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Varietal Relationship between Instrumental Skin Hardness and Climate for Grapevines (*Vitis vinifera* L.)

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ABSTRACT: The main aims of this work were to classify 30 colored and white wine grape varieties according to the berry skin hardness, to assess the influence of annual variations in climate on the berry skin hardness, and to establish significant relationships among berry skin mechanical properties and some climatic−bioclimatic indices calculated for different grape-ripening periods, close to the harvest date. The results obtained show that the most influential bioclimatic indices on the skin mechanical attributes were temperature parameters. In the same season, the influence of the production area was also evaluated, precipitation parameters being the best correlated with the berry skin hardness. This first work has permitted us to know the relationship among skin texture characteristics and seasonal climatic indices.

KEYWORDS: Puncture test, berry skin hardness, grape varieties, bioclimatic index

INTRODUCTION

The oenological potential of the grapes used for the elaboration of high quality wines depends on berry attributes. In fact, it is demonstrated that grape chemical composition, in particular the phenol profile, is influenced by several agroecological factors like cultivar, climate, soil type, and agronomical practices.[1−3] The relationship between climate and berry properties has attracted considerable attention as it affects wine quality.[4−6] In particular, temperature is recognized as the main climatic variable affecting the vintage quality.[7,8] The length of the growing season is also considered a determining factor of grape composition.[4,7,9]

In addition, it is well-known that grape composition changes continuously during the ripening period. However, the seasonal variability in climate can modify the magnitude of such changes, which implies modifications in wine quality. So, some authors emphasize the relevance of annual variations in climate because these, in addition to vineyard location, typically far outweigh any changes in berry attributes introduced by cultural practices[2] and even those arising from differences in soil conditions.[10−12]

Phenolic compounds, extractable from grape skins and seeds, have a notable influence on the quality of red wines. In this sense, the skin hardness, evaluated by the skin break force and skin break energy parameters, as well as the skin thickness, are considered mechanical properties adequate for the estimation of the skin cell wall degradability and, therefore, of the extractability of anthocyanins from berry skin to must/wine.[13,14] On the other hand, the efficiency of skin mechanical properties for the differentiation of varieties, production areas, and even vineyards has been recently assessed.[15] Within the same variety, the values of the textural parameters are also heavily influenced by growing area,[16−18] whereas a smaller influence on these skin mechanical properties is imputable to grape-ripening stages.[17,19] In different years, the same vineyards showed grapes with different skin mechanical characteristics.[15] Seasonal variations are widely accepted in viticulture as a well-recognized factor that can mask other environmental and cultural effects on berry features. However, no study has been published up until now on the effect of climatic elements on berry textural parameters.

Therefore, the influence of different climatic variables on berry skin mechanical properties was studied in this work. The main aims proposed were (i) to classify 30 colored and white wine grape varieties according to the berry skin hardness in two consecutive years, (ii) to assess the influence of annual variations in climate on skin mechanical attributes during five consecutive years, and (iii) to establish correlations among the berry skin hardness and several climatic−bioclimatic indices.

MATERIALS AND METHODS

Grape Samples. For the varietal study of the skin texture, grape samples of seven white and 23 colored cultivars, all of them belonging to *Vitis vinifera* L., were harvested in the same collection−experimental vineyard located in Piedmont (North-West Italy) in 2006 and 2007 (Table 1). To establish the relationships among the berry skin hardness and the climatic−bioclimatic indices, Arneis (ARN), Moscato bianco (MOB), and Nebbiolo (NE) wine grapes were also harvested in 2008, 2009, and 2010. Moreover, with the aim of relating, for each cultivar, the differences in the skin hardness with the seasonal climatic and bioclimatic parameters, Barbera (BAR), Freisa (FRE), MOB, and NE grape samples were harvested in 2008 from four, five, two, and four homogeneous commercial vineyards (vine age, yield, cultural practices, and clone), respectively, located in several production areas of the Piedmont.

Each sample consisted of 400 grape berries with attached pedicels, which were randomly picked up from different plants. Once in the laboratory, berries of each cultivar were visually inspected before

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Table 1. List of the Cultivars Studied, Berry Color, and Harvest Dates in the 2006−2010 Period

grape variety	berry color	harvest date (day/month) 2006	2007	2008	2009	2010
Arneis (ARN)	white	13/09	29/08	18/09	09/09	21/09
Barbarossa-Uva reina (BUR)	red	20/09	04/09			
Barbera (BAR)	black	20/09	29/08			
Becuet (BEC)	black	12/09	29/08			
Brachetto d'Acqui (BRA)	black	05/09	21/08			
Brachetto Roero (BRR)	violet	06/09	21/08			
Cabernet sauvignon (CS)	red	20/09	03/09			
Cari-Pelaverga (CP)	red	28/09	11/09			
Chardonnay (CHAR)	white	05/09	11/09			
Chasselas blanc (CHAS)	white	06/09	04/09			
Cortese (COR)	white	13/09	29/08			
Croatina (CRO)	black	13/09	11/09			
Dolcetto (DOL)	black	13/09	04/09			
Freisa (FRE)	black	13/09	29/08			
Gamba di pernice (GP)	black	28/09	03/09			
Jacquez (UF, interspecific hybrid)	black	20/09	04/09			
Malvasia bianca (MAB)	white	13/09	29/08			
Malvasia di Schierano (MAS)	violet	13/09	29/08			
Moscato d'Amburgo (MOA)	black	13/09	21/08			
Moscato bianco (MOB)	white	06/09	21/08	10/09	26/08	09/09
Moscato nero d'Acqui (MNA)	black	20/09	11/09			
Nascetta (NAS)	white	12/09	11/09			
Nebbiolo (NE)	black	20/09	04/09	08/10	02/10	01/10
Nebue (NEB)	black	05/09	21/08			
Neirano-Bouschet Alicante (NA)	black	28/09	11/09			
Neretto duro (NER)	black	06/09	21/08			
Pignolo spano (PS)	black	20/09	04/09			
Pinot noir (PIN)	black	05/09	21/08			
Teinturier ellittico (TEE)	black	06/09	21/08			
Teinturier rotondo (TER)	black	06/09	21/08			

analysis, and those with damaged skins were discarded. All samples were harvested when the technological maturity was optimal for the production of the respective wines in agreement with the different Denomination of Origin production disciplinary.

Instrumental Texture Analysis. For each cultivar, a set of 20 berries was randomly sampled.[20] The skin hardness was assessed by a puncture test carried out by a Universal Testing Machine (UTM) TAxT2i Texture Analyzer (Stable Micro System, Godalming, Surrey, United Kingdom) equipped with a HDP/90 platform, P/2N needle probe, and a 5 kg load cell. The test speed was 1 mm/s, and the penetration applied was 3 mm. All of the data acquisitions were made at 400 Hz, involving the Texture Expert Exceed software, version 2.54 for Windows. The berries were placed on the metal plate of the UTM with the pedicel in a horizontal plane to be consistently punctured in the lateral side. The berry skin hardness was assessed by the maximum break force (F_{sk}) or by the break energy (W_{sk}).[21] The first parameter corresponds to the skin resistance to the needle probe penetration, and it is expressed in N. The second parameter is represented by the area under the curve, which is limited between 0 and F_{sk}, and it is expressed in mJ.[21] The use of needle probe allows the only estimation of this skin mechanical characteristic, minimizing the possible interferences caused on the results by the pulp firmness.

Physicochemical Determinations. For each cultivar, the remaining berries were used for determining physicochemical parameters in the grape must obtained by manual crushing and filtration. In the juice obtained, °Brix was determined by refractometry using Atago refractmeter (Japan). The pH, total acidity, and reducing sugars were determined according to European Official Methods.[22] Organic acids (malic acid, tartaric acid, and citric acid) and reducing sugars (glucose and fructose) were quantified by high-performance liquid chromatography (Thermo Electron Corp., Waltham, MA) using an UV detector (UV100) at 210 nm and a refractive index detector (RI-150), respectively. The analyses were performed isocratically at 0.8 mL/min and 65 °C with a 300 mm × 7.8 mm i.d. cation exchange column (Aminex HPX-87H) and a Cation H^+ Microguard cartridge (Bio-Rad Laboratories, Hercules, CA). The mobile phase was 0.0065 mol/L sulfuric acid.

Climatic and Bioclimatic Indices. Climatic variables were measured using a Vantage PRO2 weather station (Davis Instruments, Hayward, United States), located into the vineyards or close to them (maximum distance of 250−300 m), and the following bioclimatic indices were calculated for different grape ripening periods (3, 7, 15, 31, 45, and 90−120 days prior to the harvest date for each variety): average daily minimum temperature (AMmT; °C), average daily maximum temperature (AMxT; °C), average daily mean temperature (AT; °C), average daily minimum humidity (AMmH; %), average daily maximum humidity (AMxH; %), average daily mean humidity (AH; %), total precipitations (TP; mm), daily maximum precipitations (MxP; mm), average daily thermal excursion (ATE; °C), leaf wetness duration (LWD; min), daily maximum duration of leaf wetness (MxDLW; min), absolute minimum temperature (AbMmT; °C), absolute maximum temperature (AbMxT; °C), number of frost days (DI0; days), number of rainy days (rain ≥1 mm) (DP1; days), thermal sum over a 10 °C threshold (TP10; °C), Huglin index (HI; °C),[23] and total thermal excursion (TTE; °C).

Statistical Analysis. All statistical analyses were performed using the SPSS software version 11.5 for Windows (SPSS Inc., Chicago, IL). The Tukey b test for $p < 0.05$ was used to establish statistical differences by one-way analysis of variance (ANOVA). A cluster analysis was performed to classify wine grape varieties according to their berry skin mechanical properties using Ward method and squared Euclidean distance. Pearson correlation coefficients were calculated to determine significant relationships among the berry skin hardness and the bioclimatic indices studied.

RESULTS AND DISCUSSION

Characterization and Classification of Wine Grape Varieties According to Berry Skin Hardness. Table 2 shows the values of the break force and energy of the berry skin determined at harvest in two consecutive years (2006 and 2007) for the 30 varieties harvested in the same vineyard. In general, the grapes harvested in 2007 year were softer than those harvested in 2006, as indicated by the lower values of break force and energy of berry skin in 2007. The harder varieties were Teinturier rotondo (TER) (0.815 N) and Becuet (BEC) (0.591 N) in 2006 and 2007, respectively, according to the berry skin break force, whereas the greater values of berry skin break energy were associated with Teinturier ellittico (TEE) (0.735 mJ) and Nascetta (NAS) (0.555 mJ) in 2006 and 2007, respectively. On the other hand, the softer varieties were Nebue (NEB) (0.443 N), and Cortese (COR) and NEB (0.338−0.342 N) in 2006 and 2007, respectively, taking into account the berry skin break force, whereas the lower values of berry skin break energy corresponded to Cari-Pelaverga (CP), NE, Malvasia di Schierano (MAS), Jacquez (UF), NEB, and Moscato d'Amburgo (MOA)

Table 2. Break Force (F_{sk}) and Break Energy (W_{sk}) of Berry Skin at Harvest for Wine Grape Varieties in 2006 and 2007[a]

	F_{sk} (N)			W_{sk} (mJ)		
grape variety	2006	2007	sign[2]	2006	2007	sign[2]
ARN	0.562 ± 0.128 abcdefg	0.437 ± 0.069 abcdef	***	0.388 ± 0.136 abcde	0.239 ± 0.070 ab	***
BUR	0.671 ± 0.145 fgh	0.503 ± 0.103 defg	***	0.411 ± 0.141 abcde	0.536 ± 0.473 ef	NS
BAR	0.783 ± 0.082 hi	0.499 ± 0.085 defg	***	0.579 ± 0.103 fg	0.310 ± 0.106 abcdef	***
BEC	0.683 ± 0.142 gh	0.591 ± 0.074 g	*	0.499 ± 0.172 def	0.396 ± 0.080 abcdef	*
BRA	0.604 ± 0.176 cdefg	0.437 ± 0.070 abcdef	***	0.506 ± 0.199 ef	0.244 ± 0.073 ab	***
BRR	0.647 ± 0.080 efg	0.457 ± 0.081 bcdef	***	0.406 ± 0.109 abcde	0.206 ± 0.067 ab	***
CS	0.593 ± 0.080 bcdefg	0.537 ± 0.116 fg	NS	0.308 ± 0.067 ab	0.259 ± 0.098 abc	NS
CP	0.468 ± 0.127 ab	0.388 ± 0.057 abcd	*	0.295 ± 0.100 a	0.283 ± 0.234 abcde	NS
CHAR	0.465 ± 0.125 ab	0.403 ± 0.051 abcde	NS	0.349 ± 0.126 abc	0.209 ± 0.042 ab	***
CHAS	0.502 ± 0.127 abc	0.436 ± 0.091 abcdef	NS	0.321 ± 0.117 abc	0.267 ± 0.134 abcd	NS
COR	0.502 ± 0.061 abc	0.338 ± 0.051 a	***	0.316 ± 0.056 ab	0.164 ± 0.048 a	***
CRO	0.666 ± 0.144 fgh	0.512 ± 0.120 efg	***	0.393 ± 0.133 abcde	0.514 ± 0.445 cdef	NS
DOL	0.518 ± 0.127 abcde	0.449 ± 0.147 abcdef	NS	0.387 ± 0.141 abcde	0.445 ± 0.336 bcdef	NS
FRE	0.669 ± 0.114 fgh	0.518 ± 0.078 efg	***	0.494 ± 0.136 def	0.338 ± 0.088 abcdef	***
GP	0.499 ± 0.112 abc	0.492 ± 0.081 defg	NS	0.315 ± 0.107 abc	0.385 ± 0.350 abcdef	NS
UF	0.631 ± 0.031 defg	0.451 ± 0.097 abcdef	***	0.299 ± 0.045 a	0.164 ± 0.064 a	***
MAB	0.648 ± 0.129 efg	0.530 ± 0.095 fg	**	0.453 ± 0.180 cdef	0.279 ± 0.098 abcde	***
MAS	0.542 ± 0.130 abcdef	0.467 ± 0.058 bcdef	*	0.299 ± 0.102 a	0.216 ± 0.045 ab	**
MOA	0.513 ± 0.070 abcd	0.401 ± 0.109 abcde	***	0.305 ± 0.071 a	0.231 ± 0.269 ab	NS
MOB	0.463 ± 0.069 ab	0.373 ± 0.086 abc	***	0.342 ± 0.100 abc	0.201 ± 0.107 ab	***
MNA	0.517 ± 0.064 abcd	0.443 ± 0.117 abcdef	*	0.313 ± 0.077 abc	0.309 ± 0.291 abcdef	NS
NAS	0.491 ± 0.139 abc	0.480 ± 0.139 cdefg	NS	0.364 ± 0.162 abcd	0.555 ± 0.393 f	NS
NE	0.515 ± 0.070 abcd	0.430 ± 0.113 abcdef	**	0.297 ± 0.059 a	0.381 ± 0.366 abcdef	NS
NEB	0.443 ± 0.077 a	0.342 ± 0.093 a	**	0.301 ± 0.086 a	0.187 ± 0.090 ab	***
NA	0.562 ± 0.109 abcdefg	0.362 ± 0.078 ab	***	0.364 ± 0.137 abcd	0.148 ± 0.072 a	***
NER	0.566 ± 0.121 abcdefg	0.494 ± 0.111 defg	NS	0.318 ± 0.106 abc	0.251 ± 0.136 ab	NS
PS	0.570 ± 0.105 abcdefg	0.541 ± 0.204 fg	NS	0.363 ± 0.121 abcd	0.523 ± 0.493 def	NS
PIN	0.667 ± 0.147 fgh	0.524 ± 0.118 fg	**	0.448 ± 0.160 bcde	0.340 ± 0.193 abcdef	NS
TEE	0.656 ± 0.073 fg	0.540 ± 0.104 fg	***	0.735 ± 0.121 h	0.415 ± 0.164 abcdef	***
TER	0.815 ± 0.101 i	0.537 ± 0.116 fg	***	0.632 ± 0.105 gh	0.285 ± 0.138 abcde	***
sign[1]	***	***		***	***	

[a] All data are expressed as average values ± standard deviations ($n = 20$). Different letters within the same column indicate significant differences (sign[1]) among varieties in the same year (Tukey b test; $p < 0.05$). Sign[2] indicates significant differences among the 2 years for the same variety. [1,2]*, **, ***, and NS indicate significance at $p < 0.05$, 0.01, 0.001, and not significant, respectively.

(0.295−0.305 mJ) in 2006 but Neirano-Bouschet Alicante (NA) (0.148 mJ) in 2007. Using the mechanical parameters at harvest as variables, ANOVA did not permit us to differentiate all cultivars; therefore, they were classified by cluster analysis in both 2006 and 2007 (Figures 1 and 2). The differences found in the skin hardness for the different grape varieties analyzed confirm that this parameter can be considered as a varietal marker.[19] In fact, the two clusters permitted a similar classification of the grape varieties studied. Only few varieties were differently placed in the dendrograms in the two years considered. So, the first cluster corresponding to 2006 contains UF and Brachetto Roero (BRR) varieties that are included in the second cluster corresponding to 2007. Furthermore, Cabernet sauvignon (CS), Neretto duro (NER), Pignolo spano (PS), and Gamba di pernice (GP) varieties are located in the second cluster in 2006, whereas they are associated with the first cluster in 2007. A possible explanation could be the higher variation in the values of the skin break force and skin break energy between both 2006 and 2007, with respect to other cultivars, for UF (28.5 and 45.2%), BRR (29.3 and 49.4%), CS (9.4 and 16.0%), NER (12.7 and 21.2%), PS (5.2 and 44.1%), and GP (1.4 and 22.2%) varieties. Within these exceptions, although UF, BRR, CS, and PS varieties are included in different clusters in 2006 and 2007, they are located in the closer subclusters. Instead, the GP variety showed a more different classification between 2006 and 2007, as it is located in the more distant subclusters.

Regarding the three wine grapes harvested during five consecutive years (2006−2010), in Figure 3, it can be seen that the hardest skins corresponded to 2009 and 2010, independently on the grape variety studied. In general, the highest values of berry skin break force and energy were associated with ARN, whereas the lowest ones corresponded to the aromatic variety MOB.

As previously mentioned, the values of berry skin break force for one given variety are heavily influenced by production area,[16,17] and within this, the different vineyards can be also discriminated.[15] In this work, berry skin break force also allowed the differentiation of production areas, particularly for BAR and NE wine grapes (Figure 4). Furthermore, it can be observed that

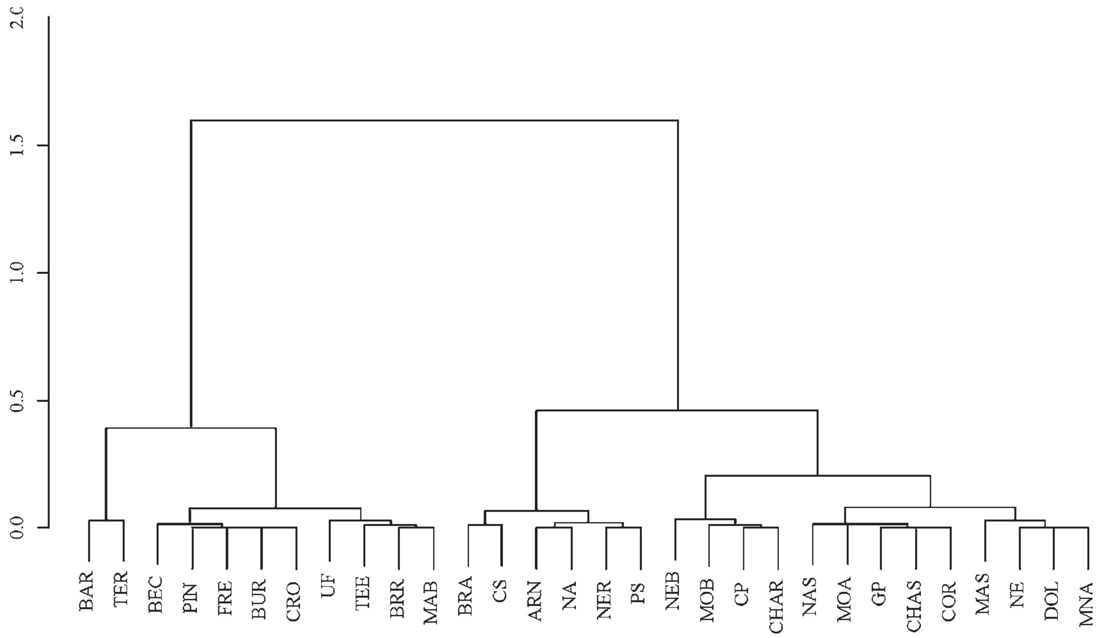

Figure 1. Dendogram of wine grape varieties by applying Ward's method hierarchical cluster analysis to their skin mechanical properties at harvest in 2006.

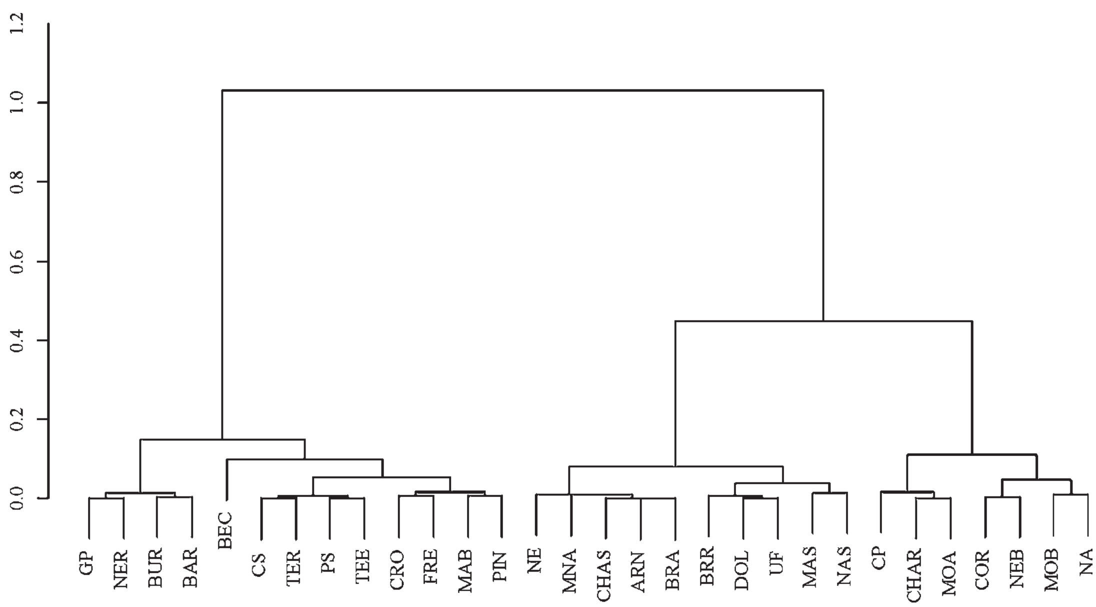

Figure 2. Dendogram of wine grape varieties by applying Ward's method hierarchical cluster analysis to their skin mechanical properties at harvest in 2007.

the same production area did not cause the same effect on the skin hardness for different grape varieties as a consequence of the genotype−environment interaction.[24] So, vineyard 2 involved the greatest values of berry skin break force and energy for BAR but the lowest ones for NE. Likewise, there is the possibility of vineyard adaptation to the environmental conditions, which could modify the response of the variety, and hence grape quality, to the variations in weather parameters. Therefore, it is of great relevance to consider the influence of the bioclimatic indices on mechanical properties of grape varieties.

The physicochemical parameters determined in 2006 and 2007 years at harvest are summarized in Tables 3 and 4, respectively. In 2006 and 2007, total soluble solids, expressed as °Brix, varied between 16.2 and 25.8. These values of total soluble solids corresponded to sugar concentrations of 147 and 255 g/L, respectively. The total acidity also varied markedly among the different varieties studied with a variation range of 4.50−15.95. The physicochemical parameters obtained in 2008, 2009, and 2010 at harvest, as well as those determined in BAR, FRE, MOB, and NE grape samples harvested from several growing locations, were not shown because they did not contribute to improve the quality of the results discussion. They corresponded to an adequate technological maturity for the production of the respective Denomination of Origin wines.

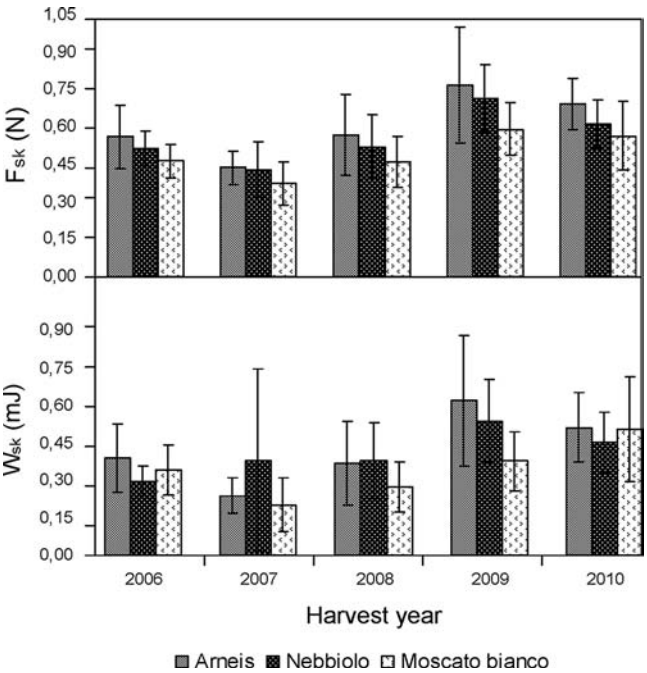

Figure 3. Break force (F_{sk}) and break energy (W_{sk}) of berry skin at harvest for ARN, MOB, and NE wine grape varieties during the 2006−2010 period.

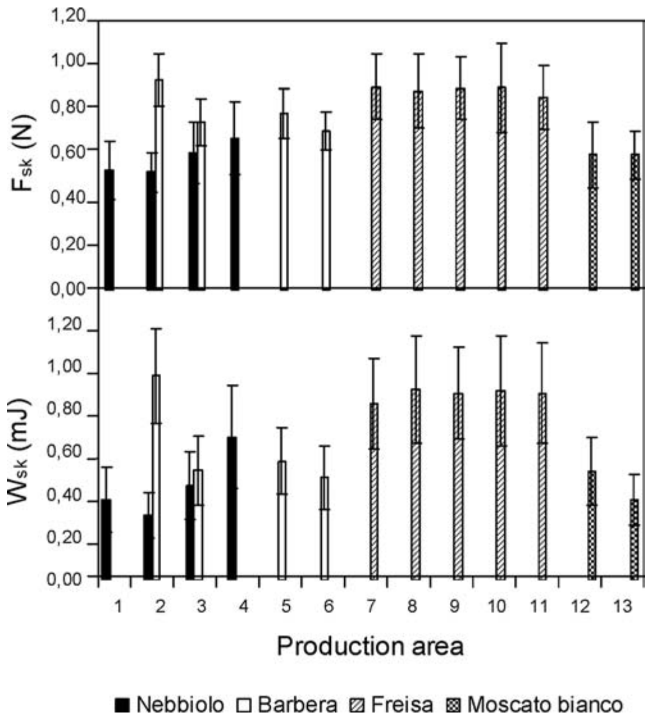

Figure 4. Break force (F_{sk}) and break energy (W_{sk}) of berry skin at harvest for BAR, FRE, MOB, and NE wine grape varieties from several production areas. Piedmont vineyards location (town, province): 1, Neive, Cuneo; 2, La Morra, Cuneo; 3, Barbaresco, Cuneo; 4, Carema, Torino; 5, Agliano Terme, Asti; 6, Tortona, Alessandria; 7, Chieri, Torino; 8, Roatto, Asti; 9, Barolo, Cuneo; 10, Casorzo, Asti; 11, Monleale, Alessandria; 12, Calosso, Asti; and 13, Carpeneto, Alessandria.

The parameters that characterize the berry skin hardness (F_{sk} and W_{sk}) do not seem to be affected by the technological ripeness parameters of wine grape varieties as the evolution of these two mechanical properties during the ripening period is not clear. Several studies suggested that the behavior of the skin break force close to the harvest could limit the choice of this parameter as a maturity indicator in grape berries. In fact, from veraison to ripeness, an increase in the skin break force is shown, particularly in the first ripening phases, with a steady value or a slight decrease close to the technological maturity.[19,20,25] A renewed increase was then observed in over-ripe berries.[26] With very few exceptions, no significant change was reported in the parameters characterizing the berry skin hardness of BAR and Cabernet franc grapes containing different soluble solid contents.[17,18]

Taking into account that the values of the physicochemical parameters determined for the cultivars studied correspond to those obtainable in the respective production area, differences in the berry skin hardness can not be attributed to the physicochemical parameters considered.

Annual Climatic Characteristics. Table 5 shows the climatic and bioclimatic indices corresponding to the grape ripening period of 31 days prior to the different harvest dates in both 2006 and 2007, whereas Table 6 reports the ones obtained in 2008, 2009, and 2010. These are shown because they are better correlated with the berry skin hardness as will be explained later. In general, AMmT, AMxT, AT, TP10, and HI were higher in 2009, whereas ATE and TTE were higher in 2006. On the other hand, AMxT, ATE, AbMxT, HI, and TTE were lower in both 2008 and 2010.

The variability in the climatic conditions during the five years studied (2006−2010) can justify the different performance of wine grape varieties as the former do not have the same influence on all of the cultivars. Considering the climatic conditions corresponding to the three grape-growing months closest to harvest, temperature was higher in 2009, whereas relative humidity and precipitations were higher in 2006. So, the frequency of days with maximum temperatures of 30−32 °C (24.1%) and 34−36 °C (23.1%) was higher in 2009, followed by 32−34 °C (20.9%), whereas the frequency of days with temperatures higher than 36 °C represented 13.2% and the 28−30 °C range involved 9.8%. Regarding 2008, it was a warm year because the most usual maximum temperatures were 30−32 °C (25.2%) and 28−30 °C (20.8%), followed by 32−34 °C (11.0%) and 34−36 °C (5.5%); temperatures higher than 36 °C represented only 1.1%. On the other hand, the percentages of dry days were 68.5, 82.6, 76.1, 78.3, and 75.0% in 2006, 2007, 2008, 2009, and 2010, respectively. Daily precipitations comprised between 10 and 40 mm were found in 5.5, 6.6, 4.4, 2.2, and 4.4% of the days evaluated in 2006, 2007, 2008, 2009, and 2010, respectively. Daily precipitations higher than 60 mm were only found in 2.2 and 1.1% of the days evaluated in 2006 and 2007, respectively. The rainiest days were September 14 and 25 in 2006, and August 30 in 2007, which affected the latest varieties. Furthermore, Table 6 shows that the lower values of relative humidity corresponded to the three last years (2008−2010).

Influence and Importance of Climate on Berry Skin Hardness. A correlation study was performed among different bioclimatic indices and the berry skin hardness. The bioclimatic indices were calculated for different grape-ripening periods close to harvest date including 90−120, 45, 31, 15, 7, and 3 days. A period of 90−120 days was selected, depending on the grape variety, to consider the time comprised from the berry growth to

Table 3. Physicochemical Parameters at Harvest for Wine Grape Varieties in 2006

grape variety	Brix	sugars (g/L)	glucose/fructose	pH	total acidity (g/L)	tartaric acid (g/L)	malic acid (g/L)	citric acid (g/L)
ARN	22.1	214	0.992	3.19	7.10	7.92	2.04	0.13
BUR	22.1	214	1.059	3.43	6.80	5.81	2.77	0.25
BAR	22.3	216	1.085	3.04	10.20	8.10	2.88	0.23
BEC	19.6	185	1.038	3.06	14.30	10.39	7.95	0.37
BRA	25.0	246	1.081	3.30	8.30	6.60	3.36	0.30
BRR	22.0	213	0.999	3.10	9.80	9.37	4.24	0.19
CS	22.8	221	1.105	3.35	7.80	6.71	3.45	0.28
CP	17.6	162	1.059	3.22	5.50	4.63	2.06	0.17
CHAR	23.7	231	0.990	3.30	8.00	7.79	3.19	0.22
CHAS	17.9	166	1.026	3.20	7.40	5.83	2.92	0.14
COR	19.4	183	0.954	3.11	8.30	8.03	2.41	0.18
CRO	22.6	219	1.003	3.13	9.00	9.85	2.43	0.30
DOL	22.4	217	0.999	3.32	5.60	6.75	1.89	0.12
FRE	21.7	209	1.004	3.19	8.60	8.00	3.27	0.17
GP	19.7	186	1.068	3.29	6.10	5.07	2.48	0.28
UF	20.4	195	1.084	3.30	12.80	5.90	8.34	0.63
MAB	16.2	147	0.956	3.06	8.20	6.51	3.32	0.22
MAS	19.4	183	0.991	3.08	9.20	9.33	3.00	0.17
MOA	19.5	183	1.027	3.28	7.90	5.76	4.24	0.31
MOB	23.5	229	0.944	3.12	8.60	7.84	3.15	0.22
MNA	18.9	178	1.000	3.55	5.60	6.79	3.02	0.22
NAS	23.5	229	0.981	3.25	4.60	5.89	0.80	0.10
NE	23.0	224	1.052	3.07	8.40	8.35	1.42	0.18
NEB	23.6	230	0.944	3.01	11.00	9.80	3.69	0.20
NA	18.5	174	1.117	3.26	8.50	5.29	3.76	0.32
NER	16.5	153	1.064	3.17	9.90	5.77	5.14	0.26
PS	22.0	213	1.053	3.28	6.50	6.72	1.72	0.34
PIN	25.8	255	1.072	3.35	6.40	5.64	0.23	0.22
TEE	21.3	204	1.034	3.27	10.40	7.89	4.15	0.21
TER	22.1	214	0.990	3.61	5.90	7.21	2.65	0.27

harvest, whereas the period of 45 days involves from veraison.[27] Furthermore, a lower number of days were also considered as the last ripening ones being considered to have more influence on grape quality. Thus, the ripening-related accumulation of sugars, anthocyanins, and most flavor and aroma compounds typically coincides with the gradual cooling trend toward the end of the growing season.[28]

When the correlation studies were carried out on the differences experienced in both bioclimatic indices and the berry skin hardness between both 2006 and 2007 for all of the varieties analyzed, the highest and most significant correlation factors corresponded to berry skin break energy (W_{sk}) for a time period of 31 days (Table 7). These were greater than 0.47 at a significance level of $p \leq 0.01$, but they did not increase for a higher number of days considered. The correlation coefficient relative to the relationship between the berry skin break energy and the AMmT was higher for the 15 days than for the 30 days prior to harvest date. Furthermore, some indices, like AT, TP10, and HI, only showed significant correlations with the berry skin hardness when they were calculated for the time period of 31 days prior to harvest. On the other hand, other bioclimatic indices were statistically correlated with the berry skin hardness at a time period less than 31 days, but the correlation coefficients were lower than 0.47 at a significance level of $p \leq 0.05$.

The correlation study was also performed in the clusters previously differentiated in both 2006 and 2007. The best results were obtained for the varieties included in the first clusters and a time period of 31 days with correlation coefficients higher than 0.60 at a significance level of $p \leq 0.05$, but the worst results were associated with the second clusters with correlation factors less than 0.60 at a significance level of $p \leq 0.05$.

The AbMxT showed the highest value of the correlation coefficients with berry skin break energy (-0.667, $p \leq 0.01$) in the 31 days prior to harvest, which is in good agreement with other studies previously published. So, other authors confirmed that there is a significant association between maximum temperature and wine quality in the 3 or 6 weeks prior to harvest date depending on the Australian wine region studied.[6] The same authors reported that years in which maturity is delayed or ripening is slow may need more sunshine hours late in the season, and the often associated warm days help to reach the sugar concentration required for fuller-bodied wines. Other authors confirmed that earlier ripening periods in a season may lead to a decrease in grape characteristics and, therefore, in wine quality.[8,29]

The correlation study was also performed on the differences experienced in both the bioclimatic indices and the berry skin hardness between two consecutive years for three grape varieties (ARN, MOB, and NE) during five years (2006−2010) to verify if

Table 4. Physicochemical Parameters at Harvest for Wine Grape Varieties in 2007

grape variety	Brix	sugars (g/L)	glucose/fructose	pH	total acidity (g/L)	tartaric acid (g/L)	malic acid (g/L)	citric acid (g/L)
ARN	25.1	248	0.989	3.30	6.40	7.60	1.93	0.12
BUR	23.2	226	1.002	3.65	4.50	5.27	1.87	0.24
BAR	20.8	201	1.031	3.00	13.55	10.20	4.82	0.32
BEC	18.8	177	1.055	3.05	15.70	11.02	6.05	0.13
BRA	20.9	200	1.015	3.14	8.40	7.33	2.76	0.07
BRR	20.8	199	1.012	3.16	7.45	6.47	3.07	0.11
CS	21.5	209	1.066	3.27	8.90	8.38	3.70	0.22
CP	18.2	169	0.988	3.37	5.35	5.03	1.73	0.13
CHAR	22.5	219	0.989	3.39	6.65	6.80	2.24	0.13
CHAS	17.5	162	0.925	3.37	5.25	5.20	1.55	0.08
COR	20.3	194	0.957	3.27	7.05	7.53	1.60	0.11
CRO	22.1	216	1.007	3.18	8.85	9.81	1.65	0.19
DOL	20.0	190	0.975	3.26	5.85	7.31	0.73	0.08
FRE	21.9	211	1.021	3.16	9.15	7.99	3.31	0.16
GP	19.9	188	1.038	3.28	6.70	5.10	2.93	0.28
UF	21.8	198	1.017	3.00	15.95	7.18	10.44	0.50
MAB	17.9	167	0.978	3.12	7.95	6.46	3.05	0.14
MAS	20.3	194	0.999	3.20	7.95	7.48	2.30	0.12
MOA	19.0	178	1.029	3.23	7.65	6.15	2.92	0.14
MOB	19.2	181	0.987	3.34	5.70	5.79	1.87	0.17
MNA	18.0	167	0.982	3.43	6.50	6.61	2.49	0.13
NAS	22.9	222	1.063	3.42	5.10	5.94	0.59	0.12
NE	23.2	226	1.008	3.01	9.00	8.88	1.82	0.10
NEB	22.8	221	1.026	3.16	8.80	7.71	1.98	0.14
NA	20.0	190	1.074	3.31	7.70	7.24	3.43	0.08
NER	16.2	147	1.024	3.26	8.85	5.85	4.19	0.21
PS	21.9	211	1.010	3.34	7.20	6.98	2.54	0.21
PIN	23.8	232	1.006	3.44	6.30	6.21	2.42	0.16
TEE	19.2	181	1.003	3.18	11.40	9.49	4.41	0.10
TER	20.1	191	1.023	3.64	5.45	5.94	2.10	0.13

the above relationships are maintained along time. In Table 8, it can be observed that the highest and most significant correlation factors (>0.700, $p \leq 0.01$) corresponded to berry skin break force (F_{sk}). When the year's number considered increased from 2 to 5, the mechanical parameter more correlated with climatic and bioclimatic indices changed from berry skin break energy to force. This aspect can be explained by the ability of the berry skin break force to differentiate varieties as it can be considered a potential varietal marker.[19] In the first correlation study (30 varieties, 2 years), the variety had a strong weight on the statistical correlations because the differences experienced in both the bioclimatic indices and the berry skin hardness between the two consecutive years are considered. Therefore, it was expected that the significant correlations were found for berry skin break energy. In the second one, the influence of annual variations acquired a higher importance, skin break force being the mechanical parameter more and better correlated with the climatic and bioclimatic indices. In spite of these differences, the AbMxT again showed a high value of the correlation coefficient with the berry skin hardness (0.729, $p \leq 0.01$) in the 31 days prior to harvest. In fact, all of the significant relationships ($p \leq 0.01$) are associated with the temperature indices in the second correlation study. Furthermore, the correlation coefficients between the skin break force and AMmT, AMxT, AT, TP10, or HI increased with the number of days considered.

Another similar study was also carried out on BAR, FRE, MOB, and NE grape samples harvested from several growing locations, with the aim of explaining the differences in the berry skin hardness, observed in the different production areas, with the climatic and bioclimatic indices of the respective zones. In this case, when the differences in the temperature parameters among the growing areas were reduced (vintage 2008) with respect to the seasonal variability, the highest and most significant correlation factors (>0.700, $p \leq 0.01$) corresponded to the berry skin hardness with the precipitation indices, like TP, MxP, and DP1, for a time period of 15 and 7 days (Table 9). Therefore, water availability in the last ripening weeks seems to be responsible for the skin physical characteristics. The influence of rain on whole berry mechanical properties and skin thickness was already reported for Cabernet franc cultivar[20] and Mondeuse grapes during on-vine drying,[26] respectively.

The optimum berry temperature for anthocyanin synthesis is around 30 °C, but above 35 °C, anthocyanins stop accumulating[30] or may even be degraded.[31] Therefore, AMxT comprised between 22.8 and 31.3 was adequate for anthocyanin synthesis in the years evaluated. Nonetheless, the influence of temperature on most aroma and flavor compounds is not well understood.[28] Moreover, the impact of temperature on harvested grape quality can vary for

Table 5. Climatic and Bioclimatic Indices Corresponding to the Grape Ripening Period of 31 Days Prior to the Different Harvest Dates (Day/Month/Year) in 2006 and 2007

index	05/09/06	06/09/06	12/09/06	13/09/06	20/09/06	28/09/06	21/08/07	29/08/07	03/09/07	04/09/07	11/09/07
AMmT (°C)	14.0	14.1	14.2	14.2	14.3	14.0	16.1	15.8	15.5	15.4	14.3
AMxT (°C)	29.7	29.9	29.6	29.7	29.1	27.4	30.6	29.5	29.3	29.1	28.7
AT (°C)	21.0	21.1	20.9	21.0	20.7	19.8	22.8	22.0	21.5	21.4	20.6
AMmH (%)	51.9	52.1	54.8	54.7	57.4	64.1	54.4	58.9	61.5	61.8	60.0
AMxH (%)	99.8	99.8	100.0	100.0	100.0	100.0	99.8	99.8	100.0	100.0	100.0
AH (%)	84.3	84.3	86.6	86.4	87.0	89.5	81.0	84.4	88.1	88.1	88.4
TP (mm)	10.8	10.8	19.2	19.2	123.6	211.2	56.6	48.6	126.4	126.4	100.0
MxP (mm)	4.6	4.6	9.0	9.0	97.8	97.8	19.2	19.2	61.4	61.4	61.4
ATE (°C)	15.7	15.8	15.4	15.5	14.8	13.5	14.5	13.7	13.8	13.7	14.4
LWD (min)	10081	10262	11296	11027	12690	14446	9002	10568	13271	13433	11916
MxDLW (min)	769	769	818	818	1425	1440	932	932	947	947	947
AbMmT (°C)	9.0	9.0	9.0	9.0	9.0	9.0	13.0	12.3	12.3	12.3	6.8
AbMxT (°C)	36.1	36.1	36.1	36.1	36.1	36.1	37.1	36.3	33.9	33.9	33.6
DI0 (days)	0	0	0	0	0	0	0	0	0	0	0
DP1 (days)	3	3	4	4	5	8	7	7	9	9	6
TP10 (°C)	380.0	383.2	381.5	382.2	373.6	342.9	428.0	405.5	396.5	392.4	367.7
HI (°C)	515.3	519.4	514.4	515.9	502.0	459.5	554.8	525.6	517.1	511.9	492.6
TTE (°C)	501.3	504.0	491.3	494.4	474.4	430.4	463.9	439.5	441.9	437.8	461.0

Table 6. Climatic and Bioclimatic Indices Corresponding to the Grape Ripening Period of 31 Days Prior to the Different Harvest Dates (Day/Month/Year) in 2008, 2009, and 2010

index	10/09/08	18/09/08	08/10/08	26/08/09	09/09/09	02/10/09	09/09/10	21/09/10	01/10/10
AMmT (°C)	16.5	14.4	11.7	18.7	17.6	14.3	15.6	14.5	13.1
AMxT (°C)	28.3	27.3	22.8	31.3	30.9	29.3	26.3	27.2	24.7
AT (°C)	22.1	20.5	16.5	24.6	23.8	20.4	20.5	20.2	18.3
AMmH (%)	43.2	51.1	47.5	42.5	41.3	48.4	68.9	47.1	50.1
AMxH (%)	88.3	100.0	89.6	87.6	93.3	93.1	96.4	96.0	93.2
AH (%)	66.8	80.6	70.6	65.7	68.3	75.8	86.7	74.5	73.4
TP (mm)	6.4	21.4	14.2	45.0	22.0	73.2	67.2	37.0	57.6
MxP (mm)	4.0	10.0	5.4	32.6	21.0	41.6	32.4	28.0	17.0
ATE (°C)	11.8	13.0	11.0	12.6	13.2	15.0	10.8	12.7	11.6
LWD (min)	10168	14929	10059	8477	6951	14143	13282	13952	11830
MxDLW (min)	864	1237	1188	968	794	1388	1406	1285	1440
AbMmT (°C)	11.9	6.2	5.3	14.7	11.1	11.6	9.4	9.1	8.7
AbMxT (°C)	32.9	31.9	30.5	35.0	34.8	37.6	31.4	32.7	28.2
DI0 (days)	0	0	0	0	0	0	0	0	0
DP1 (days)	2	3	4	4	1	5	7	4	7
TP10 (°C)	396.4	347.0	232.3	480.5	455.9	377.8	350.0	348.2	285.0
HI (°C)	500.5	459.8	327.1	592.8	573.1	507.6	444.9	458.7	385.2
TTE (°C)	377.5	415.0	353.4	402.9	423.8	479.4	344.8	406.3	370.6

different grapevine cultivars as consequence of the genotype−environment interaction.

Anthocyanins are particularly important to red wine quality because they are the pigments responsible for red color of grape berries and respective wines.[32] Since the shorter ripening period corresponded to 2007 and the wine grapes harvested in this year have lower values of berry skin break force and energy, a lesser anthocyanin extraction is expected from red wine grapes to wine. Works previously published on Italian varieties (Brachetto and NE grapes) reported that higher skin hardness probably involves greater cell wall fragility and an increase in anthocyanin extraction.[13] Taking into account the data reported in Table 8 (more significant data), higher AbMxT seem to be related with a higher berry skin break force and, therefore, with a higher and slower anthocyanin extraction.[14,25]

To conclude, the classification of the wine grape varieties studied in this work attempting to skin mechanical parameters at harvest was rather similar in both 2006 and 2007 years. The differences found in break force and energy of berry skin can probably be due to the genotype−environment interaction,[24] the temperature parameters being the stronger correlated indices with the berry skin hardness. Softer skins seem to be characterized by a

Table 7. Correlation Coefficients among Different Climatic and Bioclimatic Indices and Berry Skin Hardness for Different Grape Ripening Periods Close to Harvest Date in 2006 and 2007[a]

	90−120 days		45 days		31 days		15 days		7 days		3 days	
index	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}
AMmT (°C)	NS	−0.519**	NS	NS	NS	−0.533**	NS	−0.616**	NS	−0.401*	NS	NS
AMxT (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AT (°C)	NS	NS	NS	NS	NS	−0.548**	NS	NS	NS	NS	NS	NS
AMmH (%)	NS	−0.383*	NS	NS	NS	NS	NS	NS	NS	−0.449*	NS	−0.439*
AMxH (%)	NS	−0.492**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AH (%)	NS	−0.435*	0.371*	0.531**	NS	0.548**	NS	NS	NS	−0.479**	NS	−0.412*
TP (mm)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MxP (mm)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
ATE (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.453*	NS	0.460*
LWD (min)	NS	NS	NS	0.390*	0.371*	0.474**	NS	NS	NS	−0.392*	NS	NS
MxDLW (min)	NS	−0.429*	NS	NS	NS	NS	NS	−0.389*	NS	−0.453*	NS	NS
AbMmT (°C)	NS	−0.569**	NS	NS	NS	NS	NS	−0.423*	NS	−0.451*	NS	NS
AbMxT (°C)	NS	NS	NS	0.473**	−0.379*	−0.667**	NS	NS	NS	NS	NS	NS
DI0 (days)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
DP1 (days)	NS	−0.395*	NS	NS	NS	NS	NS	NS	NS	−0.397*	NS	−0.432*
TP10 (°C)	NS	NS	NS	NS	NS	−0.512**	NS	NS	NS	NS	NS	NS
HI (°C)	NS	NS	NS	NS	NS	−0.442*	NS	NS	NS	NS	NS	NS
TTE (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.452*	NS	0.462*

[a] Berry skin break force (F_{sk}, N) and berry skin break energy (W_{sk}, mJ). Significant: * and ** indicate significance at $p \leq 0.05$ and $p \leq 0.01$, respectively; NS, not significant.

Table 8. Correlation Coefficients among Different Climatic and Bioclimatic Indices and Berry Skin Hardness for Different Grape Ripening Periods Close to Harvest Date in 2006−2010 for ARN, MOB, and NE Wine Grapes[a]

	90−120 days		45 days		31 days		15 days		7 days		3 days	
index	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}
AMmT (°C)	0.726**	NS	0.714**	0.603*	0.662*	NS	0.600*	NS	0.592*	NS	NS	NS
AMxT (°C)	0.761**	0.644*	0.735**	0.640*	0.750**	NS	0.741**	0.586*	0.721**	0.632*	0.596*	NS
AT (°C)	0.914**	0.696*	0.730**	0.634*	0.708*	NS	0.665*	NS	0.676*	NS	NS	NS
AMmH (%)	−0.689*	NS	−0.680*	NS	NS	NS	NS	NS	NS	NS	NS	NS
AMxH (%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AH (%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
TP (mm)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MxP (mm)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
ATE (°C)	NS	NS	NS	NS	0.614*	NS	0.667*	0.634*	0.644*	0.704*	0.761**	0.713**
LWD (min)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MxDLW (min)	NS	−0.606*	NS	−0.668*	NS	−0.662*	NS	NS	−0.702*	−0.622*	NS	−0.581*
AbMmT (°C)	0.646*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AbMxT (°C)	NS	NS	0.687*	0.589*	0.729**	NS	0.629*	NS	0.649*	0.629*	NS	NS
DI0 (days)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
DP1 (days)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
TP10 (°C)	0.887**	0.663*	0.760**	0.656*	0.739**	0.577*	0.705*	NS	0.695*	NS	NS	NS
HI (°C)	0.820**	0.660*	0.750**	0.652*	0.748**	NS	0.728**	NS	0.714**	0.602*	NS	NS
TTE (°C)	NS	NS	NS	NS	0.614*	NS	0.669*	0.630*	0.646*	0.704*	0.762**	0.715**

[a] Berry skin break force (F_{sk}, N) and berry skin break energy (W_{sk}, mJ). Significant: * and ** indicate significance at $p \leq 0.05$ and $p \leq 0.01$, respectively; NS, not significant.

lesser release of red pigments from grape skin into wine during winemaking process.[14,25] The knowledge of the climatic conditions during the last days of ripening period could help to assess the anthocyanin extractability for a given production area as softer skins were associated with 2007 and, therefore, with the shorter ripening period. From the results obtained in this work, a complete study of the influence of the different climatic variables on the anthocyanin extractability in red wine grapes, and even on aroma compounds in

Table 9. Correlation Coefficients among Different Climatic and Bioclimatic Indices and Berry Skin Hardness for Different Grape Ripening Periods Close to Harvest Date in 2008 in Several Production Areas (BAR = 4, FRE = 5, MOB = 2, and NE = 4)[a]

	90−120 days		45 days		31 days		15 days		7 days		3 days	
index	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}	F_{sk}	W_{sk}
AMmT (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AMxT (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AT (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AMmH (%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AMxH (%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AH (%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
TP (mm)	NS	0.575*	0.560*	0.523*	0.565*	NS	0.750**	0.674**	0.719**	0.703**	NS	NS
MxP (mm)	NS	NS	NS	NS	NS	NS	0.717**	0.664**	0.702**	0.671**	NS	NS
ATE (°C)	NS	NS	NS	NS	NS	NS	NS	NS	−0.598*	−0.605*	NS	NS
LWD (min)	NS	NS	NS	NS	NS	NS	NS	NS	0.585*	NS	0.598*	NS
MxDLW (min)	0.643**	0.575*	0.620*	0.619*	0.604*	0.539*	NS	NS	0.652**	0.552*	0.620*	0.519*
AbMmT (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
AbMxT (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
DI0 (days)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
DP1 (days)	NS	0.531*	NS	0.548*	NS	NS	0.731**	0.629*	0.715**	0.707**	0.610*	0.591*
TP10 (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
HI (°C)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
TTE (°C)	NS	NS	NS	NS	NS	NS	NS	NS	−0.593*	−0.601*	NS	NS

[a] Berry skin break force (F_{sk}, N) and berry skin break energy (W_{sk}, mJ). Significant: * and ** indicate significance at $p \leq 0.05$ and $p \leq 0.01$, respectively; NS, not significant.

white wine grapes, in several production areas will be need for a better understanding of the possible effects of climate change on wine grape attributes for the elaboration of high quality wines.

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