# Quantifying the relative impact of physical and human factors on the viticultural expression of terroir

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**Abstract—** *This work assesses the relative importance of the terroirs factors: climate, soil and the relation source-sink, on the vegetative development, yield, berry composition and plant sanitary status.*

*The study was carried out between 2011 and 2014 in nine vineyards from six viticultural regions over the coast of Río de la Plata (Uruguay). The cultivar studied was Tannat, vertically trellised and north-south oriented. The year effect refers to climate, which was characterized using solar irradiation and three indices. The soil was characterized using pits and physico-chemical analyses, to determine three textural categories and to define soil depth and water availability. The source-sink relationship referred to four categories of relations between leaf surface and yield per vine. Statistical analyses included a Mixed Model with random effects to determine the relative importance of each factor to the total variability within the dataset.*

*Total yield per vine was explained by the source-sink relationship, the year and their interaction, both linked to the rainfall amount occurred during the maturation period. The synthesis of primary compounds in the berries was more dependent on the year and the interaction of soil and year with the source-sink relationship. Secondary compound concentrations in the berry depended mainly on the source-sink relationship and climate.*

*This study represents a significant advance to the knowledge of grapevine adaptation to the Río de la Plata terroirs, assigning a fundamental role to the vine grower actions. The growers can modulate grapevine balance as a function of the environment.*

***Keywords—** berry composition, soil, Tannat, terroir, yield.*

## I. INTRODUCTION

Terroir can be defined as the interaction amongst the elements that constitute a given ecosystem: climate, soil and grapevine within a given geographical location [1], and human factors, expressed as the viticultural practices [2]. Harvest yield and quality, as well as the typicality of its wines will depend on the interaction amongst these factors along with enological practices. Knowledge about the real functioning of the vineyard and designing technical schedules stand out among the advantages of the methodological approach that implies studying terroirs,.

Due to the complexity of systematic studies, research on viticulture tends to the use of reductionists approaches and to the analysis of cause-effect relationships. In contrast, the joint study of terroir key factors, such as climate, soil and cultivar, is more complex to deal with and, hence, the amount of these studies is lower.

As examples of climate influence, several authors worked on defining climatic indices to describe the suitability of a given region for producing wine [3][4][5][6] [7][8][9]. In addition, other researchers got deep into climate effects on vine functioning [10], on wine and vintage quality [11], on yield [12][13], or on a group of variables showing vine performance [14]. Grapevine energy balance when combined with its water balance regulates the group of responses to the environment (in this case, climate variables) of a given plant population [15]. Nowadays, a great number of climate analysis related to viticulture are focused on a climate change perspective, reporting a trend to increasing temperatures in many of the most prestigious grapevine growing regions worldwide [16]. This problem led to the study of vine response to increasing temperature over the growing cycle in several climatic regions [17].

Soil factor and its influence on vine performance have been comprehensively studied [2][18][19][20][21] [22] [23][24]. Several authors proved the huge influence of water availability on vintage quality [25] [26][27][28] [29][30]. Source-sink modulation through cultural practices can be considered a key factor since it affects vine vigour, yield and berry quality. Those techniques that modify source-sink relationships have been the subject of a great number of studies [31][32][33][34][35][36][37][38][39]. Pruning, shoot thinning, defoliation, shoot trimming and cluster thinning are relevant practices for regulating source-sink relationships and grapevine balance. In this sense, the operations performed by the vine grower represent an adaptation mechanism for rearranging vine components and directing the vineyard system in order to achieve a pre-defined goal.

Nevertheless, those studies including more than one determinant factor are scarce [40]. Recently, some authors [41] proved the significant effect of climate, soil and genetic (cultivar and rootstock) factors on a group of grapevine response variables. In particular, soil and climate had a greater incidence on the variability of the system than cultivar, likely due to their influence on grapevine water status.

From the results of partial studies it is possible to build models that allow for identifying the relative importance of each factor on the final response and, thus, generate tools that growers and technicians can use for a suitable management of the vineyard and improve its efficiency.

In order to answer these questions, the current study aimed to assess the relative importance of the climate, soil and source-sink relationship factors on grapevine vegetative growth, yield, berry composition and sanitary status. Secondly, the study aimed to establish the properties of each factor that exert more influence on vineyard performance.

## II. MATERIAL AND METHOD

In the current analysis, data from four vintages on nine commercial vineyards (cv. 'Tannat') locate on the Uruguayan coast of Río de la Plata have been used. This region contains most of the vineyard surface in the country.

### 2.1 Study sites description and locations

Nine plots located in the 300 km of the Uruguayan coast of Río de la Plata have been selected for this study. Plots were numbered from west to east, from Colonia del Sacramento (Colonia department) to Pueblo Edén (Maldonado department) (Supplementary Figure 1).

### 2.2 Climate indices ("year" factor)

Weather variables were recorded in two meteorological stations managed by the Instituto Nacional de Investigación Agropecuaria: La Estanzuela (-34.3300 /- 57.6800) and Estación Las Brujas (-34.6700 /- 56.3300). Moreover, four "Vantage Pro2" (Davis Instruments, Hayward, CA, U.S.A) automated stations were installed in the plots or close to them: Mal Abrigo (-34.1167 / -56.9333), Sayago (-34.8333 / -56.2167), Empalme Olmos (-34.6667 /-55.9000), Sierra Ballena (-34.7333/-55.3000). All the stations were installed and operated according to the World Meteorological Organization (WMO). The Multicriteria Climate Classification (MCC) [42][6] was applied using the adaptations for the Uruguayan conditions [8] The following indices were estimated: Heliothermal index (HI), Dryness index (DI) and Cool Night index (CI).

Daily solar irradiation was estimated using satellite images from GOES-East satellite using the BD-JPT model [43]. Cumulative solar irradiation (RS ac) from September 1st to harvest and daily mean solar irradiation for February of each year (RS Feb) were determined.

**TABLE 1**
**CLIMATIC INDICES FOR GRAPEVINE: HI, CI, DI AND SOLAR IRRADIATION: RS AC, RS FEB. EACH VALUE IS THE AVERAGE FOR THE YEAR ± STANDARD DEVIATION FOR EACH LOCATION**

| Year | HI (°C) | CI (°C) | DI (mm) | RS ac ($MJ*m^{-2}$) | RS Feb ($MJ*m^{-2}$) |
|---|---|---|---|---|---|
| 2011 | 2331.7 ± 72.2 | 18.5±1.2 | -24.3 ± 0.2 | 4347.0 ± 3.2 | 23.8 ± 0.1 |
| 2012 | 2327.7 ± 39.4 | 18.5±0.5 | 39.3 ± 24.5 | 4292.6 ± 44.6 | 21.2 ± 1.1 |
| 2013 | 2188.8 ± 63.9 | 17.3±0.4 | -3.2 ± 11.1 | 3778.4 ± 74.5 | 22.6 ± 0.7 |
| 2014 | 2289.3 ±160.9 | 17.4±0.8 | 61.2 ± 22.9 | 3851.3 ±205.4 | 17.2 ± 0.4 |

### 2.3 Description of the study plots and plant material

The study was conducted from 2011 to 2014 in nine commercial non-irrigated vineyards. On each location, 30 vines (*Vitis vinifera* L.) cv. 'Tannat' were randomly chosen; they were distributed on three rows with 10 vines each. Grapevines were vertically trellised on a Guyot system. Rows were north-south oriented in all vineyards. Further information on the studied plots is shown in Table 2.

**TABLE 2**
**MAIN CHARACTERISTICS OF THE STUDIED VINEYARDS**

| Plot | Coordinates | Location (name) | Rootstock | Plantation year | Spacing |
|---|---|---|---|---|---|
| 1 | 34° 23' 47,40" S; 57° 52' 49,67"W | Real de Vera | 3309C | 2000 | 2.50m x 1.20m |
| 2 | 34° 23' 17,40" S; 57°51' 07,37" W | Piedra de los Indios | 3309C | 1999 | 2.50m x 1.15m |
| 3 | 34°07' 10,46" S; 56°56' 50,98" W | Mal Abrigo | 3309C | 2000 | 2.00m x 0.90m |
| 4 | 34°36' 44,77" S; 56°14' 42,02" W | Juanicó | SO4 | 1998 | 2.50m x 1.10m |
| 5 | 34°53' 04,55" S; 56°19' 24,33" W | Punta de Yeguas | 3309C | 2005 | 2.50m x 1.00m |
| 6 | 34° 39' 30,43" S; 55°47' 56,11" W | Atlántida A | 3309C | 2006 | 2.50m x 0.90m |
| 7 | 34°39' 36,70" S; 55°47' 55,22" W | Atlántida B | 3309C | 2006 | 2.50m x 1.00m |
| 8 | 34°42' 31,74"; 55°03'31,56" W | Sierra Ballena | Gravesac | 2004 | 2.50m x 1.00m |
| 9 | 34°44'36,22" S; 55°01'16,42" W | Pueblo Edén | 101-14Mg | 2005 | 2.50m x 1.20m |

### 2.4 Root system characterization

Roots were studied digging pits in the row in front of a selected vine. Amount, diameter and distribution of roots were determined at different distances from the vine. Roots were stained, photographed, measured and mapped over a vertical grid with a cell size of 100 cm2. Roots were classified according to their diameter: < 3 mm, 3 to 5 mm and > 5 mm. The depth to which 90% of active roots (<3 mm diameter) appeared was recorded. This depth was used as a reference for estimating Dryness Index (DI), available water capacity (AWC) and soil textural class (TCra).

### 2.5 Soil characterization (soil factor)

Soil from each plot was described according to FAO (2006) and classified using USDA Soil Taxonomy [44].Two samples per horizon were collected from the pits, and they were used for determining soil physical and chemical properties. These observations were complemented with, at least, five samples per horizon, collected using a manual drill on different spots in each studied plots. These samples were used for assessing soil structure, texture, color, depth, presence of active roots, amongst others. Soil texture was determined using the method described by [45]. From clay, silt and sand fractions of each horizon, their proportion was estimated for the volume of soil explored by active roots. Textural classification from these proportions was defined as TCra. Dryness index [46] [8] and available water capacity (AWC) [47] was determined. This measurement was considered as the initial volume of water in the soil (Wo) for estimating soil water balance.

**TABLE 3**
**CHARACTERISTICS OF THE SOILS FROM THE STUDIED PLOTS**

| Plot | USDA Soil classification | Bedrock type | Depth* (cm) | AWC* (mm) | Textural class * (TCra) |
|---|---|---|---|---|---|
| 1 | Typic Argiudoll | Quaternary sediments | 50 | 96 | Silty clay loam |
| 2 | Typic Argiudoll | Quaternary sediments | 56 | 97 | Silty clay loam |
| 3 | Typic Hapludoll | Metamorphic rock (low degree) | 36 | 76 | Clay loam |
| 4 | Vertic Argiudoll | Quaternary sediments | 70 | 123 | Silty clay |
| 5 | Typic Argiudoll | Quaternary sediments | 60 | 110 | Silty clay |
| 6 | Typic Hapludert | Metamorphic rock | 43 | 67 | Clay loam |
| 7 | Abruptic Argiudoll | Metamorphic rock | 36 | 57 | Clay loam |
| 8 | Lithic Hapludoll | Metamorphic rock | 36 | 68 | Clay loam |
| 9 | Abruptic Argiudoll | Metamorphic rock/ Quaternary sediments | 54 | 85 | Clay loam |

***Soil depth with 90% of visible roots lesser than 3 mm in diameter.***

### 2.6 Vegetative growth determination

Potential exposed leaf surface (SFEp) was estimated at veraison [48]. At harvest, a shoot bearing a cluster was collected from the middle of the branch in ten vines. In each of these shoots, length (LP) was measured and fresh and dry weight for each organ was recorded. Samples were dried in an oven at 50 ºC till constant weight. Dry weight was expressed by organ, total per shoot (PST) and per linear meter of the trellising system (PSesp). In order to estimate this last variable, PST was multiplied by the number of shoots per linear meter obtained from counting the shoots of all the studied plants. In addition, dry weight per cm of wood in the shoot (Psmad) was also estimated.

### 2.7 Yield components and rot incidence

At harvest, yield (Y) and cluster number per vine were recorded. From these data, cluster average weight was obtained. Dry weight per cluster (PSRac) was obtained from the process described in the former subsection. Those clusters that showed, at least, 5% of the berries affected by diseases (mainly *Botrytis sp*) were counted and separately weighed (Yenf). Berry weight (Pb) was obtained from 3 samples of 250 berries each, randomly collected on the studied vines at harvest.

### 2.8 Determination of the leaf/fruit ratio ("source/sink" factor)

The leaf/fruit ratio (FF) was established as a factor in order to analyze its influence on vine performance. Four classes were defined within this factor that, eventually, could be determined by the vine grower by performing a series of cultural practices to reduce leaf surface and/or cluster number or some parts of the clusters.

This indicator was obtained by dividing the potential exposed leaf surface (SFEp) and the yielded per vine (Y). The categories were defined accounting for the frequency distribution for six classes. Due to the low frequency of the two highest categories, they were grouped with the former one for obtaining four categories with a balanced distribution. The defined categories were the following: < 0,40; 0.40-0.60; >0.60-0,80; >0,80 (m2*kg grape-1)

### 2.9 Determination of berry composition

Harvest was carried out at "technological maturity" for each plot, considering pH values, the ratio between sugar content and titratable acidity of the grapes and berry weight. These parameters were determined periodically using the OIV (2007) procedures. For doing this, from veraison, weekly samples of 250 berries were collected in each plot. Berry composition was determined after manually separating the berries from the raquis and obtaining the juice by crushing the flesh with an electrical grinder (HR2290, Phillips, The Netherlands). Soluble solids contents (SS) were determined using a refractometer (Atago N1, Atago, Tokyo, Japan), pH was determined with a pH-meter (HI8521, Hanna Instruments, Italy) and titratable acidity (AT) was measured by titration and was expressed as g of sulfuric acid /L juice.

In the berry samples, we also determined total anthocyanins (ApH1), extractable anthocyanins (ApH 3.2), phenolic richness (A280) and the cell maturity index (EA) [49]. All these measurements were carried out in duplicate with a Shimadzu UV-1240 Mini (Shimadzu, Japan) spectrophotometer, using crystal (for anthocyanins) and quartz (for absorbance at 280 nm) cells with 1 cm path length. The indices were calculated considering the respective dilution of the grape extracts [50].

### 2.10 Statistical analysis

In order to analyze the relative importance of the different factors (and their interactions) on the total variability of vine performance, the following classes were defined:

| Class | Levels | Values |
|---|---|---|
| Year (Year effect) | 4 | 2011; 2012; 2013; 2014 |
| Soil (Textural class or TCra) | 3 | Clay loam; Silty clay; Silty clay loam |
| Source-sink (SFEp*Y-1) | 4 | <0,40; 0.40-0.60; >0.60-0,80; >0,80 |

A Mixed Model with random effects was considered:

y = Soil, Source-sink, Year effect, interactions and residuals, except the intercept.

The model was run for each dependent variable and the variance was estimated by the Restricted Estimation by Maximum Likelihood (REML). The relative percentage of each one over the total sum was determined. In addition, ANOVA was used for assessing the effect of each individual factor (year, soil and source-sink) on vine performance (vigour, yield, berry composition and sanitary status). Fisher LSD test was used for mean separation ($p<0.10$). Furthermore, Pearson's correlation coefficients were calculated for the selected variables in order to further interpreter the effect of the source-sink factor. ANOVA was performed using the InfoStat software and the Mixed Models were estimated using R (R Development Core Team www.r-project.org).

## III. RESULTS

Table 4 shows the relative importance of each factor (“year”, “soil and “source-sink”) and their interactions on the variance of the studied dataset.

Source-sink ratio was used as a factor because the determination of its magnitude has not a lineal dependence relation with the two variables that it related (SFEp/Y), as explained later.

Most of the factors, either individually or their partial interactions, did not explain the variability in the obtained results. In many cases, the percentages were equal to 0 or their values were not significant. In general, the percentages accumulated as “residual” surpassed to the studied factors and interactions. The greatest variability assigned to “residual” corresponded to the group of variables associated with vegetative vigour.

Source-sink relation explains 82% of the yield variability in the dataset; the interaction “year*soil” explained 14% of the rot incidence and 36% of the pH value in the juice. The interaction “year*FF” reflected significant effects on the variability of yield (13%), rot incidence (43%) and titratable acidity (27%).

**TABLE 4**
**PERCENTAGE OF THE VARIABILITY WITHIN THE DATASET EXPLAINED BY THE YEAR, SOIL AND SOURCE-SINK FACTORS, AS WELL AS THEIR INTERACTIONS**

| Variable | Year | | Soil | | Source-sink | | Year* Soil | | Year* Source-sink | | Soil* Source-sink | | Residual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | p | % | p | % | p | % | p | % | p | % | p | % |
| SFEp ($m^2$ *$vine^{-1}$) | 14 | ns | 11 | ns | 0 | | 0 | | 0 | | 0 | | 75 |
| LP (cm) | 0 | | 12 | ns | 0 | | 0 | | 0 | | 0 | | 88 |
| PSmad (mg*$cm^{-1}$) | 0 | | 29 | ns | 0 | | 0 | | 0 | | 0 | | 71 |
| PST (g) | 16 | ns | 0 | | 6 | ns | 0 | | 0 | | 0 | | 78 |
| PSesp (kg*$m^{-1}$) | 16 | ns | 2 | ns | 0 | | 0 | | 0 | | 0 | | 83 |
| Pb (g) | 42 | ns | 0 | | 0 | | 0 | | 0 | | 0 | | 58 |
| Y (kg) | 0 | | 0 | | 82 | * | 1 | ns | 13 | ** | 0 | | 5 |
| Yenf (%) | 11 | ns | 22 | ns | 0 | | 14 | * | 43 | ** | 8 | ns | 1 |
| PSRac (g) | 27 | ns | 0 | | 21 | ns | 0 | | 0 | | 0 | | 52 |
| SS (g*$L^{-1}$) | 22 | ns | 0 | | 8 | ns | 0 | | 23 | ns | 0 | | 47 |
| AT (g*$L^{-1}$) | 44 | ns | 2 | ns | 0 | | 8 | ns | 27 | * | 0 | | 19 |
| PH | 6 | ns | 1 | ns | 0 | | 36 | * | 19 | ns | 21 | ns | 18 |
| ApH1 | 16 | ns | 0 | | 42 | ns | 0 | | 0 | | 0 | | 43 |
| ApH3,2 | 0 | | 0 | | 34 | ns | 0 | | 7 | ns | 0 | | 59 |
| EA% | 47 | ns | 0 | | 0 | | 0 | | 17 | ns | 0 | | 36 |
| A280 | 3 | ns | 23 | ns | 0 | | 0 | | 33 | ns | 0 | | 42 |

***, ** indicates significant at p < 0.05 and 0.01 respectively; ns indicates not significant.***

Variables associated to vegetative development tended to be influenced by soil and year factors, primarily, and for source-sink to a lesser extent. In contrast, yield variables were influenced mostly by year, source-sink and their interaction. Berry composition variables were affected by year, source-sink, the interactions year*source-sink and year*soil.

The results from the ANOVA for studying the influence of the soil factor on the response variables showed significant differences in several vegetative development variables: SFEp, LP and PSmad. The influence of soil on yield variables was relevant for Y and Yenf; finally, for berry composition, soil influenced ApH1, ApH3.2 and A280 (Table 5).

**TABLE 5**
**VINE RESPONSE AS A FUNCTION OF SOIL TEXTURAL CLASSES (MEANS ± STANDARD DEVIATION)**

| Type | Variable | Soil factor: TCra | | |
|---|---|---|---|---|
| | | Silty clay N=7 | Clay loam N=14 | Silty clay loam N=6 |
| Vegetative development | SFEp ($m^2$*$vine^{-1}$) | 1.81 ab ± 0.30 | 1.61 b ± 0.31 | 1.89 a ± 0.24 |
| | Shoot length: LP (cm) | 128.95 a ± 39.35 | 127.10 a ± 28.28 | 100.23 b ± 8.97 |
| | Shoot dry weight: PST (g) | 188.21 a ± 43.93 | 164.39 a ± 51.00 | 189.09 a ± 59.06 |
| | Dry weight per linear meter: PSesp (kg*$m^{-1}$) | 2.29 a ± 0.48 | 1.99 a ± 0.67 | 2.22 a ± 0.54 |
| | Dry weight per cm of wood: PSmad (mg*$cm^{-1}$ ) | 202.93 b ± 33.17 | 268.69 a ± 52.88 | 247.71ab ± 45.53 |
| Yield components | Berry weight Pb (g) | 1.68 a ± 0.12 | 1.66 a ± 0.16 | 1.70 a ± 0.17 |
| | Yield: Y (g*$vine^{-1}$) | 5416.59 a ± 2096.38 | 1917.73 b ± 609.70 | 4774.59 a ± 2028.27 |
| | Affected clusters: Yenf (%*$vine^{-1}$) | 53.03a ±41.00 | 15.83b ± 19.88 | 7.22b ± 9.60 |
| | Cluster dry weight: PSRac (g) | 128.22 a ± 38.24 | 102.54 a ± 38.72 | 138.40 a ± 60.95 |
| Berry composition | SS (g*$L^{-1}$) | 203.46 a±36.45 | 223.78 a ±24.65 | 216.18 a ±12.67 |
| | TA (g $H_2SO_4$ *$L^{-1}$) | 5.21 a ±1.82 | 5.13 a ±1.29 | 4.21 a ±0.64 |
| | pH | 3.37 a ±0.25 | 3.54 a ±0.11 | 3.56 a ±0.09 |
| | ApH1 (mg EMG*$L^{-1}$) | 1582.71 b ±822.30 | 2095.66 a ±516.72 | 1708.20ab ±230.28 |
| | ApH3.2 (mg EMG*$L^{-1}$) | 776.76 b ±385.82 | 981.65 a ±213.06 | 859.67 ab ±149.83 |
| | EA (%) | 49.20 a ± 10.52 | 51.39 a ± 10.53 | 49.52 a ± 7.22 |
| | A280 | 57.52 b ±17.02 | 73.64 a ±13.64 | 53.88 b ±11.92 |

***EMG = equivalent to malvidin-3-glucoside. Different letters in the row indicate significant differences according to Fisher LSD test (p <= 0.10).***

Pearson's correlation coefficients found for the proportion of sand in the soil (coarse fraction) and other variables were negative for AWC (r= -0.60, p<0.001), SFEp (r= -0.56, p<0.001), Y (r= -0.67, p<0.001) and positive with SS (r=0.36, p<0.05), ApH1 (r=0.50, p<0.01) and A280 (r= 0.52, p<0.01)

ANOVA using year as factor showed a relevant importance on vine response, influencing in 60% of vegetative development variables, in 75% of yield variables and 86% of berry composition variables. Year 2011 was the warmest, driest and with more solar irradiation over the growing cycle and during maturation. Year 2013 had the lowest register for thermal accumulation and solar irradiation, with a water balance in the soil close to 0 and high values of solar irradiation during maturation. The years 2012 and 2014 were more humid. Particularly, year 2014 had the highest rainfall values over maturation and very low solar irradiation over this period.

The year factor affected vegetative development variables (SFEp, PSesp and Psmad). Weather conditions in 2012 caused a greater development of leaf surface and a higher wood dry weight; whereas in 2014 a reduction of total dry mass per linear meter of the trellis system was observed. In the case of yield components, significant differences were detected for Pb, Tenf and PSRac. In addition, the year factor affected all the berry composition variables except for ApH3.2 (Table 6).

**TABLE 6**
**VINE PERFORMACE AS A FUNCTION OF THE YEAR (MEANS ± STANDARD DEVIATION)**

| Type | Variable | "Year" factor | | | |
|---|---|---|---|---|---|
| | | 2011 N=3 | 2012 N=8 | 2013 N=9 | 2014 N=7 |
| Vegetative development | SFEp ($m^2$*$vine^{-1}$) | 1.46b ± 0,16 | 1.91a ±0.34 | 1.64b ±0.29 | 1.73ab ±0.25 |
| | Shoot length: LP (cm) | 107.23a ±23.31 | 128.67a ±37.20 | 117.13a ±33.61 | 125.45a ±20.49 |
| | Shoot dry weight: PST (g) | 247.76a ±63.63 | 233.68a ±63,43 | 261.47a ±48.76 | 243.22a ±49.70 |
| | Dry weight per linear meter: PSesp (kg*$m^{-1}$) | 208.10a ±65.45 | 178.36ab ±40.47 | 191.32a ±60,84 | 140.06b ±21.84 |
| | Dry weight per cm of wood: PSmad (mg*$cm^{-1}$ ) | 2.26ab ±0.87 | 2.36a ±0.56 | 2.21ab ±0.56 | 1.67b ±0.40 |
| Yield components | Berry weight Pb (g) | 1.45b ±0.13 | 1.75a ±0.13 | 1.65a ±0.12 | 1.71a ±0.14 |
| | Yield: Y (g*$vine^{-1}$) | 2989.48a ±1680,03 | 3993.62a ±1890.82 | 3263.12a ±2829.39 | 3303.76a ±2002.54 |
| | Affected clusters: Yenf (%*$vine^{-1}$) | 3.87b ±3.95 | 24.94ab ±32.33 | 10.88b ± 20.60 | 46.71a ±34.37 |
| | Cluster dry weight: PSRac (g) | 151.97a ±48.18 | 118.36a ±27.34 | 132.73a ±56.94 | 80.87b ±20.53 |
| Berry composition | SS (g*$L^{-1}$) | 225.17a ±12.85 | 213.73ab ±8.80 | 232.92a ±22.71 | 196.09b ± 36.46 |
| | TA (g $H_2SO_4$ *$L^{-1}$) | 4.56bc ±0.43 | 3.81c ±0.59 | 5.07b ±0.74 | 6.27a ±1.70 |
| | pH | 3.36b ±0.07 | 3.55a ±0.12 | 3.59a ±0.15 | 3.40b ±0.18 |
| | ApH1 (mg EMG*$L^{-1}$) | 1666.07ab ±102.11 | 2147.84a ±402.86 | 2005.34a ±679.61 | 1491.19b ±642.58 |
| | ApH3.2 (mg EMG*$L^{-1}$) | 782.54a ±43.20 | 980.47a ±174.98 | 898.56a ±327.59 | 865.73a ±323.24 |
| | EA (%) | 52.68a ±5.01 | 53.85a ±6.37 | 55.35a ±5.83 | 39.15b ±9.78 |
| | A280 | 67.32ab ±8.39 | 55.08b ±14.44 | 70.65a ±17.50 | 68.35ab ±17.46 |

***EMG = equivalent to malvidin-3-glucoside. Different letters in the row indicate significant differences according to Fisher LSD test (p <= 0.10).***

The analysis of variance accounting for the source-sink factor (Table 7) determined significant differences for Psesp in the group of vegetative development variables; for Pb, Y and PSRac among yield components.

Yield was positively correlated with berry weight (Pb) and cluster dry weight (PSRac), which is the determinant of the differences in Psesp or total dry weight produced per linear meter of the trellis system.

Moreover, the source-sink factor influenced all berry composition variables, except for EA. The class ">0.80" had the highest SS values, whereas the lowest ones were observed for the "<0.40" class. The AT, pH and A280 were also higher for the ">0.80" class. Anthocyanins were greater in the intermediate categories: ApH1 was higher in the "0.61-0.80" class and ApH3.2 in "0.40-0.60" and ">0.60-0.80". Overall, the ">0.60-0.8" was associated to a response of higher quality, whereas that of "<0.40" to higher yields.

**TABLE 7**
**VINE RESPONSE ACCORDING TO THE SOURCE-SINK FACTOR (MEANS ± STANDARD DEVIATION)**

| Type | Variable | “Source-sink” factor: SFEp/kg grape ($m^2*kg^{-1}$) | | | |
|---|---|---|---|---|---|
| | | <0.40 N=6 | 0.40-0.60 N=8 | >0.60-0.80 N=5 | >0.80 N= 8 |
| Vegetative development | SFEp ($m^2*vine^{-1}$) | 1.86a ±0.31 | 1.79a ±0.26 | 1.63a ±0.27 | 1.61a ±0.37 |
| | Shoot length: LP (cm) | 109.95a ±16.95 | 121.04a ±38.84 | 130.34a ±17.41 | 125.47a ±36.06 |
| | Shoot dry weight: PST (g) | 229.43a ±47.09 | 231.43a ±55.02 | 255.24a ±66.46 | 270.54a ±46.29 |
| | Dry weight per linear meter: PSesp ($kg*m^{-1}$) | 204.86a ±63.44 | 182.08ab ±35.89 | 160.06ab ±37.03 | 158.42b ±57.49 |
| | Dry weight per cm of wood: PSmad ($mg*cm^{-1}$) | 2.36a ±0.35 | 2.24a ±0.58 | 1.87a ±0.63 | 1.97a ±0.73 |
| Yield components | Berry weight Pb (g) | 1.66ab ±0.14 | 1.69ab ±0.14 | 1.77a ±0.06 | 1.60b ±0.18 |
| | Yield: Y ($g*vine^{-1}$) | 6857.74a ±1380.00 | 3528.48b ±902.32 | 2317.40c ±327.92 | 1556.32c ±501.64 |
| | Affected clusters: Yenf ($\%*vine^{-1}$) | 20.80a ±33.25 | 37.26a ±40.33 | 21.27a ± 24.84 | 13.35a ± 18.59 |
| | Cluster dry weight: PSRac (g) | 153.66a ±58.80 | 120.91ab ±32.66 | 100.79b ±21.84 | 96.28b ±44.40 |
| Berry composition | SS ($g*L^{-1}$) | 198.38b ±35.39 | 218.57ab ±15.57 | 220.40ab ±10.09 | 226.68a ±32.35 |
| | TA (g $H_2SO_4*L^{-1}$) | 4.93ab ±2.09 | 4.63b ±0.67 | 4.17b ±0.97 | 5.76a ±1.19 |
| | pH | 3.35b ±0.14 | 3.53a ±0.21 | 3.60a ±0.10 | 3.53a ±0.10 |
| | ApH1 (mg EMG*$L^{-1}$) | 1276.71c ±480.83 | 1912.88b ±511.23 | 2407.25a ±224.11 | 1958.48ab ±588.22 |
| | ApH3.2 (mg EMG*$L^{-1}$) | 641.32b ±245.82 | 939.08a ±246.05 | 1116.33a ±87.61 | 924.53a ±237.79 |
| | EA (%) | 48.56a ±11.03 | 50.42a ±6.74 | 53.18a ±6.35 | 50.05a ±13.35 |
| | A280 | 51.88c ±12.61 | 60.30bc 15.04 | 71.75ab ±14.24 | 75.57a ±14.76 |

***EMG = equivalent to malvidin-3-glucoside. Different letters in the row indicate significant differences according to Fisher LSD test (p <= 0.10).***

In order to better understand the causes that explain the source-sink factor, a series of partial correlations were analyzed (Figure 1). Soil water availability (AWC) was positively correlated with yield (r= 0.53; p= 0.004) and with SFEp (r= 0.54; p= 0.003), yield being the main explaining factor of the ratio source-sink (r= -0.57; p=0.002). In contrast, leaf surface (SFEp) did not present a correlation with this ratio (r=0.21; p> 0.1), although it was significantly correlated with yield (r= 0.36; p= 0.06). Therefore, an increasing in vegetative development explains a greater yield, although it has not a significant effect on the leaf/grape ratio. Complementarily, we observed that shoot number per linear meter of the trellis system had an incidence on vegetative development (r= 0.40; p= 0.04) and that the increase in yield was negatively correlated with the exposure of the clusters to solar radiation.

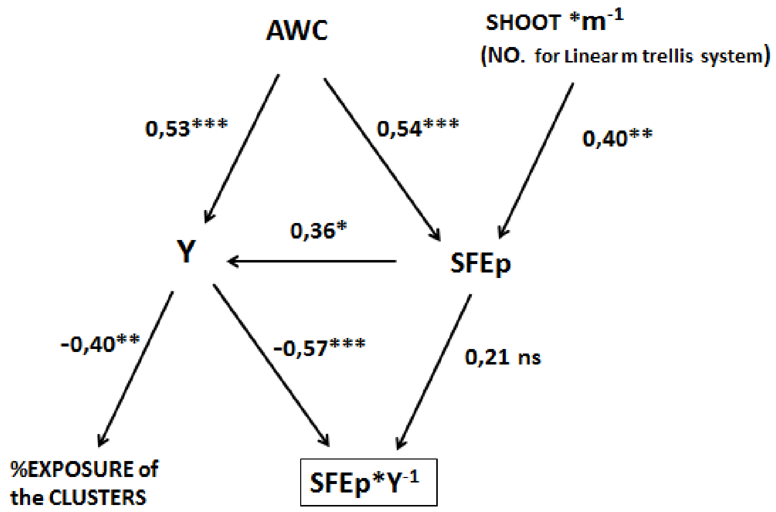


**FIGURE 1: SCHEMATIC REPRESENTATION OF THE PEARSON'S CORRELATION COEFFICIENTS AMONGST THE DIFFERENT VARIABLES CONSIDERED IN THE CURRENT STUDY. THE SYMBOLS: *, **, *** AND NS, INDICATE SIGNIFICANCES AT P< 0.1; 0.05; 0.001; AND NOT SIGNIFICANT, RESPECTIVELY.**

## IV. DISCUSSION

The analysis of the relative importance of factors (and their interactions) to the variance allows interpreting a complex effect on determining plant performance, and that cannot be attributed only to the selected elements or to their partial interactions. The high percentages accumulated in "residual" might reveal the effect of other factors and interactions that have not been considered; for instance, soil fertility, in-row weed management, vine reserve accumulation or the occurrence of extreme climate events. In addition, the use of simple indices, such as DI or HI, for characterizing a productive cycle might not be sufficient for explaining the physiological dynamics of the plants, at least to a refined level, and the adaption processes to different constraints. In order to obtain a zonification with a more homogeneous response, it will be necessary to carry out studies that integrate climate variability at different scales, including extreme values, with key physiological processes and wine quality [10].

Apart from these limitation, the significant effects of the studied factors on the variance of our dataset, and even those that can only be taken as showing trends in the mixed model, are in accordance with the ANOVA results when the effect of each factor is analyzed independently. This accordance justifies the pertinence of the applied analysis, since it allows for a global vision of viticulture production at the territory level by jerarquizing the weight of the factors.

### 4.1 Effect of the studied factors on the vegetative development

Vegetative development variables were not influenced by the studied factors and their interactions. However, the "year" and "soil" factors exerted a significant influence on some vegetative development variables [41].

Water availability is the soil component with the greatest influence on grapevine physiology, and it is dependent on soil texture, depth [19] and soil organic matter content. Silty clay and Silty clay loam soils showed a greater volume explored by roots and a greater proportion of sitl and clay; whereas Clay loam soils were associated to greater water availability for the vines. A strong correlation between soil available water capacity and canopy development, yield, berry size and must quality has been detected, as observed by other authors [27] [28][29][21][22][30][23]. Weather conditions in 2012 and, especially, in 2014, with high rainfall amounts in summer, promoted a greater biomass development; this situation was more marked in those vineyards located on soils with high AWC. The different measures of plant water status (leaf water potential, carbon isotope discrimination, water balance models) were strongly correlated with soil water availability [51]. Therefore, it is possible to infer plant water status from indices such as DI and RSFeb [52].

### 4.2 Effect of the studied factors on yield components

The influence of the three studied factors and their interaction on the determination of yield components was evident. Yield per plant was correlated positively with rainfall amount over the maturation period. According to our results, the greatest weight in the determination of yield components corresponded to the "Source-sink" and "Year" factors, but also to their interaction. Our results proved that the driver of the "Source-sink" factor was yield and not leaf surface, since differences on SFEp have not been detected.

In this case, the different categories of the "Source-sink" ratio were the result of the influence of weather conditions in a given year and soil type; although, usually, vine balance is also managed by the vine grower. Even though AWC affects to the vegetative and reproductive development, it induces a differential variability between both dimensions that is more beneficial to yield. Increasing crop load in the vines reduces vegetative growth and reserve accumulation in the shoots due to the competition established among the different organs, particularly in the period from fruit-set to pea-size stage, when photo-assimilate translocation is multidirectional [53]. The opposite effect was observed, for instance, in plants with severe pruning or excessive cluster thinning that promote a greater vegetative development. Clusters have greater sink strength for photo-assimilates than other organs, but also a scarce capacity for acting as a source [54]. Soil showed a lower influence on vine yield than the other factors considered in this study. Nevertheless, the analysis without accounting for the other factors reflected soil effects on this variable. Soil affected yield mainly by differences in water availability, due to soil water retention and volume explored by roots. Fine-textured soils (Clay loam and Silty clay loam), developed over quaternary sediments and with greater depths, had highest AWC values. Partial correlation analysis allowed to prove the effect of AWC on vegetative growth and, mostly, on yield.

The analysis of the relative weight of the studied factors on yield components showed that vine sanitary status was the parameter most affected by soil. In the current study, soils with favourable conditions for higher vegetative development and yield were associated with a greater incidence of diseases. Nevertheless, this response is not linear. It is important to bear in mind that, when analyzing disease incidence due to soil type, a given site is considered. Soils classified as Silty clay loam, corresponding to plots 1 and 2, located in the western part of the region, showed a lower proportion of yield losses caused by rot incidence (data not shown), than those located in the other studied areas independently of the year (this fact is known by vine growers in the area). Even though bunch rot is usually associated to *Botrytis cinerea*, it is possible that in the Colonia del Sacramento region, other low-damaging species are present. In this sense, several authors worked on the morphological characterization and on the molecular identification of *Botrytis sp.*; they found three different species that affect to a higher or lesser extent to the different grapevine organs [55] [56] [57].

Sanitary status was also affected by the "Year" factor and the interactions "Year*Source-sink" and "Source-sink*Soil". Under the conditions of the current study, the greater categories of source-sink ratio (potentially regulated by the grower) could be associated to a lower cluster volume and to a canopy microclimate with less risk of disease incidence. However, this ratio itself is not enough for reducing yield losses in years characterized by high rainfall amounts, high DI values and low solar irradiation during maturation (RS Feb). Under these conditions, high bunch disease incidence is the main cause of yield reduction.

### 4.3 Effect of the studied factors on berry composition

Berry composition variables were affected to different extents by the three studied factors: "Year", "Soil" and "Source-sink".

The seasonal variation in berry primary components depended less on the source-sink ratio than on vine water status [58], which is mainly associated with the "Year" factor and its interaction with "Soil", but also with "Source-sink". In the conditions of the current study, the best global quality was obtained in 2013.

The influence of the "source-sink" factor on the synthesis of primary components in the berries showed a relative linearity, when studied separately from other factors. The synthesis of SS increases with higher "source-sink" values, while AT decreases. However, when source-sink ratio is ">0.80", the trend was inverted and the AT concentration reached its maximum. This fact could be explained by the combined effect of shading inside the canopy and less exposure of clusters to solar radiation that would promote a reduction in the respiration rate of malic acid and the dilution of organic acids due to a lower dehydration of the berries [59].

The main factor determining pH values was the interaction "Year*Soil". The year acted through its influence on organic acid synthesis (malic and tartaric acids) at pre-veraison and on their degradation rate during maturation. This process is highly dependent on solar radiation, temperature and vine water status. Soil had and indirect influence through modulating water availability, thus conditioning the energy balance and vine response [15]. Water stress limits the concentration of cations in the berries, particularly $K^+$, affecting AT and pH [58]

Regarding the synthesis of secondary components, such as anthocyanins and tannins, the separate ANOVA for the "Soil" factor allowed to observe the different responses according to TCra. Clay Loam soils, with lower water storage ability than Silty clay and Silty clay loam soils, generated moderate water stress conditions during maturation, favoring phenolic compounds synthesis. In addition, water availability differences for a given soil class, caused by the particular physical conditions and organic matter of each specific site, were evident on the level of vine water stress. For instance, plots 6 and 7, with water availabilities of 67 and 57 mm, respectively, during 2011, caused differences of 15% in the measures of pre-dawn leaf water potential over the entire growing season (data not shown), even though both plots corresponded to the same soil textural class (Clay Loam). On the other hand, the effect of soil water availability was greater than that of cultivar when accounting for the determination of yield potential in a vineyard [60], influencing in hormonal signaling from roots to shoots and on stomata control.

"Source-sink" factor was determinant for phenolic concentrations, especially those of anthocyanins, but it did not show a linear relationship with the synthesis of these compounds, which increased till the ">0.60-0.80" class and then decreased. The reduction in concentration for "Source-sink" ">0.80" could be explained by an excessive increase on leaf surface in relation to fruit load, determining a low percentage of clusters exposed to solar irradiation, limiting anthocyanins synthesis and other secondary metabolites [31]. Apart from the environment, the relative availability of carbon established by the leaf/fruit ratio affects the synthesis of both primary and secondary metabolites. In carbon-limited situations, the grape can manage the metabolic pathway of carbon and, thus, sugar accumulation remains while secondary metabolites synthesis is reduced [35]. Our results showed that, taking leaf/fruit ratio of "0.60-0.80" as a reference for the maximum accumulation of SS and ApH1, leaf/fruit ratio of "0.40-0.60" reduced SS synthesis in 0.8% and ApH1 in 20.5%. When carbon availability is lower, as in the case of leaf/fruit ratio "<0.40", SS concentration was reduced by 10%, whereas ApH1 was reduced in 47%. These results are in accordance with the report by other authors [38], who indicated that reducing canopy size would decrease the SS/AT ratio and retards maturation.

Leaf/fruit ratio values that promoted a better berry composition were associated to lower yields and similar SFEp. This result agrees with [61], who proved that berry composition was correlated to yield and berry size more strongly [30] than to canopy size.

When leaf/fruit ratio depends on viticultural practices, it is necessary to understand how this value is reached. According to [33], different pruning intensities may lead to similar leaf/fruit ratios but different preferences for the resultant wines. Similarly, leaf removal practices that lead to a given leaf/fruit ratio might cause different effects on the vines depending on the time of application and the position of the removed leaves. For instance, post-veraison removing the leaves located over the clusters might cause retarding of the maturation process [34]. When leaf removal is performed at pre-flowering, it can promote yield and cluster compactness reductions, as well as accelerating the maturation process [62]; in some cases, it can lead to an excessive decrease of berry acidity if clusters were over-exposed to solar radiation [36].

According to these considerations, canopy and leaf/fruit ratio management should be adapted to the particular environment and cultivar conditions, in order to solve site-specific productive problems. Under the current study conditions, the best SFEp/Y ratio was >0.60-0.80 m2*kg-1, with a SFEp of 1.63m2*vine-1. This balanced ratio guaranteed berry maturation and also other processes such as assimilable nitrogen accumulation and recovery of N in the reserves [39].

## V. CONCLUSION

The combined analysis of "year", "soil", "leaf/fruit ratio" and their partial interactions on vine performance proved to be useful for understanding viticulture terroir functioning.

In the studied terroirs, vegetative development variables were dependent on climate and soil, but also on other factors and interactions not included in the current study, leading to the need for research including new explaining factors and their interactions.

Yield per vine was explained mainly by the "source-sink" ratio, the "year" effect and their interaction; both were linked to rainfall amount during maturation. Crop load carried by vines was determinant of this "source-sink" ratio, surpassing the leaf surface influence. In this sense, higher water availability would displace vine balance to fruit (sink).

Berry primary components synthesis depended on year and the interactions of year with soil and source-sink ratio. Concentrations of secondary metabolites in the berry were dependent on "source-sink" ratio and weather. Different features linked to "source-sink" ratio, such as vine balance, amount of available carbon during maturation and canopy microclimate, with weather conditions that influence grapevine water status, are key processes in the synthesis of phenolic substances.

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