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ORIGINAL RESEARCH ARTICLE

Effects of soil water-holding capacity and soil $N\text{-}NO_3^-$ and K on the nutrient content, vigour and yield of cv. Tempranillo vine and the composition of its must and wine

José María Martínez-Vidaurre[1], Eva Pilar Pérez-Álvarez[1], Enrique García-Escudero[1] and Fernando Peregrina[2*]

[1] Instituto de Ciencias de la Vid y del Vino-ICVV (CSIC, Gobierno de La Rioja, Universidad de La Rioja), 26007, Logroño, Spain

[2] Área de Edafología, Departamento Producción Agraria, E. T. S. I. Agronómica, Alimentaria y de Biosistemas, Universidad Politécnica de Madrid, 2040, Madrid, Spain

*correspondence: fernando.peregrina@upm.es

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ABSTRACT

The aim of this study was to assess the relationships between the soil water-holding capacity (SWHC), nitrate nitrogen ($N\text{-}NO_3^-$) and extractable potassium (K) content of soil; the vine nutrient content, vigour and yield; and the quality of the musts and wines in DOCa Rioja vineyards over a five-year period (2010–2014). The SWHC, $N\text{-}NO_3^-$ and extractable K content of the soil were analysed in twelve cv. Tempranillo (*Vitis vinifera* L.) plots. Vine yield, nutritional parameters and the K and polyphenol compounds in the musts and wines were determined. In general, both the SWHC and the soil $N\text{-}NO_3^-$ content were positively correlated with the N and K content of the petiole, the shoot weight and the bunch weight, but negatively correlated with the polyphenol and anthocyanin content of the musts and wines. The K extractable content was also correlated with the K content of the petiole and with the K in the musts and wines. The SWHC, the $N\text{-}NO_3^-$ and the extractable K are soil parameters which have been linked to the growth and ripening of the vine plant and to the composition of the must and wine. For DOCa Rioja agroclimatic conditions, assessment of these soil parameters would enable selecting soils that support obtaining wines of better quality.

KEYWORDS: soil water-holding capacity, must quality, soil $N\text{-}NO_3^-$, soil extractable K, wine quality

INTRODUCTION

The key variables for vine cultivation and quality grape (*Vitis vinifera* L.) production are climate, soil, and plant material. Together with topography and agronomic practices, these variables constitute a unique ecosystem known as the terroir (Seguin, 1986; van Leeuwen *et al.*, 2004; van Leeuwen and Seguin, 2006; van Leeuwen *et al.*, 2018).

Climate has the greatest effect on most vine parameters, followed by soil and cultivar, and its characteristics strongly influence berry growth and composition (Tomasi *et al.*, 2015). With regard to climatic parameters, sunshine hours and temperature do not have a decisive impact on the quality of the vintage, in contrast to rainfall and its distribution throughout the vines' growing cycle, especially in summer. Therefore, the effects of climate and soil on vine development and grape composition can largely be explained by their influence on vine water status (van Leeuwen *et al.*, 2004). In regions with a Mediterranean climate, rainfall varies greatly from year to year, and the availability of water for the vineyard can thus vary substantially between vintages (Catarino *et al.*, 2018; Grainger *et al.*, 2021; Lima *et al.*, 2021). In addition, the impact of soil characteristics on the vine plant can also be shaped by this inter- and intra-annual climatic variability.

The soil in which vines grow influences both the quality and the style of a wine (Reynolds *et al.*, 2010). Soil characteristics may directly influence the water availability for plants, which will in turn determine the physiological performance of the grapevines (Brillante *et al.*, 2015; Brillante *et al.*, 2016). Variations in whole plant physiology are associated with grape flavonoid composition (Yu *et al.*, 2020) and thus affect wine quality. Ideally, vineyards should be established in areas where soil temperature (relative to air temperature), soil water-holding capacity (relative to rainfall and potential evapotranspiration), and soil nitrogen (N) availability are optimum for the type of wine to be produced (van Leeuwen *et al.*, 2018).

The effect of the soil on vine behaviour is well known to be mediated through the varying water content levels and the consequent effects on vine water status (Seguin, 1970, 1986; van Leeuwen and Seguin, 1994). The available water in the root zone is one of the factors affecting plant growth, yield, bunch rot and berry composition (Echeverría *et al.*, 2017). In addition, mild water deficits can reduce berry size (Smart, 1974; Intrigliolo and Castel, 2010; Intrigliolo *et al.*, 2016) and increase the anthocyanin and tannin content in the berry skin of red grape varieties (Matthews and Anderson, 1988; van Leeuwen and Seguin, 1994; Koundouras *et al.*, 1999; García-Esparza *et al.*, 2018; Pérez-Álvarez *et al.*, 2021; Lizama *et al.*, 2021). Consequently, determining the moisture retention capacity of the complete soil profile can help to identify how much water is available for the cultivation of the vine in each type of soil, therefore aiding in assessing the effect of the vineyard development.

Moreover, the availability of mineral soil nutrients is vital for vine development due to the impact of the soil nutrients on growth, ripening, vigour and yield (Keller, 2005). However, Seguin (1986) found no relationship between soil minerals and wine quality, except for N. Both N deficiency and N excess have negative impacts on grapevine development and grape composition (Verdenal *et al.*, 2021), but otherwise, little evidence indicates that soil minerals are major drivers of terroir expression (van Leeuwen *et al.*, 2018). Previous research has shown that N fertilization increases vigour and yield (Kliewer and Cook, 1971; Spayd *et al.*, 1994; Verdenal *et al.*, 2021), extends the vegetative growth period (competing with and delaying grape ripening), increases grape sensitivity to fungal diseases (Thomidis *et al.*, 2016) and can also decrease the polyphenol and anthocyanin content (Hilbert *et al.*, 2003; Delgado *et al.*, 2004; Schreiner *et al.*, 2018). Without the addition of N fertilizer, the vine N status depends on the organic matter content in the soil, its mineralization rate and the carbon/nitrogen (C/N) ratio. Since nitrate N ($N\text{-}NO_3^-$) is the main form of N that grapevines can assimilate, its content in the soil at the point of maximum growth of the vine (flowering) may be related to the nutritional level of N in the vine and its vigour and to the polyphenol and anthocyanin levels in the grape (Pérez-Álvarez *et al.*, 2013). Consequently, it is necessary to look more deeply into determining the $N\text{-}NO_3^-$ levels of soils in which vines are grown to better understand the effect of $N\text{-}NO_3^-$ on vine development and grape quality.

With respect to potassium (K), vine roots absorb this nutrient very easily as a monovalent cation that has high mobility in the plant at the intracellular level and at longer distances between organs through the phloem and the xylem (Arrobas *et al.*, 2014). This element is essential for shoot growth, resistance to water stress and diseases, and the transport and translocation of the assimilated substances (Mpelasoka *et al.*, 2003; Wang *et al.*, 2013). Potassium indirectly benefits the synthesis of phenolic compounds during ripening, which is related to the presence of carbohydrates in the berries (Mohammed *et al.*, 1993).

Vine K deficiency leads to the production of grapes with high acidity and lower anthocyanin content (Griesser *et al.*, 2017). However, an excess of K may lead to a magnesium (Mg) deficiency in the vine, producing musts with higher pH and considerable reduction in total acidity, accompanied by a loss of colour in red wines (Ramos and Romero, 2017). These musts and wines are strongly susceptible to biological spoilage (Mpelasoka *et al.*, 2003), and wines from grapevines with an excess of K need the addition of acid to prevent a lack freshness due to high pH (Rühl *et al.*, 1992). In summary, the availability of K in the soil could be related to the vigour and yield of grapevines and to the quality of the musts and the wines.

The current study was based on the hypothesis that the edaphic parameters, including moisture reserves and levels of K and N, strongly influence the physiological processes of the vines by directly affecting the balance between their vegetative vigour and the production of grapes (van Leeuwen and Seguin, 1994).

The literature contains virtually no studies that have investigated the link between the soil moisture reserves and the available N-NO_3^- and K with respect to the nutrient content, growth and yield of the vine, while also analysing the composition of the musts and the wines. To better understand how soil and possible interactions with climate affect vine nutrient content, vigour and yield, as well as the composition of musts and wine, the available water reserves, soil N-NO_3^- availability and soil extractable K were studied in various cv. Tempranillo vineyards in the Najerilla Valley (DOCa, Rioja, Spain), over five seasons.

MATERIALS AND METHODS

1. Study area

The study was conducted in the Uruñuela vine-growing area, in the Rioja Alta subzone of the Denominación de Origen Calificada (DOCa) Rioja in northern Spain. This area encompasses fluvial (terrace) and torrential (alluvial fan and glacis) quaternary deposits that cover Neogene sedimentary materials. The primary landforms are slopes and platforms caused by intense water modelling, with altitudes ranging from 440 to 583 m above sea level.

In general, the climate in the area is Mediterranean according to the UNESCO aridity index, with a slight influence of the Atlantic or Oceanic climate. Annual average temperature, rainfall and evapotranspiration data were registered by an agro-climatic station of the Government of La Rioja (www.larioja.org/siar) located in the same mesoclimate area as the experimental plots (42°27′43″N, 2°42′46″W; altitude: 465 m above sea level).

The climatic parameters studied included annual mean temperature (°C), annual mean rainfall (mm), annual solar radiation (MJ m^{-2}), annual potential evapotranspiration (ETo) calculated using the Penman-Monteith formula, and precipitation intervals (mm) during various phases of the vine cycle. The climatic parameters were recorded for five seasons (2010–2014) and are summarized in Table 1. Table 1 also shows the climate series from 2004 to 2018.

Previous soil mapping of this area characterized 24 cartographic units of soils over 1,000 ha, revealing moderate to high variability. The soils were formed from silt-sand parent materials with gravel, pebbles and stones. The main pedogenesis processes were a translocation of carbonates and clay illuviation (Martínez-Vidaurre, 2017; Martínez-Vidaurre *et al*., 2003).

2. Experimental design and description of vineyards plots

This study was conducted over five seasons (2010–2014) in twelve vineyards of Tempranillo grafted on Richter-110 rootstock. The geographic coordinates of each plot selected are shown in Table 2. All the vineyards were located over platforms with field slopes lower than 2 % and the twelve vineyards were less than 1 km apart, so that the climatic

TABLE 1. Climatic data (annual mean temperature (°C) and precipitation (mm), solar radiation (MJ m^{-2}) and reference evapotranspiration (mm) of years 2010 to 2014 in the study area and variation (%) respect to average value of the historical series 2004-2018.

	Climatic data*	2010	2011	2012	2013	2014
Tª m	12.5	11.6	12.8	12.5	12.0	13.1
(° C)		(-7.2)	(2.4)	(0.0)	(-4.0)	(4.8)
Annual mean P (mm)	476	383.6	345.4	455.8	677.6	559.2
		(-19.4)	(-27.4)	(-4.2)	(42.4)	(17.5)
P Jan-May (mm)	227.9	152.2	172.8	179.0	380.8	221.4
		(-33.2)	(-24.2)	(-21.5)	(67.1)	(-2.9)
P Apr-Oct (mm)	240.1	209.4	176.8	300.4	314.0	235.0
		(-12.8)	(-26.4)	(20.1)	(30.8)	(-2.1)
P Sept-Oct (mm)	67.1	73.4	33.4	122.2	68.8	86.8
		(9.4)	(-50.2)	(82.1)	(2.5)	(29.4)
Solar Rad. (MJ.m^{-2})	5216	5089	5262	5284	4909	5177
		(-2.4)	(0.9)	(1.3)	(-5.9)	(0.7)
ETo	977	945	977	998	880	958
(mm)		(-3.2)	(0.0)	(2.1)	(-9.9)	(-1.9)

*Complete climatic series (2004-2018); Tª m: mean temperature; P: precipitation; Jan: January; Apr: April; Oct: October; Sept: September; Rad: Radiation; ETo: crop reference Evapotranspiration.

TABLE 2. Geographic coordinates (ETRS89 projection system) and average altitude (m) of each vineyard plot.

Plot	Longitude	Latitude	Altitude (m)
1	2°42′56″	42°27′5″	476
2	2°42′54″	42°27′10″	475
3	2°41′6″	42°27′49″	508
4	2°41′22″	42°27′36″	517
5	2°41′34″	42°27′30″	510
6	2°42′28″	42°27′40″	472
7	2°40′59″	42°27′21″	552
8	2°41′15″	42°27′18″	558
9	2°40′29″	42°27′21″	565
10	2°40′22″	42°27′28″	566
11	2°42′9″	42°27′55″	467
12	2°40′30″	42°27′36″	564

conditions are considered homogeneous between the vineyards for a given vintage.

The plant material was between 20 and 35 years old, so grapevines were in full production. Planting density was 2,900 to 3,100 grapevines per hectare with vines at approximately 1.20 × 2.70 m (vine and row spacing) in an east-west row orientation. Vine training systems were bilateral cordon and goblet/bush vine. Within each vineyard, three adjacent rows of 50 vines were selected (plots) for taking samples and measurements.

Chemical weed control was achieved beneath the vines. Soil tillage to eliminate competitive sward was carried out in the inter-row every four to six weeks during the growing season (February to August) using a cultivator. The vines were not irrigated or fertilised.

3. Soil description and soil analysis

In each vineyard plot, a mini-bagger excavator was used to make two pits, each measuring 2 m long, 1 m wide and 1 to 2 m deep (May 2010). These pits were used to determine the effective soil depth, the depth reached by vine roots (rooting depth), the soil horizons, and the percentage of coarse elements (> 2 mm) by volume in each horizon. Horizons were sampled, soil samples were air dried, and the ground soil was sieved to 2 mm. The soil samples were analysed to determine pH and electrical conductivity in water with a soil/solution ratio of 1:2.5. Organic matter content was determined by dichromate oxidation (Nelson and Sommers, 1982), soil texture by laser diffraction particle size (Diffractometer LSTM 13 320, Beckman Coulter) and carbonate total by infrared (EQUILAB CO-202). In addition, soil extractable K content was determined by the Mehlich 3 method (Zhang *et al.*, 2009).

Each year, four soil sub-samples were collected by auger when vines were at the flowering phenological stage (12 to 21 June) in each vineyard. For each sub-sample, soil was collected randomly in the inter-row at three depths (0–15, 15–30 and 30–45 cm) and bulked to give a composite sample.

The soil samples were air dried, ground and passed through 2 mm sieves. Next, $N\text{-}NO_3^-$ was extracted from soil samples with 2 mol l^{-1} KCl and measured by colorimetry at 550 and 660 nm, using a SEAL AutoAnalyzer 3HR (Seal Analytical, Hamburg, Germany), based on segmented flow. To express N as $N\text{-}NO_3^-$ and in kilograms per hectare, the percentage of coarse fragments (> 2 mm) and the soil bulk density, recorded using the core method, were also determined in each sample.

The water-holding capacity (SWHC) for each identified horizon within the root zone was calculated according to the equations of Saxton and Rawls (2006) which use electrical conductivity, organic matter content, particle size distribution and the percentage by volume of coarse elements. The total SWHC for each plot was calculated by the sum of SWHC in each horizon described at rooting depth.

Table 3 presents the soil classification (USDA, 2006) and the main soil physical-chemical characteristics of each vineyard plot.

TABLE 3. Soil classification and main soil physicochemical characteristics of each vineyard plot.

Plot	Soil classification (USDA, 2006)	Ap horizon (0-15 cm)								Control section
		pH (H_2O)	Electric conductivity (dS/m)	Organic Matter (%)	Clay (%)	Silt (%)	Sand (%)	$CaCO_3$ (%)	Rooting depth (cm)	Soil water-holding capacity (SWHC) (mm)
1	Fluventic Haploxerept	8.20	0.13	1.05	24.1	28.7	47.2	1.3	110	146.5
2	Fluventic Haploxerept	8.15	0.15	1.00	20.6	38.8	40.6	0.5	110	128.5
3	Typic Calcixerept	8.40	0.20	1.30	17.8	56.9	25.3	28.7	90	87.7
4	Calcic Palexeralf	8.35	0.12	0.73	17.1	56	26.9	1.5	72.5	78.1
5	Calcic Palexeralf	8.60	0.11	0.48	16.3	56.8	26.9	1.2	82	73.6
6	Calcic Haploxeralf	8.55	0.13	0.69	18.7	49.5	31.8	6.5	78	62.2
7	Petrocalcic Palexeroll	8.50	0.14	1.11	19.6	45.5	34.9	23.8	63.5	63.1
8	Petrocalcic Palexeroll	8.40	0.15	1.87	22.9	40	37.1	14.7	62.5	60.2
9	Petrocalcic Palexeralf	8.50	0.11	0.65	21.9	51.3	26.8	3.4	73	59.4
10	Petrocalcic Palexeralf	7.95	0.19	0.73	14.1	58.6	27.3	1.0	75	58.6
11	Calcic Haploxeralf	7.20	0.43	0.61	17.1	52.4	30.5	0.5	85	57.3
12	Typic Calcixerept	8.35	0.14	0.97	18.5	52.5	29	3.5	71	56.3

TABLE 4. Mean values in each plot of soil, grapevine, must and wine properties studied in period 2010-2014.

Plot	SWHC (mm)	soil extractable K Ap horizon (ppm)	soil N-NO_3^- 0-45 cm (kg/ha	petiole % N	petiole % K	shoot weight (g)	bunch weight (g)	pH	Malic acid (g/l)	(mg/l)	TPI	Anthoc. (mg/g)	pH	colour intensity	K (mg/l)	TPI	Anthoc. (mg/l)
	soil			grapevine				must					wine				
1	146.5	348	41.74b	0.54d	1.24d	125.14c	314.29bc	3.42ab	2.88bc	1738de	79.28a	1.37ab	3.74b	7.14a	1484c	45.40a	526.66ab
2	128.5	424	65.11c	0.62e	2.49e	166.52d	422.80d	3.45b	3.45c	1949e	76.75a	1.21a	3.79b	7.14ab	1724d	48.57a	523.53a
3	87.7	179	32.74ab	0.48c	0.73bc	112.90bc	320.68c	3.43ab	2.27ab	1584bcd	82.74a	1.46abc	3.70b	8.51ab	1333bc	51.75ab	610.32abc
4	78.1	120	28.69ab	0.55d	0.60bc	103.95b	231.80a	3.39ab	2.24ab	1523bcd	94.66bc	2.04fg	3.63b	13.98def	1256b	64.59bcd	876.61ef
5	73.6	170	21.70a	0.47bc	0.70bc	66.54a	200.77a	3.39ab	1.85a	1488bc	96.79bc	1.88ef	3.64b	16.63fg	1280bc	70.86d	883.16f
6	62.2	205	34.88ab	0.47bc	0.61bc	97.91b	264.81abc	3.40ab	2.05ab	1551bcd	82.15a	1.59bcd	3.63b	10.76bcd	1279bc	56.85abcd	698.65bcde
7	63.1	113	17.51a	0.38a	0.55b	60.02a	254.73abc	3.30ab	1.56a	1384ab	105.45c	1.84def	3.42a	18.60g	1029a	69.94cd	726.64cdef
8	60.2	399	28.70ab	0.44b	0.75bc	65.52a	212.55a	3.47b	1.87a	1548bcd	94.60bc	1.93fg	3.72b	13.52def	1252b	64.22bcd	777.67cdef
9	59.4	155	20.02a	0.44bc	0.24a	73.02a	236.13a	3.25a	1.75a	1180a	96.48bc	1.66cde	3.30a	14.90ef	886a	57.53abcd	674.22abcd
10	58.6	157	20.39a	0.48c	0.72bc	116.02bc	259.99abc	3.44b	2.18ab	1581bcd	104.00c	2.19g	3.63b	14.21def	1254b	65.42bcd	851.44ef
11	57.3	416	26.67ab	0.47bc	0.73bc	116.08bc	272.05abc	3.45b	2.12ab	1653cd	86.66ab	1.58bcd	3.70b	9.31abc	1352bc	55.15abc	689.51abcde
12	56.3	244	23.89ab	0.45bc	0.86c	69.20a	243.57ab	3.39ab	2.36ab	1664cd	100.26c	1.96fg	3.70b	12.73cde	1372bc	65.13bcd	830.86def

Different letters indicate significant differences among plots by LSD test ($p < 0.05$).
SWHC: soil water-holding capacity; TPI: total polyphenol index.

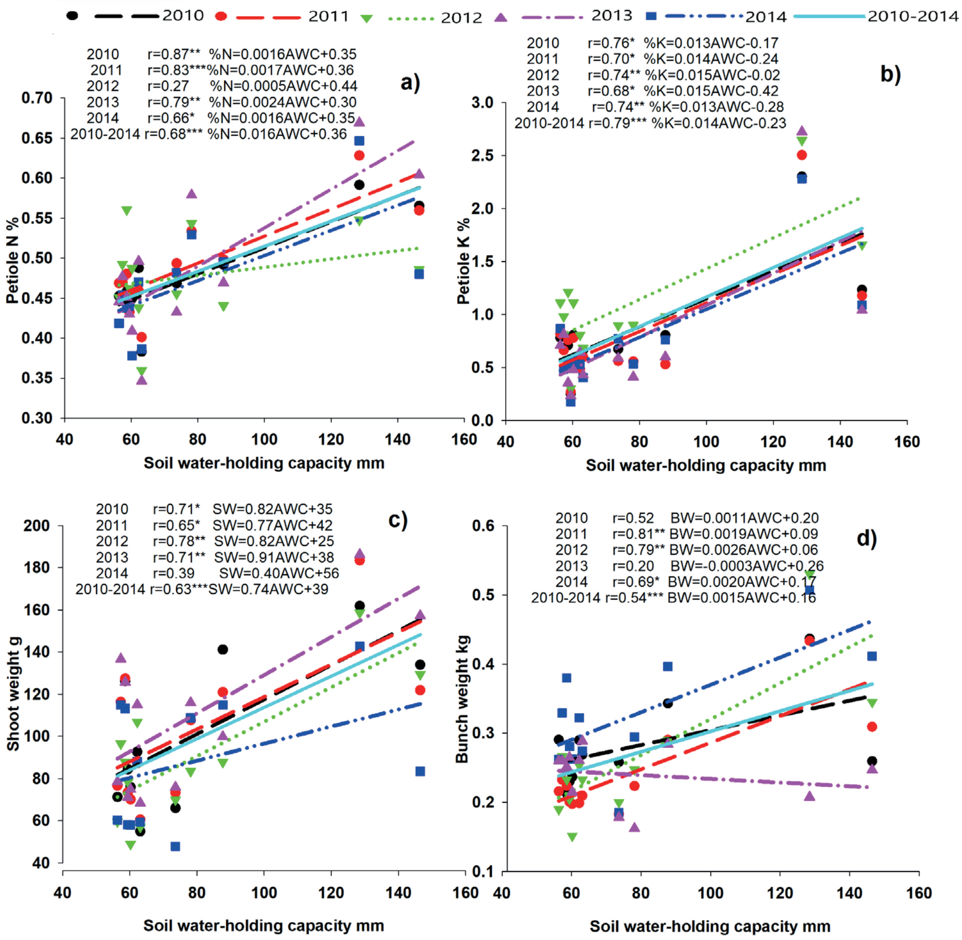

FIGURE 1. Linear correlations between petiole N (%) and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. b) Linear correlations between petiole K (%) and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. c) Linear correlations between shoot weight (g) and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. d) Linear correlations between bunch weight (kg) and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. Symbols *, ** and *** indicate that the correlations are significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

4. Grapevine nutrient content

In each plot at the veraison stage (23 August 2010, 24 August 2011, 16 August 2012, 28 August 2013 and 19 August 2014), 60 leaves were sampled on leaves opposite to the second cluster (Romero *et al.*, 2010). In each leaf, petioles were separated, washed with tap water and rinsed with distilled water. Plant material samples were dried at 60 °C in a forced-air oven for 72 h, and ground through a 0.5 mm sieve with an ultra centrifugal mill (Retsch ZM1).

Total N content in leaf petioles was determined with a CNS elemental analyser (TruSpec CN, LECO). Contents were expressed on a dry weight basis as grams per 100 g of sample material. Potassium content was determined in petiole tissue by microwave hydrogen peroxide digestion and inductively coupled plasma–optical emission spectroscopy (ICP-3300 DV, Perkin Elmer).

5. Grapevine agronomic performance

All the vineyard plots were hand harvested when berries reached the optimum technical maturity for Tempranillo in Rioja, which occurred when berries presented approximately 13 % v/v probable alcoholic strength. The harvest was normally carried out between 22 September and 6 October for all vintages. At harvest, in each plot, the number of clusters per vine and yield (total harvest weight ha^{-1}) were recorded to calculate the average bunch weight per vine (kg $vine^{-1}$).

Finally, at postharvest (end of November or beginning of December), 20 vines were randomly chosen in each plot, and wood pruning weight (g) and shoot number were determined to calculate the average shoot weight (g).

6. Grape sampling and analytical parameters of must

Just before the start of the harvest, random samples of 600 berries were collected. Six clusters were collected from 20 grapevines distributed randomly throughout each experimental plot, and five berries (two on opposite sides from the top of the cluster, two on opposite sides from the middle, and one at the tip of the cluster) were picked from each cluster. In the laboratory, 200 berries were separated, counted and weighed to obtain the average berry weight (g). These 200 berries were then crushed using a masticator (IUL Instruments GmbH, Königswinter, Germany) to obtain must. Malic acid and K contents of the must were determined according to Organization International of the Vine and Wine (OIV) methods (OIV, 2014).

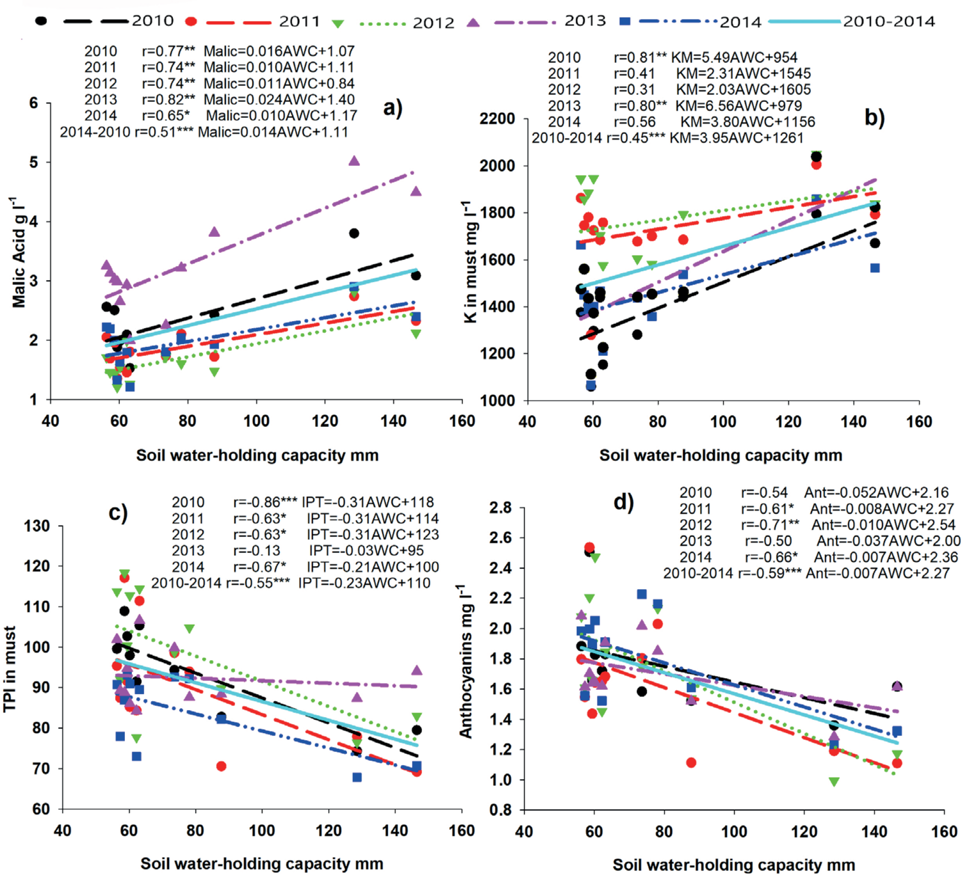

FIGURE 2. a) Linear correlations between musts acid malic (mg l^{-1}) and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. b) Linear correlations between K in musts (mg l^{-1}) and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. c) Linear correlations between total polyphenols index (TPI) in musts and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. d) Linear correlations between anthocyanins in musts (mg l^{-1}) and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. Symbols * ** and *** indicate that the correlations are significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

An additional 200 berries were treated with HCl 1 % heated at 40 °C for 30 min. In this extract, the anthocyanin content in berry skins was determined by the method of Ribéreau-Gayon and Stonestreet (1965) and the total polyphenol index (TPI) in the berry skin extract was determined by spectroscopy, with ultraviolet absorption measured at 280 nm (Ribéreau-Gayon *et al.*, 1972). Finally, colour intensity was determined after measuring absorption at 420, 520 and 620 nm in a UV-V spectrophotometer, according to the European Community Official Methods (European Commission, 1990).

7. Vinification

Microvinification was conducted identically for all plots. At harvest, for every plot, 30 to 45 kg of grapes were taken for vinification. First, the hand-harvested grapes were weighed for each plot and then crushed, after which stems were removed. Later, an aliquot of 3.5 kg of paste from each plot was placed in a glass vessel adapted for winemaking. Alcoholic and malolactic fermentations were performed by selected yeast strains of *Saccharomyces cerevisiae* and a selected bacteria strain of *Oenococcus oeni*, respectively. The wines were made following the protocol established by Sampaio *et al.* (2007).

8. Wine analysis

The oenological parameters K and colour intensity were measured according to OIV methods (OIV, 2014), anthocyanin content was determined by the method of Ribéreau-Gayon and Stonestreet (1965) and the TPI was determined by measuring the absorbance at 280 nm after conventional dilution of samples.

9. Statistical analysis

Correlations between soil, vine, must and wine properties data were calculated. Plot effects on mean values (2010–2014) of measured variables were tested using ANOVA (univariate linear model), and comparisons among treatment means were made using the LSD multiple range test calculated at $P < 0.05$. The percentages of variance attributable to plot and year factors and their interaction were also determined. Principal component analysis (PCA) was conducted considering soil, vine, must and wine properties. All statistical analysis were done using SPSS for Windows (Chicago, IL, USA).

RESULTS

Table 3 shows the main physical-chemical characteristics of the soils described in the twelve selected plots.

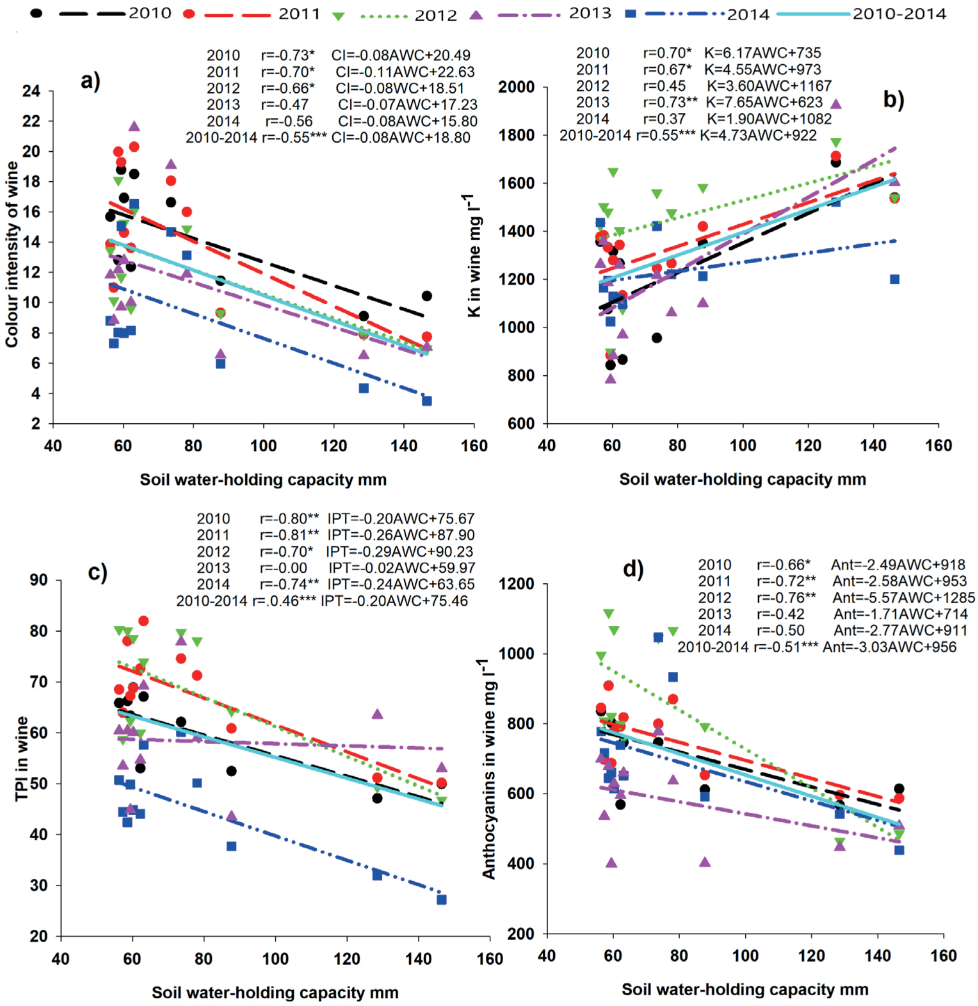

FIGURE 3. a) Linear correlations between colour intensity of wines and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. b) Linear correlations between K in wine (mg l^{-1}) and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. c) Linear correlations between total polyphenols index (TPI) in wines and soil water-holding capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. d) Linear correlations between anthocyanin in wines (mg l^{-1}) and available water capacity (mm) for each year 2010, 2011, 2012, 2013 and 2014. Symbols *, ** and *** indicate that the correlations are significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

Their Ap horizons were characterised as having a basic pH, low organic matter content and a silt-loam texture. The range of SWHC, estimated from the control section of each profile, ranged from 56 to 146 mm.

Table 4 shows the mean values of soil, grapevine, must and wine properties for each plot in the period of 2010–2014. The analysed parameters of grapevine must and wine did not change significantly based on the SWHC. Compared with plots with a SWHC < 87.7 mm, plots with a SWHC > 128 mm tended to present higher percentages of N and K (% N and % K, respectively) in petiole, higher shoot and bunch weights; higher K content in must and wine; and lower TPI and anthocyanin content in must and wine. This tendency was only a trend since some plots that had an SWHC < 87.7 mm did not present significant differences with respect to plots with SWHC ≥ 128 mm. Similarly, with respect to soil K, plots with higher soil K tended to have higher petiole % K, must and wine K, and must and wine pH. In addition, the significant differences of soil N-NO_3^- among plots were related to significant changes in the analysed properties. Thus plots 1 and 2, which had a higher soil N-NO_3^- than plots 5, 7, 9 and 10, had higher % N and % K in the petiole, lower TPI and anthocyanin content in the must, and lower wine colour index than plots 5, 7, 9 and 10.

Figure 1 presents the correlations between the SWHC of the soil profile and the nutritional parameters, vigour and yield of the vine studied with regard to the percentage of N and K of the petioles at veraison, the mean shoot weight and the mean bunch weight in the five years studied (2010–2014). The SWHC of soils was positively correlated with % N of the petioles in 2010, 2011, 2013 and 2014. Similarly, % K in the petioles was positively correlated with the soil SWHC in all years studied. The parameters of vine vigour, shoot weight and bunch weight were also positively correlated with the SWHC in the years 2010, 2011, 2012 and 2013 and in 2011, 2012 and 2014, respectively.

In Figure 2, the correlations between the SWHC and the parameters analysed in the musts (malic acid, K, polyphenols and anthocyanins) are shown for each of the five

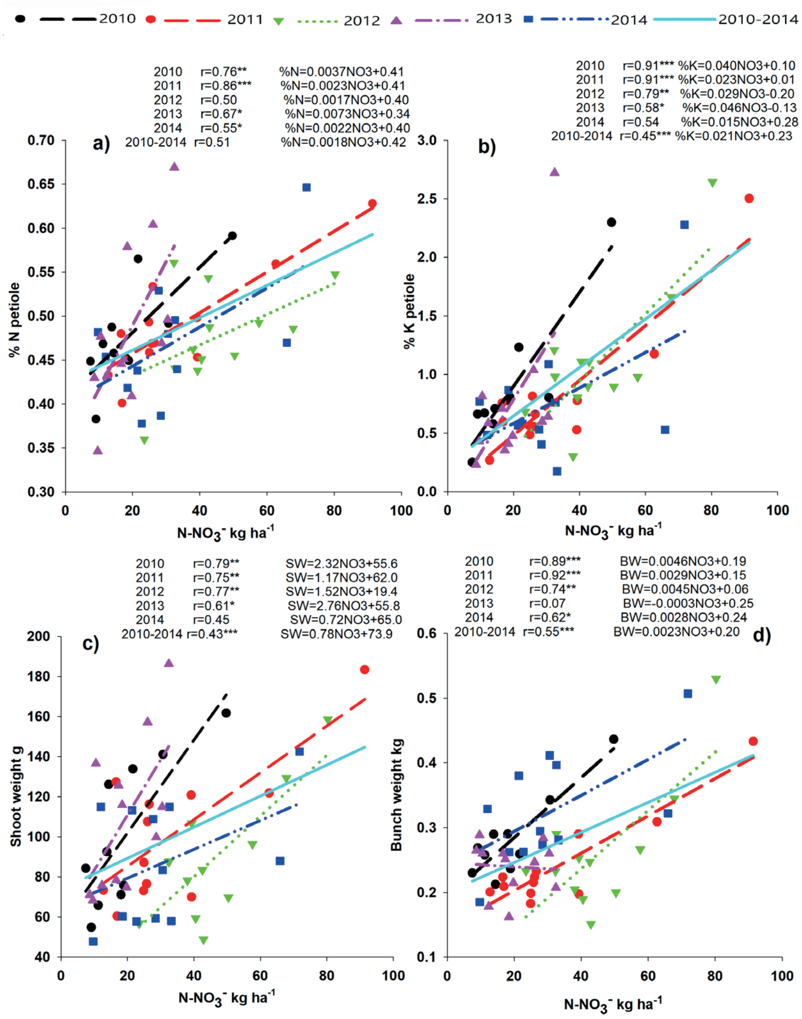

FIGURE 4. a) Linear correlations between petiole N (%) and soil N-NO_3^- (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. b) Linear correlations between petiole K (%) and soil N-NO_3^- (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. c) Linear correlations between shoot weight (g) and soil N-NO_3^- (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. d) Linear correlations between bunch weight (kg) and soil N-NO_3^- (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. Symbols *, ** and *** indicate that the correlations are significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

vintages studied. The SWHC was positively correlated with the malic acid content in the five years analysed and with the K content in the musts in 2010 and 2013 seasons. In the case of TPI of the musts, the correlation with the SWHC was negative for the years 2010, 2011, 2012 and 2014. Similarly, in 2011, 2012 and 2014, the correlation between the SWHC in the soil and the anthocyanin content of the musts was negative.

Regarding the effects of the SWHC on the wine properties, Figure 3 shows the correlations of the SWHC with the wine parameters, including the colour intensity, K, TPI and anthocyanins over the years of the study (2010–2014). The wine colour intensity was negatively correlated with the SWHC in 2010, 2011 and 2012. Similarly, the TPI of wines was negatively correlated with the SWHC in 2010, 2011, 2012 and 2014, as was the anthocyanins content for the years 2010, 2011 and 2012. The content of K in the wines was positively correlated with the SWHC in the 2010, 2011 and 2013 seasons.

The correlations between the soil N-NO_3^- (kg ha^{-1}) present in the 0–45 cm layer of the soil of each plot and the % N and % K in the petioles and the shoot and bunch weight in the years 2010–2014 are shown in Figure 4. The content of N in the petioles was positively correlated with the soil N-NO_3^- in the 2010, 2011, 2013 and 2014 seasons, and also with the K petiole content in 2010, 2011, 2012 and 2013. Moreover, the shoot weight was positively correlated with the N-NO_3^- in the soil in 2010, 2011, 2012 and 2013. The bunch weight was positively correlated with the soil N-NO_3^- in the 2010, 2011, 2012 and 2014 seasons.

Regarding the effect of the N-NO_3^- available in the soil on the characteristics of the musts, Figure 5 shows the correlations of the N-NO_3^- available at a depth of 0 to 45 cm in the soil with the TPI and the content of malic acid, K and anthocyanins of the must in the years 2010 to 2014. The malic acid content was positively correlated with the N-NO_3^- in the soils in 2010, 2011, 2012 and 2013. In the same way, the correlation was positive between the must K content and N-NO_3^- in the

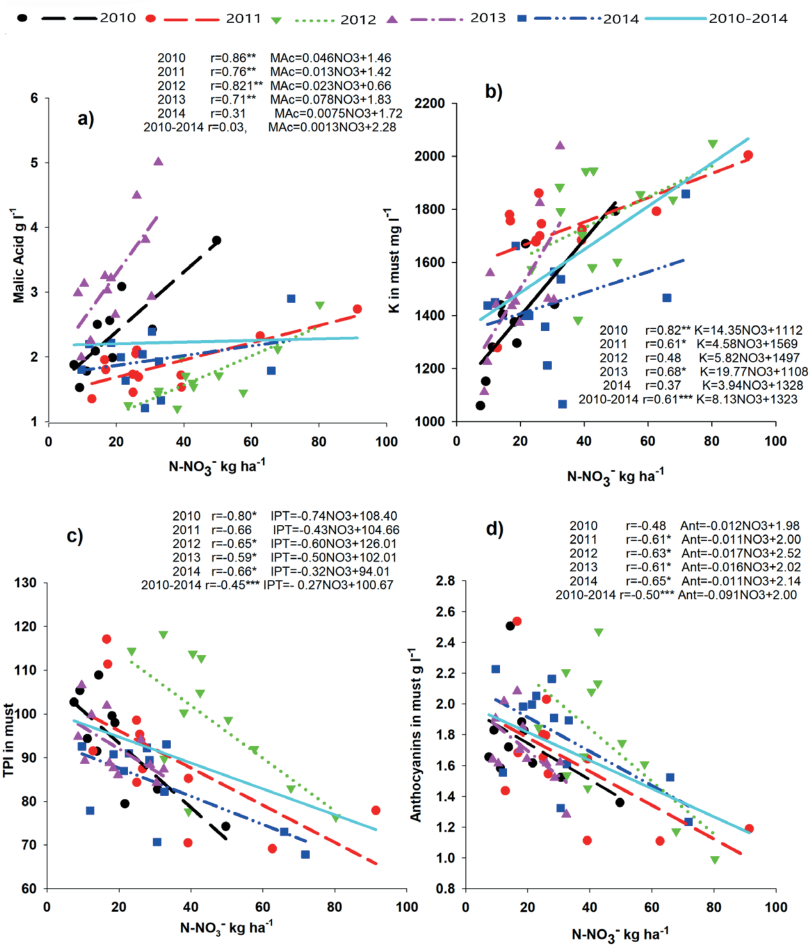

FIGURE 5. a) Linear correlations between malic acid (mg l^{-1}) and soil N-NO$_3^-$ (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. b) Linear correlations between K in must (mg l^{-1}) and soil N-NO$_3^-$ (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. c) Linear correlations between total polyphenol index (TPI) in musts and soil N-NO$_3^-$ (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. d) Linear correlations between anthocyanins in musts (mg l^{-1}) and soil N-NO$_3^-$ (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. Symbols *, **, and *** indicate that the correlations are significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

soil in 2010, 2011 and 2013. In turn, the values of TPI of the musts were negatively correlated with the content of N-NO$_3^-$ in all the years under study, with similar behaviour for the anthocyanin content in the musts in 2011, 2012, 2013 and 2014.

Figure 6 shows the correlations between the soil N-NO$_3^-$ available at a depth of 0–45 cm in the soil and the following wine parameters: colour intensity, K, TPI and anthocyanins over the period 2010–2014. The colour intensity showed a negative correlation with the soil N-NO$_3^-$ in 2010, 2011, 2012 and 2013. For K, a positive correlation with the soil N-NO$_3^-$ was observed for the years 2010, 2011, 2012 and 2013. In contrast, the wine TPI values were negatively correlated with the soil N-NO$_3^-$ in the years 2010, 2011 and 2012, as was the anthocyanin content in the wines in 2011 and 2012. These results agree with the negative correlations observed between the N-NO$_3^-$ available in the soil and the total polyphenols and anthocyanins in the musts.

Figure 7 shows the correlations of the soil extractable K from the Ap horizon (0–15 cm) of the soil and the petiole % K at veraison and the K content in the musts and in the wines. The soil extractable K in the superficial horizon was positively correlated with the levels of K in the petioles in the vintages of 2010, 2011, 2012 and 2013 and with the K in the musts in 2010, 2012, 2013 and 2014. This correlation was maintained with the K in the wines, such that positive correlations were found between the K content in the wines and the soil extractable K in the years 2010, 2011, 2012 and 2013.

Table 5 shows correlation coefficients of SWHC, soil N-NO$_3^-$ and soil extractable K with pH of must and wine for each year and for the period 2010–2014. For each year individually, must pH was only correlated with soil N-NO$_3^-$ in 2014 and with soil K in 2012. Regarding wine, pH was correlated with soil N-NO$_3^-$ and with soil extractable K in 2010, 2011 and 2013, and with SWHC in 2013. For the overall period of 2010–2014, must pH was correlated with soil N-NO$_3^-$ and soil extractable K, and wine pH was correlated with SWHC, soil N-NO$_3^-$ and soil extractable K.

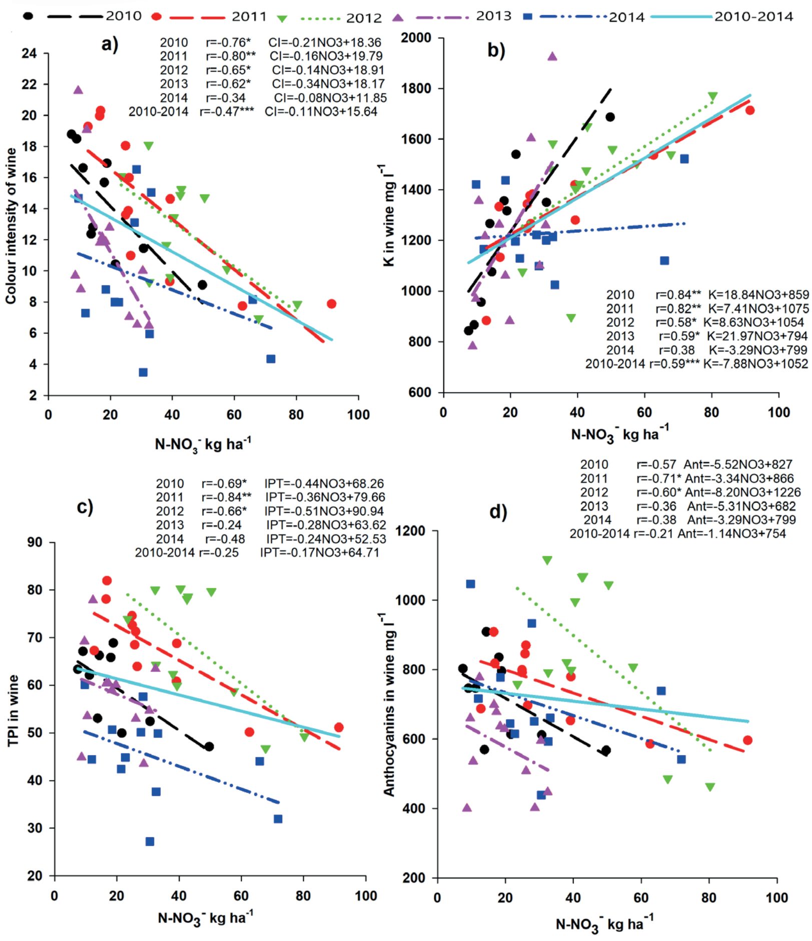

FIGURE 6. a) Linear correlations between colour intensity of wines and soil N-NO_3^- (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. b) Linear correlations between K in wines (mg l^{-1}) and soil N-NO_3^- (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. c) Linear correlations between total polyphenols index (TPI) in wines and soil N-NO_3^- (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. d) Linear correlations between anthocyanins in wines (mg l^{-1}) and soil N-NO_3^- (kg ha^{-1}) content in 0-45 cm soil depth for each year 2010, 2011, 2012, 2013 and 2014. Symbols *, **, and *** indicate that the correlations are significant at $p < 0.05$, $p<0.01$ and $p < 0.001$, respectively.

Table 6 shows the variance percentage attributable to plot and year and their interaction for each parameter studied. The percentage variance of the petiole % N, petiole % K and shoot weight fundamentally depended on plot factor, while the plot factor contributed more to the variance than the year factor for bunch weight; K, TPI and anthocyanins of must; and pH, K, colour index and anthocyanins of wines. For must pH and malic acid and for wine TPI, the variance due to the year factor was higher than that due to the plot factor. As for the interaction between plot and year factors, the highest variance percentage values were for the bunch weight, TPI and must anthocyanins.

A PCA graphical representation in two dimensions of the studied properties, projected on the plane defined by component 1 and component 2, is shown in Figure 8. In the PCA, the first and second principal components explained 45.869 and 22.728 % of the total variance, respectively (Table 7). The first principal component was strong and positively correlated with SWHC, soil N-NO_3^-, soil K, petiole % N and % K, shoot weight, bunch weight, must malic acid, wine pH and wine K. Component 1 was also negatively and strongly correlated with the TPI and anthocyanins of must and the colour index, TPI and anthocyanins of wine. Principal component 2 was positively correlated with K, TPI and anthocyanins of must and the pH, K, TPI and anthocyanins of wines. Component 2 was also negatively correlated with bunch weight and malic acid (Table 7).

DISCUSSION

The soils of plots in this study present properties similar to the 123 vineyard soils distributed throughout the Rioja characterized by Peregrina et al. (2010). The SWHC values of the soils of the plots fall within the range for SWHC for vine growing soils (30–200 mm) reported by van Leeuwen (2018).

The variability of SWHC, soil N-NO_3^- and soil extractable K in the plots suggests that the average values of vine, must and wine cannot be grouped by type of plot (Table 4). Therefore, in order to study the effect of soil, it is necessary to analyse the relationship between each soil parameter and the grapevine, must and wine properties.

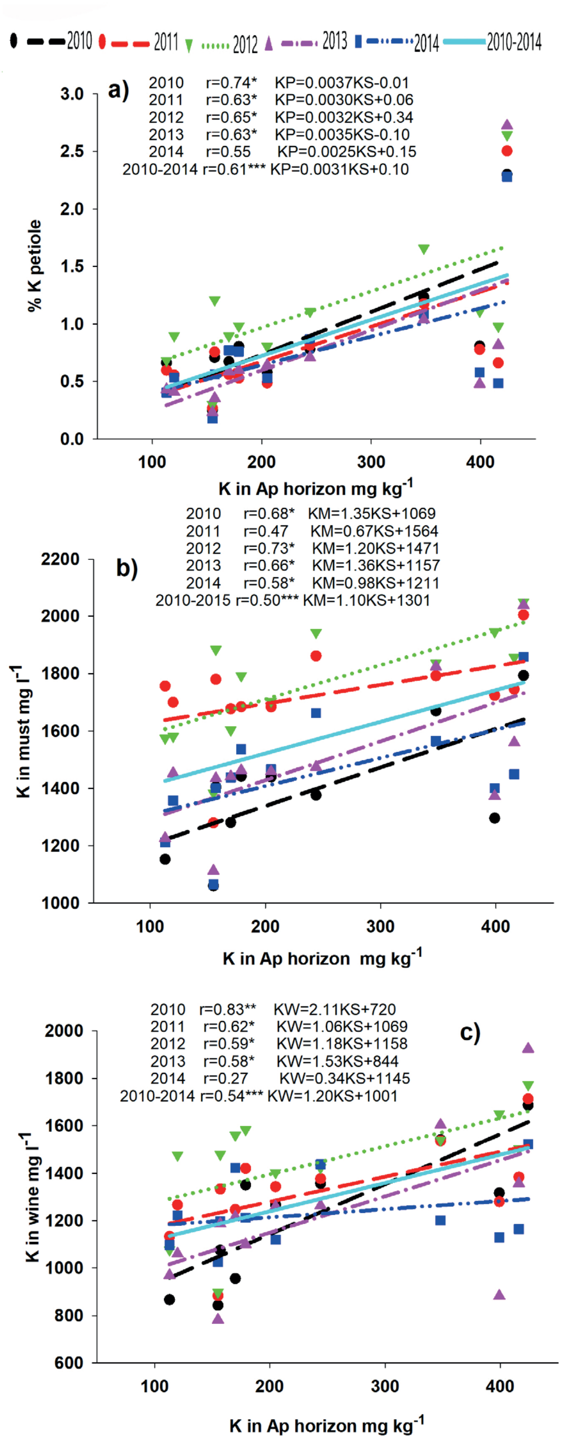

FIGURE 7. a) Linear correlations between petioles K (%) and extractable K in soil Ap horizon for each year 2010, 2011, 2012, 2013 and 2014. b) Linear correlations between K in musts (mg l-1) and extractable K in soil Ap horizon for each year 2010, 2011, 2012, 2013 and 2014 c) Linear correlations between K in wine (mg l-1) and extractable K in soil Ap horizon for each year 2010, 2011, 2012, 2013 and 2014. Symbols *, **, *** indicate that the correlations are significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$ respectively.

Under our conditions, correlations existed between the SWHC and the percentage of leaf N in vines (Figure 1). The absorption of nutrients in ionic form from the soil by the vine roots and the conversion of nutrients into organic compounds consume considerable amounts of energy (Keller, 2010). In the case of the N-NO_3^-, the roots absorb this ionic active form through proton/nitrate cotransport, with an ATP pump (Crawford and Glass, 1998). Hence, the higher the water status of the vine, the greater its capacity to produce the energy necessary for the absorption of N-NO_3^-, which would explain the correlations found in this study. Rühl *et al.* (1992) studied the fertilisation of N, P and K in vines of the Riesling, Chardonnay and Cabernet-Sauvignon varieties, and they similarly established that a water deficit could reduce the mineral absorption due to less root activity and radicular development. Furthermore, in a study on a Cabernet-Sauvignon vineyard in New Zealand, King *et al.* (2014) found a greater N-NO_3^- content in petioles of the vines with greater vigour which developed in the zones of the vineyard with greater soil water-holding capacity.

The positive correlations found between SWHC and vine foliar K content could be related to K being a nutrient that plays a fundamental role in the regulation of water in the vine (Keller, 2010) and its assimilation being reduced under limited moisture conditions (Dundon *et al.*, 1984; Esteban *et al.*, 1999). A similar relationship was found by King *et al.* (2014), who showed that vines from zones with more moisture reserves in the soil showed greater foliar K content. Foliar K was greater as the availability of moisture increased with irrigation in vineyards of Tempranillo in La Rioja (Spain) (Zaballa and García-Escudero, 1997). This positive relationship was also observed for Cabernet-Sauvignon and Merlot varieties in vineyards in Israel (Klein *et al.*, 2000).

In our study, the positive correlations found between SWHC and K in the must (Figure 2) were likely due to greater K levels in the vegetative tissues causing an increase in K levels in the berries because they represent an important sink for K (Mpelasoka *et al.*, 2003). In the years for which this correlation was not significant, values followed a similar trend as in the years in which they were significant. This finding seems to indicate that the effect of SWHC on the K content of the must is consistent in all the cycles.

This increase of K in the must related to greater SWHC was sufficiently important for it to be transferred to the wine after microvinification, and in this way, provided positive correlations between SWHC and the K content in the wines (Figure 3).

Greater availability of moisture was previously found to lead to increased growth and vegetative development of grapevines (Conradie, 2001; Keller, 2010). Under our conditions, this response was reflected in the positive correlations observed between SWHC and the shoot weight (Figure 1). A similar result, with increased shoot length of vines planted in soils with higher SWHC, was found by Tramontini *et al.* (2013) in Bordeaux vineyards. In our trial, 2013 was the year with the highest amount of precipitation, which led to good vegetative

TABLE 5. Correlation coefficients of soil holding-water capacity, soil N-NO_3^- and soil K with pH of must and wine.

	2010 *n = 12*			2011 *n = 12*			2012 *n = 12*		
	SWHC	soil N-NO_3^-	soil K	SWHC	soil N-NO_3^-	soil K	SWHC	soil N-NO_3^-	soil K
must pH	0.54	0.51	0.47	0.05	0.26	0.54	0.17	0.27	0.59*
wine pH	0.60	0.73*	0.78**	0.44	0.60*	0.63*	0.07	0.25	0.45

	2013 *n = 12*			2014 *n = 12*			2010-2014 *n = 60*		
	SWHC	soil N-NO_3^-	soil K	SWHC	soil N-NO_3^-	soil K	SWHC	soil N-NO_3^-	soil K
must pH	0.42	0.46	0.48	-0.04	0.25*	0.12	0.12	0.51***	0.27*
wine pH	0.60*	0.62*	0.68*	0.45	0.04	0.48	0.34**	0.53***	0.47***

Symbols *, **, *** indicate that the correlations are significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$ respectively. SWHC, soil water-holding capacity.

TABLE 6. Percentage of variance attributable to plot and year and its interaction.

	plot	year	plot x year
		% variance	
petiole % N	80.39	1.32	18.29
petiole % K	90.89	5.46	3.65
shoot weight	83.80	6.27	9.93
bunch weight	54.86	16.28	28.86
must pH	18.21	66.03	15.76
Malic acid	40.13	49.54	10.34
must K	53.54	36.49	9.97
must TPI	59.53	15.24	25.23
must anthocyanins	69.99	2.82	27.20
wine pH	51.55	37.32	11.14
wine K	65.58	12.80	21.62
wine color intensity	66.78	16.86	16.36
wine TPI	40.06	43.28	16.67
wine anthocyanins	49.97	27.06	22.97

TPI: total polyphenol index.

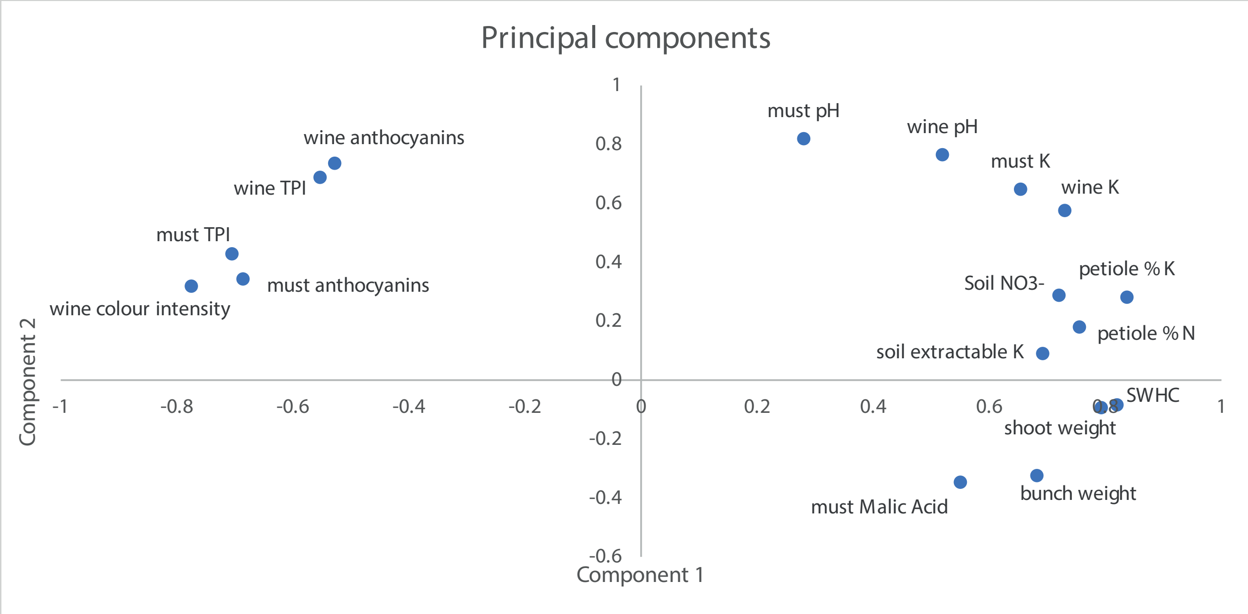

FIGURE 8. Principal components analysis. Graphical representation of the loadings of the soil, vine, must and wine properties projected on the dimension defined by the two first components loadings. SWHC (soil water-holding capacity).

TPI: total polyphenol index.

TABLE 7. Variance explained by each component and component loadings of a two-factor model of the soil, grapevine, must and wine properties studied.

	Component	
	1	2
% variance explained	45.869	22.728
soil water-holding capacity	0.820	-0.085
soil extractable K in Ap horizon	0.692	0.090
soil N-NO_3^- (0-45 cm)	0.72	0.287
petiole % N	0.755	0.18
petiole % K	0.837	0.281
shoot weight	0.793	-0.094
bunch weight	0.682	-0.325
must pH	0.280	0.819
must Malic Acid	0.550	-0.347
must K	0.654	0.647
must TPI	-0.705	0.428
must anthocyanins	-0.686	0.343
wine pH	0.519	0.764
wine K	0.73	0.575
wine colour intensity	-0.775	0.318
wine TPI	-0.553	0.688
wine anthocyanins	-0.528	0.735

TPI: total polyphenol index.

development and a greater accumulation of reserves in the living tissues of the plants. This could possibly be one reason why the SWHC did not correlate significantly with the shoot weight in 2014, as the vigour differences of the vines grown in soils with different SWHC were reduced.

Another aspect of the vine expression that may be affected by water availability is the development and size of the berry. The water content of the soil from the first stages of growth of the berry until pre-veraison has a strong influence on berry size and thus the weight of the final clusters (Esteban *et al.*, 1999; Ollat *et al.*, 2002). This response would explain the positive correlations found between SWHC and bunch weight (Figure 1). Similar results, with a positive correlation between the SWHC and bunch weight, were reported by Echeverría *et al.* (2017) in Uruguay, Tramontini *et al.* (2013) in Bordeaux and Costantini *et al.* (1996) in the region of Siena (Italy). In La Rioja, berry size was previously observed to be positively correlated with water available in the soil (Ramos and Martínez de Toda, 2019). The lack of correlation between SWHC and bunch weight in 2013 could be due to the high precipitation recorded, which was 60 % higher in the period from January to May and 20 % higher in the period from April to October than average precipitation for this periods (Table 1) This level of precipitation would explain that the soils maintained sufficient levels of moisture prior to the growth period of the berries, hence mitigating the influence of the different SWHC levels among soils.

The content of malic acid in the musts was very sensitive to the vegetative development of the vines. Greater vegetative development resulted in a greater malic acid content. To some extent, this outcome is linked to the presence of malic acid in grapes being very closely controlled by the temperature (Hale, 1977). High vigour may favour bunch shading, which would reduce the temperature and the breakdown of malic acid. Similar results, with higher levels of malic acid in musts from vines cultivated in soils with higher water-holding capacity, were found by van Leeuwen *et al.* (2004) in Bordeaux and by Costantini *et al.* (1996) in the region of Siena (Italy). This response of the malic acid to the increase in vigour resulting in a lower temperature at bunch level could explain the higher malic acid content in all the vineyards studied in 2013 compared with the other years studied.

The total polyphenols and anthocyanins were negatively correlated with the SWHC (Figure 2). This decrease in the content of polyphenols and anthocyanins is associated with higher vigour and canopy development caused by the higher SWHC (as previously mentioned). Higher vigour can induce competition between reproductive and vegetative sinks (Koundouras *et al.* 1999) and interfere with the synthesis of secondary metabolites such as the anthocyanins and polyphenols (Bravdo and Hepner 1987). Similar results, with a negative correlation between SWHC and the polyphenol content of musts, were found in vineyards with cv. Tannat in Uruguay (Echevarría *et al.*, 2017). Moreover, higher polyphenol content occurred in the musts of Cabernet-Sauvignon vines grown in a soil with higher SWHC in the Conca de Barberá zone (Spain) (Ubalde et al. 2010). Regarding the anthocyanins, lower levels were observed in the musts from vines grown in a soil with higher SWHC in the Conca de Barberá with Cabernet-Sauvignon (Ubalde *et al.*, 2010), in Siena (Italy) with cv. Sangiovese (Bucelli *et al.*, 2010), and in Veneto (Italy) with Cabernet-Sauvignon (Tomasi *et al.*, 2005). In our study, the high precipitation recorded in 2013 relative to the other years reduced the influence of the SWHC in the berry development, and consequently, differences in SWHC had less of an effect on the polyphenols and anthocyanins.

The correlations between SWHC and the polyphenol and anthocyanin content of the wines () accorded with the negative correlations observed between the SWHC and the polyphenol and anthocyanin content of the musts (Figure 2). Hence the reduction in these compounds caused by the higher SWHC was significant enough to be transferred to the wines after microvinification. Similar results were obtained by Ubalde *et al.* (2010) in vineyards in the Conca de Barberá zone.

Regarding the N status of the vines, the positive correlations found between the soil N-NO_3^- and the leaf petiole N content (Figure 4) confirm that a greater availability of N-NO_3^- in the soil leads to a greater assimilation of this nutrient by the vines. Flowering is the critical period for the assimilation of N by the vine (Löhnertz, 1991; Perret, 1993). Thus, our results show that the determination of N-NO_3^- in the 0–45 cm layer of the soil at flowering is related to the N assimilated by the vines. These results confirm previous studies in Germany by Linsenmeier *et al.* (2008), who observed that higher levels of soil NO_3^- provided vines with a higher content of foliar N. In the same way, in the DOCa Rioja appellation (Spain) with Tempranillo, Pérez-Álvarez *et al.* (2013) reported a positive correlation between the N in both the blade and petiole leaf tissues and the soil N-NO_3^- determined at the vine flowering stage.

Furthermore, the correlations found between N-NO_3^- in the soils and the K content in the petioles (Figure 4) indicate that an increase in the availability of N-NO_3^- in the soil increases vine K assimilation. This result confirms a previous study by Zhang *et al.* (2010), who showed that the assimilation of NO_3^- stimulates the net assimilation of K in various crops. This process is likely due to K being a cation which mainly accompanies the anion NO_3^- during its absorption at the root level (Ivashikina and Feyziev, 1998).

This higher nutritional level of K in vines, induced by high availability of N-NO_3^-, leads to a greater K content in berries, as these represent an important sink for this nutrient (Mpelasoka *et al.*, 2003). Our results showed positive correlations between the soil N-NO_3^- and the K in the musts (Figure 5) and in the wines (Figure 6). Similar results of synergy between soil N in the soil and berry K content were reported by Brunetto *et al.* (2009) for Cabernet-Sauvignon in Brazil and by Assimakopoulou and Tsougrianis (2012) for cv. Agiorgitiko in Greece.

The great ability of N to stimulate canopy development has been noted by several authors, such as Conradie (2001) and

Pérez-Álvarez *et al.* (2015). The positive correlations found in our study between the soil $N\text{-}NO_3^-$ and the shoot weight (Figure 4) confirm the capacity of soil N to increase vegetative development. This result is consistent with Linsenmeier *et al.* (2008) in Germany, Balachandra *et al.* (2009) in New Zealand and Pérez-Álvarez *et al.* (2013) in La Rioja.

High soil $N\text{-}NO_3^-$ also results in an increase in berry size, which in turn increases bunch weight (Choné *et al.*, 2001; Thomidis *et al.*, 2016), which is confirmed in our results (Figure 4). Similar increases in grape yield induced by greater amounts of soil NO_3^- were previously described by Linsenmeier *et al.* (2008) in Germany and Pérez-Álvarez *et al.* (2013) in La Rioja.

High soil $N\text{-}NO_3^-$ is also related to higher must malic acid (Figure 4). High soil $N\text{-}NO_3^-$ increased vine vigour and vegetative development resulting in shaded microclimatic at the bunch level, a development that is unfavourable for the metabolic breakdown of the malic acid. Similar results showing an increase in malic acid content in musts from vines receiving fertilizer with N were found by other authors such as Keller *et al.* (1999) for cv. Pinot noir and Hilbert *et al.* (2003) for cv. Merlot.

Soil $N\text{-}NO_3^-$ also affects other compounds which determine the quality of the musts. In our study, soil $N\text{-}NO_3^-$ was negatively correlated with polyphenols and anthocyanins (Figure 5). The greater availability of N caused greater vine vegetative development, which is a factor that competes with the accumulation of sugar and pigments in grapes (Bravdo and Hepner 1987). This greater vegetative growth in vines could also have interfered with the metabolic pathways of compounds such as the anthocyanins and polyphenols, ultimately reducing their presence in the grapes (Bravdo and Hepner, 1987). This effect is widely described in the literature, and Pérez-Álvarez *et al.* (2013) previously found a negative correlation between soil $N\text{-}NO_3^-$ and must anthocyanins and polyphenol content for Tempranillo in the La Rioja region. Further, this negative correlation between soil $N\text{-}NO_3^-$ and the polyphenol content was found in a vineyard of Tempranillo in La Rioja with three different methods of soil management: tillage, barley and clover cover crops (Pérez-Álvarez *et al.*, 2015). Moreover, the intake of N by the vines was found to inhibit the synthesis of anthocyanins in Merlot (Hilbert *et al.*, 2003), Cabernet-Sauvignon (Keller and Hrazdina, 1998), and Pinot noir vines (Keller *et al.*, 1999). Similarly, Delgado *et al.* (2004) showed that the N intake reduced the accumulation of phenolic compounds in the skins of the grapes in Tempranillo. Finally, a low nutrient content of N in vines induced a high content of anthocyanins and polyphenols in the berries of Cabernet-Sauvignon (Choné *et al.*, 2001) and Merlot (Tregoat *et al.*, 2002) in the Bordeaux region (France).

In the 2013 season, a significant correlation was observed between must polyphenols and anthocyanins and the available soil $N\text{-}NO_3^-$ (Figure 5), but no correlation was established between the SWHC and the must polyphenol and anthocyanin content (Figure 2). These results suggest that in the case of low levels of water deficit during wet seasons, the main factor affecting polyphenols and anthocyanins in grape is the availability of soil $N\text{-}NO_3^-$. Similarly, when correlations exist between the SWHC and soil $N\text{-}NO_3^-$ and the polyphenol and anthocyanin compounds in the same year, these two factors may be mostly additive, rather than interactive (Keller, 2005). The greater availability of $N\text{-}NO_3^-$ in the soil allows the vines to assimilate more N, which also promotes vine vegetative growth. In both cases, the greater vine vegetative development leads to a lower content of anthocyanins and polyphenols in the must.

The negative correlation observed in the musts between the polyphenols and anthocyanins and the soil $N\text{-}NO_3^-$ was also noted between the soil $N\text{-}NO_3^-$ and the colour intensity and polyphenol and anthocyanin content in the wines (Figure 6). Therefore, the reduction of polyphenols and anthocyanins in the must caused by the greater soil $N\text{-}NO_3^-$ were of sufficient magnitude to have a similar effect with regard to polyphenols and anthocyanins in the wines. Hence soil $N\text{-}NO_3^-$ affects the colour and anthocyanins of the wines and therefore exerts a major influence on the oenological potential of the vines.

The positive correlations between the soil extractable K and the foliar K, the K in the musts and the K in the wines (Figure 7), confirmed that the soil extractable K directly affects K levels in the vines, since the absorption of K is a passive process (Keller, 2010). This affinity for the assimilation of K may be related to the great mobility in the vines due to the involvement of a large range of physiological processes (Leibar *et al.*, 2017). As has been pointed out previously, the greater K content of the vines has repercussions on the accumulation of K in the berries (Mpelasoka *et al.*, 2003). Similar results with correlations between the soil extractable K and the foliar K and the K in the musts were described by Assimakopoulou and Tsougrianis (2012) in Greece with Agiorgitiko. In Brazil, Tecchio *et al.* (2006) also observed such correlations for cv. Niágara Rosada, finding a relation between soil K extractable and the K content of the petioles. In this way, the greater soil extractable K increases the K content in the soil solution and consequently the absorption of K by the plant. This K enrichment in the vegetative parts can be transferred to the grape (Mpelasoka *et al.*, 2003), and finally, to the wine. The fact that the relations between the soil extractable K and the K in the wines are maintained shows the influence of the soil K content on wine quality, since K reduces the free acids in the wine and raises wine pH.

This effect on wine pH is confirmed by the correlations between pH of must and wine and the soil extractable K and soil $N\text{-}NO_3^-$ (Table 5). The correlation data also showed that the relationships were greater with wine pH than with must pH, which could be due to the fermentation that modifies the organic acid concentration in the must but not that of K.

Regarding the variance of the studied parameters, component 1 of the PCA could be attributed to the soil fertility factor. The loading of the SWHC, soil $N\text{-}NO_3^-$ and soil extractable K confirm the similar weight of the three soil parameters in the soil fertility. The great positive correlation with component

1 for petiole % N and % K, shoot weight and bunch weight (Table 7) confirms the influence of these soil properties on the nutrient content and development of the vine that was previously discussed. The importance of soil fertility in the grapevine vegetative development is confirmed by the high variance percentage attributable to the soil factor (Table 6). The negative correlation with component 1 for polyphenols and anthocyanins in must and wine confirms what was previously explained in relation to greater SWHC and a higher soil $N\text{-}NO_3^-$ reducing the polyphenol and anthocyanin content in grapes.

In contrast, component 2 could be attributed to the climatic conditions of the year, specifically to the temperature, since malic acid correlates with this component negatively and to a greater extent. This outcome would occur because the higher temperature causes the organic acids in the grape to decrease (Keller, 2010). In this way, for K and pH, a positive correlation with component 2, which coincides with the must pH increasing with temperature, was observed.

The higher percentage of the variance attributable to the year factor in the must pH and malic acid, (Table 6) confirms the great dependence of the acidity components with the climatic conditions.

The positive correlations with component 2 of polyphenols and anthocyanins in must and wine could be due to the fact that a higher temperature in the vintage would cause greater water stress during grape ripening (Ramos and Martínez de Toda, 2019), which would then cause an increase of these compounds in the grape. This effect of the year factor is attributed to a lower variance percentage relative to the soil factor for must TPI and must anthocyanins (Table 7).

The soil $N\text{-}NO_3^-$ loading factor in component 2 shows that soil $N\text{-}NO_3^-$ availability is also affected by vintage climatic conditions, since temperature affects organic N mineralization. These inter-annual variations have been observed in a vineyard from La Rioja (Pérez-Álvarez *et al.*, 2015), and this result indicates that the vintage climatic conditions could affect the grape characteristics through the soil $N\text{-}NO_3^-$ availability.

CONCLUSION

Based on the soil and climate conditions of the DOCa Rioja appellation, the SWHC may account for variations in vine vigour and yield and must and wine composition between vineyards with different soil types across seasons. Higher SWHC leads to increases in vine vigour and yield and reductions in the polyphenols and anthocyanins in musts and wines. These effects are not significant in years with high levels of precipitation, as was the case in 2013. Moreover, high SWHC promotes the assimilation of N and K, two of the most important nutrients for the vines. Therefore, to study soil N and K fertility and its effect on vines, must and wines, the SWHC also needs to be considered to enable correct assessment of the effects of these two nutrients.

In addition, the soil $N\text{-}NO_3^-$ content during flowering can explain the N levels in the vines despite changes in the soil $N\text{-}NO_3^-$ levels from year to year due to the effect of different climatic conditions on soil N organic mineralization. In this respect, high soil $N\text{-}NO_3^-$ was found to increase vine vigour and yield and to decrease the content of polyphenols and anthocyanins in musts and wines. Therefore, for managing vineyards to obtain the highest possible must and wine quality, it is important to keep the soil $N\text{-}NO_3^-$ levels in the soil under control to support balanced vine growth and production and consistent quality of musts and wines.

The soil extractable K in the Ap horizon close to the surface (0–15 cm) was positively correlated with the K content in the vines, musts and wines.

Finally, these soil parameters were found to be related to the final composition of the wines from these plots, which confirms an effect of the soil. Since the vinification process can reduce the differences observed in musts, the results obtained show the great effects that these soil parameters in this study had on the wine composition. These observations are important for the agronomic management of the vineyard, from the planning of new plantations (in the case of SWHC) to the management of fertilization (N and K).

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