Received: 22 July 2016 | Accepted: 21 March 2017 | Published: 28 September 2020
DOI:10.20870/oeno-one.2020.54.3.1067

OENO One
VINE AND WINE OPEN ACCESS JOURNAL

Modeling grape quality by multivariate analysis of viticulture practices, soil and climate

Sandra Beauchet [1,2,3], Véronique Cariou [4], Christel Renaud-Gentié [1], Michel Meunier [1], René Siret [1], Marie Thiollet-Scholtus [5-6]* and Frédérique Jourjon [1]

[1] Unité de Recherche GRAPPE (ESA-Inrae), Univ Bretagne Loire, Ecole Supérieure d'Agricultures (ESA), Inrae, 55 rue Rabelais, BP 30748, F-49007 Angers Cedex, France
[2] ADEME, SAF, 20 Avenue du Grésillé, F-49000 Angers, France
[3] IFP Energies Nouvelles, 1 et 4 Avenue de Bois-Préau, F-92852 Rueil-Malmaison, France
[4] StatSC, ONIRIS, Inrae, F-44322 Nantes, France
[5] Inrae - ACT - UR-0055-ASTER, F-68000 Colmar, France
[6] Université de Lorraine, Inrae, LAE, F-68000 Colmar, France

*corresponding author: marie.thiollet-scholtus@inrae.fr

ABSTRACT

Aims: The present study aims to model grape quality criteria by combining a large number of viticultural practices and soil and climatic variables related to the main determinants.
Methods and results: A database has been developed using the Chenin blanc grape variety in a protected designation of origin. A statistical model, namely, a partial least squares (PLS) regression, was performed for each grape quality criterion (sugar content, total acidity, malic acid, tartaric acid, yeast available nitrogen, pH and bunch rot). This statistical analysis identified the main viticultural practices as well as soil and climate variables related to the grape quality at harvest. The results highlight the relationships between the vine pruning length (spur pruning = short pruning or cane pruning = long pruning) and pH and malic acid but also reveal even more significant relationships with tartaric acid, yeast available nitrogen and bunch rot. The dryness index and the plant density have a strong influence on the grape malic acid concentration and pH, respectively. Vine perennial practices are the greatest contributors to the grape the yeast available nitrogen concentration.
Conclusion: The models note the most relevant viticultural practices and soil and climatic variables driving each studied grape quality criterion.
Significance and impact of the study: The results provide a better understanding of the major variables influencing grape quality.

KEYWORDS

explanatory model, partial least squares regression (PLS), vineyard management, chemical maturity of grapes, grape health, acid balance, fermentative capacity

 © 2020 International Viticulture and Enology Society - IVES

INTRODUCTION

Today's wine market is international, focusing on the quality of wine and led by wines carrying signs of quality, such as protected designation of origin (PDO) or protected geographical indication (PGI) in Europe. Moreover, wine consumers are changing their mode of consumption: they are drinking higher-quality wines in smaller quantities (Amine and Lacoeuilhe, 2007). Winegrowers must therefore improve grape attributes to optimize wine quality based on a good assessment of the quality of their grapes at harvest. Grape quality is a complex reality; it is mainly evaluated through several physicochemical criteria (Jackson Lombard, 1993) that depend on both viticultural practices and natural conditions (soil and climate). The influence of these factors on grape quality parameters has already been identified in numerous studies (Archer van Schalkwyk, 2007; Darriet *et al.*, 2001; Gaudillère *et al.*, 2002; Gil *et al.*, 2013; Grifoni *et al.*, 2006; Jackson and Lombard, 1993; Jones and Davis, 2000; Jourjon, 1990; Jourjon *et al.*, 1991; Jourjon *et al.*, 1992; Morlat and Jacquet, 2003; van Leeuwen *et al.*, 2004; Winkler, 1958). Because of the complexity of the interactions between natural conditions and viticultural practices, most authors have separately studied the influence of these different elements on grape quality criteria. However, notably, viticultural practices are related to each other for the same production objective. For this reason, Renaud-Gentié *et al.* (2014) speaks of the "vineyard technical management route," according to the definition given by Sébillotte (1974) and not only of a set of viticultural practices. Although models have already been developed, the influence of vineyard practices on grape quality at harvest has not been quantified as of yet. Baudrit *et al.* (2015) and Perrot *et al.* (2015) proposed a predictive model of grape quality (sugar and acidity concentration) from climate (air temperature, rainfall, sunshine hours, etc.) and grape maturity criteria (berry size, grape color, phenolic compounds, etc.). This model is based on a mathematical approach that integrates fuzzy logic inside a dynamic Bayesian network. It also uses a database and experts' statements. Even if this model enables one to follow the grape quality during grape berry maturation, it considers neither viticultural practices nor many other grape quality parameters. Alternatively, the STICS vine model (aims to provide environmental and agricultural variables (Brisson *et al.*, 2003; Fraga *et al.*, 2015). Among the objectives of the model is to simulate phenological stages. The model considers several parameters for climate (radiation, rainfall, temperature, wind, etc.), soil (water content, mineral nitrogen, etc.) and crop management (biomass, nitrogen content, leaf area, and biomass) to simulate their relationships particularly with the vine. The STICS model (Multidisciplinary stimulator for Standard cultures) was applied on the vine but also on other agricultural plants. Several authors have studied the influence of many anthropogenic and natural variables together in

TABLE 1. Characteristics of studied years studied and plot composing the dataset (TOTAL refers to the sum of studied plots and years).

Identification number of the plot investigated	Studied years				Number of years studied per plot	Pant density	Training system	Vine clone	Rootstock
	2010	2011	2012	2013					
CHA1	X	X			2	5405	Double guyot	220	Riparia
CHA2	X				1	4830	Double guyot	Massal selection	Rupestris du Lot
VAU1	X				1	5263	Simple guyot	26	SO4
VAU2	X	X			2	3333	Double guyot	26	SO4
LAM1		X			1	5555	Double guyot	23	Rupestris du Lot
HIBI	X	X	X	X	4	4785	Royat cordon	220	Fercal
HIRA	X	X	X	X	4	4785	Royat cordon	220	Fercal
JUI1	X	X			2	5050	Double guyot	20	3309
JUIG	X	X	X	X	4	4700	Double guyot	20	3309
LUEE		X	X	X	3	4884	Double guyot	290	Fercal
SAV1	X				1	4000	Double guyot	880	5BB
SAVE	X	X	X	X	4	4000	Double guyot	880	5BB
SAV3	X	X	X		3	5000	Double guyot	INE	5BB
HILbio	X	X	X		3	4785	Simple guyot	220	Fercal
HILbd	X	X	X		3	4785	Simple guyot	220	Fercal
TOTAL	13	12	8	5	38				

 © 2020 International Viticulture and Enology Society - IVES

TABLE 2. Characteristics of the natural factors (input criteria) evaluated the studied plots.

Variable	Description	Variable	Description
YEAR	Year studied		
Plot_NB	Identification number		
	Climatic criteria (Climate)		Soil criteria (Soil)
Tave	Average temperature (Celcius degree)	Scl	Percentage of clay (texture component)
Tmin	Minimum temperature (Celcius degree)	Ssi	Percentage of silt (texture component)
Tmax	Maximum temperature (Celcius degree)	Ssa	Percentage of sand (texture component)
HI	Huglin Index	S_WphR	pH residual of the water from soil
CNI	Cool night index	S_AN	Total nitrogen available ($g.kg^{-1}$)
Rain	Rainfall (mm)	S_OMr	Content of residual organic matter ($g.kg^{-1}$)
PET	Potential evapotranspiration (mm)	S_CN	Ratio of carbon/nitrogen
DI	Dryness Index	S_$CaCO_3$	Content of calcium carbonate ($g.kg^{-1}$)
SR	Solar Radiation (Wh.m-2)	S_K_2O	Content of exchangeable potassium oxide ($g.kg^{-1}$)
		Plot_NSEW	Geographical orientation of the slope (degrees)
		Slope	Slope of the plot (%)
		SWC	Soil water content (mm)
		VIG	Vine vigor
		PI	Precocity Index

evaluation of grape quality criteria (Coulon and Abbal, 2013; Coulon-Leroy *et al.*, 2012a; Valdés-Gómez *et al.*, 2009). However, these studies' results were limited by the number of quality criteria evaluated and explanatory variables. Jones *et al.* (2005) studied the relationships between climate and phenological stages of the vine until harvest evaluating berry composition, total production and grape quality (sugar content, total acidity and berry weight) (Jones *et al.*, 2005). His main purpose was to measure the evolution of these criteria during the phenological stages. Other studies have worked on different models using criteria other than quality, such as the economic impact of adopting new viticultural practices (Ugaglia *et al.*, 2007). Finally, in viticulture, many predictive models have already been used, notably to predict mildew (Park *et al.*, 1997) and 3-isobutyl-2-methoxypyrazine (IBMP) in Cabernet franc grapes (Scheiner *et al.*, 2012). In the latter study, PLS regression was used to show the correlations between viticultural variables, vine physiology, mesoclimate, microclimate and IBMP concentrations.

Sugar content, total acidity, tartaric and malic acids and grape health status are variables routinely used to assess grape quality (GQ) (Barbeau *et al.*, 2004; Coulon-Leroy *et al.*, 2013; Jourjon, 1990; Lakso and Kliewer, 1975; van Leeuwen and Seguin, 1994). New indicators such as texture and sensory parameters can also be used to characterize the grape quality at harvest (Le Moigne *et al.*, 2008a; Le Moigne *et al.*, 2008b; Maury *et al.*, 2009; Rolle *et al.*, 2012; Zouid *et al.*, 2013; Zouid *et al.*, 2010).

None of the previous works quantified the relationships relating these variables to viticultural practices (VPs) and soil and climate (SC). The objective of this paper is to propose statistical models relating the grape quality criteria to the main determinants associated with viticultural practices, soil and climatic criteria.

MATERIALS AND METHODS

1. Field sample

The statistical analysis was performed on a database of fifteen plots of the Chenin blanc variety in the middle Loire Valley (France) in PDOs, which are described by their soil and climate conditions,

 © 2020 International Viticulture and Enology Society - IVES

TABLE 3. Characteristics of the viticultural practices (input criteria) evaluated the studied plots.

Variable	Description	Variable	Description
The perennial practices on the vine (VinePerennialPractices)		Viticulture practices made on the vine during the studied year (VineAnnualPractices)	
RSrip	Riparia rootstock (yes/no)	P	Number of eyes pruned (number of buds / ha)
RSrup	Rupestis du Lot rootstock (yes/no)	LP	Vine pruning length (yes/no)
RSso4	SO4 rootstock (yes/no)	TT	Number of vine trimmings and toppings
RSferc	Fercal rootstock (yes/no)	NoL	No leaf removal performed (yes/no)
RS3309	3309 rootstock (yes/no)	Le	Number of defoliated faces: none, one or both sides (0 to 2)
RS5bb	5BB rootstock (yes/no)	Th	Number of cluster thinnings performed
SGPS	Single Guyot Pruning System (yes/no)	De	Number of desuckering performed
DGPS	Double Guyot Pruning System (yes/no)	ShT	Shoot thinning performed (yes/no)
RCPS	Royat Cordon Pruning System (yes/no)	Fu	Fungicide treatment (IFT/ha)
Y_10	Plot age below or equal to 10 years (yes/no)	In	Insecticide treatment (IFT/ha)
Y_15	Plot age between 10 and 15 years (yes/no)	HH	Harvest done by hand (yes/no)
Y_25	Plot age between 15 and 25 years (yes/no)	Viticulture practices made on the working soil during the studied year (SoilAnnualPractices)	
Y_26	Plot age between superior to 25 years (yes/no)	FO	Organic fertilizer (yes/no)
RSvig	Rootstock's vigor note (1 to 3)	FM	Mineral fertilizer (yes/no)
The perennial practices on the structure of the vineyard (StructurePerennialPractices)		FB	Biodynamic fertilizer (yes/no)
Dens	Plant density (plants.ha^{-1})	FN	Nitrogen brought by fertilization (kg N.ha^{-1})
HV	Height of the vine's trunk (m)	WMG	Number of tractor passing for mowing grass
CaH	Canopy height (m)	WC	Treatment Frequency Index for chemical weed control (IFT.ha^{-1})
CaT	Canopy thickness (m)	IG	Grass cover in the interrow (yes/no)
RS	Row spacing (m)	IT	Mechanical soil tillage in the interrow (yes/no)
AL	Exposed leaf area (m² of leaves.m^{-2} of soil)	IC	Chemical weed control in the interrow (yes/no)
		RT	Mechanical soil tillage under the row (yes/no)
		RC	Chemical weed control under the row (yes/no)

TABLE 4. Characteristics of the grape criteria (output criteria) evaluated the studied plots.

Variable	Description	Variable	Description
Chemical quality of the grapes (CHEMquality)		Rot quality of the grapes (ROTquality)	
Sug	Sugar content (Brix degree)	BunR	Bunch rot (affected berries) (%)
TotA	Total acidity (H_2SO_4.L^{-1} of grape juice)		
MA	Malic acid (g.L^{-1})		
TA	Tartaric acid (g.L^{-1})		
Nav	Yeast available nitrogen (mg.L^{-1})		
pH	pH of grapes (no unit)		

 © 2020 International Viticulture and Enology Society - IVES

viticultural practices and grape quality at harvest. These plots represented the diversity of technical management routes in the middle Loire Valley PDO for dry Chenin blanc wine (Renaud-Gentié *et al.*, 2014). Some details of the features of the plots are presented in Table 1. To account for the variability of natural variables such as climate, data were also been collected for one to four years (according to the data availability for each plot) (Table 1).

2. Variables describing the vineyard plots

Input and output variables are described in Tables 2, 3 and 4.

Sampling of the grapes at each plot was carried out on fifty identified vines according to a protocol ensuring heterogeneity of the grapes picked and a rigorous sampling of the grapes' studied plot (Carbonneau *et al.*, 1991; Le Moigne *et al.*, 2008b). Three to four berries were taken by vine stock, taking at least one berry per row side. Sampling was performed according to the berries level together with their position on the vine stock. The harvest date for the grape sample was fixed as the same day as the winegrower's harvest date. We considered this date as optimal to obtain the grape quality targeted by the winegrower, as it is chosen by the winegrower depending on the maturity of the grapes for producing dry Chenin blanc PDO wine.

Regarding grape quality, two main dimensions were chosen as follows: (i) health status of the harvested grapes and (ii) characteristics of the grapes indicating their ability to follow the desired enological management route. The bunch rot of the grapes was evaluated by observing the health status of each grape of the fifty identified vines on each plot before berry sampling. The chemical analysis of the berries considered all other quality criteria such as grape sugar content, total acidity, malic acid and tartaric acid, yeast available nitrogen and pH.

For simplicity and interpretability, the results were placed into four groups expressing different quality settings defined and selected in accordance with experts of the wine industry in the Loire Valley. The first group consisted of the grape sugar content associated with the total acidity to reflect their chemical maturity. The second group was the grape health at harvest evaluated by the intensity of the bunch rot and pH. The analysis of malic acid and tartaric acid (third group) was useful to determine the grape acid balance. This value was a ratio, but in this study, these criteria were only given separately, even though the term acid balance was used. Last, the grape yeast available nitrogen content comprised the fourth group, named the vine nitrogen status and fermentative capacity (van Leeuwen and Friant, 2011).

Forty-two criteria were used to define the winegrowers' practices, which were divided into annual (twenty-two criteria) and perennial (twenty criteria) practices. Viticulture practices were recorded via individual interviews with the winegrower of the plot studied. In addition, chemical compounds sprayed on the parcel are subject to regulation (national decrees) and depend on winegrowers' certifications (e.g., organic agriculture). Annual practices were divided into "practices conducted on the vine" (eleven criteria) and "soil management practices" (eleven criteria) of the studied plot. Perennial practices concerned the vine (fourteen criteria) and the structure (six criteria) of the vineyard. The "perennial practices on the vine" were defined by the rootstock, pruning system, vine age and rootstock's conferred vigor (RSvig). The RSvig is the level of vine vigor depending on the rootstock, determined by a value between 1 (low vigor) and 3 (high vigor). The studied plots were part of three different PDOs—Anjou Blanc, Saumur Blanc and Savennières: the plantation densities imposed by these PDO specifications had, respectively, a minimum of 4000, between 3300 and 4000 and 5000 vines per hectare. Some plots were planted before the directive or had obtained an exemption, thus explaining why the planting densities of our database do not always correspond to the PDO specifications. The "perennial practices on the structure" were defined through the plant density (Dens), trunk height (HV), canopy height (CaH), canopy thickness (CaT) and row spacing (RS). Thus, the exposed leaf area (AL) (canopy outer surface) was calculated from the three previous indicators.

The winegrower's annual practices were also studied. Annual pruning was defined in this study through the number of buds remaining on the vine per hectare (P) and pruning length (short or long pruning corresponding to, respectively, spur and cane pruning) (LP). The date of pruning was not interpreted, as it was not provided by all the winegrowers for all years studied. Trimming and topping (TT) were evaluated as well as the leaf removal (or not) (NoL) and, if present, both row sides were defoliated or only one (Le). There were many other practices carried out as annual

© 2020 International Viticulture and Enology Society - IVES

practices on the plants, such as cluster thinning (Th) (number of passages by the winegrower for thinning), desuckering (De) (number of passages by the winegrower for desuckering) or shoot thinning (ShT). Fungicide treatments (Fu) and insecticides treatments (In) were defined to identify the response of the winegrower to the annual pest and disease pressure. The harvesting method was defined by hand harvest (HH) and codified (yes/no); no meant that the harvest was mechanical. Fertilization was defined through the use (or not) of organic (FO), mineral (FM), or biodynamic fertilizer (FB) and the amount of organic or mineral nitrogen resulting from fertilization (FN). Ground cover could be managed by using chemical herbicides which is measured by the treatment frequency index of chemical weed control (WC), mechanical soil tillage or mowing the grass several times during the year. In the score evaluation, we dissociated those practices applied interrow and under the row.

Twenty-three criteria characterized the natural environment (nine for climate and fourteen for soil). In this study, several variables, known to potentially influence the grape quality, were measured for each year studied: temperature, rainfall and sunshine. Raw data were collected from the national weather station (from Météo France) nearest the plot concerned (from 2 to 25 km). The Multicriteria Climatic Classification System (MCC System) was considered through its index calculations (Conceição and Tonietto, 2005; Tonietto and Carbonneau, 2004). Climatic indices were calculated during a six months period from April to September corresponding to the vegetative growth period of the vine, except for the cool night index (CNI), which was calculated with the average minimum temperature during September. Thermal conditions were represented through average, minimum and maximum temperatures (Tave, Tmin, Tmax) calculated from April to September (the most important period during which to study the vegetative cycle of the vine until the harvest) (Champagnol, 1984; Reynier, 2012). Moreover, the Huglin Index (HI) (Huglin, 1978; Tonietto and Carbonneau, 2004) and the cool night index (Carbonneau *et al.*, 1991; Coulon *et al.*, 2011; Kliewer and Torres, 1972; Tonietto and Carbonneau, 2004) were calculated. Water supply criteria were considered through calculation of the cumulated rainfall (Rain), the potential evapotranspiration (PET) of the plot and the dryness index (DI) (Conceição and Tonietto, 2005; Coulon *et al.*, 2011; Riou, 1994; Tonietto and Carbonneau, 2004). The sunshine parameter was evaluated by the overall accumulated solar radiation (SR) from April to the end of September. Independently of the climate, the soil associated with each plot was characterized. Soil analyses were performed using soil samples collected once from each vineyard plot studied. Soil was extracted from a 0 to 25 cm depth for chemical and textural analysis in the plot part, in which the fifty vines were identified for berry sampling and observations. The GEPPA soil texture triangle was used to compute the percentage distribution of soil particles between clay, silt and sand (Scl, Ssi, and Ssa, respectively). The residual pH of the soil water from soil (S_WphR) was measured. Total yeast available nitrogen (S_AN), residual organic matter (S_OMr), the ratio of Carbon/Nitrogen in the soil (S_CN), calcium carbonate content (S_$CaCO_3$), and exchangeable potassium oxide in the soil (S_K2O) were evaluated. The soil texture was evaluated for the entire soil profile to calculate the available soil water capacity (SWC) (estimated according to (Goulet *et al.*, 2004) and vine vigor (VIG) (calculated depending on the water holding capacity, gravel percentage in the soil profile and bedrock hardness). The calculation was performed in which each variable was given a mark and then multiplied by the vigor coefficient; the results then added together were calculated (Coulon-Leroy *et al.*, 2013; Coulon-Leroy *et al.*, 2012b; Morlat and Jacquet, 2003; Morlat *et al.*, 1987). The precocity index (PI) was considered in this study (Barbeau, 2008; Barbeau *et al.*, 1998), and two geomorphological criteria were also taken into account: (i) the plot geographical orientation (Plot_NSEW) and (ii) the slope percentage (slope).

3. Statistical analysis

The explanatory models were built through partial least squares (PLS) regression (Wold, 1966). The choice of a PLS regression model was dictated by the nature of the dataset as PLS can address multicollinearity with a large number of variables (even greater than the number of observations) and provides good prediction capacity. PLS regression aims at identifying a small set of orthogonal components from X, here in the Climate, Soil and Practices variables. These components are related to Y in terms of prediction, through the maximization of the covariance between X and Y. These components are linear combinations of X variables: each component is defined by means of vector loadings providing the weights associated with each variable. PLS regression has been widely applied in sensory analysis, for example to

 © 2020 International Viticulture and Enology Society - IVES

TABLE 5. Contribution of the different input blocks to the seven grape quality criteria models.

	Chemical maturity		Grape health		Acid Balance of acids		Fermentative potential
Block contribution (%)	Sugar content (3 dims)	Total acidity (3 dims)	Bunch rot (1 dim)	pH of grapes (3 dims)	Malic acid (3 dims)	Tartaric acid (1 dim)	Yeast available nitrogen (1 dim)
Climate	5.96	13.74	9.51	10.50	14.61	9.33	10.48
Soil	16.50	18.55	**34.10**	19.75	**20.38**	**28.96**	**24.96**
Vine Perennial Practices	13.59	9.73	12.19	9.79	**19.94**	12.61	**28.42**
Structure Perennial Practices	**20.07**	**19.88**	15.08	**21.93**	16.67	15.98	15.53
Vine Annual Practices	17.28	18.48	**18.17**	**19.77**	15.37	**18.47**	19.78
Soil Annual Practices	**26.60**	**19.61**	10.94	18.27	13.02	14.64	0.84

i.e. sugar content, total acidity, bunch rot, pH, tartaric acid, malic acid and yeast available nitrogen; in brackets: number of dimensions of the model; in bold: the two most contributive blocks for each studied criterion.

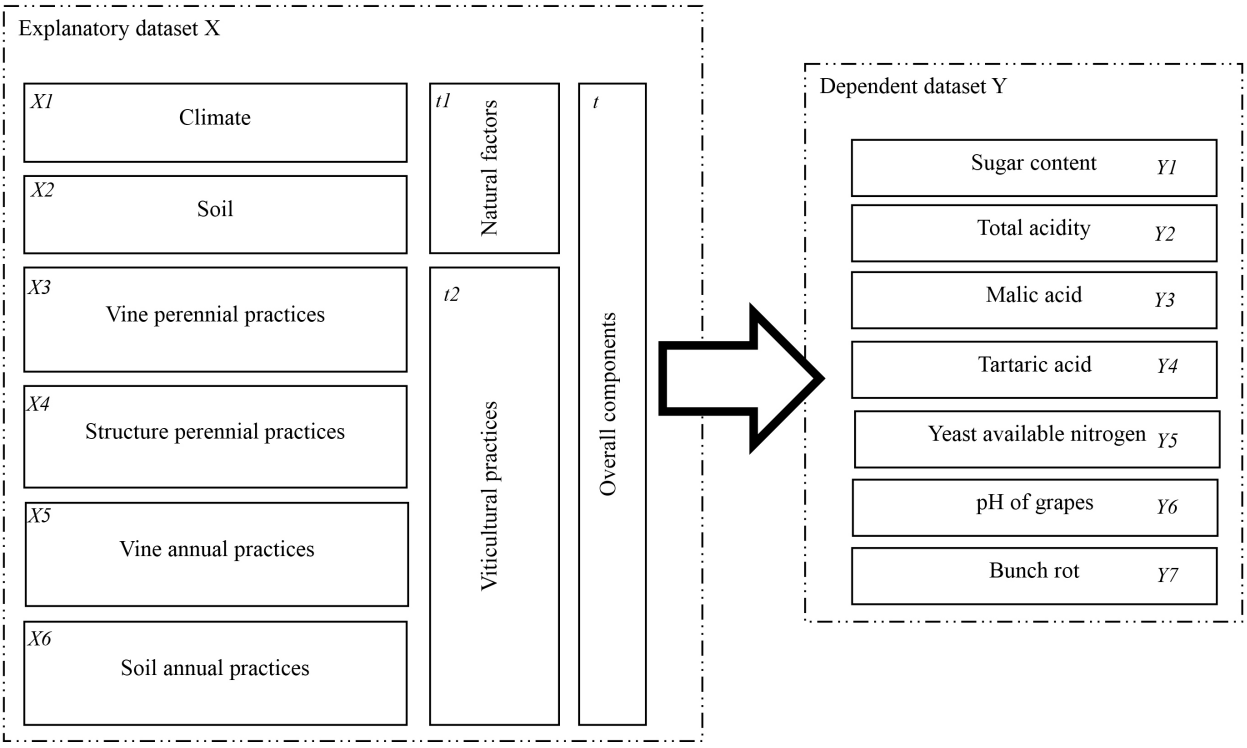


FIGURE 1. Graphical representation of the block and group datasets showing the relationships between the blocks of variables with t the common component for all individuals.
X1…X6 represent each input block, Y1…Y7 represent each output criterion.

predict sensory attributes related to wine quality, based on the definition of chemical and phenolic parameters of grapes and wines (Aleixandre-Tudo *et al.*, 2015).

The input and output variables are described in Tables 2, 3 and 4. Six meaningful conceptual blocks were determined for the analysis of climate, soil, perennial practices (vine perennial practices and structure perennial practices) and annual practices (vine annual practices and soil annual practices). All these elements are shown in Figure 1. Statistical analyses were performed using the R software.

Because the input variables (Tables 2 and 3) were structured into six blocks, an appropriate analytical strategy consisted of performing a multiblock PLS regression (MB-PLS). MB-PLS shows the importance of each block in the prediction of a quality criterion given the contribution associated with annual and perennial practices, climate and soil blocks. Before performing PLS regressions, quantitative variables were

 © 2020 International Viticulture and Enology Society - IVES

standardized because they were not in the same unit. An analogous standardization was completed on the dichotomized qualitative variables. Finally, a global scaling of each block was conducted to set all the blocks on the same footing, regardless of their number of columns.

The natural grouping of the rows of the data table, each group corresponding to a particular year, was integrated in the model leading to a multigroup multiblock PLS regression (Eslami *et al.*, 2014). To determine the number of components to retain for each multigroup multiblock PLS regression, a cross-validation procedure was conducted (Eslami *et al.*, 2014; Eslami *et al.*, 2013; Stone, 1974). The predictive capacity of the model was evaluated with the root mean square error of calibration (RMSEC) and the root mean square error of cross validation (RMSECV). Then, the total variance of X and the total variance of Y restituted by each model, given the number of components retained, were decomposed according to the blocks of variables and the groups of observations to describe the importance of each block in the prediction of a quality criterion Y. The variable influence in projection (VIP) (Wold *et al.*, 2001), which measures the importance of the variable in the prediction, was also reported. Thus, the relationships between each quality criterion and the predictive variables were analyzed on the basis of their loadings and their explanatory influence related to their regression coefficient. Finally, for each model, a subset of the most predictive variables was retained by selecting those with a VIP value greater than 0.8 (which is the standard threshold recognized in PLS).

RESULTS

A specific multigroup multiblock PLS regression was performed for each quality criterion. The overall VIP results related to the variables in all the models are shown in Table 5.

4. Chemical maturity of the grapes

The chemical maturity of the grapes is explained through analysis of the sugar content and total acidity. The inspection of

TABLE 6. Results of quantification between input criteria and grape quality criteria with a VIP ≥ 0.8 for Climate and Soil criteria.

	Chemical maturity of the grapes		Grape health		Balance of acids		Fermentation potential and vine nitrogen status
	Sugar content	Total acidity	Bunch rot	pH of grapes	Malic acid	Tartaric acid	Yeast available nitrogen
Climate							
Tmin		0.910			1.045		1.211
HI			1.317				
PET						1.273	1.226
DI	1.068	**2.387**	**1.584**	1.356	**2.408**	1.353	1.322
Soil							
Scl	1.033	0.849				1.330	1.010
Ssi	1.021		1.206	0.821			
Ssa			1.224			1.097	1.307
S_WphR		1.106	1.277		0.947	1.092	0.953
S_AN	0.899						0.975
S_OMr	1.210			0.850	1.166		1.345
S_CN	1.217			0.898			1.218
S_$CaCO_3$		1.091	1.051				
S_K_2O			0.928				
Plot_NSEW		1.110	**2.024**		1.188		
Slope			0.826				
SWC		**1.491**	1.237	1.233	**1.419**	0.938	1.121
VIG	1.090	0.918	1.520		0.912	**1.852**	1.194
PI		0.932	1.498	1.284	1.189	1.146	0.809

In bold, the five most significant results all block input data combined for each quality criterion evaluated.

 © 2020 International Viticulture and Enology Society - IVES

TABLE 7. Results of quantification between input criteria and grape quality criteria with a VIP ≥ 0.8 for Perennial Practices.

	Chemical maturity of the grapes		Grape health		Balance of acids		Fermentation potential and vine nitrogen status
	Sugar content	Total acidity	Bunch rot	pH of grapes	Malic acid	Tartaric acid	Yeast available nitrogen
Vine Perennial Practices							
RSrip							0.997
RSso4	1.241						
RSferc			1.116				
RS3309	0.950		**1.577**				
RCPS							**2.447**
Y_10	0.834	0.864			1.160	**1.412**	**1.514**
Y_15	0.834		0.890		**1.360**	0.921	1.201
Y_25					1.291		0.824
Y_26		0.864		0.903	1.160	0.803	
RSvig	1.378	1.054		1.017	1.023	1.040	
Structure Perennial Practices							
Dens	**1.600**	**1.628**	0.867	**1.653**	**1.620**	0.985	1.387
HV	**1.531**	**1.686**	**1.936**	**1.509**	1.227		0.813
CaH	1.200	0.929		1.422		1.277	
CaT		1.000			0.961		
RS	**2.650**	0.865	1.318	**2.379**	0.972		0.974
AL	**1.426**		1.092	0.827		**1.820**	**1.859**

In bold, the five most significant results all block input data combined for each quality criterion evaluated.

the RMSEcv as a function of the number of components leads to retaining three components. The RMSEc is equal to 0.070 for sugar content and 0.068 for total acidity. The RMSEcv is equal to 0.188 for sugar content and 0.152 for total acidity. The total variance explained by the first three components represents 32 % for the predictive blocks (47 % for the total acidity model) and 75 % of the response variable for the sugar content (61 % for the total acidity model). Thereafter, the relative contribution of each block in the total variance explained for the response variable is derived (Table 5). Summing to 100 %, this index reflects the relative importance of each block in the prediction of the response variable.

Sugar content and total acidity were strongly linked to Soil Annual Practices, (respectively, 26.60 % of the contribution for sugar content and 19.61 % for total acidity) and to Structure Perennial Practices (20.07 % for sugar content and 19.88 % for total acidity) (Table 5). They were also linked with Vine Annual Practices (17.28 % and 18.48 %) and finally soil criteria (16.50 % and 18.55 %). With regard to sugar content, the most important VIPs (i.e., the most important variables in the prediction) (Tables 6, 7 and 8) mainly concerned the Structure Perennial Practices block characterized by the plant density, trunk height, row spacing and exposed leaf area. The treatment frequency index of the chemical weed control from the Soil Annual Practices block is also part of the most important VIPs. Most of the relevant relationships (corresponding to a VIP value greater than 0.8) corresponded first to the Structure Perennial Practices and second to the Soil Annual Practices. With regard to total acidity, the most important VIPs (Tables 6, 7 and 8) concern the Dryness Index for the Climate bloc (VIP = 2.387), trunk height and plant density for the Structure Perennial Practices block (VIP value equal to 1.686 and 1628 respectively) and pruning length for the Vine Annual Practices

 © 2020 International Viticulture and Enology Society - IVES

TABLE 8. Results of quantification between input criteria and grape quality criteria with a VIP ≥ 0.8 for Annual Practices.

	Chemical maturity of the grapes		Grape health		Balance of acids		Fermentation potential and vine nitrogen status
	Sugar content	Total acidity	Bunch rot	pH of grapes	Malic acid	Tartaric acid	Yeast available nitrogen
				Vine Annual Practices			
P		0.945			0.859		
LP			**1.777**	0.811	0.977	**1.800**	**2.168**
TT	1.116	**1.622**		1.181	1.328		
NoL					0.859	1.054	
Le					0.859	1.054	
Th		0.960	0.953		0.931		
De		0.835	1.307				
ShT					0.870		
Fu		1.040			0.835		1.329
In	1.256		1.028	**1.774**			
HH	1.238	1.040	1.241	**1.928**	1.073		**1.445**
				Soil Annual Practices			
FO	1.236					0.918	
FM	1.012	1.253					
FB		0.981					
FN	0.916	1.352	0.879	0.853	0.983	**1.644**	
WMG	0.831		1.029	1.222	**1.536**		
WC	**1.682**	1.202	0.863	1.192			
IG			1.080			0.979	
IT			1.367				

In bold, the five most significant results all block input data combined for each quality criterion evaluated.

block (VIP value equal to 1.622). Most of the variables possessing a VIP value greater than 0.8 were associated first to the Structure Perennial Practices block and second to the Vine Annual Practices block.

Then, both loadings and regression coefficients of the selected variables were inspected to determine whether the variable had a positive or a negative effect on sugar and total acidity (Annexs 1 and 2 and Tables 9, 10 and 11). Concerning the sugar content, the vine vigor and the exposed leaf area (Soil and Structure Perennial Practices blocks, respectively) had a positive influence. The treatment frequency index of the chemical weed control (Soil Annual Practices block) was negatively correlated to the sugar content. Concerning total acidity (Tables 9, 10 and 11), the dryness index and vine trunk height, which had the greatest VIP values, were positively correlated with total acidity. This result means that if the dryness index and the vine trunk height increase, the total acidity will also increase. The plant density was negatively correlated with total acidity. Trimming and topping was positively correlated with total acidity. Finally, the available soil water capacity was positively correlated with total acidity. These correlations are also shown on the total acidity loadings' biplot (Annex 2). This figure shows that the fungicide treatments were particularly correlated with tartaric acid as the available soil water capacity, trimming and topping and amount of nitrogen for fertilization. In contrast, the harvest completed by hand, plant density, plot geographical orientation, mineral fertilizer use and the treatment frequency index of chemical weed control were negatively correlated with tartaric acid, mostly the use of mineral fertilizer and the treatment frequency index of chemical weed control. Good heterogeneity of the individuals is observed on the sugar content scores plot (Annex 3). The independence of the model with regard to annual variability is confirmed by such heterogeneity. Considering each plot, some are characterized by close observations (for instance LUEE49 or HILbio). Others show a strong

 © 2020 International Viticulture and Enology Society - IVES

TABLE 9. Results of loadings between input criteria and grape quality criteria with a VIP ≥ 0.8 for climate and soil criteria.

	Chemical maturity of the grapes						Grape health				Acid balance				Fermentation potential and vine nitrogen status
	Sugar content			Total acidity			Bunch rot	pH			Malic acid			Tartaric acid	Yeast available nitrogen
	Dim 1	Dim 2	Dim 3	Dim 1	Dim 2	Dim 3	Dim 1	Dim 1	Dim 2	Dim 3	Dim 1	Dim 2	Dim 3	Dim 1	Dim 1
Climate															
Tmin				0.094	-0.066	0.311					-0.101	-0.203	-0.293		0.181
HI							-0.183								
PET														-0.209	0.183
DI	-0.153	-0.191	0.138	**-0.469**	**0.172**	**0.119**	**0.083**	-0.229	0.183	-0.011	**-0.416**	**0.269**	**-0.082**	-0.222	0.197
Soil															
Scl	-0.170	-0.085	-0.007	-0.172	0.005	0.060								0.219	-0.151
Ssi	0.151	0.116	-0.184				-0.167	0.116	-0.149	0.221					
Ssa							0.170							-0.180	0.195
S_WphR				-0.203	0.127	-0.051	0.177				-0.113	0.203	0.047	-0.180	0.142
S_AN	-0.105	0.200	-0.196												-0.145
S_OMr	-0.182	0.152	-0.182					-0.094	-0.237	-0.001	0.174	0.185	-0.149		-0.201
S_CN	-0.199	-0.043	-0.119					-0.157	-0.094	0.008					-0.182
S_$CaCO_3$				-0.186	0.140	0.127	0.146								
S_K_2O							-0.129								
Plot_NSEW				0.112	0.251	-0.028	**0.281**				0.114	0.256	-0.253		
Slope							0.115								
SWC				**-0.304**	**-0.041**	**0.059**	0.172	-0.208	0.163	-0.016	**-0.266**	**0.053**	**-0.037**	-0.154	0.167
VIG	0.163	-0.163	0.136	-0.050	0.230	-0.032	0.211				-0.087	0.213	-0.111	**-0.305**	0.178
PI				0.154	-0.133	-0.097	-0.208	0.220	-0.153	0.001	0.214	-0.095	0.073	0.188	-0.121

In bold, the most significant best VIP criteria results.

TABLE 10. Results of loadings between input criteria and grape quality criteria with a VIP ≥ 0.8 for Perennial Practice).

	Chemical maturity of the grapes						Grape health				Acid balance				Fermentation potential and vine nitrogen status
	Sugar content			Total acidity			Bunch rot	pH			Malic acid			Tartaric acid	Yeast available nitrogen
	Dim 1	Dim 2	Dim 3	Dim 1	Dim 2	Dim 3	Dim 1	Dim 1	Dim 2	Dim 3	Dim 1	Dim 2	Dim 3	Dim 1	Dim 1
Vine Perennial Practices															
RSrip															-0.149
RSso4	-0.208	0.016	-0.041												
RSferc							0.155								
RS3309	0.152	0.078	-0.102				**-0.219**								
RCPS															**0.365**
Y_10	0.131	-0.115	-0.027	-0.086	0.179	-0.133					-0.172	0.192	-0.125	**-0.232**	**0.226**
Y_15	-0.111	0.011	0.244				0.123				**0.230**	**0.169**	**-0.001**	0.151	-0.179
Y_25											-0.151	-0.280	0.081		-0.123
Y_26				-0.086	0.179	-0.133		0.157	-0.096	-0.021	-0.172	0.192	-0.125	0.132	
RSvig	-0.204	-0.257	-0.042	0.185	-0.032	0.225		-0.132	0.193	0.335	0.094	-0.059	-0.482	-0.171	
Structure Perennial Practices															
Dens	**0.264**	**0.078**	**-0.097**	**0.141**	**0.373**	**-0.151**	-0.120	**0.300**	**0.064**	**-0.045**	**0.209**	**0.324**	**0.145**	0.162	-0.207
HV	**-0.238**	**-0.148**	**0.217**	**-0.343**	**0.047**	**0.081**	**0.268**	**-0.254**	**0.144**	**-0.313**	-0.209	0.102	0.220		0.121
CaH	-0.174	-0.221	0.124	-0.014	-0.127	0.329		-0.256	0.037	0.166				0.210	
CaT				-0.015	0.254	-0.082					-0.142	0.167	0.000		
RS	**-0.444**	**-0.040**	**0.046**	-0.044	-0.144	0.263	0.183	**-0.427**	**-0.128**	**0.178**	-0.112	-0.128	-0.344		0.145
AL	**0.222**	**-0.210**	**0.046**				-0.151	0.120	0.168	0.104				**0.299**	**-0.277**

In bold, the most significant best VIP criteria results.

© 2020 International Viticulture and Enology Society - IVES

TABLE 11. Results of loadings between input criteria and grape quality criteria with a VIP ≥ 0.8 for Annual Practices.

	Chemical maturity of the grapes						Grape health				Acid balance			Fermentation potential and vine nitrogen status	
	Sugar content			Total acidity			Bunch rot	pH			Malic acid			Tartaric acid	Yeast available nitrogen
	Dim 1	Dim 2	Dim 3	Dim 1	Dim 2	Dim 3	Dim 1	Dim 1	Dim 2	Dim 3	Dim 1	Dim 2	Dim 3	Dim 1	Dim 1
Vine Annual Practices															
P				-0.056	0.226	-0.103					-0.032	0.233	0.062		
LP							**-0.246**	-0.034	-0.250	0.244	0.167	-0.118	0.022	**0.296**	**-0.323**
TT	-0.187	-0.025	-0.036	**-0.322**	**-0.113**	**-0.012**		-0.214	-0.009	-0.103	-0.247	-0.005	0.129		
NoL											0.161	0.027	0.001	0.173	
Le											-0.161	-0.027	-0.001	-0.173	
Th				0.197	0.010	0.037	0.132				0.169	-0.072	0.000		
De				-0.093	0.171	0.106	0.181								
ShT											0.153	-0.087	0.040		
Fu				-0.139	-0.123	-0.267					-0.143	-0.047	0.169		0.198
In	0.177	0.259	0.100				-0.143	**0.321**	**-0.084**	**-0.013**					
HH	0.082	0.084	0.538	0.069	0.253	0.067	0.172	**0.247**	**0.474**	**-0.131**	0.124	0.228	-0.129		**0.215**
Soil Annual Practices															
FO	0.152	-0.264	-0.250											-0.151	
FM	-0.168	0.056	0.032	0.116	0.177	0.372									
FB				-0.124	-0.135	-0.240									
FN	0.149	0.055	-0.092	-0.093	-0.325	-0.107	-0.122	-0.014	-0.277	-0.220	-0.130	-0.188	-0.114	**-0.270**	
WMG	0.066	0.230	0.219				-0.143	0.201	0.162	0.187	**-0.270**	**-0.158**	**-0.006**		
WC	**-0.168**	**0.538**	**0.100**	0.188	0.128	-0.254	-0.120	0.179	-0.223	-0.165					
IG							0.150							-0.161	
IT							-0.190								

In bold, the five most significant best VIP criteria results.

heterogeneity according to year; this is the case of HIRA49 and JUIG49. Concerning the study of the plot maps for Total Acidity, individuals are mainly distributed around the axes defined by the first two dimensions (Annex 4). Two observations differ from the others with negative coordinates on the second axis. They correspond to 2010VAU1 and 2013HIRA49. Such a difference can also be observed on the sugar content scores plot. With regard to these observations, these differences may be explained by high total acidity and low sugar content.

4. Grape health

Cross-examination of the RMSEcv as a function of the number of components leads to retention of only one component, with an RMSEc equal to 0.118 for bunch rot and an RMSECV equal to 0.168. The total variance explained by the first component is 20 % for the predictive blocks and 48 % for the response variable bunch rot. The main contributions to the bunch rot model are associated with (in decreasing order of importance): Soil, Structure Perennial Practices and Vine Annual Practices. Greater than one-third of the overall contribution is from Soil (Table 5). Regarding bunch rot, the most important VIPs (Tables 6, 7 and 8) concern mainly the plot geographical orientation (Soil) on the one hand and the vine trunk height (Structure Perennial Practices) on the other hand. Although the top five VIPs are homogeneously distributed in all blocks studied with the exception of the block Soil Annual Practices, and most of the significant variables belong to the Soil block. Bunch rot loadings and the signs of loadings (Tables 9, 10, 11, 12, 13 and 14) show heterogeneity between loadings positively and negatively correlated with the dimensions studied. The first five criteria are also well distributed between the negative (dryness index, plot geographical orientation and vine trunk) and positive loadings (3309 rootstock and pruning length). A focus on the plot geographical orientation criteria is made with a strong correlation with the first dimension.

Concerning pH, a model with three components is developed. It corresponds to an RMSEc equal to 0.07 and an RMSEcv equal to 0.145. The total variance explained by the three components is 46 % for the predictive blocks and 75 % for the response variable pH. The respective contribution of the different input blocks to the pH and bunch rot models according to the number of their PLS components is presented in Table 5. The block Soil

TABLE 12. Results of loadings between input criteria and grape quality criteria with a VIP ≥ 0.8 for Annual Practices.

	Chemical maturity of the grapes		Grape health		Acid balance		Fermentation potential and vine nitrogen status
	Sugar content	Total acidity	Bunch rot	pH	Malic acid	Tartaric acid	Yeast available nitrogen
	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign
Climate							
Tmin		-			+		-
HI			+				
PET						+	-
DI	-	**+**	**-**	-	**+**	+	-
Soil							
Scl	-	+				-	+
Ssi	+		+	+			
Ssa			-			+	-
S_WphR		+	+		+	+	-
S_AN	-						+
S_OMr	-			-	-		+
S_CN	-			-			+
S_$CaCO_3$		+	-				
S_K_2O			+				
Plot_NSEW		-	**-**		-		
Slope			-				
SWC		**+**	-	-	**+**	+	-
VIG	+	+	-		+	**+**	-
PI		**-**	**+**	+	**-**	-	+

In bold, the five most significant best VIP criteria results.

is the most determinant followed by the blocks Structure Perennial Practices and Vine Annual Practices. The contribution is well balanced between Soil, Structure Perennial Practices, Vine Annual Practices and Soil Annual Practices at approximately 20 % each (Table 5). The most important VIPs (a VIP value greater than 1.3; see Tables 6, 7 and 8) mainly concern two blocks corresponding to Structure Perennial Practices (with variables of plant density, vine trunk height and row spacing) and Vine Annual Practices (with variables of insecticide treatment and manual harvesting). The row spacing has the greatest VIP, which is equal to 2.4. It is negatively correlated with pH and has negative loadings associated with the first two dimensions (Tables 9, 10 and 11 and Annex 5). Concerning the five most important VIPs, the number of passages for mowing grass, plant density and manual harvesting correspond to high pH values while trimming and topping and the space between rows are related to lower pH values. On the scores plot (Annex 6), several observations differ from those of the others. While 2011LAM1 and 2011JUIG49 have a high pH value, 2013HIRA49, 2010VAU1 and 2010CHA2 have a low pH level. This result is consistent with the result for the sugar content and total acidity models.

5. Acid balance

Inspection of the malic acid RMSEcv as a function of the number of components leads to retaining three components, with an RMSEc equal to 0.072 and an RMSECV equal to 0.166. The total variance explained by the three components is 44 % for the predictive blocks and 78 % for the response variable malic acid. However, the analysis of the RMSECV for tartaric acid

 © 2020 International Viticulture and Enology Society - IVES

TABLE 13. Results of the signs of loadings between input criteria and grape quality criteria with a VIP ≥ 0.8 for Perennial Practices.

	Chemical maturity of the grapes		Grape health		Acid balance		Fermentation potential and vine nitrogen status
	Sugar content	Total acidity	Bunch rot	pH	Malic acid	Tartaric acid	Yeast available nitrogen
	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign
Vine Perennial Practices							
RSrip							+
RSso4	-						
RSferc			-				
RS3309	+		**+**				
RCPS							**-**
Y_10	+	-			+	**+**	**-**
Y_15	-		-		**-**	-	+
Y_25					+		+
Y_26		+		+	+	-	
RSvig	-	**-**		-	**+**	+	
Structure Perennial Practices							
Dens	**+**	**-**	+	**+**	**-**	-	+
HV	**-**	**+**	**-**	**-**	+		-
CaH	-	+		-		-	
CaT		+			+		
RS	**-**	+	-	**-**	+		-
AL	+		**+**	**+**		-	+

In bold, the five most significant best VIP criteria results.

leads to retention of only one component, with an RMSEC equal to 0.115 and an RMSECV equal to 0.152. The total variance explained by this component is 16 % for the predictive blocks and 22 % for the response variable tartaric acid. The importance of the different blocks for malic and tartaric acids is presented in Table 5. The Soil block mostly contributes to both acids (with a contribution of 29.0 % for tartaric acid and 20.4 % for malic acid). Structure Perennial Practices remains a contributive block for the two models (tartaric acid and malic acid), with a percentage of approximately 16 %. Regarding malic acid, the most important VIPs (a value greater than 1.3; see Tables 6, 7 and 8) concern nearly all the blocks (except the Vine Annual Practices block). The dryness index has the greatest VIP (2.41). Concerning the Soil block, the highest VIP value (1.42) is associated with the available soil water capacity, while perennial criteria such as plant density (Structure Perennial Practices block) and vine age (Vine Perennial Practices block) are also critical to the model with a significant VIP value (1.62 and 1.36, respectively). Finally, regarding the tartaric acid model, the most predictive variable is vine vigor (Soil Annual Practices block), with a VIP value equal to 1.82. The exposed leaf area belonging to the Structure Perennial Practices block also significantly contributes to the model (VIP = 1.82), along with the pruning length of the Vine Annual Practices block (VIP = 1.80).

The loadings associated with the malic acid model are depicted in Tables 9, 10, 11, 12, 13 and 14. The dryness index has a positive regression coefficient in the model. Thus, if the dryness index increases, the malic acid concentration in grapes will also increase. The plant density is correlated negatively with malic acid, while the number of tractor passes when mowing grass is positively correlated. Analysis of the loadings associated with the tartaric acid model (Tables 9, 10, 11, 12, 13 and 14) shows a positive correlation between the vine vigor and the first dimension. In contrast, the exposed leaf area and the pruning length are negatively correlated with the latter. The first two dimensions of the malic acid loadings plot show that malic acid is negatively correlated to both dimensions (Annexs 7 and 8). There is a strong opposition, as expressed by a

 © 2020 International Viticulture and Enology Society - IVES

TABLE 14. Results of the signs of loadings between input criteria and grape quality criteria with a VIP ≥ 0.8 for Perennial Practices.

	Chemical maturity of the grapes		Grape health		Acid balance		Fermentation potential and vine nitrogen status
	Sugar content	Total acidity	Bunch rot	pH	Malic acid	Tartaric acid	Yeast available nitrogen
	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign	Loading sign
Vine Annual Practices							
P		+			+		
LP			**+**	-	-	**-**	**+**
TT	-	**+**		-	+		
NoL					-	-	
Le					+	+	
Th		-	-		-		
De		+	-				
ShT					-		
Fu		+			+		-
In	+		+	**+**			
HH	+	-	**-**	+	**-**		-
Soil Annual Practices							
FO	+					+	
FM	-	-					
FB		+					
FN	+	-	+	-	+	**+**	
WMG	+		+	+	**+**		
WC	-	-	+	+			
IG			-			+	
IT			**+**				

In bold, the five most significant best VIP criteria results.

high negative correlation, between malic acid and plant density. This is also the case for the plot geographical orientation, manual harvesting, residual organic matter, and a plot age less than or equal to 15 years. In contrast, the number of tractors passes when mowing grass, plot age from 15 to 25 years and minimum temperature have a positive relationship with the malic acid level. The plot of the first two-dimension scores of the malic acid model shows the relative homogeneity of the observations except CHA1 (2010CHA1 and 2011CHA1), 2010VAU1 and 2013HIAR49. For CHA1, there is a low malic acid value for its two observations while 2010VAU1 and 2013HIRA49 are characterized by high malic acid values. This latter result is consistent with previous conclusions obtained for the other quality criteria.

6. Vine nitrogen status and fermentative capacity

Investigation of the RMSECV as a function of the number of components leads to retention of only one component for the yeast available nitrogen, with an RMSEC equal to 0.121 and an RMSECV equal to 0.165. The total variance explained by this model is 22 % for the predictive blocks and 28 %

© 2020 International Viticulture and Enology Society - IVES

for the response variable yeast available nitrogen. Concerning the contribution of the different blocks in the one-component yeast available nitrogen model (Table 5), it appears that Vine Perennial Practices make the greatest contribution (28.42 %), followed by the Soil (24.96 %) and Vine Annual Practices (19.78 %). The yeast available nitrogen is mainly related to Structure Perennial Practices and Soil (67 % and 64 % of criteria with a VIP greater than 0.8, respectively) (Tables 6, 7 and 8). The greatest VIPs concern the Royat Cordon pruning system (2.447), pruning length (2.168) and exposed leaf area (1.859). None of the Soil Annual Practices variables has a significant relationship with the yeast available nitrogen criteria. There is a good balance between positive and negative loadings compared to that of the first component studied (Tables 9, 10, 11, 12, 13 and 14). Analyzing the five most important VIPs, the Royat Cordon pruning system, the plot age less than or equal to 10 years and manual harvesting demonstrate a negative correlation with the yeast available nitrogen whereas the vine pruning length and exposed leaf area are positively correlated with the first dimension for the yeast available nitrogen criteria.

Relationships between the viticultural practices and soil and climate with each grape quality criterion were studied and compiled (Tables 6 and 7). All the data comprise the explanatory models of grape quality.

DISCUSSION

1. Criteria selection

Out of the 65 input variables related to viticultural practices, soil and climate, 53 were significantly involved (i.e., with a VIP value greater than 0.8) in the modeling of at least one of the seven grape quality criteria. Among these variables, 54 % concerned viticultural practices mostly related to Vine Annual and Perennial Practices. The year effect was removed from the analysis for avoidance and to perform the multigroup model. This leads to a relatively poor contribution of the Climate block, indicating strong homogeneity of the plots regarding the Climatic variables (3 % of the variables that constitute the database). However, it is important to consider the effect of soil and climatic variables in the interpretation of the results.

2. Relevance of the resulting relationships

Scientific experts specializing in viticulture and a literature review helped to verify if some of the relationships between viticultural practices, soil and climate and grape quality had not been considered by the statistical results. Relationships considered irrelevant were then removed from the statistical analysis. It was also verified that the relationships noted by the models were not fortuitous and were accurate. We had to expand the literature review to all grape varieties because only a restricted number of studies had analyzed the relationships of the studied criteria for the Chenin blanc grape variety. Several studies have analyzed the correlations between plant density and grape quality criteria. Agreeing with our results, Hunter (2017) and Reynolds *et al.* (2004) showed that an increase in plant density allows for an increase in sugar content and pH. Dupraz (2010) showed that while plant density decreased, the total acidity increased. However, there is a contradiction between our results and those obtained by Murisier *et al.* (2007) on the Gamay grape variety in the Valais region (Switzerland) showing that there was no significant variation in the malic and tartaric acid content of the berries depending of the plant density. We observed that when the plant density decreased, both malic and tartaric acids increased.

The grape variety of this study is different from that in the literature, and the climatic years might also be different. Sometimes relationships highlighted in the literature are not significant in our results because these variables were not selected as important in the grape quality models. For example, the statistical analysis did not show any relevant relationship between nitrogen fertilization and yeast available nitrogen, as the VIP value was equal to 0.59 (a relevant relationship corresponds to a VIP value greater than 0.8).

Nevertheless, the interest of our study is to understand how viticultural practice variables influence grape quality criteria to aid the winegrower, particularly for annual practices that can change year-to-year. Cus *et al.* (2004) showed that the vine cane length influenced the total grape acidity during three different climatic years. Our results concerning pH and the number of buds remaining on vine canes show that if the number of buds increased, the pH decreased. These findings are confirmed by the literature (Hummell and Ferree, 1998; Jackson and Lombard, 1993; Kaan Kurtural *et al.*, 2006; Romelczyk, 2008). The results of Landolt (2011) and Murisier and Zufferey (2004) are consistent with those of the present study in showing that severe pruning decreases tartaric acid in berries (a

 © 2020 International Viticulture and Enology Society - IVES

VIP value equal to 1.80). Trimming and topping were negatively correlated with sugar content and positively with total acidity in the present study. In the literature, when trimming and topping become intensive, the total acidity increases (Dardeniz *et al.*, 2008; Murisier and Zufferey, 2004). We have shown that leaf removal (or not) was negatively correlated with tartaric and malic acid with respective VIP values of 1.05 (and 0.86). The more leaves that are removed the higher malic and tartaric acid contents. This correlation is also studied by trimming and topping, which can reduce the leaf area of the vine and regulate its vegetative development. Our study demonstrated these relationships between trimming and topping and total acidity (a VIP value equal to 1.622) but also between trimming and topping and sugar content of grapes (a VIP value equal to 1.12). If these viticultural practices (leaf removal and trimming and topping) are barely applied on the vine, it has been shown in the literature that berry size and total acidity increases while the sugar content of the berry juice decreases (Dardeniz *et al.*, 2008; El-Zeftawi and Weste, 1970). Our study also considered natural variables (soil and climatic variables). The potential evapotranspiration is calculated from temperature, solar radiation, wind speed and humidity (Scheff and Frierson, 2014). The Huglin index is an integrative means to assess the influence of maximum temperature on vine metabolism and development (Tonietto and Carbonneau, 2004). In our study, the Huglin index appeared to be important in explaining bunch rot. A higher Huglin index denotes more bunch rot. The precocity index is calculated to evaluate the effect of the soil on the plant. It provides information regarding the potential development of the vine by evaluating the precocity of the plant during its phenological development. Soil components such as soil texture and fertility interact with each other and with the climate to influence the functioning of the vine as its developmental precocity. The precocity can have an influence on the malic acid content of grapes at harvest (Barbeau, 2008; Barbeau *et al.*, 1998). This was confirmed in our study as the VIP value of the precocity index shows the importance of this variable in the explanation of the berry malic acid content (a VIP equal to 1.189). There is less malic acid in grapes with greater precocity.

3. The limitations on the selected criteria

3.1 Criteria that were not maintained in the database even though there were sufficient data

However, some viticultural practices were not included in the models because they did not have a significant effect on at least one of the attributes studied. This is the case for two types of rootstocks (Rupestris du Lot and 5bb), the single Guyot pruning system and the double Guyot pruning system, which had no significant relationships with any of the studied quality criteria (the other types of rootstocks and pruning systems were maintained in the database). In addition, regarding annual practices, chemical weed control in the interrow, mechanical soil tillage under the row and chemical weed control under the row were not significant. The soil was only analyzed from 0-25 cm depth while the vines' rooting depth is 1.5 m on average. This means that less than 20 % of the soil explored by the root system was considered in the study. The deeper soil (greater than 25 cm) was analyzed as the rooting system extends deeper but given the results associated with a first principal component analysis (PCA), the experts estimated that the sample of data obtained was insufficient for a statistical treatment compared to other data available in the database. However, the deeper soil characteristic influence on vine was accounted for through the vigor, precocity and soil water content variables. The analysis of the first horizon allowed us to determine the soil mineral composition of the soil.

3.2 Criteria that were not maintained in the database because of data gaps

The input variables that comprise the dataset of the study were chosen for their influence on grape quality at harvest time. They thus had to characterize the entire growing period. Some climatic criteria, such as wind and hail, did not seem relevant because they consider the internal variability. Some of the output variables are rather basic (i.e., sugar content or total acidity). Other quality parameters, such as aroma, phenolic composition (less important here as we address a white grape variety) or sensorial criteria would have been interesting to include. Although phenological variables (date of flowering, ripening, etc.) are interesting, they were not considered (Jones, 2000; van Leeuwen, 2004). For example, aroma and grape color at harvest time are particularly dependent on climate variables during the growth period (Conceição and Tonietto, 2005; Tonietto and Carbonneau, 2004).

Unfortunately, there were too many missing data for the observations made to use these output variables. Nevertheless, the basic variables for

© 2020 International Viticulture and Enology Society - IVES

which data were available enabled the robustness of the method to be tested.

4. The importance of climate

Many factors influence grape quality, including climate and soil, which determine the perennial and annual development of the vine. The role of winegrowers is to adapt their annual practices according to such natural factors by correcting the physiological development of the vine and protecting it against pests and diseases with the goal of improving grape quantity and quality (Bonnefoy *et al.*, 2010; Tonietto and Carbonneau, 2004). Climate is the most important factor for determining grape quality. van Leeuwen *et al.* (2004) shows that climate impacts are greater than those related to the soil and cultivar for growing vines. According to Ubalde *et al.* (2007), climate affects up to 70 % of grape quality.

5. Interest of the models

The models quantify the relationships between each input criterion and quality criterion of the grape. This is a first step in the search for a predictive model of grape quality assessing viticultural practices and environmental factors. These results could be useful for stakeholders (winegrowers, technicians, etc.) to appreciate the effect that a change in practices can have and help them manage their viticultural practices depending on their influence on grape quality potential criteria. Given these results, decision-makers can use simplified versions of the tables as models. Each time they decide to change a practice, they could review the relevant VIP table to determine with which quality criteria this new practice has a significant relationship. Then, they could review the loadings table to determine how the new practice influences the targeted grape quality criterion (positively or negatively). Potential relationships between grape quality criteria and viticultural practices, climate and soil have been quantified through statistical analysis. The importance of each variable in predicting the quality criteria has been measured thanks to their VIP associated with each multigroup multiblock PLS model. There is one explanatory model per grape quality criterion studied; it consists first of VIPs compared to each viticultural practice or soil and climate criterion and then the loadings assigned to each relationship. Consequently, seven explanatory models were developed in this study. The construction of this model (approach, data selection, and statistical model) provides a framework to be transferred to other varieties in other regions.

Although different years were analyzed, the aim of this study was not to assess grape quality according to a single year effect - because it is well known that annual climatic variations outperform the other variables related to quality - but rather to measure the effect of viticultural practices and identify the interactions between climate variations, soil, viticultural practices and grape quality.

Finally, notably, the more comprehensive the database is, the more reliable the results, although the statistical method allows fewer individuals than the number of criteria to be evaluated.

CONCLUSION

This study presents explanatory models linking grape quality at harvest to viticultural practices, soil and climatic variables. The models note the most important viticultural practices, along with soil and climatic variables, for explaining different grape quality criteria. The models include sixty-five input criteria to explain seven output criteria. The models were tested under different climatic conditions related of different years in the same wine-producing area. For the same grape variety (Chenin blanc), our models could consider the effects of the fifty-two main contributing criteria on the seven grape quality criteria. Not every input criterion had a significant relationship with every single quality criterion. Significant relationships were found between (i) plant density and all the grape quality potential criteria evaluated; (ii) dryness index and all the grape quality criteria and iii) amount of nitrogen fertilization with many grape quality potential criteria, such as pH, tartaric acid and total acidity. Overall, the stakeholders can identify direct relationships between each of the seven quality criteria studied and thirty-five criteria for the evaluation of viticultural practices. Of the latter, 54 % concern the evaluation of annual practices on which the winemaker can immediately act.

Our models provide stakeholders a first stage in a decision-making tool to manage the quality of the vine by reviewing the practices they would like to change depending on the VIP and loadings results. The results can be applied to other regions for the same variety by adding individuals to the database from the new region. The same method could also be applied to other varieties based on the same criteria. Finally, it would be interesting to add

 © 2020 International Viticulture and Enology Society - IVES

other quality criteria such as sensory attributes to strengthen the grape quality assessment in the future.

ACKNOWLEDGMENTS

The authors thank ADEME (French Environmental Agency), the Regional Council of Pays de Loire, ESA and CASDAR QUALENVIC for their financial support. We are also grateful to all the winegrowers for their help in this study, the staff of the GRAPPE research unit for their technical support and Fanny Bessonneau, Eloi Ferry, Victor Ludeau from Oniris and Clément Planchenault for their help. The authors declare no financial conflict of interest.

REFERENCES

Aleixandre-Tudo, J. L., Alvarez, I., Garcia, M. J., Lizama, V., & Aleixandre, J. L. (2015). Application of Multivariate Regression Methods to Predict Sensory Quality of Red Wines. *Czech Journal of Food Sciences* 33(3), 217-227. https://doi.org/10.17221/370/2014-CJFS

Amine, A., & Lacoeuilhe, J. (2007). Les pratiques de consommation du vin: rôle des représentations et des situations de consommation. *In* Actes du XXIIIème Congrès International de l'AFM, (eds.),

Archer, E., & van Schalkwyk, D. (2007). The effect of alternative pruning methods on the viticultural and oenological performance of some wine grape varieties. *South African Journal of Enology and Viticulture* 28(2), 107-139. https://doi.org/10.21548/28-2-1466

Barbeau, G. (2008). Influence du fonctionnement de la vigne sur la qualité du vin. *In* VI Foro Mundial del Vino, (eds.),

Barbeau, G., Asselin, C., & Morlat, R. (1998). Estimation du potentiel viticole des terroirs en Val de Loire selon un indice de précocité du cycle de la vigne. *Bulletin de l'OIV* 71(805–806), 247-262.

Barbeau, G., Bournand, S., Champenois, R., Bouvet, M. H., Blin, A., & Cosneau, M. (2004). The behaviour of four red grapevine varieties of Val de Loire according to climatic variables. *OENO One* 38(1), 35-40. https://doi.org/10.20870/oeno-one.2004.38.1.927

Baudrit, C., Perrot, N., Brousset, J. M., Abbal, P., Guillemin, H., Perret, B., Goulet, E., Guerin, L., Barbeau, G., & Picque, D. (2015). A probabilistic graphical model for describing the grape berry maturity. *Computers and Electronics in Agriculture* 118(C), 124–135. https://doi.org/10.1016/j.compag.2015.08.019

Bonnefoy, C., Quenol, H., Planchon, O., & Barbeau, G. (2010). Températures et indices bioclimatiques dans le vignoble du Val de Loire dans un contexte de changement climatique. *EchoGéo* 14. https://doi.org/10.4000/echogeo.12146

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y. M., Cellier, P., Debaeke, P., Gaudillère, J. P., Hénault, C., Maraux, F., Seguin, B., & Sinoquet, H. (2003). An overview of the crop model stics. *European Journal of Agronomy* 18(3), 309-332. https://doi.org/10.1016/S1161-0301(02)00110-7

Carbonneau, A., Moueix, A., & Leclair, N. (1991). Proposition d'une méthode de prélèvement de raisins à partir de l'analyse de l'hétérogénéité de maturation sur un cep. *Bulletin de l'OIV* 727-728679-690. https://pandor.u-bourgogne.fr/ead.tml?id=FRMSH021_00019&c=FRMSH021_00019_BOIV_1991_09-10_n727-n728_art02

Champagnol, F. (1984). "*Eléments de physiologie de la vigne et de viticulture générale.*," Champagnol.

Conceição, M. A. F., & Tonietto, J. (2005). Climatic potential for wine grape production in the tropical north region of Minas Gerais State, Brazil. *Revista Brasileira de Fruticultura* 27404-407. https://doi.org/10.1590/S0100-29452005000300016

Coulon, C., Ganeco, A., Neethling, E., & Thiollet-Scholtus, M. (2011). Method of typology of reference climatic years intended for modelling. Application to the middle Loire valley. *Progrès agricole et viticole* 128(17), 347-353.

Coulon, P., & Abbal, P. (2013). "*Pourquoi un vin est-il bon? L'analyse d'un vigneron et d'un scientifique.*," Eyrolles/Ed.

Coulon-Leroy, C., Charnomordic, B., Rioux, D., Thiollet-Scholtus, M., & Guillaume, S. (2012a). Prediction of vine vigor and precocity using data and knowledge-based fuzzy inference systems. *OENO One* 46(3), 185-205. https://doi.org/10.20870/oeno-one.2012.46.3.1518

Coulon-Leroy, C., Charnomordic, B., Thiollet-Scholtus, M., & Guillaume, S. (2013). Imperfect knowledge and data-based approach to model a complex agronomic feature – Application to vine vigor. *Computers and Electronics in Agriculture* 99135-145. https://doi.org/10.1016/j.compag.2013.09.010

Coulon-Leroy, C., Morlat, R., Barbeau, G., Gary, C., & Thiollet-Scholtus, M. (2012b). The Vine Functioning Pathway, A New Conceptual Representation. *In* "*Sustainable Agriculture Reviews: Volume 11*" (E. Lichtfouse, ed.), pp. 241-264. Springer Netherlands.

Cus, F., Koruza, Z. K., Koruzo, B., & Lavrencic, P. (2004). Influence of crop load and cultivar's dependent canopy management on grape must quality of 'Sipon', 'Zametovka', and 'Rebula'. *Acta Horticultural* 652141-146. https://doi.org/10.17660/ActaHortic.2004.652.16

Dardeniz, A., Yildirim, I., Gökbayrak, Z., & Akçal, A. (2008). Influence of shoot topping on yield and quality of Vitis vinifera L. *African Journal of Biotechnology* 7(20), 3625-36.

Darriet, P., Bouchilloux, P., Poupot, C., Bugaret, Y., Clerjeau, M., Medina, B., & Dubourdieu, D. (2001). Effects of copper fungicide spraying on volatile thiols of the varietal aroma od Sauvignon blanc, Cabernet Sauvignon and Merlot wines. *Vitis* 4093-99. https://doi.org/10.5073/vitis.2001.40.93-99

Dupraz, R. (2010). La vigne « en lyre » sur le terroir savoyard. *Progrès agricole et viticole* 127455-457.

El-Zeftawi, B., & Weste, H. (1970). Effects of some growth regulators on the fresh and dry yield of Zante currant (Vitis vinifera var.). *Vitis* 9(1), 47-51. https://doi.org/10.5073/vitis.1970.9.47-51

Eslami, A., Qannari, E. M., Kohler, A., & Bougeard, S. (2014). Multivariate analysis of multiblock and multigroup data. *Chemometrics and Intelligent Laboratory Systems* 13363-69. https://doi.org/10.1016/j.chemolab.2014.01.016

Eslami, A., Qannari, E. M., Kohler, A. i., & Bougeard, S. (2013). Multi-group PLS Regression: Application to Epidemiology. *In* New Perspectives in Partial Least Squares and Related Methods, H. Abdi, W. W. Chin, V. Esposito Vinzi, G. Russolillo and L. Trinchera (eds.). Springer New York, https://doi.org/10.1007/978-1-4614-8283-3_17

Fraga, H., Costa, R., Moutinho-Pereira, J., Correia, C. M., Dinis, L.-T., Gonçalves, I., Silvestre, J., Eiras-Dias, J., Malheiro, A. C., & Santos, J. A. (2015). Modeling Phenology, Water Status, and Yield Components of Three Portuguese Grapevines Using the STICS Crop Model. *American Journal of Enology and Viticulture* 66(4), 482. https://doi.org/10.5344/ajev.2015.15031

Gaudillère, J. P., Choné, X., van Leeuwen, C., & Trégoat, O. (2002). The assessment of vine water and nitrogen uptake by means of physiological indicators influence on vine development and berry potential (Vitis vinifera L. cv Merlot, 2000, Bordeaux). *OENO One* 36(3), 133-142. https://doi.org/10.20870/oeno-one.2002.36.3.967

Gil, M., Esteruelas, M., González, E., Kontoudakis, N., Jiménez, J., Fort, F., Canals, J. M., Hermosín-Gutiérrez, I., & Zamora, F. (2013). Effect of Two Different Treatments for Reducing Grape Yield in Vitis vinifera cv Syrah on Wine Composition and Quality: Berry Thinning versus Cluster Thinning. *Journal of Agricultural and Food Chemistry* 61(20), 4968-4978. https://doi.org/10.1021/jf400722z

Goulet, E., Morlat, R., Rioux, D., & Cesbron, S. (2004). A calculation method of available soil water content : application to viticultural terroirs mapping of the Loire valley. *OENO One* 38(4), 231-235. https://doi.org/10.20870/oeno-one.2004.38.4.913

Grifoni, D., Mancini, M., Maracchi, G., Orlandini, S., & Zipoli, G. (2006). Analysis of Italian Wine Quality Using Freely Available Meteorological Information. *American Journal of Enology and Viticulture* 57(3), 339. http://www.ajevonline.org/content/57/3/339.abstract

Huglin, P. (1978). Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. *Comptes rendus de l'académie d'agriculture* 641117-1126. https://gallica.bnf.fr/ark:/12148/bpt6k6243937v/f1129.item.r=huglin

Hummell, A. K., & Ferree, D. C. (1998). Interaction of crop level and fruit cluster exposure on 'Seyval blanc' fruit composition. *Journal of the American Society for Horticultural Science* 123(5), 755-761. https://doi.org/10.21273/JASHS.123.5.755

Hunter, J. J. (2017). Plant Spacing Implications for Grafted Grapevine II Soil Water, Plant Water Relations, Canopy Physiology, Vegetative and Reproductive Characteristics, Grape Composition, Wine Quality and Labour Requirements. *South African Journal of Enology and Viticulture* 19(2), 17. https://doi.org/10.21548/19-2-2243

Jackson, D. I., & Lombard, P. B. (1993). Environmental and Management Practices Affecting Grape Composition and Wine Quality - A Review. *American Journal of Enology and Viticulture* 44(4), 409. http://www.ajevonline.org/content/44/4/409.abstract

Jones, G. V., & Davis, R. E. (2000). Climate Influences on Grapevine Phenology, Grape Composition, and Wine Production and Quality for Bordeaux, France. *American Journal of Enology and Viticulture* 51(3), 249-261. http://www.ajevonline.org/content/51/3/249.abstract

Jones, G. V., White, M. A., Cooper, O. R., & Storchmann, K. (2005). Climate Change and Global Wine Quality. *Climatic Change* 73(3), 319-343. https://doi.org/10.1007/s10584-005-4704-2

Jourjon, F. (1990). "Recherche de facteurs explicatifs du milieu : influence et hiérarchisation sur la qualité et typicité des vins rouges de la Moyenne Vallée de la Loire.." Institut Œnologie de Bordeaux, Bordeaux, France.

Jourjon, F., Morlat, R., & Seguin, G. (1991). Caractérisation des terroirs viticoles de la moyenne vallée de la Loire. Parcelles expérimentales, climat, sols et alimentation en eau de la vigne (1). *OENO One* 25(4), 179-202. https://doi.org/10.20870/oeno-one.1991.25.4.1208

Jourjon, F., Morlat, R., & Seguin, G. (1992). Développement de la vigne et maturation du raisin dans différents terroirs viticoles de la moyenne vallée de la Loire (1). *OENO One* 26(2), 51-62. https://doi.org/10.20870/oeno-one.1992.26.2.1199

Kaan Kurtural, S., Dami, I. E., & Taylor, B. H. (2006). Effects of prunning and cluster thinning on yield and fruit composition of "Chambourcin" grapevines. *Horttechnology* 16233-240. https://doi.org/10.21273/HORTTECH.16.2.0233

Kliewer, W. M., & Torres, R. E. (1972). Effect of Controlled Day and Night Temperatures on Grape

Coloration. *American Journal of Enology and Viticulture* 23(2), 71. http://www.ajevonline.org/content/23/2/71.abstract

Lakso, A. N., & Kliewer, W. M. (1975). The Influence of Temperature on Malic Acid Metabolism in Grape Berries. *Plant Physiology* 56(3), 370. https://doi.org/10.1104/pp.56.3.370

Landolt, J. S. (2011). "Effects of Pruning Level and Canopy Management Practices on Berry Maturation Rate and Harvest Parameters of Syrah Wine Grapes.." California Polytechnic State University, San Luis Obispo, USA.

Le Moigne, M., Dufour, E., Bertrand, D., Maury, C., Seraphin, D., & Jourjon, F. (2008a). Front face fluorescence spectroscopy and visible spectroscopy coupled with chemometrics have the potential to characterise ripening of Cabernet Franc grapes. *Analytica Chimica Acta* 621(1), 8-18. https://doi.org/10.1016/j.aca.2007.09.054

Le Moigne, M., Maury, C., Bertrand, D., & Jourjon, F. (2008b). Sensory and instrumental characterisation of Cabernet Franc grapes according to ripening stages and growing location. *Food Quality and Preference* 19(2), 220-231. https://doi.org/10.1016/j.foodqual.2007.03.004

Maury, C., Madieta, E., Le Moigne, M., Mehinagic, E., Siret, R., & Jourjon, F. (2009). Development of a mechanical texture test to evaluate the ripening process of Cabernet Franc grapes. *Journal of Texture Studies* 40(5), 511-535. https://doi.org/10.1111/j.1745-4603.2009.00195.x

Morlat, R., & Jacquet, A. (2003). Grapevine Root System and Soil Characteristics in a Vineyard Maintained Long-term with or without Interrow Sward. *American Journal of Enology and Viticulture* 54(1), 1. http://www.ajevonline.org/content/54/1/1.abstract

Morlat, R., Venin, G., & Jacquet, A. (1987). Influence du mode d'entretien du sol sur l'alimentation en eau de la vigne en Anjou. Conséquences agronomiques. *Agronomie* 7(3), 183-191. https://doi.org/10.1051/agro:19870305

Murisier, F., & Zufferey, V. (2004). Influence de la densité de plantation sur le comportement agronomique de la vigne et sur la qualité des vins. Essais sur Chasselas . 2. Resultats oenologiques. *Revue Suisse Viticulture, Arboriculture, Horticulture* 36(1), 45-49.

Murisier, F., Zufferey, V., & Triacca, M. (2007). Influence de l'écartement des rangs et de la hauteur de la haie foliaire sur le comportement agronomique et le développement racinaire de la vigne. *Revue Suisse Viticulture, Arboriculture, Horticulture* 39(6), 361-364.

Park, E. W., Seem, R. C., Gadoury, D. M., & Pearson, R. C. (1997). DMCAST: a prediction model for grape downy mildew development. *Viticulture and Enology Sciences* 52(3), 182-189. https://www.researchgate.net/publication/258219975_DMCast_a_prediction_model_for_grape_downy_mildew_development

Perrot, N., Baudrit, C., Brousset, J. M., Abbal, P., Guillemin, H., Perret, B., Goulet, E., Guerin, L., Barbeau, G., & Picque, D. (2015). A Decision Support System Coupling Fuzzy Logic and Probabilistic Graphical Approaches for the Agri-Food Industry: Prediction of Grape Berry Maturity. *PLoS ONE* 10(7), e0134373. https://doi.org/10.1371/journal.pone.0134373

Renaud-Gentié, C., Burgos, S., & Benoît, M. (2014). Choosing the most representative technical management routes within diverse management practices: Application to vineyards in the Loire Valley for environmental and quality assessment. *European Journal of Agronomy* 5619-36. https://doi.org/10.1016/j.eja.2014.03.002

Reynier, A. (2012). "*Manuel de viticulture : guide technique du viticulteur*," Lavoisier.

Reynolds, A. G., Wardle, D. A., Cliff, M. A., & King, M. (2004). Impact of Training System and Vine Spacing on Vine Performance, Berry Composition, and Wine Sensory Attributes of Seyval and Chancellor. *American Journal of Enology and Viticulture* 55(1), 84. http://www.ajevonline.org/content/55/1/84.abstract

Riou, C. (1994). "Le determinisme climatique de la maturation du raisin: application au zonage de la teneur en sucre dans la Communaute Europeenne.." Office des Publications Officielles des Communautés Européennes.

Rolle, L., Siret, R., Segade, S. R., Maury, C., Gerbi, V., & Jourjon, F. (2012). Instrumental Texture Analysis Parameters as Markers of Table-Grape and Winegrape Quality: A Review. *American Journal of Enology and Viticulture* 63(1), 11-28. https://doi.org/10.5344/ajev.2011.11059

Romelczyk, S. M. (2008). "Effect of Pruning Severity on 'Carlos' Muscadine Grape (Vitis rotundifolia) Yield, Quality, and Disease Incidence." North Carolina State University, Raleigh, NC, USA.

Scheff, J., & Frierson, D. M. W. (2014). Scaling Potential Evapotranspiration with Greenhouse Warming. *Journal of Climate* 27(4), 1539-1558. https://doi.org/10.1175/JCLI-D-13-00233.1

Scheiner, J. J., Vanden Heuvel, J. E., Pan, B., & Sacks, G. L. (2012). Modeling Impacts of Viticultural and Environmental Factors on 3-Isobutyl-2-Methoxypyrazine in Cabernet franc Grapes. *American Journal of Enology and Viticulture* 63(1), 94. https://doi.org/10.5344/ajev.2011.11002

Sébillotte, M. (1974). Agronomie et agriculture : essai d'analyse des t,ches de l'agronome. *Cahiers de l'ORSTOM* 243-25.

Stone, M. (1974). Cross-Validatory Choice and Assessment of Statistical Predictions. *Journal of the Royal Statistical Society: Series B (Methodological)* 36(2), 111-133. https://doi.org/10.1111/j.2517-6161.1974.tb00994.x

Tonietto, J., & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology* 124(1), 81-97. https://doi.org/10.1016/j.agrformet.2003.06.001

Ubalde, J. M., Sort, X., Poch, R. M., & Porta, M. (2007). Influence of edapho-climatic factors on grape quality in Conca de Baberà vineyards (Catalonia, Spain). *OENO One* 41(1), 33-41. https://doi.org/10.20870/oeno-one.2007.41.1.859

Ugaglia, A., Del'Homme, B., & Steffe, J. (2007). Economic evaluation of technical practices: a model of wine growing farms. *In* Proceedings of the Actes du colloque international Oenométrie XIV VDQS, IFV (eds.). Vineyard Data Quantification Society,

Valdés-Gómez, H., Celette, F., García de Cortázar-Atauri, I., Jara-Rojas, F., Ortega-Farías, S., & Gary, C. (2009). Modelling soil water content and grapevine growth and development with the stics crop-soil model under two different water management strategies. *OENO One* 43(1), 13-28. https://doi.org/10.20870/oeno-one.2007.41.1.859

van Leeuwen, C., & Friant, P. (2011). Les méthodes d'estimation de l'alimentation azotée de la vigne et des raisins au vignoble : état de l'art. *In* Colloque « l'azote : un élément clé en viticulture et en œnologie IFV (eds.). IFV, Sud-Ouest, Toulouse.

van Leeuwen, C., Friant, P., Chone, X., Tregoat, O., Koundouras, S., & Dubourdieu, D. (2004). Influence of climate, soil, and cultivar on terroir. *American Journal of Enology and Viticulture* 55(3), 207-217. <Go to ISI>://20043185584

van Leeuwen, C., & Seguin, G. (1994). Incidence de l'alimentation en eau de la vigne, appreciée par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (*Vitis vinifera*, variété Cabernet franc, Saint-Emilion 1990). *OENO One* 28(2), 81-110. https://doi.org/10.20870/oeno-one.1994.28.2.1152

Winkler, A. (1958). The relation of leaf area and climate to vine performance and grape quality. *American Journal of Enology and Viticulture* 9(1), 10-23. http://www.ajevonline.org/content/23/2/71.abstract

Wold, H. (1966). Estimation of Principal Components and Related Models by Iterative Least Squares. *In* "*Multivariate Analysis, Academic Press* " (P. R. Krishnaiah, ed.), pp. 391-420. Springer Netherlands.

Wold, S., Sjöström, M., & Eriksson, L. (2001). PLS-regression: a basic tool of chemometrics. *Chemometrics and Intelligent Laboratory Systems* 58(2), 109-130. https://doi.org/10.1016/S0169-7439(01)00155-1

Zouid, I., Siret, R., Jourjon, F., Mehinagic, E., & Rolle, L. (2013). Impact of Grapes Heterogeneity According to Sugar Level on both Physical and Mechanical Berries Properties and Their Anthocyanins Extractability at Harvest. *Journal of Texture Studies* 44(2), 95-103. https://doi.org/10.1111/jtxs.12001

Zouid, I., Siret, R., Mehinagic, E., Maury, C., Chevalier, M., & Jourjon, F. (2010). Evolution of grape berries during ripening: investigations into the links between their mechanical properties and the extractability of their skin anthocyanins. *OENO One* 44(2), 87-99. https://doi.org/10.20870/oeno-one.2010.44.2.1466