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Adaptation of Syrah wine grape cultivar to changing climatic conditions of the Bekaa valley, Lebanon

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Abstract. Climatic factors play a key role in determining the suitability of a given region for specific cultivars and wine types and the responses of individual grapevine cultivars to climate are of utmost importance for activity planning and decision making in viticulture. The study investigated the effect of climate conditions from 2006 till 2018 on the performance of cv. Syrah cultivated in two vineyards in Lebanon; Kanafar (at 1,020 m.a.s.l) and Mansoura (at 850 m.a.s.l). Cluster analysis based on climate indicators divided years into two clusters; in Kanafar (cluster 1: 2006–2015, cluster 2: 2016–2018) and in Mansoura (cluster 1: 2006 to 2008, cluster 2: 2009 to 2018). Solar radiation (May-June) and average wind speed (July-August-September) were the most influential predictors in Kanafar and Mansoura, respectively. In Kanafar, average yield and weight of 200 berries decreased by 21% and 22.7 g respectively in cluster 2, but in Mansoura only average yield increased by 3.7% in cluster 2. Total soluble solids and titratable acidity were not significantly affected by the shift in climate conditions at both vineyards, however total anthocyanin potential was significantly lower in Kanafar (by 114.2 mg kg^{-1}) and higher in Mansoura (by 353.4 mg kg^{-1}) in cluster 2. Total polyphenolic richness was only affected in Kanafar (reduction by 42 mg GAE g^{-1} in cluster 2). Syrah performance was more negatively affected by the changing climate conditions at Kanafar rather than Mansoura vineyards and it seems to better adapt to climate conditions of Mansoura overcoming the shift in climate that occurred after 2008 there.

Key words: climate change, winegrapes, production, quality, years.

INTRODUCTION

Lebanon is characterized by a natural complex diversity offering a great opportunity for a wide range of wine grape cultivars to adapt and grow in different terroirs at different altitudes (Moukarzel, 2013). Grape growing and wine making is a traditional heritage in Lebanon due to its climatic and geographical conditions. The last decades marked an important growth of the wine sector, ranking Lebanon as 45th largest wine producer in the world with 0.05% of global supply (Blominvest, 2013). Lebanon's climate is Mediterranean by excellence; it is characterized by hot, dry summers with low precipitation levels (June-Sept) and cool, rainy winters (Dec-mid-March) (USAID, 2016). The maximum amounts of rainfall occur in January and the highest temperatures occur in July, during which maximum daily temperatures may exceed 35 °C, mainly in the Bekaa Valley (Karam, 2002). In general, geographic, climatic, demographic, and economic characteristics of the Bekaa valley play a key role in the development of wine production in Lebanon. With a mixed soil of limestone and clay, a gap of 15 °C between day and night, the Bekaa valleys ensures good climate conditions for the development of vines (Bou Antoun, 2014). In particular, the region of West-Bekaa is the main producing area for wine grapes holding the highest concentration of vineyards (56%), and diversity of wine grape cultivars. It is followed by North Bekaa (26%), Central Bekaa (11%), Mount Lebanon (3%), North Lebanon (3%), South Lebanon (1%), and East Bekaa (1%) in terms of vineyards concentration (Mohasseb et al., 2020).

Wine grape cultivars adapt differently to various climate conditions; their sunlight, heat, and water demands vary throughout the different stages of development (Fraga et al., 2014). Eventually, climatic factors are known as the main drivers of grapevine development and physiology (El Masri et al., 2018; Yu et al., 2022). As such, solar radiation, rainfall, and temperature could greatly influence the phenology, yields, and grape berry quality (Andreoli et al., 2019). Climatic factors play a key role in determining the suitability of a given region for specific cultivars and wine types (Jones et al., 2005; Fraga et al., 2014) and the responses of individual grapevine cultivars to climate are of utmost importance for activity planning and decision making in viticulture (Malheiro et al., 2013). Therefore, studying the phenology of different winegrapes cultivars under changing climate conditions would help viticulturists better adapt to climate change (Merrill et al., 2020).

With the climate change posing problems to the viticulture sector worldwide, Lebanon is not an exception. Eventually, average precipitation for the period 1986–2005 to 2081–2100 will likely to decrease between 20% and 30% coupled with an increase in temperature of 2 °C to 3 °C in the Middle East region (IPCC, 2013), and in Lebanon drought periods are expected to be 9 days longer by 2040, and 18 days longer by 2090. Indeed, changes in climate conditions over years may have direct impacts on vine yield, and wine production, therefore on winegrower's income (Santos, 2020). As grapevine cultivation is a part of the agricultural, economic, and cultural heritage of Lebanon, changes in the wine production chain as affected by changes of prevailing climate conditions may heavily affect socioeconomic aspects, unless adaptation measures are taken. Therefore, the present study investigated whether ther was a shift in climate conditions at the vineyards of Chateau KSARA, located at the Bekaa valley from 2006 until 2018, whether such a shift had an effect on the production and quality of Syrah cultivar, widely cultivated there, and whether such a cultivar had an adaptational behavior to the changing in climate conditions during the studied years. To our knowledge, this is the first attempt to examine temporal trends in vines' phenology and corresponding climate links in Lebanese vineyards, which highlights the importance of this study on the agricultural sector and its future implications for the country's economy.

MATERIALS AND METHODS

Vineyards description

To investigate the effect of climate factors on the performance of Syrah, data two vineyards located in the Bekaa valley, Lebanon were selected; 'Mansoura' (West Bekaa, at 850 m.a.s.l, latitude of 33,6794 and longitude of 35,8150) and Kanafar' (West Bekaa, at 1,020 m.a.s.l, latitude of 33,6406 and longitude of 35,7169). Both vineyards were managed by a local winery 'Chateau Ksara'. Experimental plantations were established in 2003 in Mansoura vineyards and in 2001 in Kanafar vineyards. In both vineyards, Syrah was planted at a 2.5 m × 1.25 m distance between plants, grafted on Ru140 rootstock, and pruned using the Royal Cordon technique leaving 10 buds per vine. Vines rows were oriented North-South at Mansoura, and South-East at Kanafar vineyards. Soil was clay at Kanafar vineyards and calcareous at Mansoura vineyards.

Climate data

Climate data for 2006 till 2018 was sourced from meteorological stations (Kanafar, Haouch Ammiq, and Tal-Amara stations) of the Lebanese Agricultural Research Institute (LARI). To interpret the effect of climate factors on the different phenological events of the vines, climate data was used either as yearly mean values of temperature, relative humidity, precipitation, wind speed (average and maximum), and solar radiation, or average values of same climate factors at specific intervals of the growing season for a more accurate determination of these climate factors' effects on tested indicators.

Studied indicators

Every season, at fruit set, defoliation was done to improve canopy microclimate, maintain berry health, and improve its composition. Only leaves covering the berries were removed to allow enough sunlight to reach the berries allowing berry veraison. Studied indicators included both quantitative and qualitative variables. Harvested yield (kg ha^{-1}) was recorded per plant and then expressed as kg ha^{-1}. The weight of 200 berries (W200B) was also measured in grams. For conducting analytical tests of quality, a sample of two hundred berries was collected randomly from vines in a way to cover the whole planted area; by walking in a W shaped pattern accross the field.

The Total Soluble Solids (TSS) content was determined in degree Brix at 20 °C using a digital refractometer (PR101, Atago, Bellevue, WA, USA) according to the ITV database (Blouin & Guimberteau, 2000). TSS was assessed in triplicates. The acid/base titration was used to measure the titratable acidity (TA), using NaOH 0.1 N and bromothymol blue (4g L^{-1}) as an indicator dye.

The ITV (Institut Technique de la Vigne et du Vin) method was used to measure anthocyanins and total phenolic compound contents of grapes after harvest (Lamadon, 1995). The concentration of anthocyanins (Ant) and the total anthocyanin potential (TAP) were estimated as follows: Anthocyanins (mg L^{-1}) = OD_{520} × 22.75 × 20.

Total anthocyanins potential (mg kg^{-1}) = Anthocyanins (mg L^{-1}) × 100 × (weight of grape juice (mg) + 100) / (weight of grape juice (mg)).

To estimate total phenolic richness (TPR) in the extracts macerated at pH 3.2, a dilution to 1/100 was performed and the optical density was measured at 280 nm against distilled water. Then total phenolic richness was calculated: TPR = 2 × OD_{280} × 100.

Statistical analysis

Cluster analysis was performed dividing years (2006 till 2018) into two distinct clusters based on climatic data for the determination of possible variability in climatic conditions in the two selected vineyards during the thirteen years of study. Each cluster included a separate set of years showing more or less comparable means of the predetermined climatic factors. The contribution of each climatic factor in the cluster analysis was determined using the factor analysis option provided by SPSS program. Also, *ANOVA* test was performed to investigate the separate and combined effects of year and vineyards on studied indicators. *t-test* was performed for mean comparison of indicators among two distinct groups of years at each vineyard. Principal Component Analysis (*PCA*) was performed over the thirteen years of study separately in each vineyard to investigate the correlations between Syrah indicators and climate predictors assessed as the most contributing to the results of cluster analysis. Tests were performed at a 95% confidence level using SPSS program.

RESULTS AND DISCUSSION

Climate variability at Syrah vineyards

Results of cluster analysis (Table 1) showed that in both vineyards, the level of importance of studied climate indicators (predictors) divided years (between 2006 and 2018) into two separate clusters. In vineyards of Kanafar, the first cluster enclosed years between 2006 till 2015, while cluster 2 enclosed years from 2016 till 2018. In the vineyards of Mansourah, the first cluster of years consisted of years from 2006 till 2008, and the second clusterincluded years from 2009 till 2018.

Table 1. Cluster analysis of climate predictors at the vineyards of Kanafar and Mansoura

Clusters	Kanafar		Clusters	Mansoura	
	year	frequency		year	frequency
One	2006	1	One	2006	1
	2007	1		2007	1
	2008	1		2008	1
	2009	1		Total	3
	2010	1	Two	2009	1
	2011	1		2010	1
	2012	1		2011	1
	2013	1		2012	1
	2014	1		2013	1
	2015	1		2014	1
	Total	10		2015	1
Two	2016	1		2016	1
	2017	1		2017	1
	2018	1		2018	1
	Total	3		Total	10

Influence of climate predictors

In the vineyards of Kanafar, solar radiation was the most influential predictor (Table 2), precisely solar radiation during May-June, followed by annual solar radiation, solar radiation during March-April, and solar radiation during March- September in respective decreasing order. Average wind speed during July-August-September was the most influencing predictor in Mansoura vineyards (Table 2).

Table 2. Contribution levels of climate predictors to results of cluster analysis

Predictor	Importance
Kanafar	
Solar radiation (May-June) ($W.m^{-2}$)	1
Yearly solar radiation ($W.m^{-2}$)	0.91
Solar radiation (March-April) ($W.m^{-2}$)	0.89
Solar radiation (March-September) ($W.m^{-2}$)	0.88
Maximum wind speed (March-April) ($m.sec^{-1}$)	0.83
Solar radiation (August-September) ($W.m^{-2}$)	0.82
Average wind speed (July-August) ($m.sec^{-1}$)	0.73
Temperature (March-September) (°C)	0.67
Average wind speed (March-April) ($m.sec^{-1}$)	0.65
Maximum wind speed (July-August) ($m.sec^{-1}$)	0.62
Mansoura	
Average wind speed (July-August-September) ($m.sec^{-1}$)	1
Maximum wind speed (July-August-September) ($m.sec^{-1}$)	0.72
Solar radiation (August-September) ($W\ m^{-2}$)	0.47
Average Humidity (March-September) (%)	0.40
Solar radiation (May-June) ($W\ m^{-2}$)	0.35
Average Humidity (September-August) (%)	0.35
Average Humidity (May-June) (%)	0.32
Annual solar radiation ($W.m^{-2}$)	0.31
Precipitation (September-August) (mm)	0.26
Solar radiation (March-September) ($W.m^{-2}$)	0.24

Vineyards and year's effects on Syrah

Results of ANOVA test (Table 3) showed that the separate effects of the factors vineyard and years were significant ($P_{value} < 0.05$) on all studied indicators, except for the separate effect of vineyard on sugar content in berries. The combined effects of both factors were also significant on all tested indicators, except on titratable acidity.

Table 3. Separate and combined effects of vineyard and year on Syrah production and quality ($P_{value} < 0.05$)

	P_{value} Yield	P_{value} W200B	P_{value} TSS	P_{value} TA	P_{value} TAP	P_{value} TPR
Vineyard	0.00	0.00	0.61	0.00	0.00	0.00
Years	0.00	0.00	0.00	0.00	0.00	0.00
Vineyard*year	0.00	0.00	0.00	0.40	0.00	0.00

W200b: weight of 200 berries; TSS: total soluble solids; TA: titratable acidity; TAP: total anthocyanin potential; TPR: total polyphenolic richness.

The analysis of tested productive and qualitative indicators in the two sets of years of clusters 1 and 2 (Tables 4 and 5) showed that average yield was significantly lower in cluster 2 compared to cluster 1 in Kanafar (reduction by 21.4%), but it was significantly higher in cluster 2 in Mansoura (increase by 3.7%).

Syrah yields recorded during 2008 and 2009 in Mansoura (15.2 and 15.1 t ha^{-1}, respectively) were significantly higher than all values recorded at both vineyards during the thirteen years of study. Overall, average yield ranged between 1,253.0 and 13.2 t ha^{-1} in Kanafar, and between 4.3 and 15.3 t ha^{-1} in Mansoura vineyards. At both vieyards average yield recorded was higher than that reported by Favero et al. (2011) on the same cultivar cultivated in the Brazilian Southeast. Variability in yield observed even within the same vineyard may be associated with stable physical features, like soil and topography, that interact with seasonal biotic and abiotic factors, such as water and nitrogen availability, the presence of diseases, and climate (Pereyra et al., 2023). It also could be due to changing agronomic management strategies with years at the vineyard adopted to continously improve crop production. The current study deals with the factor climate and its impact on yield in time.

Table 4. Variation of Syrah production and quality as affected by year

Years	Yield (t. ha^{-1})	W200B (g)	TSS (° Brix)	TA (g. L^{-1})	TAP (mg kg^{-1})	TPR (mg GAE.g^{-1})
Kan2006	13.1 n	293.7 de	13.2 abcde	3.4 abcd	1,351.6 p	94.4 q
Kan2007	13.2 no	319.6 fg	12.8 ab	3.4 abc	1,368.3 p	158.7 s
Kan2008	1.2 a	277.0 c	13.0 abcd	3.3 ab	578.3 b	41.7 gh
Kan2009	12.7 lm	320.9 fg	12.9 abc	4.1 efghijkl	741.6 d	76.4 o
Kan2010	7.6 g	336.6 gh	13.8 defg	4.2 ghijkl	891.4 j	32.5 cd
Kan2011	9.6 k	339.0 ghi	12.9 abc	3.6 abcdefg	1,024.6 l	78.0 o
Kan2012	8.5 h	280.8 cde	14.1 fg	3.5 abcde	1,077.5 m	64.0 mn
Kan2013	8.9 ij	299.6 ef	13.5 bcdef	3.9 bcdefghi	1,214.9 n	83.2 p
Kan2014	7.11 f	299.8 ef	13.3 abcdef	4.5 jkl	1,215.2 n	56.0 j
Kan2015	4.8 c	202.3 a	13.5 bcdef	3.2 a	825.4 h	29.3 bc
Kan2016	6.0 d	274.1 cd	13.8 defg	3.9 bcdefghi	792.85 g	24.7 a
Kan2017	8.2 h	236.6 b	14.1 fg	3.8 abefghi	746.08 de	26.3 ab
Kan2018	6.2 de	292.2 de	15.5 h	4.2 hijkl	1,205.1 n	35.2 de
Man2006	7.1 f	326.6 g	13.0 abcd	3.9 cdefghijk	709.4 c	49.2 i
Man2007	9.2 j	388.4 k	12.9 abc	3.3 ab	768.8 f	63.4 lm
Man2008	15.2 p	227.9 b	13.8 cdefg	4.2 hijkl	338.9 a	57.3 jk
Man2009	15.0 p	330.0 g	12.9 abc	4.1 fghijkl	774.9 fg	67.3 n
Man2010	15.6 q	301.6 ef	14.1 efg	4.4 ijkl	699.2 c	44.1 h
Man2011	13.2 no	383.8 k	12.5 a	3.6 abcdefgh	877.7 ij	60.4 kl
Man2012	12.9 mn	373.4 jk	13.8 cdefg	3.5 abcdef	965.0 k	66.8 n
Man2013	13.4 o	359.8 ij	13.6 bcdef	3.9 bcdefghi	1,369.9 p	130.0 r
Man2014	8.8 i	240.8 b	13.9 defg	4.6 l	1,290.1 o	67.4 n
Man2015	4.3 b	353.2 hij	14.6 g	3.4 abcd	861.8 i	30.0 c
Man2016	6.9f	286.7 cde	13.9 defg	4.5 jkl	764.2 ef	39.2 fg
Man2017	6.5e	236.4 b	13.7 bcdef	4.0 defghijkl	1,042.0 l	40.0 fg
Man2018	12.6l	301.5 ef	13.3 abcdef	4.6 kl	946.32k	38.0 ef

Kan: Kanafar vineyards; Man: Mansoura vineyards; W200b: weight of 200 berries; TSS: total soluble solids; TA: titratable acidity; TAP: total anthocyanin potential; TPR: total polyphenolic richness.

Average weight of 200 berries was significantly lower in cluster 2 compared to cluster 1 in Kanafar (reduction by 22.7 g), but it did not significantly differ in Mansoura considering the two clusters of years. In Kanafar, AW200B ranged between 202.3 g in 2015 and 339.05 in 2011, while in Mansoura, this indicator recorded the lowest and highest values in 2008 and 2007, respectively (227.8 and 388.4 g).

Total soluble solids content and titratable acidity were not significantly affected by the shift in climate conditions at both vineyards, however total anthocyanin potential was significantly lower in Kanafar (by 114.2 mg kg^{-1}) and higher in Mansoura (by 353.4 mg kg^{-1}) in cluster 2 years. TSS content ranged between 12.7 and 13.8 Brix recorded in 2007 and 2010, respectively in Kanafar vineyards, and between 12.47 and 14.6 ° Brix recorded in 2011 and 2015, respectively in Mansoura vineyards. Total polyphenolic richness was only affected in Kanafar (reduction in average by 42 mg GAE g^{-1} in cluster 2 compared to cluster 1). Ranges of TA, TAP, and TPR were as follows: 3.23–4.23 g L^{-1}, 578.3–1,368.3 mg kg^{-1}, and 24.7–158.7 mg GAE g^{-1}, respectively in Kanafar and 3.30–4.60 g L^{-1}, 338.91–1,369.9 mg kg^{-1}, and 30.0–130.03 mg GAE g^{-1} in Mansoura vineyards.

Table 5. *t-test* results comparing productive and qualitative indicators in two clusters of years in Kanafar and Mansoura vineyards

	Yield (t ha^{-1})	W200B (g)	TSS (° Brix)	TA (g L^{-1})	TAP (mg kg^{-1})	TPR (mg GAE g^{-1})
Kanafar cluster 1	8.7a	290.0a	13.3 a	3.7a	1,028.9a	71.4a
Kanafar cluster 2	6.8b	267.3b	14.5a	4.0a	914.7b	28.8b
P value	0.00	0.00	0.18	0.07	0.00	0.00
Mansoura cluster 1	10.5a	314.3a	13.2a	3.77a	605.7a	56.6a
Mansoura cluster 2	10.9b	316.7a	13.58a	4.10a	959.1b	58.3a
P value	0.00	0.55	0.20	0.28	0.00	0.45

Kanafar cluster 1: years from 2006 till 2015; Kanafar cluster 2: years from 2016 till 2018; Mansoura cluster 1: years from 2006 till 2008; Mansoura cluster 2: years from 2009 till 2018; W200B: weight of 200 berries; TSS: total soluble solids; TA: titratable acidity; TAP: total anthocyanin potential; TPR: total polyphenolic richness.

It is noteworhy that in particular years, values of TAP recorded in Mansoura vineyards were higher than those in Kanafar (2009, 2013, 2014, 2015, and 2017). Such findings contradict those of de Oliveira et al. (2019) who recorded higher anthocyanins concentrations in Syrah grapes cultivated at vineyards of higher altitudes in northeast Brazil. Considering that the optimal temperature range for anthocyanin accumulation is 17–26 °C, and that low night temperatures favor coloration in red grapes (Azuma et al., 2019), the higher TAP values recorded in Mansoura during the particular years of cluster 2 may be due to more suitable temperatures for berry coloration at such altitude compared to those at higher altitude. Assumably, temperature during these years did not overcome 35 °C, a temperature which generally inhibits anthocyanin synthesis (Liang et al., 2012). Consequently, the climate shift occuring in 2009 at Mansoura did not negatively impact on this indicator.

Correlation of climate with Syrah quantity and quality

Correlations were established between productive and qualitative indicators of Syrah and climate factors which were found to be main predictors influencing the variations of tested indicators among the two obtained clusters of years at relative vineyards.

Results of PCA analysis concerning Kanafar vineyards (Fig. 1), over the thirteen years of study, showed that there was a strong negative correlation between Syrah average yield and solar radiation at the vineyards of Kanafar, mostly with solar radiation during May to June (SRMayJun) and March to April (SRMarApr), and a weak negative correlation between this indicator and average temperature during March to September (TemMarSep). However, average yield was strongly positively correlated with maximum wind speed from March to April (MWSMarApr). In Kanafar, average solar radiation during May-June (SR MayJun) and March-April (SR MarApr), and average temperature during March-September (tem MarSep) were lower in cluster 1 compared to cluster 2 (234.35 and 268.07 W m^{-2}, 172.2 and 188.7 W m^{-2}, and 19.8 and 20.8 °C, respectively) (Table 6). On the contrary, maximum wind speed during March-April (MWSMarApr) was higher in cluster 1 compared to cluster 2 (3.19 and 2.57 m.sec^{-1}, respectively) (Table 6). Comparing climate factors and Syrah yields at both vineyards, it was evident that lower solar radiation during spring and early summer months and lower temperatures from spring to late summer correlated to higher Syrah yields in cluster 1 years and higher values of these climate predictors correlated to the reduction in Syrah yields occurring in cluster 2. Besides, stronger winds during early spring correlated to higher Syrah yields in cluster 1 compared to cluster 2. Average weight of 200 berries was weakly negatively correlated to average values of solar radiation recorded annually (ASR), at different intervals of the growing season (SR MayJun, SRMarApr, SRMarSep, and SRAugSep), which were higher in cluster 2, causing a reduction in W200B compared to cluster 1. Assumably, lower yields in cluster 2 were caused by a lower weight of berries. Temperature is an important factor regulating berry growth and metabolism (Rienth et al., 2021). In particular, high heat during berry development is known to dramatically reduce berry growth by affecting berry size (Gouot et al., 2019). Besides, light and temperature may also have a synergistic effect on bud fruitfulness, anthesis, fruit set and berry growth (Vasconcelos et al., 2009). An increase in temperature of 1 °C during the growing season of the years 2016, 2017, and 2018 in Kanafar caused a reduction in yield and W200B of 21.4% and 22.2 g.

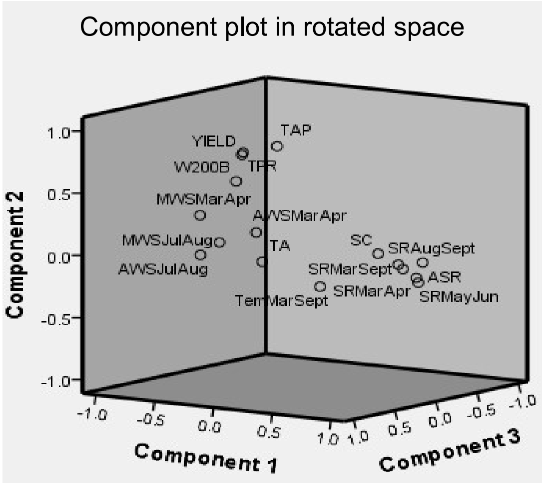

Figure 1. Correlations of Syrah quantitative and qualitative indicators to influencing climate predictors (average seasonal/annual values) from 2006 till 2018 at Kanafar vineyards.

(TAP: total anthocyanin potential; TPR: total polyphenolic richness; W200B: weight of 200 berries; TA: titratable acidity; SC: sugar content (TSS); AWS: average windspeed, MWS: Maximum windspeed; SR: solar radiation, Temp: temperature).

Winds occuring in spring season may have reduced the negative impact of high temperature on berry growth, by avoiding extra-heating of bunches, and causing better yields in years of cluster 1 at Kanafar vineyards. While Sadras & Soar (2009) found that increasing temperature in different timings of the growing season did not affect Syrah yield or yield components, Pagay & Collins (2017) reported negative impacts of an increase in the average growing season temperature on crop yield. Further, de Souza et al. (2019) reported that the sunlight and heating effects on leaves and grapes are directly influenced by row orientation in vineyards. However, in their study they observed no significant effect of varying sunlight intensities caused by different vineyards' orientation on Syrah yield and cluster weight per vine.

Table 6. Mean/annual values of climate predictors found as main influencers on tested indicators in Kanafar and Mansoura vineyards during clusters 1 and 2 years

	Clusters	Kanafar			Mansoura	
		Mean	SD		Mean	SD
SR MayJun	One	234.35	5.97	AWS JulAugSep	3.85	0.40
	Two	268.07	4.94		0.67	0.07
ASR	One	53.65	1.93	MWS JulAugSep	0.75	0.01
	Two	162.15	4.43		3.04	0.40
SR MarApr	One	172.19	3.55	SR AugSep	194.22	8.75
	Two	188.69	2.56		238.26	11.92
SR MarSep	One	213.97	9.48	Hum MarSep	46.40	1.54
	Two	254.89	4.72		55.37	3.05
MWS MarApr	One	3.19	0.11	SR MayJun	231.39	8.40
	Two	2.57	0.17		258.55	9.48
SR AugSep	One	209.65	10.10	Hum SeptAug	49.85	2.17
	Two	255.75	9.83		55.56	4.16
AWS JulAug	One	0.78	0.03	Hum MayJun	42.95	2.89
	Two	0.65	0.04		53.72	4.39
Tem MarSep	One	19.85	0.19	ASR	157.99	8.27
	Two	20.82	0.36		173.99	4.23
AWS MarApr	One	0.77	0.03	Prec SepAug	1.83	4.49
	Two	0.67	0.03		3.11	4.41
MWS JulAug	One	3.43	0.20	SR MarSep	206.39	5.82
	Two	2.88	0.06		235.24	16.66

Kanafar cluster 1: years from 2006 till 2015; Kanafar cluster 2: years from 2016 till 2018; Mansoura cluster 1: years from 2006 till 2008; Mansoura cluster 2: years from 2009 till 2018; SR: solar radiation; ASR: annual solar radiation; MWS: maximum wind speed; Tem: temperature; AWS: average wind speed; Hum: Relative humidity; Prec: precipitation.

Total soluble solids content was strongly positively correlated to ASR and SR at different intervals of the growing season (SR MayJun, SRMarApr, SRMarSep, and SRAugSep), and to average temperature recorded during March-September (temp MarSep) of every year. Such correlations reflected a slightly higher sugar content in berries recorded in 2016, 2017, and 2018 compared to earlier years.

TAP and TPR were negatively correlated with average temperature during March-September (temp MarSep). Higher temperature recorded during the growing season of the years 2016, 2017, and 2018 caused a reduction in TAP and TPR compared to earlier years of study. Besides, in these three years, lower MWS values during early spring and higher SR values during late spring caused lower values of TPR at Kanafar. Eventually, TPR values were strongly positively correlated with MWS during March-April (MWSMarApr) and negatively correlated to SR during May-June (SRMayJun).

Climate and microclimate exert a good influence on berry composition (de Orduña, 2010). Eventually, in the last three years of study, the increase in temperature coupled with high solar radiation and low windspeed at Kanafar, had not only exerted a negative influence on berry growth, but also on its composition, which may consequently alter the quality of wine produced from Syrah at these vineyards. High berry temperature in sun-exposed clusters can increase anthocyanin content, but extreme temperatures may alter the anthocyanin production in grapes (Haselgrove et al., 2000). Also, in warmer climates, winds can have a cooling effect, helping to slow down the ripening process and giving grapes more time to develop flavors (Tonietto et al., 2012). Using a long-time of biochemical data in field conditions for various berry quality aspects over a period of 6–19 years, Costa et al. (2020) also concluded that at maturity, high temperatures tend to decrease berry weight, titratable acidity, anthocyanins, and total phenols index and increase pH and potential alcohol.

Sugars have a fundamental role in the composition of the wines (Jordão et al., 2001) and the phenolic compounds present in the skin and seed of the grape are particularly important in enology (Andres et al., 2007). Anthocyanins are accumulated in grape skins after veraison. They are responsible fro grape berry and wine color because of their interactions with other phenolic compounds, proteins, and polysaccharides (Torres et al., 2021). Therefore, changes in the biosynthesis, translocation, degradation and accumulation of substances in the berry because of climate will directly impact on wine quality, defining its color, aroma, and flavor (Lima et al., 2011). The level of sugars and anthocyanins in grapes depends also on microclimatic conditions around the cluster zone (Barreiro et al., 2015).

With respect to correlations established relatively to Mansoura vineyards (Fig. 2), results showed that annual solar radiation (ASR) was slightly positively correlated with TSS, TA, TAP, TPR, and yield. At these vineyards, ASR was higher in cluster 2 than cluster 1 years (157.9 and 173.9 W m^{-2}, respectively) (Table 6) which might have correlated with a slight increase in TSS, TA, and TPR, a strong increase in yield and TAP during the years from 2009 till 2018, compared to earlier years. Furthermore, solar radiation during Mid-spring (SR MayJun) and late summer (SR AugSep) showed a slight negative correlation with W200B.

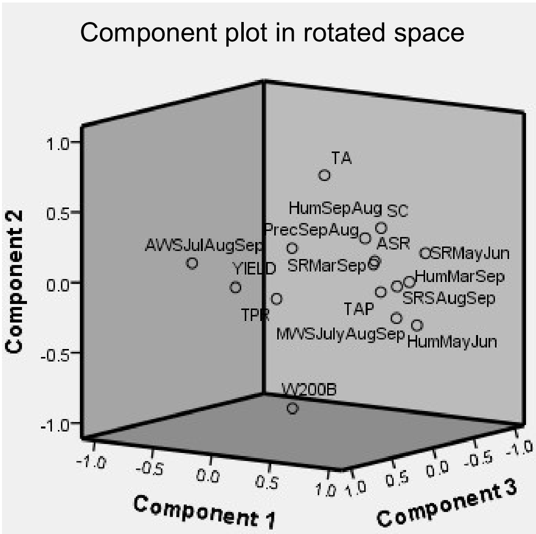

Figure 2. Correlations of Syrah quantitative and qualitative indicators to influencing climate predictors (average seasonal/annual values) from 2006 till 2018 at Mansoura vineyards.

((TAP: total anthocyanin potential; TPR: total polyphenolic richness; W200B: weight of 200 berries; TA: titratable acidity, SC: sugar content (TSS); AWS: average windspeed; MWS: Maximum windspeed; SR: solar radiation; Temp: temperature, Hum: humidity; Prec: precipitations).

Furthermore, solar radiation during May-June (SR MayJun) and August-September (SR AugSep), which were higher in average in cluster 2 (Table 6), showed a slight negative correlation with W200B. Thus, the increase in average yield occurring in cluster 2 could have been caused by higher average number of clusters produced in these years compared to earlier ones.

Average wind speed during July-August-September (AWS JulAugSep) showed a strong negative correlation with TAP and AW200B, and slightly negative correlation with TSS, TA, yield, and TPR. AWS decreased strongly in years of cluster 2 compared to cluster 1 (0.67 and 3.85 and m sec^{-1}, respectively) (Table 6) causing an increase, whether low or high, in yield as well as accumulation of sugars, anthocyanins, and polyphenols. Wind activity influences on fruit transpiration, and according to Pascual et al. (2022) fruit transpiration acts as one of the driving forces for sugar accumulation. Also, Further, Rebucci et al. (1997) postulated that water loss through transpiration leads to a lower turgor within the berry and maintains the gradient of water potential between the fruit and the stem, thus promoting the importing of assimilates into the berry. Zhang et al. (2017) reported that forced reduction in transpiration caused a lower solute accumulation rate in grape berries of Syrah, contradicting results of the current study.

Relative humidity during September-August (Hum SepAug) had a slight positive correlation with the majority of studied indicators, except W200B. Eventually, average value of this climate indicator was lower in cluster 1 compared to cluster 2 (49.8 and 55.6%, respectively) (Table 6) and correlated with slightly lower values of all indicators in the years 2006, 2007, and 2008 compared to later years. Temperature and relative humidity are other external factors determining berry transpiration, thus affecting solute accumulation in berries, though such a phenomenon is also influenced by cultivar-specific internal factors, such as primarily berry surface area and cuticular conductance (Zhang & Keller, 2015).

Precipitation during September-August (Pre SepAug), which were lower in cluster 1 (2006–2008) compared to cluster 2 (2009–2018) (1.83 and 3.1 mm, respectively) (Table 6) were slightly negatively correlated with all indicators. However, yield, W200B, TAP, and TPR were not negatively affected by an increase in precipitation of around 1.3 mm in average occurring during the years 2009 till 2018 in Mansoura. Camps & Ramos (2011) observed a decrease in grape yield coupled with lower precipitation during 1996–2009 in Penedès region, Spain.

CONCLUSIONS

There was a shift in climate conditions occurring after 2015 in Kanafar vineyards and after 2008 in Mansoura. The most influential predictors to such as shift were solar radiation during mid-late spring in Kanafar vineyards and average windspeed during mid-late summer at Mansoura vineyards. Changes in climate conditions had a varying effect on Syrah performance depending on the vineyard's location. In Kanafar, lower yields were recorded coupled with lower anthocyanins and polyphenols accumulation in berries, while in Mansoura there was a significant improvement in yield with no negative impact on berry composition. Conclusively, the quality of wine produced from Syrah cultivated at Mansoura may be preserved despite the changing climate occurring at these vineyards.

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