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Grapevine yield and wine quality in ancient Spanish Pyrenean vineyards: Influence of climatic and physiographic parameters

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Summary

Climate, edaphic, and physiographic parameters influence wine quality. In this study, we evaluated if climate and sediment connectivity had an effect on the grapevine yield (GY) and wine quality of three ancient (more than 100 years old) vineyards, with 'Garnacha Tinta' variety, managed using the head-pruned system, and during three agronomic years (October 2015 - September 2018). The three rain-fed vineyards are managed using the head-pruned system and named VA (1233 vines), VB (1584 vines) and VS (897 vines). They are located in the Spanish Pyrenees, with oceanic Mediterranean climate, have the same soil type (Haplic Cambisol) and the soil is ploughed to prevent weeds. GY ranged from 380 to 2646 kg·ha^{-1}, and from 0.08 to 0.60 kg·vine^{-1}. The annual production significantly correlated with the total annual rainfall (positive), and with the air temperature during the growing period (negative). A frozen spell and intense rainfall events in spring explained the lower GY observed in 2017 and 2018, respectively. We observed a good correlation between GY (kg·ha^{-1}) in 2018 and wine parameters such as, pH (*r* = 0.992), titratable acidity (*r* = -0.862), malic acid (*r* = 0.979), and potassium (*r* = 0.998). Annual runoff and sediment connectivity was estimated at each field (and its upslope drainage area) using the aggregated index of connectivity (*AIC*) at high spatial resolution (1 m of cell size). The lowest connectivity was found in VB, whereas VA and VS presented moderate and high values of connectivity, respectively. *AIC* correlated very well and negatively with GY (kg·ha^{-1}, *r* = -0.955; and kg·vine^{-1}, *r* = -0.972). Higher connectivity - intense overland flow dynamic - favoured lower yield. We concluded that the climate parameters mainly explained the temporal changes of GY, whereas distinct overland flow connectivity clearly influenced the spatial variations of GY under the same climatic conditions.

K e y w o r d s : ancient vineyard; grapevine yield; wine quality; 'Garnacha Tinta'; sediment connectivity.

Introduction

Grape's sugar level, canopy cover and vineyard yield are influenced by climatic parameters, such as temperature and soil water content (Martínez De Toda and Balda 2013, Ferlito *et al.* 2014). At field scale, the soil physical and chemical properties of the different soil horizons, such as the water-holding capacity, permeability, and water extractable organic carbon, influence vineyard performance, plant vigour and wine quality (Unamunzaga *et al.* 2014, Novara *et al.* 2018). Topography, lithology and soil erosion (net soil loss, delivery and deposition) cause the spatial variability of soil depth and contribute to the spatial redistribution of the different particle size fractions, nutrients and organic carbon in the topsoil. The combined analysis of the soil-plant parameters and the hydrological response of the soil can detect changes in vineyard fertility, and vine vigour. At large scale, a significant relationship was observed between the presence of rough morphologies and high environmental variability, and the limited quantity and quality of wine yield. Besides, heterogeneous soil and morphological conditions fitted well with relatively low quality production (Costantini *et al.* 2016). Vineyards and orchards are part of the most exposed agricultural systems deteriorated by soil erosion processes (Cerdan *et al.* 2010). Recently, Rodrigo-Comino *et al.* (2018) assessed with field (improved stock unearthing method, ISUM) and LiDAR (Light Detection and Ranging) techniques different sediment connectivity (water-mediated transfer of soil particles) rates in the inter-row (predominant depletion) and row (predominant accumulation) areas in Mediterranean vineyards. The magnitude of sediment connectivity in sloping vineyards depends on several topographic factors, such as the contributing area, the flow width, the soil roughness, and the convergence index (local concentration or dispersion) (López-Vicente and Álvarez 2018).

The soil of the inter-row areas in woody crops can be managed as conventional tillage (CT: plough and/or herbicide application), or with vegetation cover (PC: spontaneous vegetation or cover crops). Higher runoff and soil erosion rates are commonly observed in European vineyards under CT than under PC (Rodrigo-Comino *et al.* 2016), despite the use of cover crops has been prescribed for soil and water conservation and as a mitigation measure for offsite contamination, as they reduce sediment and agrochemical loads, thus reducing the hydrological connectivity of the land (Burguet *et al.* 2018). In the Autonomous Community of Aragon (NE Spain), only 8 % of vineyards use plant cover and 10 % have no tillage practices; the remaining vineyards are managed with CT (source: Spanish Ministry of Agriculture; MAPA-ESYRCE). Thus, the study of the

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correlation between sediment connectivity and grapevine yield (GY) and wine quality is necessary to highlight the interrelationship between both systems.

In this study we aim to evaluate the influence of climatic and physiographic parameters on the changes in GY and wine quality in a set of fields planted with the same variety and similarly managed. To achieve this goal we selected three ancient vineyards in the Spanish Pyrenees, located in the same valley, and measured several parameters of GY during three agronomic years and of wine quality during one year. The climatic variables were analysed at monthly scale, and the overland flow processes were evaluated by means of running the aggregated index of runoff and sediment connectivity (*AIC*) at annual scale and high spatial resolution. The statistical analysis of the data allow understanding the relative role played by the climatic and physiographic components. The results of this study are of interest to viticulturists and landowners, and for agronomic and environmental studies.

Material and Methods

S t u d y s i t e a n d t e s t p e r i o d : Three ancient commercial vineyards were selected to perform this study, which are called 'Viña Ángel' (VA; 2784 m^2; 23 rows; ca. 1233 vines; at 728 m a.s.l.; 42° 36′ 14″ N, 0° 43′ 34″ W), 'Viña Balén' (VB; 3786 m^2; 24 rows; ca. 1584 vines; at 673 m a.s.l.; 42° 36′ 23″ N, 0° 43′ 44″ W), and 'Viña Sarnés' (VS; 1934 m^2; 29 rows; ca. 897 vines; at 706 m a.s.l.; 42° 37' 50"N, 0° 42′ 59" W). The three rain-fed fields are located in the Spanish Pyrenees, in the province of Huesca, between the villages of Javierregay and Embún, and are farmed by BAL MINUTA winery (Fig. 1). The three fields are located in the Aragón Subordán River valley, at short distance between them, and had a mean slope steepness of 16.9 % (VA), 19.8 % (VB) and 21.4 % (VS). The three vineyards

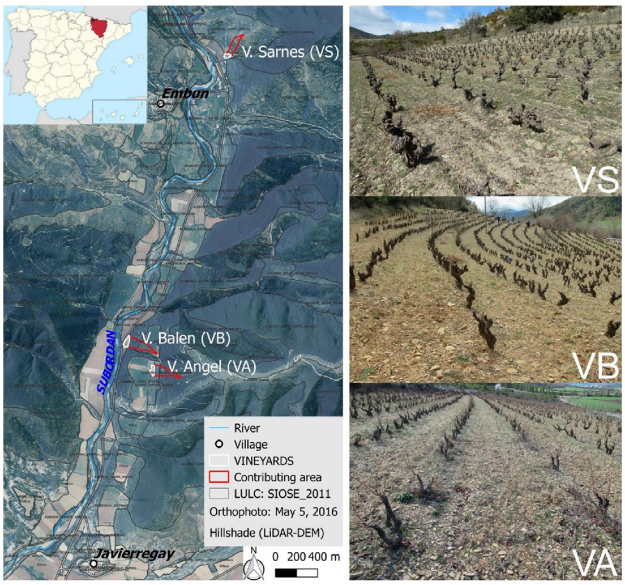

Fig. 1: Location of the study area in Huesca province (NE Spain), and of the three vineyards and their upslope catchment areas near the Aragón Subordán River. Pictures of the three fields at the end of winter are also shown.

are cultivated with the Spanish variety 'Garnacha Tinta' (*Vitis vinifera* L.). Vines were planted over 100 years ago (personal communication of the landowner) and have been managed using the head-pruned system. The plantation density is similar between the three fields: 4429, 4184 and 4639 vines·ha^{-1} in VA, VB and VS, respectively.

The inter-row areas of the vineyards were managed as conventional tillage consisting of two chisel plough passes every year, usually in spring, at 10-15 cm depth, and without herbicide application, to control weed growth. Thus, the percentage of the soil surface protected by vegetation remained below 10-15 % during all the year. In the three fields, the distance between rows is ca. 2 m and the distance between the vines of the same row is ca. 1 m. The mean (± standard deviation) height of the pruning point was 40 ± 6, 56 ± 9 and 51 ± 8 cm in VA, VB and VS, respectively. The soil of the three fields is classified as Haplic Cambisol with a significant content of coarse fragments, ca. 16 % per volume (source: https://soilgrids.org/). Soil bulk density ranges between 1.1 (topsoil) and 1.4 (at 60-cm depth) g·cm^{-3}; and soil texture is loam. The soil organic carbon content ranges between 6 % (topsoil) and 1.4 % (at 60-cm depth). We did not observe significant changes in the soil physical and chemical properties among the three fields. Any rill or ephemeral gully effects the soil surface, except in the vineyard boundary of VS although this rill did not affect the vineyard plantation. The upslope contributing areas (UpA) of VA and VS are directly connected with the vineyards, without any obstacle for overland flow, whereas the UpA of VB appears partially separated from the field due to the presence of a dry-stone wall. This wall does not isolate the field but may reduce runoff velocity and thus overland flow connectivity (Fig. 1).

The climate is oceanic Mediterranean with a mean annual temperature of 9.6 (± 15 %) °C, during the last ten agronomic years, from October 2008 to September 2018; with six months, from November to April, with a mean temperature between 1.2 °C (February) and 7.9 °C (April). The mean annual rainfall was 746 mm, with an interannual oscillation of 167 % (475 mm on average in 2014/2015 and 1269 mm in 2012/2013). Rainfall was well distributed along the year, although 24 % was concentrated in two months, October and November. The mean accumulated rainfall during the growing season, from April to September, was 329 mm. Thunderstorms were common during the summer and occasional snowfall events took place in winter (data source: Ebro river water authorities - CHEbro-SAIH; and Regional irrigation bureau - "Oficina del Regante").

The test period (TP) of this study lasted three agronomic years: from October 2015 to September 2018. During TP the annual rainfall and potential evapotranspiration (ET_0) were 788, 677 and 752 mm, and 1191, 1219 and 1148 mm, respectively. The mean annual temperature was 11.2, 11.8 and 10.9 °C. Thus, the three years had hydrological deficit. During the growing season, from April to September, the accumulated precipitation was 374, 291 and 474 mm, respectively; and the mean temperature was 15.8, 16.8 and 16.3 °C.

G r a p e v i n e y i e l d a n d w i n e c h e m i c a l c h a r a c t e r i z a t i o n : The harvesting dates were similar in the three years: the last week of September in 2016 and 2018, and the first days of October in 2017. We did not have data of 'Viña Sarnés' in 2016 because this field was not managed by Bal Minuta winery this year. Grapes were hand harvested into 15-kg baskets and immediately carried out to the winery, weighted and processed. Winemaking was carried out in Bal Minuta winery following its manufacture conditions. In 2018, wine samples were taken after approximately two months and at half of harvest time for further chemical analysis.

The chemical analysis was only done with the wine produced in 2018. We measured the following parameters: relative density, alcoholic grade (%: v v^{-1}), total dry extract ($g·L^{-1}$), pH, titratable acidity (grams of Tartaric acid·L^{-1}), volatile acidity ($g·L^{-1}$), reducing sugars ($g·L^{-1}$), malic and lactic acids ($g·L^{-1}$), potassium ($mg·L^{-1}$), the colour intensity, and the total polyphenol index (TPI) OD 280. Two samples were used for the analyses performed in the 'Laboratorio Agroambiental' (Government of Aragon) according to the standard laboratory procedures, which are accredited according to ENAC (Entidad Nacional de Acreditación).

Aggregated index of sediment connectivity: In this study, we used the aggregated index of flow and sediment connectivity (*AIC*; López-Vicente and Ben-Salem 2019) to study spatial and temporal dynamics of flow and sediment connectivity. This index is based on the Borselli's *et al.* index of structural runoff and sediment connectivity (2008) and on the modifications proposed by Cavalli *et al.* (2013). The aggregated index added new factors related to rainfall erosivity, soil permeability, and residual topography as well as introduced the temporal component (variability) of the precipitation and vegetation parameters to model functional connectivity. The three mentioned indices include two modules for each pixel. The downslope module (D_{dn}) contemplates the probability that runoff and sediment arrive at a defined sink along the flow path. The upslope module (D_{up}) represents the potential for downward routing of overland flow occurring upslope and also implements a "stream power"-like approach, taking into account six physiographic parameters:

$$AIC_k = \log_{10}\left(\frac{D_{up,k}}{D_{dn,k}}\right) = \log_{10}\left(\frac{\overline{R_t} \cdot \overline{RT} \cdot \overline{C_t} \cdot \overline{K_p} \cdot \bar{S} \cdot \sqrt{A_k}}{\sum_k^n = i\,\frac{d_i}{AWC_i}}\right) \quad (1)$$

$$AWC_i = R_{ti} \cdot RT_i \cdot C_{ti} \cdot K_{pi} \cdot S_i \quad (2)$$

where A is the upslope contributing area (m^2), AWC is the aggregated weighting factor at catchment or sub-catchment scale, R_t is the normalized rainfall erosivity factor for the period t (values between 0-1), RT is the residual topography factor (normalized values between 0 and 1), C_t is the vegetation and crop management factor for the period t (values between 0-1), K_p is the soil permeability factor (normalized values between 0 and 1), and S is the slope gradient (m m^{-1}). The subscript K indicates that each cell "i" has its own AIC value. This index is defined in the range of $[-\infty, +\infty]$ and connectivity increases when AIC grows towards $+\infty$. The weighted flow path length and upslope factors were calculated with the D-infinity flow accumulation algorithm (*SAGA© 2.1.2 64 bit*). More details about the estimation of each factor, such as equations and value normalization, can be found in López-Vicente and Ben-Salem (2019).

The index parameterization included several tasks. We generated two LiDAR-derived DEMs (one for VA and VB, and another for VS) at high spatial resolution, 1 m of cell size, by using the available point cloud (source: Spanish Geographic Institute - IGN; http://centrodedescargas.cnig.es/CentroDescargas/index.jsp#) and several tools of *LAStools* and *ArcGIS© 10.3* software. Before computing *AIC*, the continuity of the flow path lines across the entire hillslopes and in the fields was guaranteed by removing the local depressions (artifacts) using the Planchon and Darboux algorithm (available in *SAGA© 2.1.2 64 bit*). This algorithm imposes a gradient to avoid the typically unrepresentative flat surfaces induced by other sink-filling tools. We considered that a minimum gradient of 0.01° would enable flow routing across the filled sinks. The boundary of the upslope contributing area of each field was calculated from the field border upwards using the flow accumulation map.

Rainfall erosivity was calculated for TP by using precipitation records, every 15 min, from two weather stations located next to the fields (data source: CHEbro-SAIH; codes A061 and R033). The residual topography factor, RT in equation (2), was estimated as the normalized and inverse values of the standard deviation of the slope gradient (SSD). The map of SSD was generated with the 'Residual Analysis (Grid)' tool (*SAGA© 2.1.2 64 bit*), with a radius of 2 cells (including the centre cell). We considered a minimum RT value of 0.001 to avoid computational errors. The C_t factor of equation (2) reflects the effect of cropping and management practices of the different land uses on the soil erosion rates. This factor is equal to the C-factor of the RUSLE (bi-monthly time step; Renard *et al.* 1997) and RUSLE2 (daily time step; USDA 2008) soil erosion models. The SIOSE Spanish land cover map (year 2011) was freely obtained from the IGN, and 5 different land uses were distinguished with 8 polygons. Annual RUSLE C-factors were obtained from Panagos *et al.* (2015) for the vineyards and the land uses of the upslope contributing areas (herbaceous crop, pastures, coniferous forest, and agricultural areas mixed with disperse scrubland). Although the C-factors could change over the 3-year test period (TP) owing to several reasons (e.g. different plant growth and canopy covers during the wet and dry years), we did not consider temporal changes in the C-factors, as we did not observe any significant evolution of the vegetation cover. Thus, constant C-annual factors were used during TP.

The K_p factor allows evaluating the influence of the soil physical properties on the runoff and sediment connectivity at catchment or large scales where significant spatial changes appear between the values of soil water infiltration and the soil water retention capacity. As the total area of the three fields and their upslope contributing areas is small, 5.2 ha, and the three fields have the same type of soil, we did not consider spatial changes in the K_p factor. In equation (2), slope steepness of less than 0.005 must be adjusted to S_i = 0.005 and those higher than 1 must be set to a maximum value of 1. During AIC computation, the bottom of each field was considered as the target of the simulation. We chose this criterion to avoid the influence of the downslope component from the bottom of the vineyards to the Aragón Subordán River.

Statistical analysis and metrics: The mean, minimum, maximum, standard deviation and error were calculated for the grapevine yield, wine quality indicators and physiographic - including runoff and sediment connectivity - parameters of each field and year. Linear (Pearson) and non-linear correlations between the data of the different parameters were done with *SigmaPlot*© *13.0* software at *p*-value ≤ 0.05 (significantly) and ≤ 0.01 (very significantly) using the Shapiro-Wilks test for normality. Based on the wine quality indicators, we did a principal component analysis (PCA), with *R* free software environment for statistical computing and graphics, in order to cluster the different measured wine parameters of the three fields.

Results and Discussion

Vineyard productivity: The total grape production (GP) of the three fields clearly changed during TP. The GP of VA and VB reached 736.5, 265.5 and 413.0 kg, and 927.0, 806.0 and 542.5 kg in 2016, 2017 and 2018, respectively. The GP of VS added up to 73.5 and 346.5 kg in 2017 and 2018, respectively (data source: Bal Minuta, 2018). The highest production was obtained in 2016 (832 kg·field^{-1}) and the lowest in 2017 (382 kg·field^{-1}). The low values of GP in VA and VS in 2017 were explained by an intense frozen spell that happened after vine sprouting. This climatic event did not affect the vines of VB because sprouting in this field took place after this spell. On average, the GP in 2018 (434 kg·field^{-1}) was higher than in 2017 but lower than that obtained in 2016 owing to the influence of intense rainfall events that damaged the bunches during flowering. The total rainfall depth (R) and erosivity (EI_{30}) in May and June in 2018 was 227 mm and 330 MJ mm·ha^{-1}·h^{-1}, respectively, these values being much higher than those of R and EI_{30} in 2016 (69 % and 73 % higher) and 2017 (37 % and 20 % higher) (Fig. 2). Besides, powdery mildew slightly affected vineyards in 2018. Apparently, no adverse climatic event affected the vines in 2016. We observed a very high and positive correlation between the annual values of R and the average annual GP of the three fields (r = 0.995; p < 0.0001), whereas no correlation was found between the values of R during the growing season and those of the GP (r = 0.053; p < 0.0001). This correlation, related to the precipitation, decreased when rainfall erosivity (EI_{30}) was considered instead of R, due to the negative effects of soil erosion on the GP. Regarding temperature (T), we found a high and negative linear correlation between the average annual GP and the mean T during the growing season (r = -0.941; p < 0.0001), and a weak correlation with the mean annual T (r = -0.240; p < 0.0001). As most vineyards are located in areas with Mediterranean or temperate climate, with marked seasonal variability, our results are of international interest.

In order to compare the grapevine yield (GY) of the three fields, we calculated the mean values for GY per ha (GY-ha), and vine (GY-v). 'Viña Balén' (VB) had the highest mean values (2004 kg·ha^{-1}, and 0.48 kg·vine^{-1}), followed by VA (1694 kg·ha^{-1}, and 0.38 kg·vine^{-1}), and VS (1086 kg·ha^{-1}, and 0.23 kg·vine^{-1}) (Fig. 3). All these values were lower than those of GY-ha obtained in rain-fed vineyards by the year 2018 in Huesca province (3500 kg·ha^{-1}), the Autonomous Community of Aragon (5283 kg·ha^{-1}), and Spain (5986 kg·ha^{-1}) (data source: Spanish Ministry of Agriculture - MAPA 2018). Related to GY-v, our results were markedly lower than those values obtained by Balda (2014) in vine-

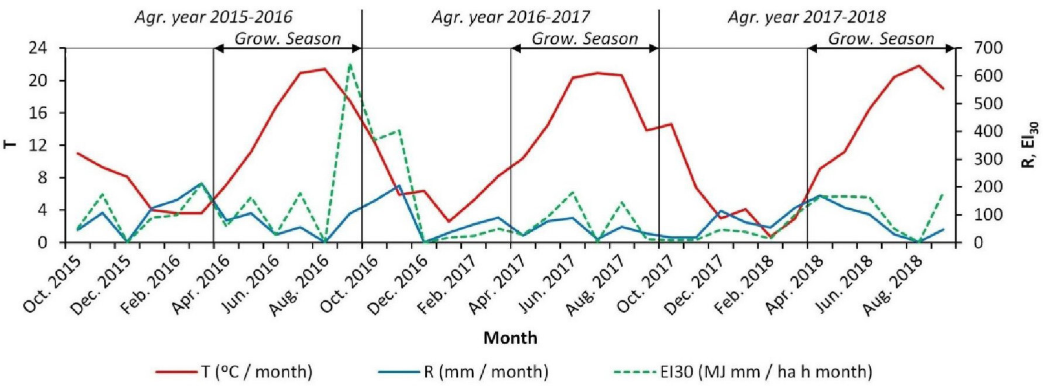

Fig. 2: Monthly values of temperature (T), rainfall depth (R), and erosivity (EI_{30}) during the test period.

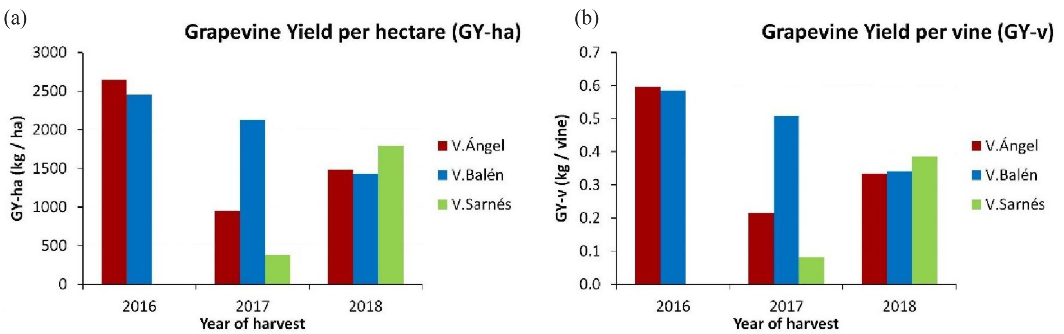

Fig. 3: Grapevine yield per ha (**a**) and vine (**b**) in the three fields and during the test period.

yards with 'Garnacha Roya' variety, in Navarre (NE Spain), with mean values between 4.2 and 7.4 kg·vine^{-1} in 2009 and 2010, respectively. Also in Navarre, Rodríguez-Lorenzo *et al.* (2019) found mean values of GY in vineyards with 'Garnacha Blanca' variety between 2.3 and 3.8 kg·vine^{-1}.

Table 1

Mean ± standard error values of the main chemical parameters of the wine from the three 'Garnacha Tinta' vineyards (GT), and the three international references: 'Coupage-White' (C.White: mix of 'Chardonnay', 'Gewürztraminer', and 'Riesling' varieties), 'Cabernet Franc' (CF), and 'Pinot Noir' (PN); all harvested in 2018

Wine	AlcG	TDS	pH	TAc	VAc	RS	MAc	LAc	Colour	TPI	Potassium
	(% v·v^{-1})	(g·L^{-1})	(-)	(g TA·L^{-1})	(g·L^{-1})	(g·L^{-1})	(g·L^{-1})	(g·L^{-1})	Intensity	(-)	(mg·L^{-1})
GT_VA	15.42 ± 5E-3	28.7 ± 4E-2	3.11 ± 1E-7	9.83 ± 4E-2	0.41 ± 1E-2	1.57 ± 5E-3	0.90 ± 5E-3	0.050 ± 1E-7	16.73 ± 5E-2	60.85 ± 4E-1	6.31 ± 8E-2
GT_VB	14.13 ± 5E-3	27.0 ± 5E-3	3.11 ± 1E-7	9.63 ± 2E-2	0.33 ± 5E-3	1.07 ± 1E-2	1.10 ± 1E-7	0.190 ± 1E-7	9.22 ± 2E-2	46.70 ± 3E-1	6.70 ± 9E-2
GT_VS	14.92 ± 5E-3	28.6 ± 1E-7	3.21 ± 5E-3	9.50 ± 4E-2	0.36 ± 1E-7	1.37 ± 1E-7	1.51 ± 1E-2	0.055 ± 5E-3	10.39 ± 2E-2	58.65 ± 3E-1	8.22 ± 1E-1
C.White	12.61 ± 1E-7	22.7 ± 1E-2	2.96 ± 1E-7	10.65 ± 2E-2	0.42 ± 5E-3	0.85 ± 1E-7	2.74 ± 1E-7	0.015 ± 1E-7	1.98 ± 3E-3	10.70 ± 1E-7	5.34 ± 5E-2
CF	12.38 ± 5E-3	28.8 ± 3E-2	3.13 ± 5E-3	9.69 ± 3E-2	0.24 ± 5E-3	1.15 ± 1E-7	2.61 ± 5E-2	0.110 ± 1E-2	17.19 ± 4E-2	72.70 ± 5E-1	7.93 ± 1E-1
PN	14.28 ± 5E-3	28.4 ± 3E-1	3.35 ± 1E-7	8.39 ± 6E-2	0.45 ± 2E-2	1.28 ± 3E-2	0.12 ± 5E-3	1.630 ± 5E-3	12.84 ± 3E-2	54.70 ± 5E-1	8.75 ± 2E-1

AlcG: Alcoholic grade; TDS: Total dry extract; TAc: Titratable acidity; VAc: Volatile acidity; RS: Reducing sugars; MAc: Malic acid; LAc: Lactic acid; TPI: Total polyphenol index 280; *: Tartaric acid. Systematic errors reported by the accredited laboratory not shown.

Chemical wine characterization: The wine chemical parameters from the three vineyards are shown in Tab. 1. All samples showed the same relative density (around 0.99 g·mL^{-1}) but concerning the other parameters, small differences were found among the vineyards. The malic/lactic acid ratio indicated that at the time of the chemical analysis fermentation was still incomplete. The chemical analysis of the VB wine showed slight differences in TDS, RS and TPI compared to VA and VS wines. All wines showed moderate alcohol content, and adequate colour intensity that is appropriate to produce red quality wines in the Protected Designation of Origin (PDO) of Aragón.

The PCA analysis of the 'Garnacha Tinta' wines from VB, VS and VA vineyards, along with the references added in Tab. 1 ('Coupage-White', 'Cabernet Franc', and 'Pinot Noir') are distributed in Fig. 4 along the wine chemical parameters. The wines of the three international references added in the PCA analysis were also produced by Bal Minuta winery, and were included in order to make the statistical analysis more robust and of international interest. 'C.White' is a coupage of wines of 'Gewürztraminer', 'Chardonnay', and 'Riesling'. VB-wine showed lower values for TPI-280 than VS and VA wines; as consequence, in the PCA, VB-wine was in the opposite side to TPI-280 (called 'IPT' in the chart).

We observed a good and positive relationship between the values of GY-ha in 2018 in the three fields, and those of pH (r = 0.992; p < 0.0001), and potassium (r = 0.998; p < 0.0001), and a negative relationship with those of titratable acidity (r = –0.862; p < 0.0001). A moderate relationship (Pearson's r ca. 0.5) was found with the values of total dry extract, lactic acid, colour intensity, and TPI-280. The relationship was weak (r < 0.3) with the alcoholic grade, volatile acidity, and reducing sugars. These results were consistent with those obtained by Balda (2014). Further statistical analysis will include the wine's and must's parameters of more harvests.

Runoff and sediment connectivity: The values of the aggregated index of runoff and sediment connectivity (*AIC*) clearly changed between the different vineyards and in a minor way over the test period (Tab. 2). On average, the lowest overland flow connectivity was found in VB (-4.581), whereas VA (-4.012) and VS (-3.633) presented moderate and high values of connectivity, respectively. These values correlated very well with those of GY-ha (r = –0.955; p < 0.0001), and GY-v (r = –0.972; p < 0.0001). Thus, higher values of sediment connectivity – intense overland flow dynamic – favoured lower values of grapevine yield (GY). These results totally agreed with those reported by Costantini *et al.* (2018) after evaluating the negative effects of soil erosion on grape yield in nineteen European and Turkish vineyards. Ben-Salem *et al.* (2018) also found higher values of connectivity in rainfed vineyards, under semi-arid conditions, in those fields with higher observed rates of runoff and sediment yield. Prosdocimi *et al.* (2017) obtained in a Mediterranean vineyard, located in eastern Spain, at very fine scales, comparable results, in terms of accuracy and magnitude, between the index of connectivity, soil loss estimated with the surface elevation change-based method, and plots with simulated rainfall. On a temporal scale, the annual values of *AIC* increased with

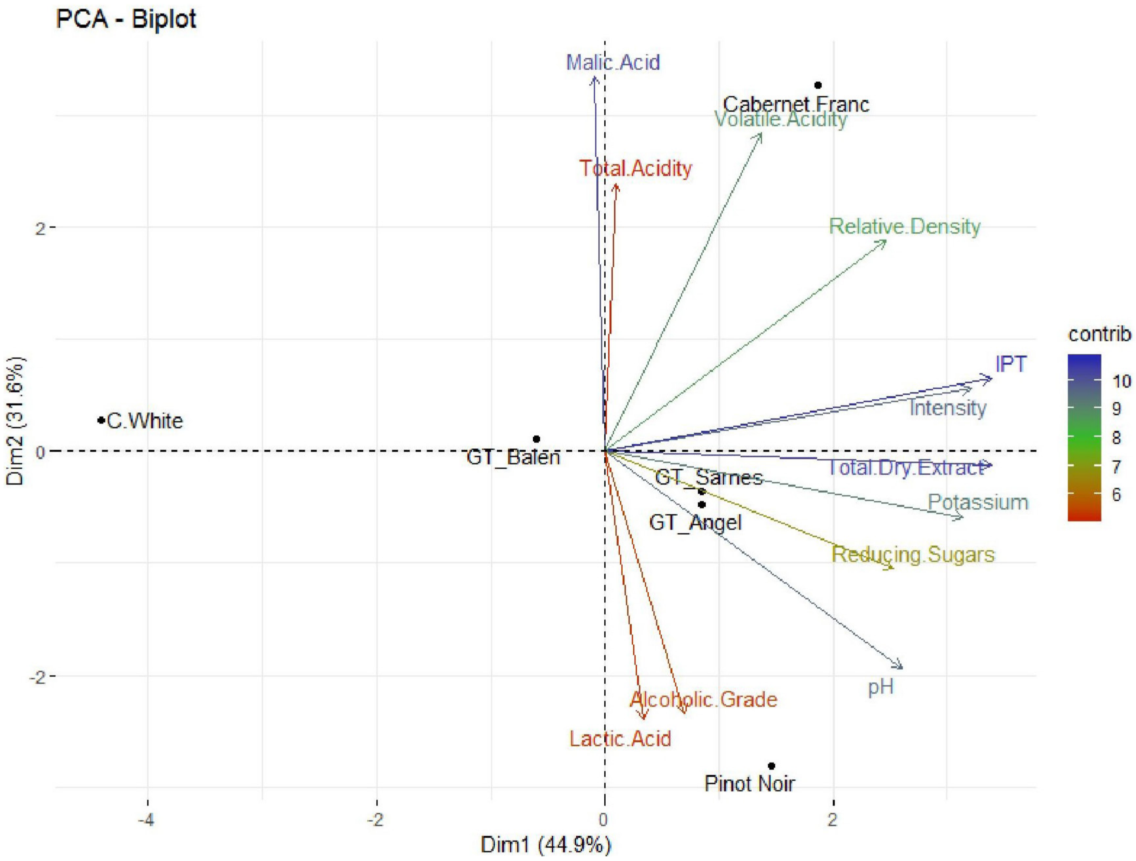

Fig. 4: Principal component analysis (PCA) biplot for wines from the three vineyards, and chemical parameters. 'GT_Balen', 'GT_Sarnes', and 'GT_Angel' in the chart represent the 'Garnacha Tinta' of the three vineyards. 'C.White', 'Cabernet Franc' and 'Pinot Noir' are included in the analysis as international references. 'C.White' is a *coupage* of wines of 'Gewürztraminer', 'Chardonnay', and 'Riesling'. On the right side, the legend colour represents the contribution of each parameter.

Table 2

Physiographic characteristics of the three fields and their upslope contributing areas, and estimated values (mean ± standard deviation) of runoff and sediment connectivity during the test period

Vineyard	Area	Slope	C-RUSLE	*AIC*		
	m^2	%	[0-1]	Year 2015-16	Year 2016-17	Year 2017-18
VA – field	2,784	16.9	0.3963	-3.770 ± 0.375	-3.984 ± 0.375	-4.282 ± 0.375
VA – UpA	14,947	33.6	0.0323	-7.267 ± 1.781	-7.481 ± 1.781	-7.780 ± 1.781
VA – ratio UpA·field^{-1}	5.4	2.0	0.08	1.93	1.88	1.82
VB – field	3,786	19.8	0.3963	-4.339 ± 0.534	-4.553 ± 0.534	-4.851 ± 0.534
VB – UpA	17,082	30.7	0.0825	-7.081 ± 1.102	-7.295 ± 1.102	-7.594 ± 1.102
VB – ratio UpA·field^{-1}	4.5	1.6	0.21	1.63	1.60	1.57
VS – field	1,934	21.4	0.3963	-3.391 ± 0.563	-3.605 ± 0.563	-3.904 ± 0.563
VS – UpA	11,249	48.7	0.1330	-4.236 ± 0.505	-4.450 ± 0.505	-4.749 ± 0.505
VS – ratio UpA·field^{-1}	5.8	2.3	0.34	1.25	1.23	1.22

UpA: upslope contributing area; *AIC*: aggregated index of connectivity.

increasing the annual rainfall depth ($r = 0.680$; $p < 0.0001$). This relationship was expected as *AIC* depends on rainfall erosivity. However, this result might be inconsistent with the previous results of increasing grape production with increasing precipitation. Thus, we can conclude that *AIC* is a good approach to predict spatial changes of GY although it is not a good tool to evaluate temporal dynamics of GY.

Related to the data of the chemical parameters of the wine produced in 2018 at each field, we observed a good correlation between the values of *AIC* and those of the total dry extract ($r = 0.903$; $p < 0.0001$), the lactic acid ($r = –0.905$; $p < 0.0001$), and TPI-280 ($r = 0.851$; $p < 0.0001$). The correlation was weak with the titratable acidity, and the colour intensity; whereas a moderate correlation was found with the remaining chemical parameters. Further research, including the data of the wine that will be produced in the next years, is necessary to evaluate the potential correlation between the overland flow processes and the wine quality indicators. Ongoing and further research will create a more complete database, with more agronomic years, to extend the analysis performed in this study.

The maps of runoff and sediment connectivity showed the complexity of the spatial patterns of overland flow processes (Fig. 5). The relative influence of the different land uses (the C-RUSLE factor), and the topographic characteristics (*RT*, *S* and *A* factors) of the upslope contributing area explained these spatial patterns. Further research should be focussed on a better characterisation of the soil properties, such as the total and effective hydrological depth, and detailed maps of soil water infiltration, as well as to assess the eventual changes in the soil texture and coarse fragments in the different soil horizons.

Conclusions

The total grape production clearly changed between the three fields and during the three agronomic years. On the one hand, the mean grapevine yield per hectare and vine of the three fields was lower than the average yield observed in other vineyards with 'Garnacha' variety in northern Spain. On the other hand, the temporal variability of the vineyard yield was successfully explained by climatic parameters, such as the annual rainfall depth, the mean air temperature during the growing period, the occurrence of frozen spells and intense rainfall events in spring. Higher precipitation records during the whole year, and cooler conditions from April to September favoured higher values of grape production. Related to the wine quality, the field with the highest grapevine yield presented the highest values of pH, malic acid, and potassium, and the lowest of titratable acidity.

Within the same year, grapevine yield significantly correlated very well and negatively with the aggregated index of runoff and sediment connectivity. Higher connectivity values, which mean intense overland flow dynamics, in the upslope contributing areas, and especially within the vineyards, favoured lower values of grapevine yield. Thus, climatic parameters explained the temporal dynamics of grapevine productivity whereas the magnitude of the overland flow processes can be used as a tool to predict spatial changes in grapevine productivity between fields under the same climatic conditions. These results are of interest for farmers and landowners within the current scenario of climate and global changes.

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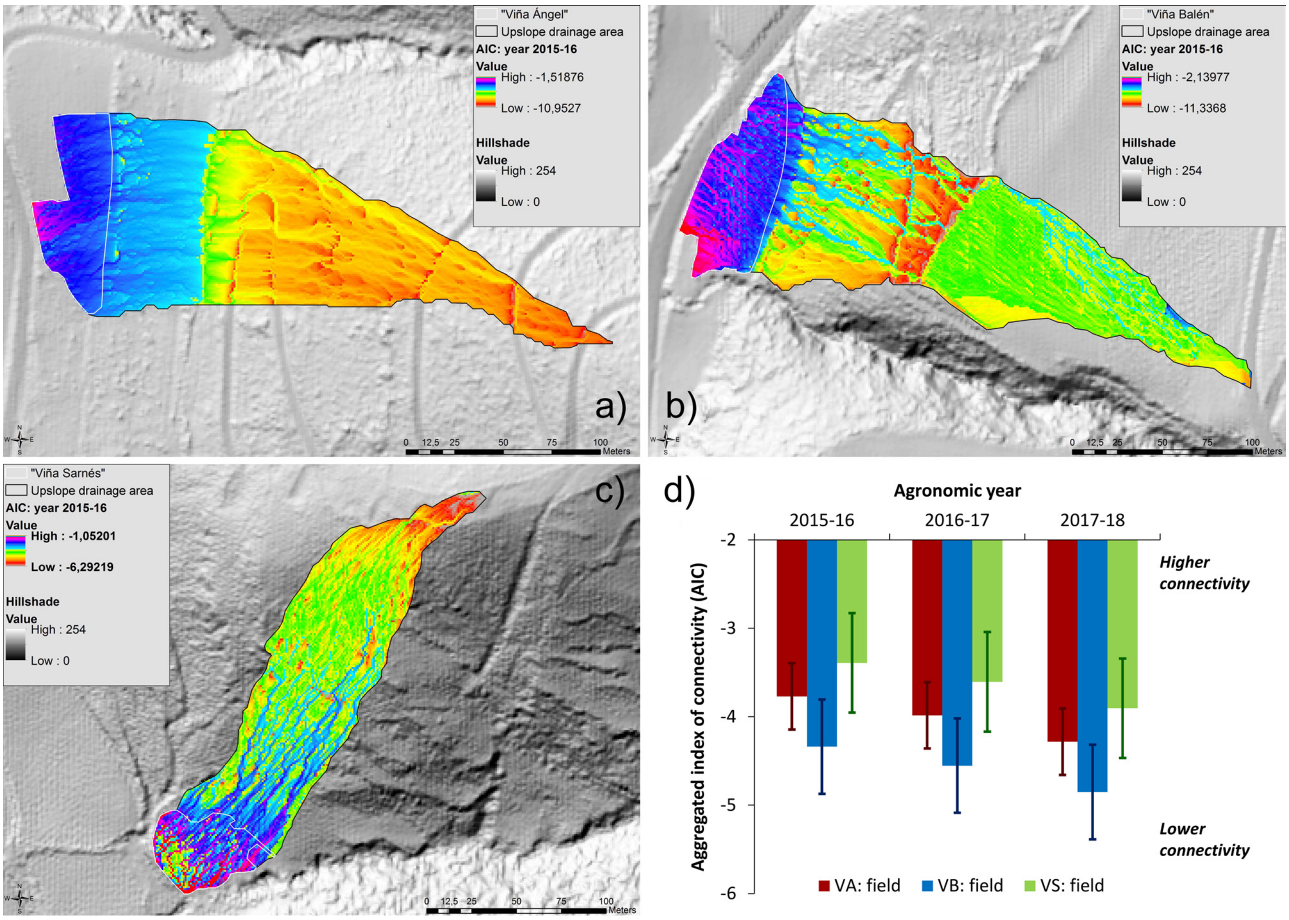

Fig. 5: Maps of runoff and sediment connectivity estimated with *AIC* in VA (**a**), VB (**b**), and VS (**c**) for the agronomic year 2015-2016. The mean and standard deviation values of *AIC* in the three vineyards during the test period are also shown (**d**).

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