall wine quality (QI_{wine}) were significant in all irrigation treatments (Table 9). This shows that in SDI vines, rainfall, hours of sunshine,

Table 7 Multiple linear regression models for phenolic berry quality index ($QI_{phenolicberry}$) for each irrigation treatment

Predictors	SDI		PRI-1		PRI-2		RDI-1		RDI-2	
	B (SE)	T	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t
Budburst–fruit set	7.95 (1.67)	4.75***	6.82 (2.07)	3.29**	7.28 (2.03)	3.59***	4.18 (1.79)	2.34*	8.35 (1.78)	4.7***
Fruit set–véraison	11.51 (2.15)	5.36***	12.38 (2.63)	4.71***	14.64 (2.57)	5.7***	9.87 (2.27)	4.34***	11.69 (2.28)	5.14***
Véraison–harvest	10.48 (2.2)	4.77***	10.71 (2.66)	4.03***	15.15 (2.58)	5.88***	8.79 (2.3)	3.83***	12.11 (2.28)	5.32***
Postharvest	5.87 (2.03)	2.9**	3.01 (2.5)	1.21	8.74 (2.41)	3.63***	1.77 (2.16)	0.82	9.35 (2.13)	4.4***
Rainfall	0.01 (0.01)	0.79	–0.02 (0.01)	–1.51	0.03 (0.01)	2.03*	–0.01 (0.01)	–1.21	0.02 (0.01)	2.15*
Hours of sunshine	0.01 (0.01)	1.44	0 (0.01)	0.55	0.01 (0.01)	1.91	0 (0.01)	0.66	0.01 (0.01)	1.59
Solar radiation	0 (0.01)	–0.12	0 (0.01)	0.33	0.03 (0.01)	2.33*	0.02 (0.01)	1.79	0.04 (0.01)	3.23**
T^{a}max	–0.03 (0.01)	–2.4*	–0.01 (0.02)	–0.66	–0.03 (0.02)	–1.77	0 (0.01)	–0.35	–0.07 (0.01)	–4.75***
T^{a}min	–0.72 (0.21)	–3.49**	–0.89 (0.25)	–3.5**	–0.94 (0.25)	–3.84***	–0.73 (0.22)	–3.33**	–0.6 (0.22)	–2.77**
ETo	–0.08 (0.13)	–0.58	–0.07 (0.16)	–0.46	–0.11 (0.16)	–0.68	–0.1 (0.14)	–0.75	–0.26 (0.14)	–1.84
VPD	0.03 (0.02)	1.51	–0.01 (0.02)	–0.42	0.03 (0.02)	1.7	–0.02 (0.02)	–0.96	0.05 (0.02)	3.03**
(Constant)	13.34 (3.56)	3.75***	19.7 (4.39)	4.48***	10.15 (4.18)	2.43*	15.89 (3.8)	4.18***	3.7 (3.69)	1
R^2_{adj} (%)	22.8		20.3		42.2		23.6		37.4	
Model	F (12,127)=3.13***		F (12,127)=2.69***		F (12,127)=7.72***		F (12,127)=3.28***		F (12,127)=6.33***	

Note: Significant at *P<0.05, **P<0.01, ***P<0.001.
Abbreviations: ETo, evapotranspiration; PRI, partial root-zone drying irrigation; RDI, regulated deficit irrigation; SDI, sustained deficit irrigation; SE, standard error; VPD, vapor pressure deficit.

Table 8 Multiple linear regression models for overall berry quality index ($QI_{overallberry}$) for each irrigation treatment

Predictors	SDI		PRI-1		PRI-2		RDI-1		RDI-2	
	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t
Budburst–fruit set	12.17 (3.12)	3.9***	15.41 (4.24)	3.64***	15.28 (4.01)	3.81***	8.33 (3.76)	2.22*	15.7 (3.2)	4.91***
Fruit set–véraison	21.61 (4)	5.4***	30.57 (5.38)	5.68***	32.3 (5.08)	6.36***	24.49 (4.78)	5.13***	26.38 (4.1)	6.44***
Véraison–harvest	20.44 (4.09)	5***	26.92 (5.43)	4.95***	30.35 (5.1)	5.95***	20.94 (4.83)	4.34***	24.98 (4.1)	6.09***
Postharvest	10.11 (3.77)	2.68**	7.89 (5.11)	1.54	12.08 (4.76)	2.54*	1.81 (4.53)	0.4	13.57 (3.83)	3.54**
Rainfall	0.02 (0.01)	1.67	–0.02 (0.02)	–1.03	0.01 (0.02)	0.38	–0.02 (0.02)	–1.07	0.02 (0.02)	1.01
Hours of sunshine	0.02 (0.01)	2.1*	0.01 (0.01)	0.85	0.02 (0.01)	1.46	0.01 (0.01)	0.44	0.01 (0.01)	1.44
Solar radiation	–0.04 (0.02)	–1.88	–0.01 (0.03)	–0.23	0.06 (0.03)	2.16*	0.04 (0.03)	1.79	0.03 (0.02)	1.55
T^{a}max	0.01 (0.02)	0.5	0 (0.03)	–0.02	–0.04 (0.03)	–1.38	0.01 (0.03)	0.44	–0.07 (0.03)	–2.84**
T^{a}min	–1.89 (0.38)	–4.96***	–2.26 (0.52)	–4.36***	–2.15 (0.49)	–4.42***	–1.93 (0.46)	–4.2***	–1.53 (0.39)	–3.92***
ETo	0.16 (0.24)	0.66	0.1 (0.33)	0.31	–0.06 (0.31)	–0.2	0.07 (0.29)	0.25	–0.09 (0.25)	–0.35
VPD	0.03 (0.03)	0.84	–0.02 (0.04)	–0.35	0.02 (0.04)	0.38	–0.06 (0.04)	–1.66	0.06 (0.03)	1.79
(Constant)	39.58 (6.63)	5.97***	49.01 (8.99)	5.45***	34.41 (8.27)	4.16***	42.93 (7.99)	5.37***	25.4 (6.65)	3.82***
R_{adj}^2 (%)	30.4		27.2		39.4		32.8		35.4	
Model	F (12,127)=4.63***		F (12,127)=3.95***		F (12,127)=6.88***		F (12,127)=5.18***		F (12,127)=5.58***	

Note: Significant at *P<0.05, **P<0.01, ***P<0.001.
Abbreviations: ETo, evapotranspiration; PRI, partial root-zone drying irrigation; RDI, regulated deficit irrigation; SDI, sustained deficit irrigation; SE, standard error; VPD, vapor pressure deficit.

and VPD influenced positively the wine quality, while solar radiation affected it negatively. In the other irrigation treatments, climatic factors did not have a significant influence on QI_{wine}.

Multiple stepwise regression models and relationships between climatic factors and irrigation systems

The stepwise multiple regression model fitted to the yield data of the PRI system (PRI-1 and PRI-2) (F-ratio 54.60, r^2=0.75***) and revealed significant positive effects of rainfall during dormancy and the budburst–fruit set period on the yield response (Table 10). In contrast, in the RDI system (RDI-1 and RDI-2), the model (F-ratio 30.21, r^2=0.76***) indicated that other climatic factors, besides rainfall during the budburst–fruit set period, influenced significantly the yield response. Thus, the number of solar hours during dormancy and the ETo during the budburst–fruit set period had a positive effect on the yield response, while the number of solar hours and VPD early in the season as well as T^{a}max during véraison–harvest had a significant negative effect on the yield response in RDI. Similarly, in the SDI model (F-ratio 13.81, r^2=0.59***), rainfall early in the season and during ripening influenced the yield response positively, while VPD (budburst–fruit set [B–F]) did not (Table 10).

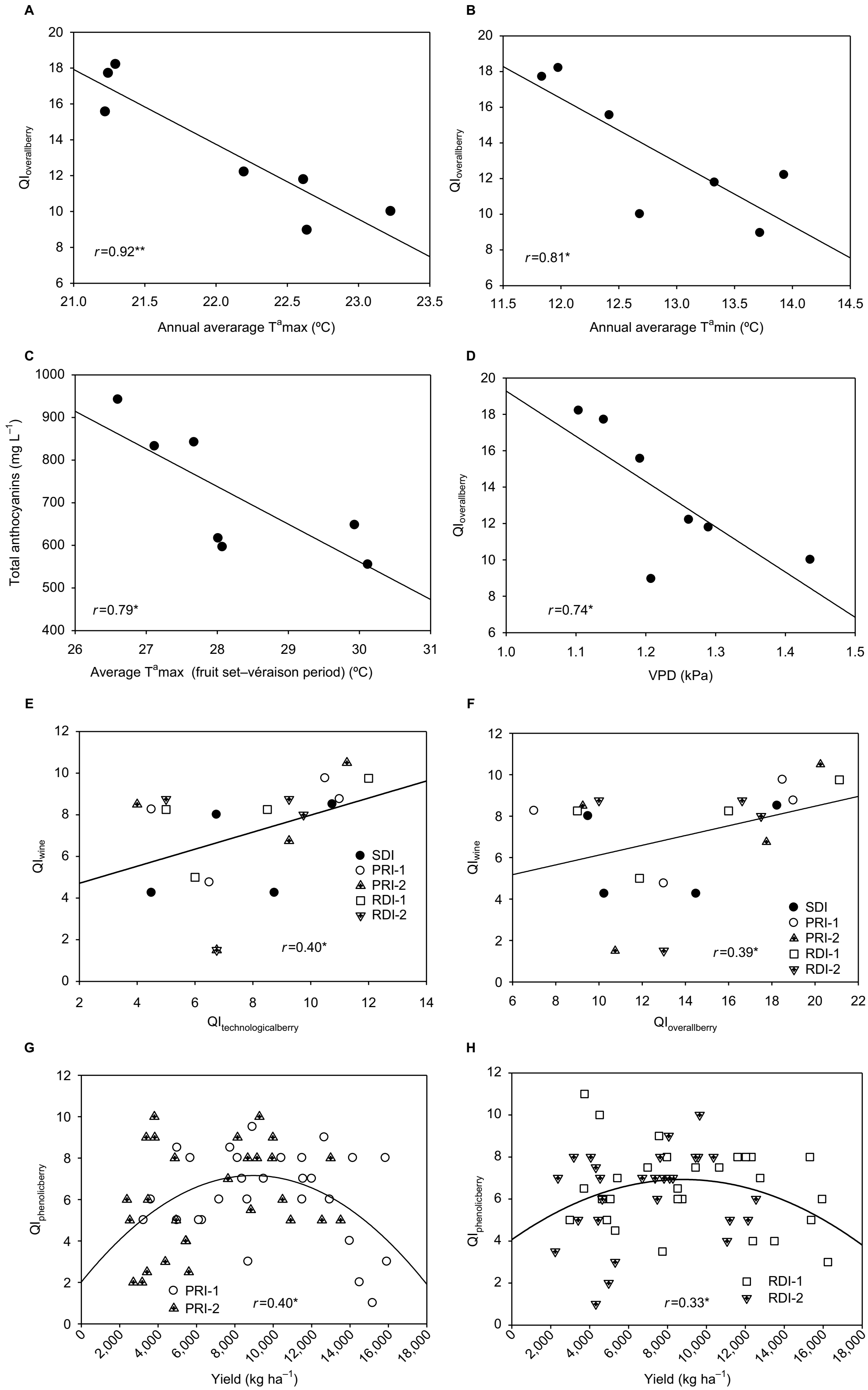

Figure 1 Significant relationships between annual average Tªmax, Tªmin, VPD, and $QI_{overallberry}$, and between Tªmax during fruit set–véraison period and total anthocyanins (**A**–**D**). Relationships between several berry quality indices and wine quality index, and between yield and berry quality indices in PRI and RDI systems (**E**–**H**).

Notes: In (**A**–**D**), each point is the average of 1 year involving the five irrigation treatments. In (**E**–**F**), each point is the average (involving the four plots) for each year and treatment. In (**G**–**H**), each point is the average of one plot and treatment for different years (7 years for berry quality and 5 years for wine quality). *$P<0.05$, **$P<0.01$, ***$P<0.001$.

Abbreviations: PRI, partial root-zone drying irrigation; $QI_{overallberry}$, technological berry quality; $QI_{phenolicberry}$, phenolic quality; QI_{wine}, wine quality; RDI, regulated deficit irrigation; SDI, sustained deficit irrigation; VPD, vapor pressure deficit.

Table 9 Multiple linear regression models for wine quality index (QI_{wine}) for each irrigation treatment

Predictors	SDI		PRI-1		PRI-2		RDI-1		RDI-2	
	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t	B (SE)	t
Budburst–fruit set	6.91 (2.87)	2.41*	2.38 (2.64)	0.9	−3.6 (3.41)	−1.06	0.69 (1.93)	0.36	1.68 (3.32)	0.5
Fruit set–véraison	4.4 (3.63)	1.21	10.69 (3.44)	3.11**	9.51 (4.34)	2.19*	8.65 (2.52)	3.43**	12.27 (4.29)	2.86**
Véraison–harvest	7.83 (3.67)	2.13*	10.03 (3.38)	2.97**	8.04 (4.34)	1.85	7.6 (2.47)	3.08**	12.79 (4.25)	3.01**
Postharvest	13.81 (3.75)	3.68***	5.17 (3.46)	1.5	0.18 (4.44)	0.04	2.56 (2.53)	1.01	8.61 (4.34)	1.99
Rainfall	0.02 (0.01)	2.49*	0.02 (0.02)	1.18	0.01 (0.02)	0.46	0.01 (0.01)	1.11	0.04 (0.02)	1.8
Hours of sunshine	0.02 (0.01)	2.5*	0.01 (0.01)	0.65	0 (0.01)	−0.29	0 (0.01)	0.29	0.01 (0.01)	0.64
Solar radiation	−0.07 (0.03)	−2.22*	0.05 (0.03)	1.65	0.07 (0.04)	1.88	0.05 (0.02)	2.36*	0.03 (0.04)	0.88
T^amax	−0.01 (0.03)	−0.29	−0.02 (0.03)	−0.56	0.03 (0.04)	0.65	−0.01 (0.02)	−0.39	0.01 (0.04)	0.13
T^amin	−0.36 (0.45)	−0.79	−0.42 (0.43)	−0.98	−0.18 (0.57)	−0.32	−0.29 (0.32)	−0.92	−0.53 (0.54)	−0.98
ETo	0.43 (0.27)	1.6	0.13 (0.25)	0.51	0.32 (0.32)	1	0.1 (0.18)	0.54	0.36 (0.31)	1.16
VPD	0.12 (0.03)	3.76***	0.01 (0.03)	0.4	−0.04 (0.04)	−0.98	−0.01 (0.02)	−0.32	0.04 (0.04)	1.02
(Constant)	3.05 (8.59)	0.36	7.58 (8.09)	0.94	6.64 (10.34)	0.64	7.85 (5.91)	1.33	5.52 (9.98)	0.55
R_{adj}^2 (%)	38.2		38.5		52.8		50.0		50.2	
Model	F (12,67)=3.45***		F (12,67)=3.49***		F (12,67)=6.24***		F (12,67)=5.58***		F (12,67)=5.63***	

Note: Significant at *P<0.05, **P<0.01, ***P<0.001.
Abbreviations: ETo, evapotranspiration; PRI, partial root-zone drying irrigation; RDI, regulated deficit irrigation; SDI, sustained deficit irrigation; SE, standard error; VPD, vapor pressure deficit.

The regression models revealed different climatic factors affecting technological berry QI ($QI_{technologicalberry}$) in the PRI, SDI, and RDI systems (Table 10). The model for PRI (F-ratio 53.06, r^2_{adj}=0.74***) indicated that T^a was the main climatic factor affecting technological quality, while for RDI (F-ratio 25.29, r^2_{adj}=0.69***) and SDI (F-ratio 20.28, r^2_{adj}=0.68), other climatic factors, besides T^a, such as rainfall, ETo, and the number of hours of sunshine, had greater importance. Thus, according to these models, for PRI, greater T^amin during dormancy and fruit set–véraison and T^amax postharvest had a significant negative impact on berry technological quality, while for RDI, greater T^amax and ETo early in the season (budburst–fruit set) and a higher number of hours of sunshine postharvest affected it negatively. In addition, for RDI, greater rainfall during dormancy and ETo in the véraison–harvest period influenced the technological quality positively. For SDI, the early season T^amax influenced the technological quality positively, but the early season radiation and rainfall during ripening had a negative impact (Table 10).

With regard to the phenolic quality of the berry $QI_{phenolicberry}$ (Table 10), the regression model for PRI indicates that solar radiation during the véraison–harvest period had a positive impact, while T^amax during budburst–fruit set influenced it negatively. Similarly, the RDI regression model showed that T^amax and T^amin during budburst–fruit set affected the phenolic quality of the berry negatively, while ETo during véraison–harvest had a significant positive effect. For SDI, the early season T^amax was also the main climatic factor affecting the phenolic quality negatively (Table 10).

Considering the global quality of the berry (technological and phenolic quality, $QI_{overallberry}$), the regression model shows that, for PRI, greater solar radiation and T^amax postharvest and greater T^amin during dormancy affected it negatively (Table 10). For RDI, the regression model indicates that a greater number of hours of sunshine postharvest – and higher solar radiation, T^amax, and T^amin during the budburst–fruit set period – impacted negatively the global quality of the berry, while greater rainfall during dormancy and higher ETo during the véraison–harvest period influenced it positively. For SDI, the global incident solar radiation early in the season and rainfall during ripening affected the global berry quality negatively (Table 10).

For the global wine quality (QI_{wine}), while the behavior of the PRI model was explained only by the (positive) effect of the postharvest rainfall, for RDI and SDI, more climatic variables and phenological periods came into play. Thus, for the RDI system, the number of solar hours and ETo early in the season impacted negatively the wine quality, while, in contrast, the number of solar hours and VPD pre-véraison (fruit set–véraison [F–V]) had a positive effect on the wine quality, as did rainfall during ripening. For SDI, greater rainfall and T^amin in early season and T^amax post-véraison (during ripening) impacted positively on the wine quality in the more irrigated SDI vines, while greater T^amin during dormancy impacted it negatively (Table 10).

Relationships between agronomic factors, yield, grape and wine characteristics

The correlation coefficient matrix relating yield–vine vigor parameters, berry quality attributes, and wine quality showed positive and significant correlations between some cluster microclimate parameters ($PAR_{clusterzone}$ post-véraison, berryT^a pre-véraison) and color intensity (CI) in wines and significant

Table 10 Stepwise multiple regression models for yield, berry and wine quality indices for each irrigation system, PRI, RDI, and SDI

Parameter	**PRI system**			**RDI system**			**SDI system**		
	Independent variable	**Coefficient (SE)**	***t*-value**	**Independent variable**	**Coefficient (SE)**	***t*-value**	**Independent variable**	**Coefficient (SE)**	***t*-value**
Yield response	Rainfall B–F	110.39 (9.16)	12.06***	Rainfall B–F	60.01 (7.57)	7.93***	Rainfall B–F	65.39 (14.16)	4.62***
	Rainfall D	61.95 (11.18)	5.54***	Hours of sunshine B–F	−194.97 (52.88)	−3.69***	Rainfall V–H	78.33 (30.56)	2.56*
	T^amin PO	420.78 (113.19)	3.72***	Hours of sunshine D	82.00 (20.99)	3.91***	VPD B–F	-1.58×10^4 (4,879)	−3.24**
	Constant	−7,182.48 (1,608.45)	−4.47***	T^amax V–H	−650.01 (311.17)	−2.09*	Constant	23,071.03 (5,607.89)	4.11***
	R^2_{adj}=0.75	*F*=54.60***		ETo B–F	328.06 (81.15)	4.04***	R^2_{adj}=0.59	*F*=13.81***	
				VPD B–F	-3.84×10^4 (7,665.37)	−5.01***			
				Constant	24,583.31 (9,355.85)	2.63*			
				R^2_{adj}=0.76	*F*=30.21***				
Technological berry quality ($QI_{technological\ berry}$)	T^amax PO	−1.84 (0.19)	−9.89***	Rainfall D	0.014 (0.0062)	2.19*	Rainfall V–H	−0.047 (0.015)	−3.20**
	T^amin F–V	−0.44 (0.16)	−2.68**	Hours of sunshine PO	−0.028 (0.0094)	−2.98**	Radiation B–F	−0.135 (0.018)	−7.25***
	T^amin D	−2.11 (0.30)	−7.08***	T^amax B–F	−1.23 (0.18)	−6.97***	T^amax B–F	0.678 (0.256)	2.64*
	Constant	59.62 (4.56)	13.06***	ETo B–F	−0.0480 (0.013)	−3.75***	Constant	30.41 (5.38)	5.65***
	R^2_{adj}=0.74	*F*=53.06***		ETo V–H	0.014 (0.0057)	2.52*	R^2_{adj}=0.68	*F*=20.28***	
				Constant	46.93 (5.34)	8.78***			
				R^2_{adj}=0.69	*F*=25.29***				
Phenolic quality $QI_{phenolicberry}$	Radiation V–H	0.02 (0.0049)	4.50***	T^amax B–F	−0.51 (0.22)	−2.33*	T^amax B–F	−1.13 (0.217)	−5.19***
	T^amax B–F	−1.69 (0.21)	−8.09***	T^amin B–F	−0.71 (0.19)	−3.67***	Constant	29.18 (4.64)	6.29***
	Constant	37.37 (4.11)	9.09***	ETo V–H	0.019 (0.0050)	3.86***	R^2_{adj}=0.49	*F*=27.00***	
	R^2_{adj}=0.54	*F*=33.34***		Constant	20.56 (3.96)	5.19***			
				R^2_{adj}=0.58	*F*=26.81***				
Global berry quality ($QI_{overallberry}$)	Radiation PO	−0.099 (0.04)	−2.45*	Rainfall D	0.024 (0.0088)	2.70**	Rainfall V–H	−0.072 (0.022)	−3.18**
	T^amax PO	−3.54 (0.30)	−11.67***	Hours of sunshine PO	−0.045 (0.013)	−3.50**	Radiation B–F	−0.168 (0.027)	−6.12***
	T^amin D	−4.09 (0.61)	−6.66***	Radiation B–F	−0.056 (0.020)	−2.78**	Constant	59.62 (7.064)	8.44***
	Constant	109.82 (9.91)	11.08***	T^amax B–F	−1.45 (0.35)	−4.17***	R^2_{adj}=0.64	*F*=24.73***	
	R^2_{adj}=0.72	*F*=48.48***		T^amin B–F	−0.86 (0.30)	−2.90**			
				ETo V–H	0.031 (0.0080)	3.90***			
				Constant	68.65 (7.50)	9.15***			
				R^2_{adj}=0.77	*F*=30.96***				
Global wine quality (QI_{wine})	Rainfall PO	0.13 (0.01)	8.91***	Rainfall V–H	0.07 (0.01)	6.98***	Rainfall B–F	0.05 (0.005)	9.61***
	Constant	1.75 (0.69)	2.54*	Hours of sunshine B–F	−0.21 (0.02)	−11.69***	T^amax V–H	1.178 (0.233)	5.05***
	R^2_{adj}=0.72	*F*=79.30***		Hours of sunshine F–V	0.15 (0.06)	2.36*	T^amin B–F	0.509 (0.195)	2.61*
				T^amax PO	−0.47 (0.14)	−3.34**	T^amin D	−0.56 (0.207)	−2.70*
				ETo B–F	−0.24 (0.03)	−9.32***	T^amin PO	0.272 (0.089)	3.05*
				ETo F–V	−0.32 (0.06)	−5.17***	Constant	−36.05 (7.22)	−4.99***
				VPD F–V	15.73 (3.71)	4.25***	R^2_{adj}=0.91	*F*=30.33***	
				Constant	176.22 (17.03)	10.35***			
				R^2_{adj}=0.93	*F*=59.11***				

Notes: The models included climatic factors and phenological periods. $^*P<0.05$, $^{**}P<0.01$, $^{***}P<0.001$.
Abbreviations: B–F, budburst–fruit set; D, dormancy; ETo, evapotranspiration; F–V, fruit set–véraison; PO, postharvest; PRI, partial root-zone drying irrigation; RDI, regulated deficit irrigation; SDI, sustained deficit irrigation; SE, standard error; V–H, véraison–harvest; VPD, vapor pressure deficit.

Table 11 Pearson's correlation coefficients (*r*) between microclimate and agronomic factors of grape and wine variables

Parameter	CI_{wine}	TPI_{wine}	Total anthocyanins wine (mg L^{-1})	L_{wine}*	a_{wine}*
Yield	–0.56*	–0.32	0.08	0.68***	0.79***
Berry weight	–0.50*	–0.25	0.12	0.66**	0.79***
TSSberry (°Brix)	–0.078	0.076	0.40	0.22	0.33
Tartaric acid berry (mg L^{-1})	0.40	0.34	0.18	–0.36	–0.38
pHberry	0.37	0.097	–0.151	–0.49*	–0.65**
CIberry	0.44*	0.19	0.21	–0.41	–0.39
Total anthocyan. berry	0.68**	0.55*	0.54*	–0.60**	–0.33
Ext anthocyan. berry	0.68**	0.46*	0.21	–0.68***	–0.62**
Extractable polyph. Berry	0.58**	0.32	–0.047	–0.70***	–0.84***
WUE_{yield}	0.043	–0.085	0.050	0.080	0.21
PAR cluster zone pre-véraison	0.18	–0.029	–0.17	–0.38	–0.65**
PAR cluster zone post-véraison	0.45*	0.24	–0.054	–0.58**	–0.75***
Berry temperature pre-véraison	0.56**	0.42	0.086	–0.53*	–0.46*
Berry temperature post-véraison	0.28	0.15	–0.18	–0.36	–0.40
Total leaf area	–0.55*	–0.33	0.071	0.69***	0.83***
Exposed leaf area	–0.58**	–0.26	0.047	0.67**	0.75***

Note: Significant at *P<0.05, **P<0.01, ***P<0.001.
Abbreviations: CI, color intensity; TPI, total phenol index; TSS, total soluble solids; WUE, water use efficiency.

negative correlations with L* (wine lightness) and a* (red color component) (Table 11).

Besides, vine vegetative development – measured as total and exposed leaf area – was correlated negatively with CIwine, but positively and significantly with L* and a*. Yield (kg vine^{-1}) and berry weight were significantly and negatively correlated, especially with CIwine (Table 11), although they also showed strong positive correlations with the CIElab parameters (L* and a*) in wines. Berry pH was also negatively correlated with L* and a*. As expected, CIberry, total and extractable anthocyanins, and extractable polyphenols in the berries were correlated highly positively and significantly with CIwine, TPI, and total anthocyanins in wines and negatively with L* and a* (Table 11). We also found relationships between the long-term yield and the berry and wine QIs in Monastrell grapevines (Figure 1E–H).

Discussion

Influence of climate on global response of yield, berry and wine quality in the different DI treatments: comparison of the irrigation systems

The multiple linear regression models using climate variables revealed significant effects of different climatic variables on yield, berry and wine quality (Tables 5–10). These findings indicate that, under semiarid conditions, climate is a very strong modulator of yield, berry and wine composition[41] and can be satisfactorily described using climate variable–based empirical models.[42] Besides, our results demonstrate that the climate is more influential in determining berry composition at maturity in some important physiological periods than in other periods[42,43] and can have a negative or beneficial effect depending on the phenological period (Table 10).

In this study, the multiple linear regression models (using climatic factors) for each irrigation treatment showed that, in general, rainfall, ETo, and VPD influenced the yield response significantly and positively in a similar way in all the long-term DI treatments (Tables 5–10). By contrast, T^amax had – almost always – a significant negative effect on yield and T^amin also had a significant negative impact on technological, phenolic, and overall berry QIs in all treatments (Figure 1A–D), highlighting the importance of this climatic factor in determining the global berry quality. Under warm, semiarid conditions, as in this study, and especially in warmer years, high daytime and night-time temperatures (higher T^amin and T^amax) may act as a key negative factor for berry quality, especially for the synthesis and accumulation of total anthocyanins (Figure 1A–D). The T^amin during ripening (August to mid-September) generally exceeded 15°C (Table S1) and night/day temperature difference ranged 15°C or below, and therefore may have also exerted a negative influence on the synthesis and accumulation of anthocyanins and other polyphenols,[44–46] reducing global berry and wine quality. Besides, a significant positive effect of rainfall and negative effect of T^amax on yield in all treatments suggest that regardless of the irrigation, warmer and drier years have a negative impact on the yield-quality response. This is in contrast to other wine-growing regions (Franconia, Germany) where the regression models related increased temperatures with higher yields,[47] perhaps because they have a colder climate compared to our warm study area. Although increased mean air temperatures (warmer years) and lower rainfall have been frequently related with greater potential berry and wine quality in terms of sugar, acidity, sugar/acidity ratio, or berry weight,[43,47–49] other studies found that berries from warmer regions had low levels of anthocyanins and titratable acidity as well as high pH, compared to berries from the cooler regions.[42] Besides, interestingly, in more irrigated SDI vines, greater T^amax was positive for $QI_{technologicalberry}$, but negative for $QI_{phenolicberry}$. These contrasting results provide evidence for the differential influence of temperature, not only among cultivars and wine-growing regions but also on different berry traits.[42]

Interestingly, for the wine QI (QI_{wine}) (Table 9), the multiple linear regression models showed a significant influence of several climatic factors (rainfall, hours of sunshine, solar radiation, and VPD) in SDI vines, but not in DI vines. According to this model, in general, greater rainfall, more hours of sunshine, and higher VPD impacted the wine quality positively in the more irrigated SDI vines. We hypothesize that in SDI vines, a greater soil water availability and low water stress, together with higher evaporative demand of the atmosphere (high VPD) and, consequently, greater transpiration and water use by the plant are beneficial for final wine quality.

According to the stepwise multiple regression calculated for each irrigation system, the models which fitted the PRI system best were less complex (with a lower number of climatic variables) than the ones for the RDI system, suggesting the PRI system is influenced by climatic factors lesser than the RDI system (Table 10). Thus, for PRI, the models for yield, berry and wine QIs were explained always by the same two or three climatic factors (rainfall, T^a, and solar radiation), whereas for RDI, more climatic factors came into play (number of hours of sunshine, ETo, and VPD). Besides, in the SDI and RDI systems involving conventional DI, two phenological periods were more critical for yield, berry and wine quality: early season (budburst–fruit set) and ripening (véraison–harvest) (Table 10). While in PRI, dormancy and postharvest periods were also important to determine long-term yield and berry–wine quality response.

Interestingly, for PRI, the stepwise multiple regression model revealed that greater rainfall distributed in different periods (during dormancy [D], early in the season [B–F], and postharvest [PO]) and greater solar radiation during ripening were the main climatic factors that influenced positively the yield response, berry and wine quality. Greater solar radiation during véraison–harvest affected the phenolic quality in PRI positively, probably associated with an improvement in photosynthesis and microclimate factors.[32–35] While greater T^amax and T^amin (during most part of the growing season) impacted the berry and wine quality negatively.

In contrast, for RDI, besides rainfall during dormancy and early ripening, other prevailing climatic conditions during early season were important and had a positive or negative influence (Table 10). In particular, greater ETo, T^amax, T^amin, radiation, VPD, and hours of sunshine early in the season (B–F) influenced the yield and berry and wine QIs in the RDI system negatively, suggesting that mild and wet weather early in the season is also better for RDI Monastrell at this site. In contrast, more hours of sunshine and higher VPD during the fruit set–véraison period, and greater ETo and rainfall and lower T^amax during véraison–harvest positively influenced the yield, berry and wine QIs in RDI. Accordingly, warmer and drier pre-véraison periods followed by higher soil water availability and associated greater crop ETo (more water use by the plants) during ripening (véraison–harvest period) also seem to be important with regard to improving the final berry and wine quality under RDI.

According to these models, PRI was more affected by extreme temperatures (high T^amax and T^amin) during the growing season than RDI and SDI, suggesting that in general, cooler and humid years may favor the PRI response more. Thus, years with cool and wet winters followed by a mild, wet spring and early summer (April–June) and a mild fruit set–véraison period (June–July), and then greater solar radiation during ripening (August–mid-September) provide adequate growth potential and increase the likelihood of higher berry and wine quality in PRI. In 2008, 2010, and 2011, which met almost all of these climatic requisites (Table S1), the yield–quality response was more positive with PRI than with RDI (Table S2).

In contrast, rainfall and T^a were the main climatic factors affecting berry and wine quality under SDI. Thus, rainfall early in the season (B–F) was also positive for yield and wine quality, while rainfall during ripening increased the yield but was negative for overall berry quality (Table 10). In addition, similar to RDI, higher VPD, solar radiation, and T^amax early season (B–F) impacted the berry and wine quality negatively in SDI; interestingly, unlike for RDI, higher T^amax and lower rainfall during ripening (véraison–harvest) increased the wine quality in SDI (Table 10), suggesting that more irrigated SDI vines are less sensitive to high temperatures and low soil water content availability during ripening, which favors berry–wine quality, perhaps to avoid important dilution effects and the problems and diseases associated with fungi. Thus, for example, in a very warm year like 2012, with scarce rainfall and a high number of days with T^amax >35°C (36 days) from budburst to harvest (Table S1), more irrigated SDI vines showed higher $QI_{technologicalberry}$ and similar $QI_{phenolicberry}$ than DI vines (Table S2).

Yield–berry–wine QIs relationships

The correlation coefficient matrix relating the yield–vine vigor parameters, berry quality attributes, and wine quality parameters showed positive and significant correlations of some cluster microclimate parameters ($PAR_{clusterzone}$ post-véraison, berryT^a pre-véraison) with CI in wines and negative correlations with vegetative development. This indicates that in general, the improvement in cluster microclimate due to lower leaf area and vine vigor positively influenced grape and wine quality in long-term RDI and PRI, as has been reported previously.[32,35,50,51] In addition, as expected, CIberry, total and extractable anthocyanins, and extractable polyphenols in the berries were highly, positively, and significantly correlated with CIwine, TPI, and total anthocyanins in wines (Table 11). In general, despite the dispersion of the data, greater QI in the berries ($QI_{technologicalberry}$, $QI_{overallberry}$) was also reflected in greater QI in the wines (QI_{wine}) (Figure 1E and F). These significant relationships also reinforce the validity of the novel QIs used in this study to evaluate long-term berry and wine quality in Monastrell grapevines. In general, climate had more influence on yield and berry quality than on wine quality, especially in DI compared to SDI vines (Tables 9 and 10), indicating that other factors, such as winemaking processes, are also important in determining the final wine quality.

According to the relationships found between the yield and phenolic berry quality in PRI and RDI, an optimum range of yield between 8,000 and 10,000 kg ha^{-1} maximizes phenolic berry QI (Figure 1G and H). This optimum yield range can be used by grape growers to find a yield–quality compromise, and thus increase their returns in long-term DI Monastrell grapevines under Mediterranean semiarid conditions.

Conclusion

The most important climatic factors for yield and berry and wine quality were rainfall, temperature, and radiation, but the phenological period was influential too. According to the multiple and stepwise linear regressions, the models which best fitted the PRI system were less complex (with fewer climatic variables) than the RDI models, suggesting that in general, the PRI system is less influenced by climatic factors than the RDI system. For PRI, the models of yield and berry and wine quality were explained by three climatic factors (rainfall, T^a, and radiation), whereas for RDI, more climatic factors were relevant. In RDI, sunny and drier pre-véraison period followed by higher soil water availability and associated greater crop ETo during ripening favored final berry and wine quality. In contrast, greater rainfall distributed in different periods and greater solar radiation during ripening were the main climatic factors that positively influenced the yield response, berry and wine quality in PRI. Besides, according to these models, berry and wine quality was more affected in PRI (negatively) by extreme temperatures (higher T^amax and T^amin) during the growing season than in RDI and SDI, indicating that cooler and humid years may favor the PRI response. According to the PRI model, years with cool and wet winters followed by a mild, wet spring and early summer (April–June) and a mild, wet fruit set–véraison period (June–July), and then greater solar radiation during ripening (August–mid-September) augment the growth potential and increase the likelihood of higher berry and wine quality under PRI. Besides, more irrigated SDI vines were less sensitive to high temperatures and low soil water content during ripening than RDI and SDI. In general, climate had more influence on berry quality than on wine QIs, and as expected, CI_{berry}, total and extractable anthocyanins, and extractable polyphenols in the berries were highly, positively, and significantly correlated with CIwine, TPI, and total anthocyanins in wines and, consequently, greater $QI_{overallberry}$ was also reflected in greater QI_{wine}. An optimum range of yield between 8,000 and 10,000 kg ha^{-1} maximized berry phenolic quality in DI Monastrell grapevines under warm, semiarid conditions of southeast Spain.

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Disclosure

The authors report no conflicts of interest in this work.

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