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A climatology of Vintage Port quality

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ABSTRACT: The Douro Valley of Portugal is a well-known wine region producing Port wine since the end of the 18th century, with quality table wines becoming increasingly important over the last 20 years. Port wine production is the most important economic sector of the region and Vintage Port is the top quality Port wine type, produced only from the best vintages. The purpose of this research was to examine how the variability of annual weather influences the quality of Vintage Port. A weather and climate data set for the period 1980–2009 and a consensus ranking that combined a collection of vintage chart scores into a ranking were used to characterize both the weather and the vintage quality. In order to more precisely model the weather influences on the quality of the vintages it was necessary to partition the growing season into smaller growth intervals in which several heat and precipitation variables were evaluated. The heat-related variables were defined according to the phenology of grapevines, using a partition of the growing season based on accumulated temperature, rather than on calendar dates. Precipitation variables were calculated using broad periods corresponding to the dormant, vegetative and maturation stages of the grapevines. A logistic regression model was used as a tool to identify the weather variables that help to explain the relationships between yearly weather characteristics and vintage quality. The results show that several weather characteristics are strongly associated with better quality vintages: growing season mean temperatures above the region's average, warm winters, cool July through *véraison* and cool temperatures during ripening. In summary, although the weather is not solely responsible for determining a vintage quality, it plays an important role on it; therefore, its understanding can provide invaluable management insights to growers and producers.

KEY WORDS Douro Valley; Vintage Port; vintage quality; weather variability

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1. Introduction

The Douro Valley is a wine-producing region, situated inland in the northern portion of Portugal (Figure 1), approximately 100 km from the Atlantic Ocean.

The region is well known for the production of Port wine, long considered one of the best wines in the world, but is also producing high-quality table wines, some of which have obtained top ratings in renowned wine magazines worldwide.

Climate characteristics determine the type of grapes that can be grown in a region and the types of wines that can be produced, while the weather specificities in the growing season influence the growth and productivity of the vines, the ripening of the grapes and the quality of the wine of each vintage (Jones *et al.*, 2012). Previous research has shown that the overall production and quality of the vintages in the Douro Valley is influenced by weather variability (Santos and Malheiro, 2011). Examining future conditions for the region, Jones and Alves (2012) studied the projected climatic changes in the Douro Valley and its implications on viticulture, finding potential impacts on quality, production and prices, which in turn will strongly affect the region's economy.

Understanding the linkages between weather variability and the variability of vintage quality has become an important scientific and economic research subject. Primault (1969), Winkler *et al.* (1974), Bindi *et al.* (1996), Jones and Davis (2000), Grifoni *et al.* (2006), Lopes *et al.* (2008), Gladstones (2011), Mattis (2011), Parker *et al.* (2011), Baciocco *et al.* (2014) and numerous other researchers have conducted research on modelling the relationships between meteorological variability and wine quality. Previous research results show that grapevine phenological timing and length of time between events is strongly tied to temperature-based measures such as degree-days and other bioclimatic indices (Jones *et al.*, 2005a). Other research has used the strong relationships between climate, vine growth, production and quality to examine climate change impacts (Duchêne and Schneider, 2005; Jones *et al.*, 2005b; Webb *et al.*, 2007; Schultz and Jones, 2010; Tomasi *et al.*, 2011). The results show that grapevine phenology trends earlier with climate warming (approximately 5–10 days per 1 °C of warming), with shorter interphases between events (shortening of 10–20 days), which has been related to higher sugar content,

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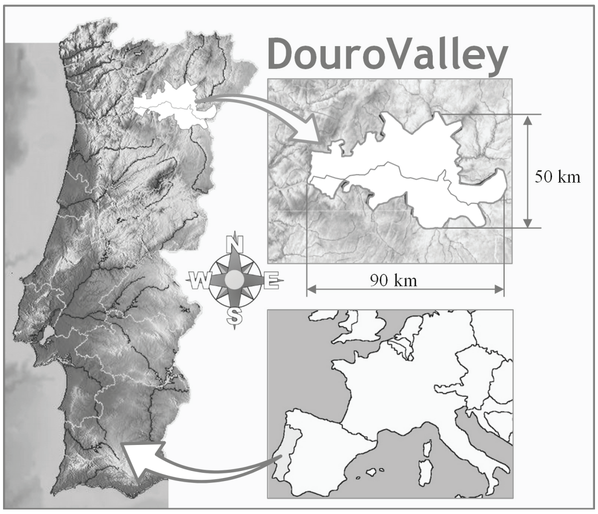

Figure 1. Portugal and the location of the Douro Valley (relief maps: www.maps-for-free.com).

lower acidity and changes in vintage ratings (often used as a proxy for quality).

Wines with the best quality result from a balance of the grapes' sugar content, the level of acidity and the level of pH at the time of harvesting. The relationship between phenology and wine quality has been studied before, but not for the Vintage Port style of Port wine. Jones and Davis (2000) make use of reference vineyard observations in Bordeaux, France, to explain the relationships between phenology, climate and composition for *Merlot* and for *Cabernet Sauvignon* varieties. Their conclusion is that the phenological timing is related to vintage quality. In addition, they observe that more important than the actual dates of each phenological event is the length of the interval between events, which gives an indication of the overall weather characteristics during those periods. Shorter intervals are associated with optimum conditions, because the rapid physiological growth and inflorescence differentiation is promoted. On the other hand, longer intervals between events indicate less than ideal conditions, because they most often lead to a delay in growth and maturation.

This paper sets out to determine and quantify the weather factors that influence whether a vintage will be of higher or lower quality. It must be stressed that this assessment is based on Vintage Port, which is produced from the very best quality grapes and only in the best years (the regulating board for the port wine trade – IVDP – allows the designation 'Vintage' only to Port wines that possess organoleptic characteristics of exceptional quality). Therefore, this research examines what sets apart the Vintage Port years that are considered exceptional, the best of the best, from those that are considered good, with regard to a better understanding of the links between the weather, grapevine phenology and Vintage Port quality.

To analyse for possible relationships between annual weather and vintage quality we used temperature data, precipitation data and ratings of quality for Vintage Port. To assess within year effects, the grapevine growing season was partitioned into smaller intervals where a set of variables were evaluated and compared among years. Instead of using the traditional calendar dates to define the boundaries of such intervals, we used the relationship between grapevine phenology and heat accumulation (van Leeuwen *et al.*, 2008) to set the interval boundaries. For vintage quality the research uses a consensus ranking based on the ratings of nine renowned vintage charts used as an unbiased measure of vintage quality (Borges *et al.*, 2012). Given the importance of vintage declarations for Port wine, the approach in this research is to examine the characteristics of annual weather profiles that promote exceptional quality vintages that helps to develop a climatology of Vintage Port wine.

2. The Douro Valley and Port wine

The Douro Valley has a total area of 250 000 ha of which 40 000 ha are planted with vineyards. The Douro River flows westward through the Douro Valley coming from Spain. Along the river, vineyards are planted on steep hillsides from the riverbanks up to 600 m in elevation. As temperature decreases, on average 5 °C per 1000 m of elevation increase (Rolland, 2003), the warmest vineyards are located at low elevations, near the Douro River or its tributaries, and typically on south-facing slopes. The geology of the Douro Valley is dominated by schistous-layered rock, oriented nearly vertical, with some outcrops of granite. Vertically oriented, schist rock allows grapevine roots to penetrate deep to find nutrients and moisture. In the summer, schist rock retains heat during the day, keeping the vine rootzone warm during the night.

The Douro Valley is sheltered from cold and wet Atlantic winds by two mountain ranges, the Marão and Montemuro, both located at its western border, and combining to enhance a Mediterranean-like climate. The region is classified as a warm temperate climate (Köppen Csb), with average annual temperatures during 1980–2009 of 15.4 °C with the average T_{min} in the coldest month dropping to 2.7 °C and the average T_{max} in the warmest month being 32.1 °C. Precipitation averages 635 mm annually, but is concentrated in the winter months with typically very dry summers.

Port wine is a fortified wine as brandy is added before the fermentation is completed, leaving some residual sugar that makes Port wine sweet and raises the alcohol to a final 20° (dry white and red wines are typically 10–15°). The choice of the ageing barrel type and the length of the ageing period will determine the Port wine type. Two broad types of Port are commonly produced: wood aged Ports, which age in various sizes of casks, vats or barrels; and bottle-aged Ports. Vintage Port, representing the very best vintages, spends some initial time in barrel, but is aged over time in bottle.

All Port wine types are blended wines. Historically the vineyards in the Douro were planted with a mix of indigenous grape varieties. For the older vineyards, winemakers are not always sure of the number or the mix of varieties being grown in each vineyard. This disorderly planting, referred to as a field-blend, is a notable element of Port wine. Vintage Port is the top, most exclusive, quality Port. It is made only in very good vintages, from perfect ripened top quality grapes, grown in the same year. Although accounting for just 1% of total Port production, Vintage Port commands the most attention from world wine markets and is usually the category of Port wine rated in renowned vintage charts.

3. Data and methods

To analyse the influence that weather variability has on the quality of the Vintage Port's vintages we collected daily data on temperature and precipitation together with yearly data on vintage quality. This section presents a description of the data sets that have been used and of the set of variables defined to characterize the weather. Additionally, the methodologies conducted to partition the growing season into smaller growth intervals and to analyze the data are described.

3.1. Weather, climate and phenology data

3.1.1. Weather data

To characterize the weather in the Douro Valley, data sets containing daily series of maximum temperature, minimum temperature and precipitation for the period 1980–2009 were collected from four local meteorological stations belonging to the Portuguese National Meteorological Service (referred to IM hereafter) – Mirandela, Pinhão, Régua and Vila Real (Figure 2). In addition, data sets for the period 2006–2014 were collected from three weather stations located at Cambres (near the city of Régua), Pinhão and Vilariça (near the city of Foz Côa) (Figure 2). These latter data sets were obtained from Associação para o Desenvolvimento da Viticultura Duriense (referred to ADVID hereafter). Data from IM (1980–2009) was used to develop the observed models, and the ADVID data sets (2010–2014) were used to test the resulting model predictions for the quality of the vintages of Vintage Port.

The IM data sets were cleaned of erroneous values using the methodology proposed by Feng *et al.* (2004) and homogenized in order to correct non-climatic jumps and changes that may have occurred due, e.g. to relocations or changes in instrumentation. The abnormal changes in the series were identified by the comparison of the values among the stations. This procedure was performed using the software package for data homogenization RHtestsV3 (Wang, 2011).

Three weather stations (Régua, Pinhão and Mirandela) were selected to represent the three generally accepted climatic sub-regions of the Douro Valley (Baixo Corgo, Cima Corgo and Douro Superior, see Figure 2). The series from the three stations were averaged in order to obtain a series that is representative of the weather and climate of the Douro Valley region for the period 1980–2009.

The ADVID data sets were collected from different weather stations, using different procedures and instruments. A procedure similar to the described earlier was used to obtain representative series for the 2006–2014 period. The period of time 2006–2009, common to both IM and ADVID data sets, was used for the homogenization of the series of the two data sets. The series from the three ADVID's stations were averaged in order to obtain a series that is representative of the weather and climate of the Douro Valley region for the period 2010–2014.

3.1.2. Phenology data

Previous research has shown that measures of accumulated heat can be used to describe grapevine growth in numerous settings and across many varieties (e.g. Lopes *et al.*, 2008; van Leeuwen *et al.*, 2008; Gladstones, 2011; Parker *et al.*, 2011). These studies use a thermal time concept that is based on the observation that each phenological event occurs when a critical amount of accumulated heat above a given critical base temperature is reached (Bonhomme, 2000). While it is generally accepted that 10 °C is the base temperature (Winkler *et al.*, 1974; Huglin, 1978; Carbonneau *et al.*, 1992), others have found that this threshold varies according to the grape variety, the location, the period of vine growth and the water status of the plants in the season of interest (Jones, 2003). One common measure of accumulated heat is growing degree-days (GDD), which is defined as the sum of the daily average temperature, T_{avg}, above a baseline temperature (10 °C is the most common). For this research, the GDD were accumulated from 1 January to a given date:

$$\mathbf{GDD} = \sum_{\mathbf{January}\ 1}^{\mathbf{Date}} \left(T_{\mathbf{avg}} - 10\ ^{\circ}\mathbf{C}\right), T_{\mathbf{avg}} \geq 10\ ^{\circ}\mathbf{C}$$

We refer to phenology data as the yearly dates of the main phenological events: budburst, flowering, *véraison* and maturity. There are no such data available covering the entire region over a long period in the Douro Valley (Real *et al.*, 2015). However, we were able to obtain the average dates of the main phenological events for vineyards near the city of Régua from ADVID, 2012, which are given in Table 1 (no information was provided on the number of years used to calculate the averages). The dates are expressed as the ordinal date that identifies the day of year, ranging from 1 to 365 starting on January 1. The main phenological events have been determined using the ADVID phenology records that are based on the Baggiolini system (Baggiolini, 1952):

i. budburst – the budding out of the vine before the floral parts develop (when 50% of vine buds are present with green leafs tips perceptible, stage 'C' of Baggiolini system);
ii. flowering – flower clusters differentiate at nodes along the clusters (when 50% of the flowers' caps have fallen off, stage 'I' of Baggiolini system);

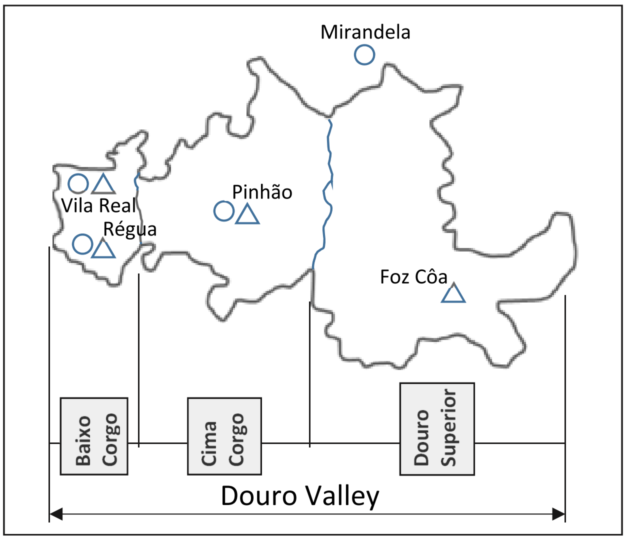

Figure 2. Location of the local weather stations. ○ IM weather station; △ ADVID weather station.

Table 1. Average ordinal dates and accumulated heat for the main phenological events.

Event	Ordinal date	Calendar date	Accumulated heat (GDD)
Budburst	79	21 March	50
Flowering	139	20 May	300
Véraison	201	21 July	1000
Maturity	254	12 September	1700

iii. *véraison* – the berries change colour from green to red-purple (when 50% of the berries in most clusters are red-purple, stage 'M' of Baggiolini system);
iv. maturity – the most subjective phenological event as it depends on the ripeness target that the winegrowers want to achieve (beginning of the harvest, stage 'N' of Baggiolini system).

The average dates of grapevine phenology in the region were used to estimate the corresponding accumulated heat that characterize the phenological moments.

In order to characterize the weather variability within the growth cycle of the vine, it is necessary to partition the season into smaller intervals in which the weather variables are evaluated and compared. A significant part of past and ongoing research on the relationships between weather and wine quality uses calendar-defined intervals to partition the growing season. The development cycle of the grapevine is usually divided into three major phases that are defined by the phenological events that determine the beginning/ending of each phase (Jones, 2003): budburst to flowering, flowering to *véraison* and *véraison* to maturity. The partitioning of the growing season used in this research was based on plant phenology in the sense that the boundaries of each growth interval were defined using the yearly estimated dates in which the accumulated heat necessary to trigger each phenological event was reached (Real *et al.*, 2015). When using such partitioning, the growth interval lengths (number of days of each interval) may be used as an indirect measure of the heat distribution and intensity in each interval. In fact, short intervals have been related to above-average heat accumulation and long intervals are related to below-average heat accumulation (e.g. Jones and Davis, 2000 and others).

Four growth intervals were defined: the three major growing phases described earlier and a preceding interval from 1 January to budburst. However, in order to characterize the variability of the heat variables along the growing season with a higher level of detail, each of the last three growth intervals was divided in two halves. As a result, the growing season was partitioned into the seven intervals presented in Table 2.

For the analysis of precipitation, a different approach was used. In fact, the utilization of intervals with varying amplitude would make it difficult to detect and interpret differences in precipitation among years. Therefore, for this analysis a calendar-based partitioning was used. For the sake of simplicity, three equal length intervals were used: the period from 1 January to 30 September was partitioned into three trimesters according to Table 2 that roughly equates to the breaking of dormancy stage, the vegetative growth stage and the maturation stage.

3.2. Weather and climate variables

In order to characterize the weather profile of each year, a set of heat-related variables and a set of precipitation-related variables were defined. In respect to heat, for each of the seven intervals, a variable that represents the number of days necessary to obtain the required accumulated heat was defined. Regarding precipitation, for each of the three precipitation intervals, a variable that represents the accumulated precipitation in the interval was defined.

In addition, in order to characterize relationships that may exist between climate and vintage quality, a variable that represents the growing season mean temperature (GST) was used. The GST variable was defined using

Table 2. Partition of the period from 1 January to the end of the growing season for heat and for precipitation modelling (weather and climate variables).

Interval	Variable	Interval boundaries	Description	Units
1 (heat)	JB0	Heat accumulation	1 January (0 GDD) to budburst (50 GDD) length	days
2 (heat)	BF1	Heat accumulation	Length of period from budburst (50 GDD) to 175 GDD	days
3 (heat)	BF2	Heat accumulation	Length of period from 175 GDD to flowering (300 GDD)	days
4 (heat)	FV1	Heat accumulation	Length of period from flowering (300 GDD) to 650 GDD	days
5 (heat)	FV2	Heat accumulation	Length of period from 650 GDD to *véraison* (1000 GDD)	days
6 (heat)	VM1	Heat accumulation	Length of period from *véraison* (1000 GDD) to 1350 GDD	days
7 (heat)	VM2	Heat accumulation	Length of period from 1350 GDD to Maturity (1700 GDD)	days
–	GST	Calendar	Gr. season mean temperature (March 1 to September 30)	°C
1 (precipitation)	PT1	Calendar	Accumulated precipitation from 1 January to 31 March	mm
2 (precipitation)	PT2	Calendar	Accumulated precipitation from 1 April to 30 June	mm
3 (precipitation)	PT3	Calendar	Accumulated precipitation from 1 July to 30 September	mm

calendar bounds for the growing season so that it refers to the same period of the year (March–September), during the analysis period of 1980–2009.

Table 2 shows the set of defined variables that have been used to characterize the weather and Table 3 presents the descriptive statistics for these variables. As expected, the precipitation amount in the winter (PT1) and in the spring (PT2) show a large variability. In addition, it is interesting to note that the date of the budburst stage (JB0) also shows a wide range of values, from day 59, which corresponds to the end of February, to day 98 which corresponds to mid-April.

3.3. Data on vintage Quality

Ratings for Vintage Port years, collected from eight renowned published vintage-charts, plus the list of vintage years published by the regulating board for the Port wine trade (IVDP) were used as input quality data (Table 4). The ratings issued by each source are presented in Table 5.

To assess the degree of consensus among vintage charts, the pairwise correlation coefficients for the normalized ratings were calculated. The scores were normalized using the following expression:

$$x_{\mathrm{i}}^{\mathrm{norm}} = \frac{x_{\mathrm{i}} - x_{\mathrm{min}}}{x_{\mathrm{max}} - x_{\mathrm{min}}}$$

The analysis of the correlations among vintage chart ratings reveals that although there is some general agreement regarding high-quality vintages, there is not widespread consensus among publishers. For example, a correlation value as low as 0.21 was obtained between Wine Advocate (WA) and Wine Enthusiast (WE) and a correlation value of 0.89 was obtained between Berry Bros & Rudd (BBR) and Wine Spectator (WS) (see Table A1).

In order to obtain an independent measure of the relative quality for the vintages in 1980–2009, the method proposed in Borges *et al.* (2012) was used and a consensus ranking was obtained (Table 6). The method makes use of a rank aggregation algorithm to combine a collection of vintage chart scores into a ranking of the vintages that represents the consensus of the input vintage charts. This ranking represents an impartial consensus of the collection of input vintage charts, in the sense that no assumption is made on how the classifications in each vintage chart were formulated. The consensus ranking for Vintage Port in 1980–2009 was used throughout this research as a relative measure of vintage quality.

3.4. Analysis methods

In order to analyse the influence of the weather variables on the vintage quality, Vintage Port years have been grouped into classes corresponding to three levels of quality: top, middle and bottom. The classes have been formed in order to keep the number of vintages in each class adequate to correspond to the occurrence of vintage year declarations for Port wine in the Douro Valley, which occurs approximately 2–3 years per decade (General Vintage Port Declaration – vintage year – is a year of an outstanding quality having the majority of the producers releasing Vintage Port). Based on the consensus ranking, the first eight vintages were assigned to class 1 (top quality vintages) and the last eight vintages to class 3 (bottom quality vintages), corresponding to 27% of the 30 vintages. The remaining vintages were assigned to middle class (see Table A2).

As quality classes have been determined by the consensus ranking of the vintages, a LOGIT regression is considered appropriate to model the probability of a vintage to fall into one of the defined quality classes. We performed a series of two separate binary logistic regressions instead of a single multinomial logistic regression (Begg and Gray, 1984): one regression to model the probability of a vintage to be a class 1 vintage (top quality) and a second regression to model the probability of a vintage to be a class 3 vintage (bottom quality). In this context, a binary LOGIT regression returns the probability that a vintage belongs to class 1 conditional on the values of the weather regressors $\boldsymbol{X}$, according to Equation (1) (class 1 may signify top quality or bottom quality, depending on the model).

$$p\,(class = 1|\boldsymbol{X}) = \frac{1}{1 + e^{-(\beta_0 + \beta \boldsymbol{X})}} \tag{1}$$

The logistic regression uses the maximum likelihood method to estimate the coefficient values for β_1, β_2, …, β_n. When the regressor X_j with a coefficient β_j, increases by one unit, controlling for the other variables, the odds, $p/(1-p)$, increase by a multiplicative amount of e^{β_j}, where p is the probability associated to class 1.

Table 3. Descriptive statistics for weather and climate variables in 1980–2009.

	Heat variables (days)								Precipitation variables (mm)		
	JB0	BF1	BF2	FV1	FV2	VM1	VM2	GST	PT1	PT2	PT3
Average	79	38	22	36	27	25	28	18.8	180	131	60
Maximum	98	58	37	53	36	30	63	20.3	718	276	153
Minimum	59	19	12	28	20	21	20	17.4	43	36	12
Standard deviation	10.0	9.0	5.7	5.6	2.8	2.4	7.5	0.7	127.6	67.4	32.6

Table 4. Sources of quality ratings for Vintage Port years.

Source	Acronym	Rating
Berry Bros & Rudd (Berry Bros and Rudd, 2013)	BBR	1–10
Decanter (Decanter.com, 2013)	DC	1–5
Instituto dos Vinhos do Douro e do Porto (IVDP, 2013)	IVDP	0–1
Michael Broadbent (Broadbent, 2007)	MB	0–5
Sotheby's Wine Encyclopedia (Stevenson, 2011)	SWE	0–100
Vintages.com (Vintages.com, 2013)	VT	0–10
Wine Advocate (Parker, 2013)	WA	50–100
Wine Enthusiast (Wine Enthusiast, 2013)	WE	50–100
Wine Spectator (Wine Spectator, 2013)	WS	50–100

The variables given in Table 2 are the regressors used in the model. In addition, in order to account for effects, which are not weather dependent (better viticulture and enological practices, better technology or changes in tasting resulting in ratings inflation or deflation), a trend variable (TRN) was included. The trend variable starts with the value 1 in 1980, growing in one-unit steps to the value of 30 in 2009.

Multicollinearity between variables was analysed using the variance inflation factor (VIF). Only variables having a VIF value less than 5.5 were kept to be used in model as potential predictors. As a result, the BF1 variable - length of period from budburst (50 GDD) to 175 GDD (see Table 2) was discarded because it had a VIF greater than 10. The remaining seven variables were maintained to be used as potential predictors. We stress that because the sample size, $N = 30$ vintages, was smaller than the recommended size of at least 100 observations for logistic regression models (Long, 1997), moderate confidence should be used in the interpretation of the regression coefficients.

4. Results

In this section, we present the results of the logistic regression models. As overall goodness-of-fit statistics, we present: (1) the logarithm of the likelihood function associated with the intercept-only model; (2) the logarithm of the likelihood function associated with the full model (the model that includes the independent predictors as well as the intercept); (3) the likelihood ratio (LR) statistic; and (4) and McFadden's R^2. A forward stepwise regression method was used to select the regressors. For each regressor the *p*-value (Pr > LR) of the significance test is given, meaning that if its value is smaller than a significance threshold (0.05 was used), the contribution of the regressor to the adjustment of the model is considered significant. The statistical analysis was performed using XLSTAT-Pro, version 5.01, 2015 (Addinsoft, Inc., New York, NY, USA).

4.1. Model for the top quality vintages

The goodness-of-fit statistics presented in Table 7 show that the model is an overall good representation of the relationship between vintage quality and weather variability. In fact, $R^2 = 0.714$ reveals a quite good accuracy, as well as the $\chi^2 = 34.944$ value that shows that the variables included in the model are significant.

Only 5 of 11 potential regressors were selected to be incorporated in the model. The significance of the five selected regressors is presented in Table 8. Interestingly, none of the three variables related to precipitation or the trend regressor have been selected to be included in the model.

Equation (2) shows the expression for the calculation of the probability of a vintage being a class 1 vintage (top quality), conditional to the regressors $\boldsymbol{X}$.

$$p\,(class = 1|\boldsymbol{X}) = \frac{1}{1+e^{-(-85.967-0.0749*\mathrm{JB0}-0.123*\mathrm{FV1}+0.399*\mathrm{FV2}+1.271*\mathrm{VM1}+2.823*\mathrm{GST})}} \quad (2)$$

4.2. Model for the bottom quality vintages

The goodness-of-fit statistics presented in Table 9 show that the model for the bottom quality is an overall good representation of the relationship between vintage quality and weather variability, although not as good as the model for top quality. A $R^2 = 0.556$ reveals a reasonable accuracy and the $\chi^2 = 27.217$ value shows that the variables included in the model are significant.

The four regressors ($\alpha = 0.05$) selected by the model are presented in Table 10. As in the model for top quality, none of the three variables related to precipitation or the trend regressor have been selected to be included in the model.

Equation (3) shows the expression for the calculation of the probability of a vintage being a class 3 vintage (bottom quality), conditional to the regressors $\boldsymbol{X}$.

$$p\,(class = 3|\boldsymbol{X}) = \frac{1}{1+e^{-(53.529+0.100*\mathrm{BF2}-0.272*\mathrm{FV2}-0.374*\mathrm{VM1}-2.091*\mathrm{GST})}} \quad (3)$$

Table 5. Original vintage chart ratings for Vintage Port for 1980–2009.

	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
BBR	7		6	8		8						7	8		9			8	6		9			8				9	1	8
DC	3		3	4		3		3				4	4		5	1	2	4	3		5	4	2	4	4	5	3	5	3	
IVDP	1		1	1		1		1		1		1	1		1			1			1			1				1		
MB	3		4	4		4		3		3	3	4	4		4	3	3	4	3	3	5	3	3	5	4	5				
SWE	85		80	95		95						95	85		95	88		90	80	75	95	86	70	94	88	80	70	95		
VT	6		7	8		9		8				9	9		10	9		10			10	8		10	9	8				
WA	84		86	92		92						90	95		92			89			92			90				93	90	94
WE					81	90	84	85	83	86	85	92	93		96	91	85	93	87	86	90	84	84	96	90	91	89	95	89	95
WS	90		84	92		93		88				93	94		99	92		96			97			98				98		

Rating source acronyms are as defined in Table 4.

4.3. Analysis of the variables included in the models

In order to compare the effects of quantitative predictors measured in different units, it is helpful to report the results by means of standardized coefficients, b_j^*, which are obtained by fitting the model replacing each X_j by its corresponding standardized value. In the standardized model, one standard deviation (SD) increase in $X_{j,}$ produces a b_j^* SD change on the logit(Y) = ln[p/(1 − p)], controlling for the other variables (Menard, 2001). The standardized coefficients for the model for top quality show that VM1 and GST are the most influential regressors on the probability of vintage quality being of high quality and that the remaining four (JB0, BF2, FV1 and FV2) are relatively less influential (Figure 3).

The model for top quality highlights the existence of relationships between the level of quality of a vintage and the magnitude of some weather variables. For example, large values of variables FV2, VM1 and GST and small values of variables JB0 and FV1 increase the probability that vintage quality will be high. This means that shorter than average periods from January 1 to budburst (JB0) as well as shorter than average first half period from flowering to *véraison* (FV1) promote good quality vintages. Small values of JB0 and FV1 are both related to temperatures that are above average during the corresponding time periods. Additionally, large values of the second half period from flowering to *véraison* (FV2), which are related to cool temperatures approaching *véraison*; large values of VM1, which are related to cool temperatures from *véraison* to maturity; and above average GST also promote high-quality vintages.

A similar analysis for the model for bottom quality reveals that the GST is the regressor most influential on the probability of vintage quality being low (Figure 3). Similarly to the top quality model, this model shows the existence of relationships between the level of quality of a vintage and the magnitude of some weather variables. Small values of variables FV2, VM1 and GST increase the probability of vintage quality being low. Shorter than average second half periods from flowering to *véraison* (FV2), which are related to high temperatures approaching *véraison*; shorter than average first half periods from *véraison* to maturity (VM1), which are related to high temperatures during the ripening period of the grapes; cool GST; and a large value of BF2, which is related to temperatures below average during the time period approaching the flowering stage, promote low-quality vintages.

4.4. Assessing model quality

Equations (2) and (3) were used to estimate the probabilities necessary to classify each of the 30 vintages in class 1 or class 3. A vintage is classified as class 1 if the probability estimated by Equation (2) is above a threshold and classified as class 3 if the probability estimated by Equation (3) is above the same threshold. If the estimated probabilities, calculated using Equations (2) and (3) are both below or both above the threshold (none of the 30 vintages in this research), then the vintage is classified as class 2. We have considered 8 vintages out of 30 belonging to class 1 (better quality) and 8 vintages out of 30 belonging to class 3 (worse quality) (see Table A2). The threshold probability was defined as $1-8/30=0.73$. Table 11 shows the summary classification table obtained from Table A3 showing that the use of the two logistic regression models produced an overall good level of accuracy in classifying the quality of the vintages.

4.5. Marginal effects of model regressors on vintage quality

In order to assess the sensitivity of the model's results to small variations on the input variables, we analysed the marginal effects of the regressors on the independent variable (see Figures 4 and 5). This analysis provides a measure of the relative impact of a variation of ±1 SD in the value of each regressor on the probability of a vintage belonging to class K (K = 1 or K = 3, depending on the model), maintaining all the other regressors at their mean value.

Figure 4 shows the change on the probability of a vintage belonging to class 1 (top quality vintages) when the value of a single regressor varies in the range −1 to +1 SD from its mean value (x-axis of the graph), maintaining all the remaining regressors at their mean values.

For example, GST represents the GST and has a mean value of 18.8 °C and a SD of 0.7 °C. Increasing GST by 1 SD, from its mean value of 18.8–19.5 °C, increases the probability of a vintage belonging to class 1 by nearly 50%. Decreasing GST by 1 SD, from its mean value of 18.8–18.1 °C, decreases the probability of a vintage belonging to class 1 by 25%.

Table 6. Consensus ranking for Vintage Port vintages in 1980–2009, sorted by rank.

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Vintage	94	07	00	03	09	97	83	85	91	92	05	04	95	89	80

Rank	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Vintage	08	82	87	01	98	06	02	99	96	90	86	84	88	93	81

Table 7. Goodness-of-fit statistics for top quality model.

Statistics	Intercept-only model	Full model	LR (χ^2)	df	Pr > χ^2
−2 Log likelihood	48.957	14.013	34.944	5	<0.0001
R^2 (McFadden)	0.000	0.714	–	–	–

Table 8. Significance analysis for the regressors.

Source	Pr > LR
JB0	0.005
FV1	0.007
FV2	0.001
VM1	0.000
GST	0.000

Table 9. Goodness-of-fit statistics for bottom quality model.

Statistics	Intercept-only model	Full model	LR (χ^2)	df	Pr > χ^2
−2 Log likelihood	48.957	21.741	27.217	4	<0.0001
R^2 (McFadden)	0.000	0.556	–	–	–

Figure 5 shows the change in the probability of a vintage belonging to class 3 (bottom quality vintages) when the value of a single regressor varies in the range −1 to +1 SD from its mean value (*x*-axis of the graph), maintaining all the remaining regressors at their mean values. For example, decreasing GST by 1 SD from its mean value of 18.8–18.1 °C, increases the probability of a vintage belonging to class 3 by over 30%.

5. Discussion and conclusions

In this research, historical daily weather data and Vintage Port ratings from a collection of vintage charts were used to examine how the variability of annual weather influences the quality of Vintage Port. A collection of heat- and precipitation-related variables were defined to characterize the weather profile of each year. Two binary logistic regression models were run in order to model the probabilities of a vintage to be a top quality vintage or a bottom quality vintage.

The model for top quality vintages reveals good accuracy and the model for bottom quality reveals reasonable accuracy. As expected, there is some overlap in the variables selected by both models (although with different signs) because they model opposite levels of vintage quality.

Interestingly, the precipitation variables were not selected to be included in any of the models, suggesting that vintage quality has a stronger link to the yearly temperature profile than to the yearly precipitation profile.

The trend variable that was used as a potential regressor to capture steady rating changes, which are not connected to weather variability or climate trends, was not selected to be included in either top or bottom quality models.

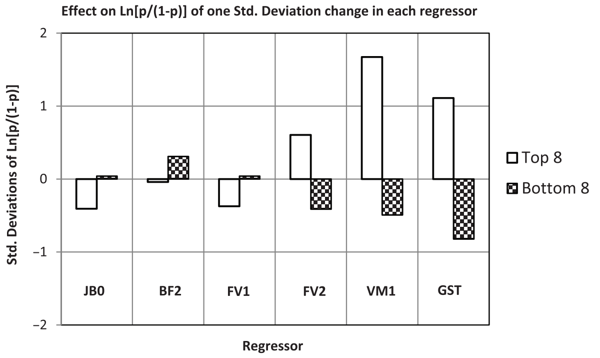

Figure 3. Standardized regression coefficients for top quality and bottom quality models.

Table 10. Significance analysis for the regressors.

Source	Pr > LR
BF2	0.003
FV2	0.002
VM1	0.002
GST	0.000

Table 11. Classification table showing the ratio of correct outputs of the logistic models in predicting the quality of the vintages in 1980–2009.

	Predicted class			
	1	2	3	
Class 1	5	3	0	8
2	0	14	0	14
3	1	3	4	8
	6	18	6	30
% Correct prediction	5/8 = 0.63	14/14 = 1.00	4/8 = 0.50	Overall correct (5 + 14 + 4)/30 = 0.77

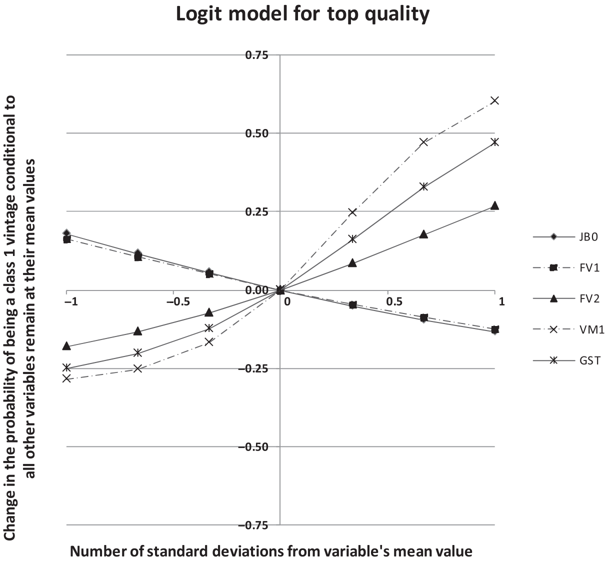

Figure 4. Marginal effects of class 1 (top vintages) model's regressors. *X*-axis ranges from −1 to +1 SD relative to the mean value of each regressor. *Y*-axis shows the impact in the probability of a vintage belong to class 1 when a regressor varies along *x*-axis, maintaining all the other regressors at their mean values.

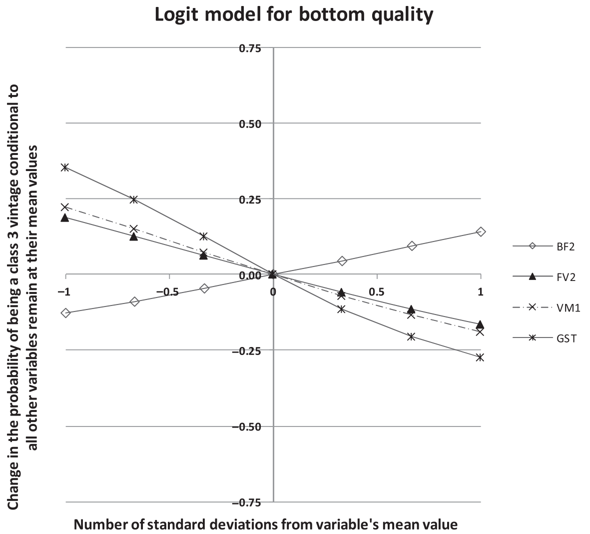

Figure 5. Marginal effects of class 3 (bottom vintages) model's regressors. *X*-axis ranges from −1 to +1 SD relative to the mean value of each regressor. *Y*-axis shows the impact in the probability of a vintage belong to class 3 when a regressor varies along *x*-axis, maintaining all the other regressores at their mean values.

The climate variable representing the GST was selected as significant by both models, promoting low-quality vintages when below average and promoting high-quality vintages when above average. Further research is necessary in order to assess if, as other research results show for several wine regions (Jones *et al.*, 2005a, 2005b), there is a maximum for the GST that, when exceeded, leads to a decrease in vintage quality.

Analysing both models allows for the development of a general weather/climate profile that promotes top quality vintages for Vintage Port: a GST above average, a warm winter that causes the budburst stage to occur earlier than average, a warm June that promotes a shorter than average first part of the period from flowering to *véraison*, a cool July through *véraison* producing a longer than average growth stage and a cool end of summer from *véraison* until harvest. These weather characteristics promote Vintage Port declarations by providing the best ripening balance in terms of sugar and acidity that will result in outstanding quality wines. The importance of winegrape sugar/acid ratios was shown by Jones and Davis (2000) in which it was found to be one of the most significant independent variables describing the overall vintage quality in Bordeaux, France. In addition, their research was able to show variety differences with the Cabernet Sauvignon ratio describing 78% of the vintage rating and the Merlot ratio describing 61% of the vintage rating.

We compared the weather variables that are associated to outstanding quality vintages for Vintage Port to the results of other researchers for different types of wines produced

Table 12. Quality prediction for the vintages in 2010–2014 period.

Vintage	*p* (Higher quality)	*p* (Lower quality)	Class prediction
2010	0.01	0.63	2
2011	0.99	0.01	1
2012	0.49	0.14	2
2013	0.03	0.74	3
2014	0.78	0.13	1

Class 1 – better; class 3 – worse.

in different wine regions and found some characteristics that coincide:

- Warm years, having a GST above the region's average, are for most regions and for most types of wines, related to better quality vintages (Jones et al., 2005a, 2005b; Grifoni *et al.*, 2006; Ashenfelter, 2008; Baciocco *et al.*, 2014; and others);
- Warm winters and cool temperatures during ripening were associated to quality vintages by Mattis (2011) in a research focused on single varietal red wines made from Pinot Noir in Sonoma County in California.

Some characteristics from this research that have not been met in other research that we are aware of include:

- A cool period until the *véraison* stage is important for quality;
- Precipitation was not a significant factor in vintage quality.

Our results indicate that cool temperatures during both (1) pre-*véraison* and (2) post-*véraison* play a role in producing the best vintages in the region. These characteristics are likely tied to lowering heat stress, which ultimately allows for optimum ripening conditions and balanced fruit (Mullins *et al.*, 1992; Greer and Weedon, 2013).

In terms of precipitation not being significant in this research, this may be explained by the fact that rain has high geographical variability and does not evenly affect all the vineyards in a region. As a result, it is possible to find vineyards having exceptional quality grapes, independent of the global average amount of precipitation in the region (Vintage Port only represents 1% of total Port wine production). Precipitation may be more influential in the association of weather to vintage quality for wine types with broader production throughout the entire Douro Valley compared to Vintage Port, such as Port wine (other than Vintage Port) and Douro red and white table wines.

To examine our model's effectiveness, we ran the model for the 2010–2014 period to obtain the probabilities of each vintage belonging to class 1 (higher quality) and class 3 (lower quality) and the corresponding quality class. At the time of this research few of the vintage chart publishers had made available the ratings for Vintage Port quality in the period 2010–2014, making it impossible to validate the model predictions. Moreover, the forecast of a class ranging from 1 (top) to 3 (bottom), for only five vintages, is not statistically significant. However, we believe it is worthwhile to present the model's prediction for the vintages in 2010–2014, which are given in Table 12. While complete ratings on Vintage Port are not available across these vintages, early assessments have praised the 2011 vintage as the best in the last 50 years (WS), while 2013 has received mixed reviews. Our model results here agree with preliminary assessments with 2011 having a high probability (0.99) of being a class 1 year and 2013 having a high probability (0.74) of being a class 3 year.

As this research focused on a 30-year time window (1980–2009), it would be prudent to study longer periods in order to better understand and confirm the relationships between vintage quality and yearly weather found here. Unfortunately, meteorological data covering the entire region over a longer time period are not available for the Douro Valley. Moreover, data on more widely distributed grapevine phenology, soil water holding capacities, pests, production, sales and vineyard area are also limited or exist only for the years after 2000. This issue highlights the need for wine regions to keep consistent data on all types of variables that may be useful for future research.

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Appendix:

Table A1. Correlation among rating sources.

	BBR	DC	MB	SWE	VT	WA	WE	WS
BBR	1.00	0.66	0.68	0.79	0.74	0.34	0.55	0.89
DC		1.00	0.71	0.48	0.33	0.58	0.54	0.63
MB			1.00	0.55	0.53	0.41	0.73	0.69
SWE				1.00	0.63	0.54	0.67	0.74
VT					1.00	0.68	0.76	0.84
WA						1.00	0.21	0.60
WE							1.00	0.86
WS								1.00

Rating source acronyms are as defined in Table 4. Shadowed cells show the two most extreme correlation values (0.21 between WA and WE, and 0.89 between BBR and WS).

Table A2. The vintages used to define class 1 and class 3 for top quality and bottom quality models are marked as 1.

Vintage	94	07	00	03	09	97	83	85	91	92	...	98	06	02	99	96	90	86	84	88	93	81
Rank	1	2	3	4	5	6	7	8	9	10	...	20	21	22	23	24	25	26	27	28	29	30
Top quality	1	1	1	1	1	1	1	1	0	0	...	0	0	0	0	0	0	0	0	0	0	0
Bottom quality	0	0	0	0	0	0	0	0	0	0	...	0	0	0	1	1	1	1	1	1	1	1

Table A3. Accuracy of the logistic models in supervised learning: correctly/incorrectly predicted vintage quality classes based on model's output probabilities for the training sample (quality ranks and weather variables in 1980–2009 period).

Model's output						Model's output					
1980	2	0.06	0.66	2	Yes	1995	2	0.51	0.25	2	Yes
1981	3	0.04	0.75	3	Yes	1996	3	0.04	0.87	3	Yes
1982	2	0.55	0.30	2	Yes	1997	1	0.74	0.03	1	Yes
1983	1	0.99	0.44	1	Yes	1998	2	0.14	0.44	2	Yes
1984	3	0.42	0.91	3	Yes	1999	3	0.23	0.40	2	No
1985	1	0.42	0.62	2	No	2000	1	0.65	0.24	2	No
1986	3	0.28	0.52	2	No	2001	2	0.71	0.54	2	Yes
1987	2	0.56	0.23	2	Yes	2002	2	0.14	0.49	2	Yes
1988	3	0.76	0.58	1	No	2003	1	0.91	0.09	1	Yes
1989	2	0.01	0.48	2	Yes	2004	2	0.08	0.45	2	Yes
1990	3	0.16	0.30	2	No	2005	2	0.16	0.20	2	Yes
1991	2	0.07	0.26	2	Yes	2006	2	0.19	0.05	2	Yes
1992	2	0.01	0.55	2	Yes	2007	1	0.85	0.10	1	Yes
1993	3	0.00	0.96	3	Yes	2008	2	0.24	0.47	2	Yes
1994	1	0.50	0.56	2	No	2009	1	0.98	0.05	1	Yes

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