HIERARCHY OF THE ROLE OF CLIMATE, SOIL AND CULTIVAR IN TERROIR EFFECT CAN LARGELY BE EXPLAINED BY VINE WATER STATUS

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Abstract

Terroir can be defined as an interactive ecosystem, in a given place, including climate, soil and the vine. The three main components of terroir effect, soil, climate and cultivar, have been studied simultaneously. Vine development and berry composition of non-irrigated *Vitis vinifera* L. cv Merlot, Cabernet franc and Cabernet-Sauvignon were compared on a gravely soil (G), a soil with a heavy clay sub soil (C) and a sandy soil with a water table within the reach of the roots (S). The influence of climate was assessed with year-to-year climatic variations (vintage effect) over the period 1996 to 2003. Effects of climate, soil and cultivar on vine behaviour and berry ripening were highly significant. On most variables, the impact of climate was greater than the effect of soil and cultivar. Most variables were correlated with the intensity of vine water stress, which was assessed by measurements of pre-dawn leaf water potential and carbon isotope discrimination measured on grape sugar ($\delta^{13}C$). It is likely that the effect of climate and soil on fruit quality is mediated through their influence on vine water status.

Résumé

Le terroir peut être défini comme un écosystème dans lequel la vigne interagit avec le climat et le sol et dont la résultante est le vin. Dans ce travail, les trois principaux composants de l'effet terroir, à savoir le climat, le sol et le cépage ont été étudié simultanément. Le développement de la vigne et la constitution du raisin de *Vitis vinifera* L. cv Merlot, Cabernet franc et Cabernet-Sauvignon ont été comparés sur trois parcelles non irriguées, comportant respectivement un sol graveleux (G), un sol à sous-sol très argileux (C) et un sol sableux à nappe d'eau à portée des racines (S). L'effet du climat a été étudié à partir des variations climatiques annuelles (effet millésime) sur la période 1996-2003. Les effets du climat, du sol et du cépage ont été hautement significatif sur la plupart des variables mesurées. Sur une majorité de variables, l'effet du climat a été plus important que l'effet du sol et du cépage. La plupart des variables sont corrélées à l'intensité du déficit hydrique, qui a été évalué par la mesure du potentiel foliaire de base et par la mesure de la discrimination isotopique du carbone 13 sur les sucres du moût ($\delta^{13}C$). L'effet du climat et du sol semblent agir principalement par leur incidence sur le régime hydrique de la vigne.

INTRODUCTION

Terroir can be defined as an interactive ecosystem, in a given place, including climate, soil and the vine (rootstock and cultivar) (Seguin 1988). Some authors also include human factors (Seguin, 1986). It has since long been acknowledged as an important factor for wine quality and style in European vineyards (Falcetti, 1994). More recently, New World producers have show a growing interest in terroir. The terroir effect includes several parameters (climate, soil, cultivar…), which raises the fundamental question wether a hierarchy can be dressed among them. If so, this would provide a scientific basis to a better understanding of the impact of terroir on grape composition.

The effect of climate in viticulture is largely documented (Winkler *et al.*, 1974; Gladstones, 1992), as is the effect of soil (Seguin, 1986; van Leeuwen and Seguin, 1994) and cultivar (Huglin and Schneider, 1998). Effect of vine water and nitrogen status, linked to soil type, have been shown for Cabernet-Sauvignon (Choné *et al.,* 2001). Few experiments relate the combined effect of two parameters (soil and climate: Duteau *et al.*, 1981; soil and cultivar: van Leeuwen and Seguin, 1996). Only Rankine *et al.* (1971) attempted to study the effects of soil, climate and cultivar. However, the soils in that study were located in different climatic zones, which makes it difficult to separate effect of soil and climate.

In this research, climate, soil and cultivar are studied simultaneously. Three way analysis of variance are carried out to hierarchize the effect of climate, soil and cultivar on each variable measured. The combined effect of climate and soil on vine water status is measured and discussed.

MATERIALS AND METHODS

I – Experimental design

This study was carried out from 1996 through 2003 in three Saint-Emilion vineyards, located in the Bordeaux region. Each vineyard was planted with three *Vitis vinifera* L. cultivars: Merlot (cl. 181), Cabernet-Sauvignon (cl. 191) and Cabernet franc (cl. 326). All cultivars were grafted onto *Vitis riparia x Vitis rupestris* 3309C rootstock. Each vineyard was characterized by a particular soil type: a gravely soil (G), a soil with a heavy clay sub-soil (C) and a sandy soil with a water table within the reach of the roots (S). For more details about the soils see van Leeuwen *et al.* 2004. The soils were known for producing wines varying in quality and style. The three vineyards are located less than one km apart in a flat area. Climate can be considered homogeneous among the plots in a given vintage. Inside each vineyard, four rows of respectively Merlot, Cabernet-Sauvignon and Cabernet franc were grafted next to each other, by means of a T-bud grafting. The purpose was to dispose rapidly of vines of each combination soil * cultivar with a completely developed root system. Vine density is 6,000 vines per hectare. Vines were simple guyot pruned (one cane with five buds, one spur with two buds). Weed was controlled by cultivation. Pesticide applications were carried out on the same dates with the same products in each plot. All the plots were dry farmed. As climate was homogeneous among the plots, the effect of climate was limited in this study to year-to-year variations over the period 1996-2003 (vintage effect). 1996 showed temperatures close to average or slightly above average, except for September, which was cool (table 1). Water deficit was moderate, because of high rainfall in August. In 1997, temperatures were high at the beginning and the end of the growing season and average in July and in August. Water deficit was weak, because of high summer rainfall. 1998 temperatures were close to average. The summer was very dry, but April and September were rainy. 1999 was a very warm vintage. Rainfall close to average or slightly above average resulted in moderate water deficits at the end of August. 2000 was warm, except for July. Low rainfall in June and August resulted in high water deficit at the end of the season. In 2001, temperatures and water deficit were close to average for the region. 2002 was wet, with temperatures close to average. 2003 was dry and very warm. Wine quality in Saint-Emilion in this series of vintages can be resumed as following: 2000 = 1998 > 2003 = 2001 > 1999 = 1996 > 1997 = 2002.

II – Variables measured

Phenology, vine development, vigour and yield

Dates of budburst, flowering and veraison were noted when 50% of the buds, flowers or berries reached the given phenological event. On 30 vines per plot, the length of one shoot per vine was measured every 10 days up to the cessation of growth. Growth cessation (expressed in the number of days after April 1) was considered to have occurred when average shoot growth within a plot was less than five mm/day (which is about one-tenth of maximum shoot growth rate). Total shoot length at growth cessation was used as an indicator of vine vigour. Vine vigour was also estimated by average pruning weight, measured in December. Total leaf area per vine was determined before harvest with a leaf area meter (LI-

COR, Lincoln, Nebraska, USA), according to Ollat *et al.* (1998). Yield was limited by severe pruning (seven buds per vine). Average yield was 1.1 kg / vine (6.6 tonnes / ha). Yield variations among plots were mainly due to variations in berry and cluster weight. Berry weight was measured once a week from veraison until ripeness on a sample of approximately 800 berries.

Berry and must composition

While 800 berries per plot were sampled once a week from veraison to harvest, only berry composition at harvest date was used in the analysis presented here. The sample was pressed at 0.5 MPa in a pneumatic micropress (Bellot, Gradignan, France), except for 200 berries used for skin analysis. Methods for analysing pulp and skin components are detailed in van Leeuwen *et al.*, 2004. Pulp ripening was calculated by assessing the sugar/acid ratio as a function of a climatic index (Duteau 1990). According to this author, during the first four weeks after veraison, S/TA ratio is a linear function of Σ {((Average temperature-10) + (Maximum temperature-10)) / 2}. The slope of the linear regression represents the pulp ripening speed.

Vine water status

Vine water status was assessed by measuring pre-dawn leaf water potential (Ψd, Scholander *et al.* 1965) once every two weeks from three weeks after flowering until harvest (each value given is the result of 6 replicates). We considered the minimum pre-dawn leaf water potential values before veraison as an indicator of early season water stress and minimum pre-dawn leaf water potential values between veraison and harvest as an indicator of the intensity of the stress. Vine water status was also assessed by measuring $^{13}C/^{12}C$ ratio on grape sugar at ripeness ($\delta^{13}C$, Gaudillère *et al*., 2003). $\delta^{13}C$ is an indicator that is particularly suitable for estimating average water deficit experienced by the vines in terroir studies.

Statistical Analysis

Data analysis was done by three factor analysis of variance (ANOVA). Means were separated by Newman-Keuls tests (p<0.05). Percentages of variance attributable to soil, cultivar and vintage were calculated. The software used was Grimmersoft StatBox and Microsoft Excel (Redmond, WA).

RESULTS

Most of the considered variables are significantly influenced by the climate of the vintage, the soil and the cultivar (table 2). The percentage of variance explained by each factor is given in table 3.

A - Precociousness, vine vigor and yield

The date of veraison is very much influenced by the vintage (88% of the total variance). The span between veraison in the most precocious vintage (1997) and the latest vintage (2001) of this series is 20 days. Differences among cultivars are small (8% of the total variance), but remain highly significant. Merlot is the most precocious among the studied cultivars. Veraison occurs later for Cabernet franc than for Cabernet-Sauvignon, although Cabernet-Sauvignon reaches ripeness after Cabernet franc because of a much lower ripening speed. Differences in veraison among soils are very small (one day later on S compared to G and C), but significant.

Total shoot length and the date of growth cessation are highly influenced by the vintage (respectively 26% and 74% of the total variance) and the soil type (52% and 15%), and much less so by the cultivar. Growth cessation is precocious in dry vintages (1998, 2000 and 2003) and on soils subjected to water stress (G and C). The span between growth cessation in a dry vintage (2003) and a wet vintage (1999) reaches as much as 81 days. The difference between the clayey soil (C) and the sandy soil (S) is 25 days. Berry weight depends on the soil type (32%), the climate (25%) and the cultivar (19%). Berry weight is high on the sandy soil S (high water supply to the vines) and low on the gravely soil (G) and the clayey soil (C). Berry weight is low for Cabernet-Sauvignon, medium for Cabernet franc and high for Merlot. Berry weight was high in 1997 and 2002 (wet vintages), but differences in berry weight among the other vintages were small and not always easy to explain.

B - Berry and must composition at harvest date

Berry sugar content is explained by the cultivar (37% of the total variance), the soil type (35%) and the vintage (13%). Merlot produces grapes with more sugar compared to Cabernet-Sauvignon. Cabernet franc berry sugar content is average, but closer to Merlot than Cabernet-Sauvignon. The clayey soil (C) is characterized by very high berry sugar content at ripeness. Sugar content is high in good vintages and low in poor vintages. The difference between the 2000 vintage (very good), and the 1997 vintage (poor) reaches in average 20 g/L. The berry sugar content at ripeness is related to the ripening speed (r = 0.64, n = 72, $p \leq 0.001$).

Grape juice acidity is mainly determined by the vintage. The vintage explains 66% and 62% of the total variance of respectively Total Acidity and pH. For tartaric acid, some variation exists among vintages (45% of the total variance); 1998 is characterized by a low berry tartrate content. Grape juice tartaric acid content does not vary to a considerable extent depending on soil (only 4% of the total variance) and cultivar (2%). Berry malic acid content varies also depending on the vintage (60% of the total variance), 1996 being characterized by very high concentrations and 1998 and 2003 by very low concentrations. The effect of the cultivar on malic acid (21% of the total variance) is also highly significant: Cabernet-Sauvignon contains in average 70% more malate than Cabernet franc and Merlot. Variation depending on soil is significant (more malate in grapes on the sandy soil), but not very big (5% of the total variance). Total acidity is closely related to malic acid content (r = 0.92, n = 72, $p \leq 0.001$), but not to tartaric acid content (r = 0.05, n = 72, n.s.)

C - Berry anthocyanin content

Berry anthocyanin content, expressed in mg/kg of grapes, is surprisingly not very much influenced by the cultivar (11% of the total variance). The effect of vintage (52%) is higher than that of soil type (14%). 2000, which is a very good vintage, produced grapes with high anthocyanin content, but so did 1996, which was an average vintage. Anthocyanin content is low in 1997. Among soils, the gravely soil (G) and the clayey soil (C) produce grapes with a high anthocyanin content, unlike the sandy soil (S).

D - Vine water status

Vine water status is assessed in this study by means of pre-dawn leaf water potential (Ψd). Minimum pre-dawn leaf water potential before veraison can be considered as an indicator of early water deficit stress and minimum pre-dawn leaf water potential between veraison and harvest as an indicator of late water deficit stress. The lowest pre-dawn leaf water values have been reached every year between veraison and harvest.

Vintage effect on vine water status was greatest in this study (42% of the total variance). In 1998, 2000, 2001 and 2003, which were dry vintages, vines were subject to marked water stress. In these vintages vines showed a beginning of defoliation after veraison on the gravely soil. Water stress occurred very early in the season in 1998. Only small water deficit was shown in 1996, 1997 and 2002. In 1996 and 2002, water deficit was greater than in 1997 at veraison (respectively Ψd = -0.17, -0.19 and -0.10 Mpa), but the period veraison until harvest was wet in 1996 and 2002 and water deficit did not increase. In 1997, no water deficit occurred before veraison, because of heavy rains in June, but September was dry and a slight water deficit was registered just prior to harvest (Ψd = -0.24).

A highly significant effect of soil on vine water status is shown (39% of the total variance). On the sandy soil (S), where the vine roots meet a water table, Ψd remains close to zero, which indicates no water deficit. On the clayey soil (C), water deficit occurs early in the season (lower Ψd pre-veraison compared to the gravely soil), but the intensity of water stress between veraison and harvest is greater on gravely soil (G). Therefore, vines are subjected to moderate water deficits for a longer period on C, compared to G.

A small, but significant effect of the cultivar on vine water status is shown: Ψd is less negative for Cabernet-Sauvignon. This cultivar had in average less leaf area, which can explain that it consumed less water.

Carbon isotope discrimination measured on grape sugar at ripeness ($\delta^{13}C$) indicate similar tendencies. $\delta^{13}C$ values are well correlated with the lowest pre-dawn leaf water potential values obtained between veraison and harvest ($r = -0.79$, $n = 72$, $p \leq 0.001$).

DISCUSSION

This study showed that the climatic conditions of the vintage, the soil type and the cultivar can influence vine behaviour and berry composition. Influences of climate (Winkler *et al.*, 1974; Gladstones, 1992) and cultivar (Huglin and Schneider, 1998) have since long been acknowledged, but little data have been published about the impact of different soil types. Among the variables measured in this research, berry weight, berry sugar content, berry anthocyanin content and must total acidity have a direct influence on wine quality. Berry weight is mainly influenced by the soil type, followed by the vintage and the cultivar. Berry sugar content depends mainly on the cultivar and the soil type, but also on the vintage. There is a highly significant effect of vintage on berry anthocyanin content, but this variable is less determined by the soil type and the cultivar. Total acidity of the grape juice depends on the vintage and, to a lesser extent, on the cultivar.

Vine water status has an effect on vine development and berry composition. Even when the three cultivars are plotted together, this effect remains in many cases significant (table 4). Water deficit provokes early growth cessation. Berry sugar and anthocyanin content (expressed in g/kg of grapes) is increased, because of a higher ripening speed and a smaller berry size. Water deficit reduces total acidity, because berries contain less malic acid. Most variables, except for those linked to the acidity, are equally correlated to early water deficit (Ψd veraison) as to the intensity of the water stress (Ψd minimum). The relationship between grape quality and water deficit seems to take place before veraison. Water deficit affects grape quality probably indirectly. Early water deficit provokes early shoot growth cessation and reduces berry size. In these conditions, a greater amount of assimilates is available for the ripening of the berries.

The variations in water deficit from one vintage to another in the Bordeaux area are mainly due to the amount of summer rainfall. At bud break, the soils are always at field capacity. In those conditions, the intensity of the water stress depends on the water balance (Rainfall (mm) – ET (mm)) from May through September. While ET_0 does not vary to a considerable extent from one vintage to another in the Bordeaux area, rainfall from May through September can be highly variable (392 mm in 1996; 207 mm in 2000). Temperature seems to have less influence on the quality of the vintage than water balance. 1997 was warmer than 1998, but the latter of the two is a much better vintage.

The intensity of the water stress, especially in a dry vintage, depends highly on the water holding capacity of the soil. In this study, the sandy soil (S) contains a water table within the reach of the roots. Even in a dry vintage, the vines do not face water stress on this soil type. The gravely soil (G) has a very low water holding capacity. Water stress can be severe on this soil. Grape quality is high on the soils that induce water deficit, especially on C where water deficits are precocious but remain moderate.

CONCLUSION

In this research, the three main parameters of the terroir effect, soil, cultivar and climate (through the vintage effect) are studied simultaneously. Highly significant effects of these three parameters on vine development and berry constitution are shown. Climate and soil effects on vine development and grape composition can partly be explained by their influence on vine water status. The vintage influences vine water status by the amount of summer rain, and the soil by its water holding capacity. Water deficits result in early shoot growth cessation, reduced berry size and high fruit quality.

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LIST OF TABLES

Table 1 - Temperatures from April through September and water deficit on 31 August (Saint-Emilion, France)
Water deficit calculated according to water balance model by Riou and Lebon (2000)

Temperature (°C)	1996	1997	1998	1999	2000	2001	2002	2003	mean temp. (1955-1979)
April	12.9	13.5	11.2	12.6	12.1	10.9	12.8	13.7	11.8
May	15.4	17.3	16.8	18.0	17.4	16.7	15.0	18.0	15.3
June	20.3	18.0	18.4	19.0	20.0	18.8	19.5	22.4	18.5
July	21.4	20.6	19.5	22.2	19.7	20.5	19.4	21.2	20.5
August	19.9	23.3	21.2	21.4	21.3	21.5	19.4	23.0	19.9
September	16.0	19.0	18.2	19.2	18.6	15.7	16.8	17.9	17.9
Average April-September	17.7	18.6	17.6	18.7	18.2	17.4	17.2	19.4	17.3
Water deficit 31 August (mm)	-204	-166	-282	-213	-241	-201	-131	-255	

Table 2 - 3 way analysis of variance of the effect of climate, soil and cultivar on precociousness, vigour, yield, berry composition and vine water status. Letters indicate homogeneous groups obtained by Newman-Keuls test (p < 5%)

	VINTAGE (CLIMATE EFFECT)								SOIL			CULTIVAR		
	1996	1997	1998	1999	2000	2001	2002	2003	Gravel	Sand	Clay	Merlot	Cab. Franc	Cab. Sauvignon
Precociousness and vine vigor														
Budbreak (50%)	102 a	77 g	89 de	91 c	98 b	86 f	87 e	89 d	89 c	91 a	90 b	85 c	89 b	95 a
Flowering (50%)	157 a	141 f	155 b	151 d	153 c	154 b	155 b	147 e	151 b	152 a	152 ab	150 c	152 b	154 a
Veraison (50%)	221 b	204 f	220 c	217 d	217 d	224 a	222 b	208 e	216 b	217 a	216 b	215 c	219 a	216 b
Pruning weight (g/vine)	328 cd	410 b	350 bcd	298 d	354 bcd	385 bc	307 d	475 a	358 b	427 a	306 c	354 b	414 a	322 c
Ripening speed	0,92 de	0,85 e	1,25 b	1,05 cd	1,10 bc	1,14 bc	1,02 cd	1,53 a	1,13 b	0,97 c	1,22 a	1,33 a	1,24 b	0,76 c
Total shoot length (cm)	347 cd	409 b	256 f	477 a	308 e	319 de	378 c	366 c	321 b	480 a	271 c	378 a	360 a	334 b
Shoot growth cessation (Day Of the Year)	275 b	269 c	240 f	283 a	231 g	249 e	261 d	202 h	244 b	267 a	242 b	248 b	252 a	253 a
Leaf Area Index (m^2/m^2)		1,2 d	2,16 a	1,81 b	1,48 c	1,41 c	1,55 c	1,56 c	1,47 b	1,90 a	1,41 b	1,86 a	1,59 b	1,33 b
Yield														
Yield (kg/vine)		1,02 bc	0,92 c	1,29 a	1,42 a	1,12 b	1,11 b	0,77 d	0,85 c	1,38 a	1,05 b	1,09 ab	1,18 a	1,01 b
Berry weight (g)	1,23 bc	1,39 a	1,26 b	1,18 bc	1,28 b	1,27 b	1,42 a	1,14 c	1,21 b	1,41 a	1,19 b	1,38 a	1,24 b	1,19 b
Berry and grape must composition at ripeness														
Sugar (g/L)	206 c	200 d	209 c	206 c	220 a	216 ab	215 ab	213 b	203 b	204 b	225 a	223 a	212 b	196 c
Tartrate (meq/L)	81 ab	77 bc	67 d	84 a	82 a	68 d	75 c	82 a	80 a	76 b	76 b	79 a	78 a	75 b
Malate (meq/L)	53 a	22 d	12 e	28 c	28 c	33 c	38 b	16 e	28 b	33 a	25 b	22 c	25 b	39 a
Total Acidity (meq/L)	102 a	67 d	60 e	69 d	75 c	74 c	88 b	60 e	73 b	79 a	72 b	67 c	71 b	85 a
Potassium (meq/L)	51 a	48 ab	46 cd	49 ad	45 cd	44 d	43 d	47 bc	47 NS	46 NS	47 NS	49 a	45 c	46 b
pH	3,24 e	3,49 b	3,61 a	3,46 bc	3,5 b	3,44 c	3,31 d	3,58 a	3,51 a	3,42 b	3,44 b	3,53 a	3,43 b	3,40 b
Anthocyanin (g/kg)	1,00 a	0,66 d	0,88 bc	0,86 c	0,96 ab	0,87 bc	0,83 c	0,85 c	0,9 b	0,72 c	0,98 a	0,84 b	0,84 b	0,91 a
Botrytis intensity (%)				1,56 a	0,02 b	0,22 b	1,82 a	0,15 b	1,2	0,75	0,31	0,59 b	0,37 b	1,31 a
Assimilable Nitrogen (mg N/L)				146 c	183 ab	160 bc	158 bc	206 a	248 a	145 b	119 c	199 a	139 c	174 b
Vine water status														
Minimum pre-dawn leaf water potential before veraison (MPa)	-0,17 bc	-0,11 a	-0,36 e	-0,15 b	-0,22 d	-0,15 bc	-0,19 c	-0,16 bc	-0,21 b	-0,10 a	-0,26 c	-0,19 b	-0,21 c	-0,16 a
Minimum pre-dawn leaf water potential after veraison (MPa)	-0,17 a	-0,24 bc	-0,54 f	-0,27 c	-0,43 e	-0,44 e	-0,21 b	-0,39 d	-0,45 c	-0,17 a	-0,39 b	-0,35 b	-0,37 b	-0,29 a
Carbon isotope discrimination on grape sugar ($^{13}C/^{12}C$)		-24,1 cd	-22,2 a	-24,1 c	-23,2 b	-24 c	-25,6 e	-24,37 e	-22,6 a	-25,0 c	-24,3 b	-24,1 b	-23,8 a	-23,9 a

Table 3 - 3 way analysis of variance : percentage of variance attributable to climate (vintage effect), soil, cultivar and their interactions

	climate	*p*	soil	*p*	cultivar	*p*	climat*soil	*p*	climate*cultivar	*p*	coil*cultivar	*p*	residual
Precouciousness, vigour													
Budbreak (50%)	71	***	1	***	23	***	2	***	2	**	0	NS	1
Flowering (50%)	87	***	0	*	7	***	1	NS	2	*	0	NS	2
Veraison (50%)	88	***	1	***	8	***	0	NS	2	**	0	NS	1
Pruning weight (g/vine)	30	***	25	***	15	***	5	NS	12	NS	12	***	10
Ripening speed	30	***	8	***	48	***	3	NS	5	NS	1	NS	5
Total shoot length (cm)	26	***	52	***	2	***	9	***	3	*	5	***	3
Shoot growth cessation (Day Of the Year)	74	***	15	***	0	***	8	***	2	***	1	***	1
Leaf Area Index (m^2/m^2)	37	***	22	***	21	***	6	*	4	NS	5	**	5
Yield components													
Yield (kg/vine)	25	***	31	***	3	**	7	*	17	***	11	***	5
Berry weight (g)	25	***	32	***	19	***	7	NS	7	*	4	**	7
Berry and grape must composition at ripeness													
Sugar (g/L)	13	***	35	***	37	***	4	**	4	***	2	***	2
Tartrate (meq/L)	45	***	4	**	2	*	13	**	28	***	1	NS	7
Malate (meq/L)	60	***	5	***	21	***	2	NS	6	**	3	**	3
Total acidity (meq/L)	66	***	4	***	22	***	1	NS	4	**	0	NS	3
Potassium (meq/L)	32	***	0	NS	13	***	9	NS	30	***	6	**	10
pH	62	***	6	***	15	***	4	**	8	***	1	*	3
Anthocyanin (mg/L)	52	***	14	***	11	***	7	NS	8	NS	2	NS	12
Botrytis intensity (%)	27	**	6	NS	7	*	18	*	23	*	4	NS	14
Assimilable nitrogen (mg N/L)	9	***	60	***	12	***	9	**	4	NS	3	NS	4
Vine water status													
Minimum pre-dawn leaf water potential before veraison (MPa)	41	***	34	***	3	***	17	***	1	NS	1	**	2
Minimum pre-dawn leaf water potential after veraison (MPa)	42	***	39	***	3	***	14	***	0	NS	1	*	2
Carbon isotope discrimination on grape sugar ($^{13}C/^{12}C$)	44	***	47	***	1	***	5	***	2	**	0	NS	1

NS : p > 0,05
* : p < 0,05
** : p < 0,01
*** : p < 0,001

Table 4 - Correlations between vine water status, and vine development and berry composition

	Minimum dawn water potential pre-veraison	Minimum dawn water potential veraison-harvest
Shoot growth cessation (day of the year)	0.45***[a]	0.66***
Total shoot length (cm)	0.63***	0.63**
Sugar (g/L)	-0.33***	-0.25*
Anthocyanin (mg/kg)	-0.51***	-0.43***
Ripening speed	-0.37***	-0.48***
Berry weight (g)	0.35**	0.44***
Total acidity (meq/L)	0.29**	0.53***
pH	-0.27*	-0.58***
Malate (meq/L)	0.36***	0.51***
Tartrate (meq/L)	0.12NS	0.04NS
Sugar/acid ratio	-0.36***	-0.52***
Veraison (day of the year)	-0.19NS	-0.04NS

[a]NS = $p > 0.05$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$