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ORIGINAL RESEARCH ARTICLE

How soil and climate variability within a vineyard can affect the heterogeneity of grapevine vigour and production

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ABSTRACT

This study aimed to determine how within-plot soil heterogeneity combined with yearly climate variability can promote the heterogeneity of vine growth at plot level, and which soil-climate parameters influence final yield and berry composition the most. An 8-year experiment was conducted on grapevine in two zones of a vineyard (1 ha) differentiated according to grapevine vigour as determined by NDVI: high vigour (HV) and low vigour (LV). The heterogeneity of the soil properties (depth, texture and composition), plant growth (shoots and roots) and plant production (yield components and berry composition) were determined at plot level. Compared to the LV zone, the HV zone was associated with deeper soils, higher soil water and nitrogen availability, CEC and montmorillonite/illite ratio. More extended root systems, higher vegetative growth and higher yield were observed in the HV zone compared to the LV zone. Drier and warmer vintages increased the difference in heterogeneity of vine growth and yield between the two zones. Berry composition (primary and secondary metabolites) also differed between HV and LV zones but seemed unconnected to vigour and mainly depended on soil-climate-plant interactions over the years. The heterogeneity of plant vigour within the vineyard mainly resulted from differences in root exploration, soil profile and composition (notably montmorillonite/illite ratio). The present study identified soil and crop factors that, depending on weather conditions, can be drivers for reducing the heterogeneity of plant development and improving productivity at vineyard level.

KEYWORDS: within-field heterogeneity, precision viticulture, root growth, berry composition, soil water, *Vitis vinifera* L., Tannat

INTRODUCTION

One of the main issues that farmers face is the within-plot variability of production. Spatial (within-plot) yield variability is associated with stable seasonal physical features (soil and topography) that interact with seasonal abiotic and biotic conditions (climate, water and nitrogen availability and presence of disease) and agronomic management strategy (Machado *et al.,* 2002; Tisseyre *et al.,* 2008; Jasse *et al.,* 2021). The availability of water and nutrients (mainly nitrogen) are well known factors that condition plant development, growth and yield. Water is one of the most critical factors determining the vegetative development of grapevine (Pellegrino *et al.,* 2005). Severe water deficit can result in limited aerial and root growth due to decreased cell turgor and increased root penetration resistance in dry soil (Bengough *et al.,* 2011). In addition, water availability determines nutrient uptake (Keller, 2015), stomatal conductance, photosynthesis (Flexas *et al.,* 1998) and berry growth. Several studies have reported a reduction in stomatal conductance without impact on photosynthesis during a water deficit, thus increasing water use efficiency. $\delta^{13}C$ in berry must can be used as an integrative indicator of water status and water use efficiency during the ripening period (Brillante *et al.,* 2018; Yu *et al*., 2021). Another factor that impacts plant functioning is soil temperature, which depends on soil characteristics and water availability. Notably, soil temperature influences shoot and root growth in grapevine through its impacts on carbon and nitrogen allocations from the pool of reserves (Clarke *et al.,* 2015; Field *et al.,* 2020). Ultimately, the physical characteristics of soil, including texture, structure and depth, are important factors to consider because of their effects on root temperature and on water and mineral supply to the plant (Schmitz and Sourell, 2000; Brillante *et al.,* 2016). The above physical characteristics (soil/climate) of the vineyard are part of the "Terroir" concept. Indeed, "Terroir" refers to the combination of geographical (soil) and climatic characteristics of a region that are influenced by human practices, and which in turn enables the production of a product with unique characteristics (Vaudour, 2003; van Leeuwen *et al.,* 2006; OIV, 2010).

Precision viticulture (PV) comprises a set of tools that allows the viticulturist to characterise the spatial variability of terroir components at the vineyard scale to make well-informed decisions. It enables resource management to be optimised or selective harvesting based on yield or quality parameters to be conducted (Bramley and Hamilton, 2004). The use of a vegetation index like the NDVI (normalised difference vegetation index, defined by Rouse *et al.,* 1973) provides a source of information for potential delimitation of zones with contrasting plant growth (Bramley *et al.,* 2011; Ferrer *et al.,* 2020a; Sams *et al.,* 2022). The NDVI is often used in viticulture to estimate vine vigour (Tisseyre *et al.,* 2007). The concept of vine vigour refers to the vine's growth capacity; i.e., vegetative and productive growth (Winkler *et al.,* 1974; Smart and Robinson, 1991). Thus, 'vigour' is a term that encompasses both the plant growth rate and its production potential (total dry matter produced). The heterogeneity of weather, together with non-uniform topography and soil characteristics, generate plant vigour or an NDVI with high spatial and temporal heterogeneity within a single vineyard (Bramley and Hamilton, 2004; Jasse *et al.,* 2021). Many studies have reported the impact of grapevine vigour on yield and grape composition. In general, vines with high vigour are associated with high yields and big berries (Bramley *et al.,* 2011; van Leeuwen *et al.,* 2018), but they are prone to greater sensitivity to *Botrytis cinerea* (Filippetti *et al.,* 2013; Ferrer *et al.,* 2020a; Gatti *et al.,* 2022) and to a delay in ripening (van Leeuwen *et al.,* 2018) compared to low vigour vines. By contrast, vines with low vigour, which often result from lower water and nitrogen availability at the plot level, generate lower yields (Arnó *et al*., 2012) and can result in excessive exposure of the bunches to sunlight (Tardaguila *et al.,* 2011; McClymont *et al.,* 2012; Ferrer *et al.,* 2020b). Vigour has been shown to affect berry composition (sugars, acids and anthocyanins) in different ways, depending on the climatic conditions in a given year (Tisseyre *et al.,* 2008; McClymont *et al.,* 2012; Gatti *et al.,* 2022).

While the physical characteristics of soil generate consistent heterogeneous zones of productivity over the years, specific weather conditions and/or crop management during the cropping cycle can alternatively lower or exacerbate the within-plot variability of production (Tisseyre *et al.,* 2007; Gatti *et al.,* 2022). Thus, understanding the factors underlying soil heterogeneity at the plot level and how weather conditions can enhance their effects on plant development and productivity is essential for optimal and more sustainable crop management.

The present study was conducted over eight consecutive growing seasons in a representative vineyard in the south of Uruguay characterised by a temperate climate, with the aim of mapping soil heterogeneity (texture, depth, organic matter, nitrogen stock and temperature) within the vineyard. The influence of soil factors combined with weather conditions on the expression of plant vigour, yield and berry quality components were then assessed. Whether precise vineyard management could help to reduce the effects of heterogeneity on plant growth and production is discussed.

MATERIALS AND METHODS

1. Study site

The experiment was carried out over eight consecutive years (2014-2021) in a commercial vineyard of 1.1 ha planted in 1998 with *Vitis vinifera* L. cv. Tannat grafted on SO_4 rootstock. This vineyard was located in Canelones, Uruguay (geographic coordinates: 34° 36 S, 56° 14 W), 56 km from Montevideo. The vineyard was on a gradual slope of 1-2 % (north /south). The rows were orientated north-south. The vine spacing was 2.5 m x 1.2 m (3333 vines /ha). The vines were pruned using a double guyot system (12 buds per plant) and the shoots trained to a VSP (vertical shoot position). The vineyard was not irrigated. Standard post-harvest fertilisation was carried out using urea, at a dose of 64 units of N per ha, half of which was distributed at pre-flowering and half at post-harvest.

The vineyard has high variability from east to west in terms of vigour and yield/pruning ratio (Ravaz Index), which ranged between 5 and 20. Crop vigour was assessed at veraison (January in the southern hemisphere) in 2015, 2016 and 2017 using the Normalized Difference Vegetation Index (NDVI), which was calculated using aerial imagery (altitude 620 m and speed 50 m/s), as described by Ferrer *et al.,* 2020a. High resolution (0.2 m) multispectral aerial images were obtained to define three vigour zones: high (NDVI 0.57 to 0.61), medium (NDVI 0.55 to 0.57) and low (NDVI 0.55 to 0.48) (Figure 1A). The reflectance generated by the cover crop in the intermediate rows was eliminated using the algorithm described by Primicerio *et al.* (2015). Further details on sensor type and image processing are available in Ferrer *et al.,* 2020a. The high and low NDVI zones were located in the same part of the plot in all three years (2015, 2016 and 2017), indicating perennial stability in terms of the spatial heterogeneity of the vegetative growth. Two random blocks with three replications were then defined in each the zones of high vigour (HV) and low vigour (LV). Each replication comprised twenty-one vines distributed within two rows. The vines were geo-referenced using a GPS (Thales Navigation Inc., San Dimas, CA, USA). In 2020, the variability of trunk diameter (TD_{10}) in the different vigour zones was determined. Eighty-four points were measured in the plot following a grid design (Figure 1B) and a trunk diameter variation map was produced. TD_{10} was evaluated at 10 cm above the graft using a digital caliper (Neiko 01407 ± 0.2 mm). The value obtained was the average of the transverse and longitudinal diameters with reference to the direction of the row.

Both zones (HV/LV) were managed by the winegrower in the same way: the weeds were controlled under the row using herbicides, mixed grass comprising oats and Asteraceae was grown in the inter-row, and growth was systematically controlled in the middle row by periodic mowing (six times a year).

2. Climate characterisation

The climate in this region is temperate, with warm nights (14 to 18 ºC) and moderate drought. Uruguay has an average annual rainfall of 1100 mm. However, the inter-annual variability of rain is high, and the distribution of monthly rainfall is not homogenous over the years (0 mm to 300 mm per month). During the growing season (September to March, in the southern hemisphere) the average rainfall is 600 mm.

The mesoclimatic data were collected from a meteorological station (geographic coordinates: 34° 40’ S, 56° 20’ W), which is less than 10 km from the study plot and managed according to WMO (World Meteorological Organization) standards. The weather of the area was characterised based on the following variables: maximum temperature (Tmax), minimum temperature (Tmin), average temperature (Tx), reference evapotranspiration (ETo) and rainfall. From these

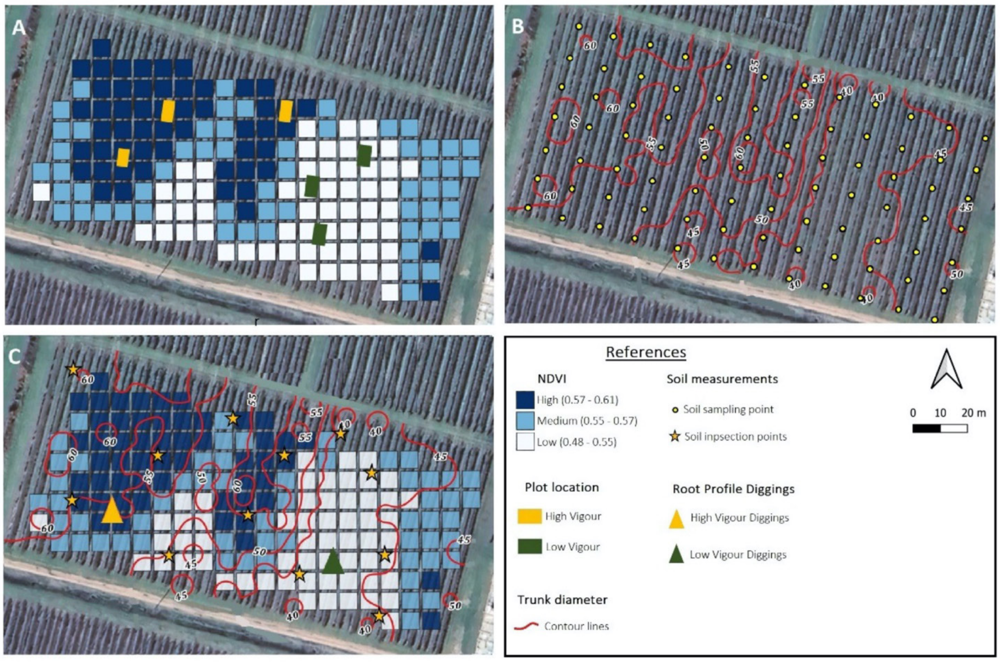

FIGURE 1. Experimental site location and vigour maps.

A: Map of average NDVI (aerial images) values at veraison (2015 to 2017) depicting the three vigour zones (white: low; sky-blue: medium; dark blue: high) for an experimental site (34° 36 S, 56° 14 W). The distribution of replicates in rectangles (yellow: high vigour, green: low vigour). B: Trunk diameter distribution map. Trunk diameter in mm. It was evaluated at bud-break in 2020 (September). Yellow points in B correspond to the soil sampling location (n = 84). C: Combination map of NDVI and trunk diameter. Triangles indicate locations of representative plants for each vigor zone (yellow: high vigour; green: low vigour), selected for root profile diggings determination. Stars indicate auger-based soil inspection points.

data, the following indicators (Ferrer *et al.,* 2020b) were determined: cumulated rainfall from budbreak to flowering (September to November; RRbb), cumulated rainfall from flowering to fruit set (November to December; RRff) and cumulated rainfall during ripening (January to March; RRrip).

Plant and soil microclimates were measured using Ibutton thermochron sensors (USA, DS-1921g, ± 0.5 °C increment). Three sensors were randomly distributed in the canopy within each zone (HV/LV) during the 8 years of experimentation (2014-2021). Using the temperature data, the following indicators (Ferrer *et al.,* 2020b) were determined: number of days with temperatures above 30°C from flowering to harvest (November to March; ND30), maximum temperature at Veraison (January, TMv) and maximum temperature at harvest (February, TMh). Soil temperature (Ts) was also determined from bud-break to leaf fall in 2019 and 2020. For this purpose, three sensors were randomly installed in each vigour zone under the row at depths of 20 and 40 cm. Using a base temperature of 10 °C GD10 (Lebon *et al.,* 2004), the growing degree days were calculated using the data obtained from these sensors (soil and canopy).

3. Soil measurements

The soil types in Uruguay are very heterogeneous, but the predominant soils in the study region have been classified as Fine Smectitic Thermic Vertic Argiudoll (Durán *et al.,* 2005). The soil was characterised in the field according to FAO (2006) and classified following the USDA Soil Taxonomy (Soil Survey Staff, 1999). Two soil diggings and twelve soil profile inspection points, using a soil auger, were made in the middle of the row (see location in Figure 2C) to determine the chemical and physical properties of the soils. A characteristic soil profile for each vigour zone is shown in Figure 4. In the winter of 2015, 252 soil samples were taken within the vineyard at three sampling depths (0-20, 20-40 and 40-60 cm) within a grid area design (10.8 m x 12.5 m) (Figure 1B, yellow points) applying the methodology proposed by Alliaume *et al.* (2017). Extractable phosphorus (Bray method), pH, exchangeable bases (calcium, magnesium, potassium and sodium), organic matter (OM), nitrates, cation exchange capacity (CEC), % of sand (Sa), clay (Cl) and silt (Si) were determined from samples taken at 0-20 and 20-40 cm. From the 40-60 cm samples, only OM and pH were determined. Furthermore, six soil inspections were performed with an auger in each vigour zone. The horizons, depth, texture, consistency, structure, bulk density and percentage of organic matter were determined in each inspection. According to its physical and chemical characteristics, in particular its CEC (14.5 – 33.7 cmol$^+$/kg) and total cations (12.6 – 33.5 cmol$^+$/kg) the soil belongs to the Vertic Argiudoll unit of the regional map (Silva *et al.,* 2018).

In addition, organic matter, nitrate and ammonium contents at three depths (0-20, 20-40 and 40-60 cm) were determined in the winter of 2018, 2019 and 2020 in both vigour zones. The N stock was calculated as the sum of NO_3^- and NH_4^+ contents and a yearly O.M. mineralisation rate. The O.M. mineralisation rate was set to 0.02 g/g/year, which is slightly less than the rate observed by Salvo *et al.* (2014) for a no till crop system (with rotation) in similar soils of Uruguay. Nitrogen leaching was not taken into account.

To estimate the distribution of water and nitrogen in the root zone, a 0.1 m x 0.1 m grid was used in the soil profile at dormancy in 2020 (see supplement 4C). Two samples of 30 g of soil were taken at every 0.2 m depth and every horizontal distance separated by 0.2 m. A total of 50 samples were collected from each vigour zone. Soil moisture and N

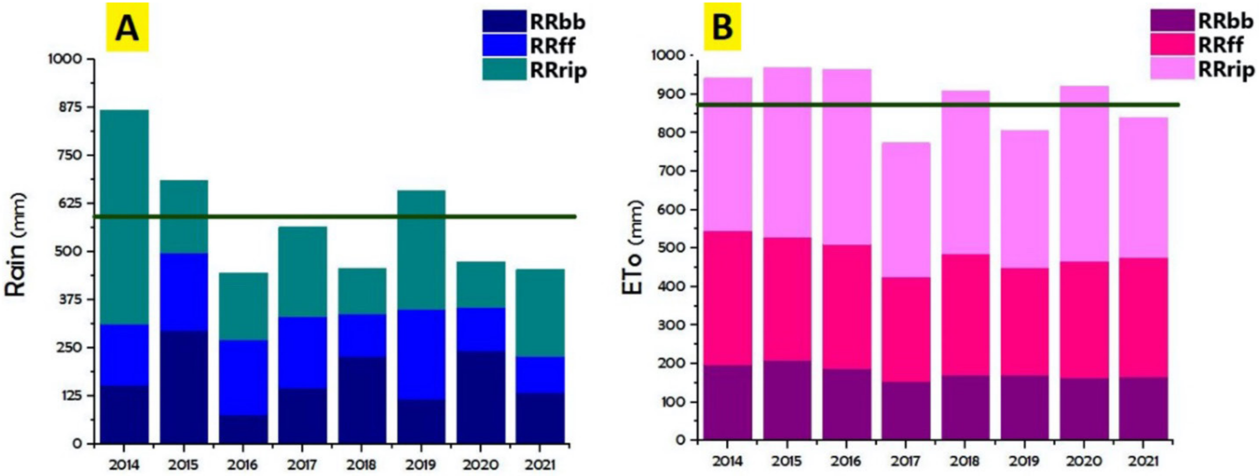

FIGURE 2. Cumulative rain and reference evapotranspiration (ETo) along the trial (2014-2021).

A- Cumulated rainfall. Black line indicates the mean rainfall over the growing cycle (601 mm). B- Cumulated reference evapotranspiration (ETo). Black line indicates the mean ETo over the growing cycle (877 mm). RRbb: cumulated rainfall/ETo from budbreak to flowering (September to November); RRff: cumulated rainfall/ETo from flowering to fruit set (November to December); RRrip: cumulated rainfall/ETo during ripening (January to March).

stock were determined in these samples. Soil moisture was measured using the gravimetric method.

In each vigour zone (HV/LV) a mixed soil sample was taken at a depth of 20-30 cm in order to quantify and identify the different clay mineralogy (CM). Clay mineralogy was determined by X-ray diffractometry (XRD), as described by Beaux *et al.* (2019), in the laboratory of the Technological Development Department of CURE (http://www.cure.edu.uy/). The methodology for sample preparation and clay analysis was adapted from Carroll (1970). Organic matter, carbonates and gypsum were removed from the samples, then the samples were deflocculated and the clay fraction was separated. Three oriented samples were prepared from this fraction: one was measured naturally (without processing), another was placed in a glycol chamber (for ethylene glycol saturation) for 24 hours and then measured, and another was calcined at 550^{o}C for 2 hr and then measured.

The Total Available Water (TAW) (Allen *et al.,* 1998) was calculated from the soil and root analyses as described below.

The TAW over the soil depth (SD) was calculated from Eq. 1:

$$\text{TAW (mm)} = (\text{FC} - \text{PWP}) * \text{soil depth} / 10\text{ cm} \quad (1)$$

with FC (volumetric moisture at field capacity) and PWP (volumetric moisture at permanent wilting point) both in cubic centimetres of water per cubic centimetre of dry soil, and BD as bulk density. FC and PWP in the soil profile were estimated using Eqs. (2) and (3) developed by Fernández (1979) and Silva *et al.,* (1988) for Uruguayan soils:

$$\text{FC (\% vol.)} = [21.977 - 0.168*(\text{Sa, \%}) + 2.601*(\text{OM, \%}) + 0.127*(\text{Cl, \%})]*\text{BD}/D_w \quad (2)$$

$$\text{PWP (\%vol.)} = [-58.1313 + 0.3718\ (\text{OM, \%}) + 0.5682\ (\text{Sa ;\%}) + 0.6414\ (\text{Si ;\%}) + 0.9755\ (\text{Cl ; \%})]*\text{BD}/D_w \quad (3)$$

In Eqs. 2 and 3, BD (bulk density, g/cc^{-1}) is divided by Dw (volumetric mass of water, 1 g/cc^{-1}) in order to keep RHS dimensionless.

The soil depth applied in Eq. (1) was the maximum depth of the root system observed from the soil profile. Following Fernández (1979) and Silva *et al.* (1988), BD/Dw was determined using Eq. (4):

$$\text{BD/Dw} = 3.6725 - 0.0531*(\text{OM, \%}) - 0.0210*(\text{Sa, \%}) - 0.0228*(\text{Si, \%}) - 0.0221\ (\text{Cl, \%}) \quad (4)$$

4. Plant growth and yield components

4.1. Root growth

One representative plant per zone (HV/LV) was selected based on average trunk diameter in each vigour zone. Root exploration (up to the maximum root depth) of each selected plant was assessed at dormancy (2020) 5 and 30 cm from the trunk. A 0.1 m x 0.1 m grid was placed on the root profile after the surrounding soil was removed according to Böhm (1979). The roots were grouped according to their diameter as follows (Van Zyl, 1988): less than 0.5 mm (fine), between 0.5 and 2 mm (thin), between 2 and 5 mm (medium), more than 5 mm (thick). The location and number of the roots per category in each grid were recorded using a digital caliper. The rooting index (RI) was calculated from the number of roots in each class (Eq. 5, Callejas-Rodríguez *et al.,* 2012):

$$\text{RI} = [(\text{fine roots number} + \text{thin roots number}) / (\text{medium roots number} + \text{thick roots number})] \quad (5)$$

4.2. Aboveground growth and nutrient status

Canopy variables were measured over 8 consecutive years (2014-2021) in each vigour zone. Exposed Leaf Area (ELA, in m^{2}/ha) was assessed at veraison on 9 vines per zone (HV/LV) according to Carbonneau (1995). Leaf nitrogen (%Nl) and potassium (%Kl) were measured on 20 healthy and exposed leaves at veraison. Yield per vine (Y, kg/vine), number of bunches per plant (B/v) and bunch size (Bz) were determined at harvest on 63 plants per vigour zone. Pruning Weight (PW, kg/vine) was measured during winter on the same 63 plants that were used for yield assessment. The Ravaz index was calculated using this information (Y.PW^{-1}).

4.3. Berry weight and composition

Two samples of 250 berries were collected at harvest for each replicate (21 plants), with three replicates for each zone (HV/LV), using the method proposed by Carbonneau *et al.* (1991). One sample was used for classical grape analysis and another for phenolic analysis.

For the basic berry analysis, the weight of the berries (Bw, g) was determined with an Ohaus Scout scale (Ohaus Corp., USA). The juice was obtained from manual crushing of the berries and the crushing of the pulp with a juice extractor, Phillips HR2290 (Phillips, Netherlands). Berry analyses (sugar content, total acidity and pH) were carried following the OIV protocol (OIV, 2014) using an Atago N1 refractometer (Atago, Japan) for Brix, Hanna HI8521 pH meter (Hanna Instruments, Italy) and burette for acidity (gH_2SO_4/L).

The other berry samples were assayed for total potential in anthocyanins (ApH1, g/l) and total phenols index (Tp), according to Glories and Augustin (1993) and González-Neves *et al.* (2004). The measurements were carried out by duplication with a Shimadzu UV-1240 Mini (Shimadzu, Japan) spectrophotometer, using glass (for the anthocyanin analyses, absorbance at 520 nm) and quartz cells (for the analyses of phenols, absorbance at 280 nm) with 1 cm path length.

5. Statistical analyses

We used the QGIS (Geographic Information System; 2021) programme to create the vineyard maps of available soil water, CEC, % clay, total cations (TC) and trunk diameter using IDW (Inverse Distance Weighting) interpolation. The maps of soil moisture, nitrogen concentration and root density in the area of influence of the vine were made using OriginPro 9.1 software.

Statistical analyses were conducted with the statistical package InfoStat Version 2011. Analyses of variance, followed by the Fisher test for means comparison, were conducted to determine the effect of vigour on soil microclimate and plant responses. Correlations between all plant and soil variables were determined though a correspondence factor analysis (ACF). Multiple linear regression models were used to quantify the effects of edaphoclimatic variables (13) on the most important plant variables during the period 2014 to 2021. Although the characterisation of soil variables (TAW, Cl, CEC, CM) had been done in 2015, it was considered unlikely for these parameters to vary throughout the duration of this trial. Taking this into account, it was feasible to perform the interannual analysis on the variables analysed. Parameters such as O.M., Stock N and Ts were adjusted according to the values obtained in 2018, 2019 and 2020. The mt explanatory models were selected through step-wise selection by setting limits of the model parameters at 0.10 p-value.

RESULTS

1. Temporal and spatial variabilities in weather and soil at the plot level

The average air temperatures (mean, minimum and maximum) over the cropping season were similar for all years (2014 to 2021) (Supplementary data 1). The mean temperature was 20 °C, with a minimum of 13.5 °C and a maximum of 25 °C for the average temperatures. The cumulated thermal time (GD10) was higher than 2100 °Cd in all years, and even higher than 2200 °Cd in 2016, 2020 and 2021. Water supply could be characterised according to three groups of years (Figure 2A): i) cumulated rainfall of over 600 mm during the plant cycle (wet years) in 2014, 2015 and 2019, ii) rainfall of less than 500 mm (dry years) in 2016, 2018 and 2020, and iii) rainfall of between 500 and 600 mm (intermediate) in 2017 and 2021. For the wettest years, 60 % of rainfall occurred during the ripening months. The atmospheric evaporative demand (ETo) was higher than the cumulated rainfall for all years, reaching 870 mm over the cropping season on average (Figure 2B). The dynamics of soil temperature (Supplement 3) over two contrasting wet/dry seasons (2019 and 2020 respectively) did not show any significant differences between vigour zones. The average temperature was 20 °C, regardless of soil depth (0-20 cm; 20-40 cm).

The classical physical and chemical characteristics of the soil showed a strong spatial variability, mainly in percentage of clay, cation exchange capacity (CEC), total cations and total available water (TAW) (Figure 3). Clay content ranged from 26-45 % in the HV zone (west side of the vineyard) to 27-35 % in the LV zone (east side), with a CV for the whole plot of 20 % (Figure 3A). The mean CEC decreased from the HV to the LV zone, ranging from 24-35 cmol^+/kg in the HV zone and 14-23 cmol^+/kg in the LV zone (Figure 3E). The CV of CEC for the plot was 54 %. The total cations ranged between 14 and 37 cmol^+/kg, and the overall CV for total cations was 44 % (Figure 3D). Among the different cations, calcium showed the most significant within-plot variation of the two zones (CV 29 %), followed by potassium (CV 25 %). The TAW estimated from soil texture and root depth (Figure 3C, 4 and 6A see below) was more than 180 mm in the HV zone, and less than 140 mm in the LV zone, with a CV of 15 % for the plot. Soil pH (data not shown) was close to neutral (6.3) and slightly varied within the plot (CV: 6.4 %). Organic matter (O.M.) tended to be slightly higher (0.4 %) in the HV zone than in the LV zone (Figure 3B). However, O.M. was high in both zones, reaching 0.7 to 1 % in the deepest soil layers (50 cm).

2. Variability of soil and plant mineral status in the vigour zones

In the HV zone, the the main soil horizons were: A_p (0- 0.10 m), B_{ss} (0.15-0.40 m) and C (> 0.60 m), with transitional horizons (Figure 4). The texture was mainly clay loam. Slicken-sides (= pressure faces) were present from 0.20 m down to the deepest horizon. Carbonates increased from the surface to reach up to 20 % in the C horizon. No physical limitations were observed for root exploration and grapevine roots were detected in horizon C.

The soil was shallower in the LV zone than in the HV zone (0.20 m), and the variability of soil depth (SD) at the plot level was 19 %. The profile was characterised as: horizon Ap (0-0.15 m); B_{ss} (0.15 to 0.40 m) and C (> 40 m). No transitional horizon was present. In addition, the B_{ss} horizon had an extremely firm consistency. The presence of carbonates was also lower than in the HV zone. No roots were observed at a depth greater than 60 cm (Figure 6C) in the LV zone.

The mineralogical analysis of the clay showed differences in the abundance of 2:1 clay types between the vigour zones (Supplement 4). The abundance of the clays in the HV zone was 79 % montmorillonite and 20 % illite, tn contrast to 34 % montmorillonite and 60 % illite in the LV zone. Both soil zones had a low content of kaolinite, the 1:1 clay type, (between 1 % for HV zone to 6 % for the LV zone).

Differences were observed in the absolute amounts of nitrogen stock between the vigour zones (Figure 5). A higher availability of N was observed in the HV zone than in the LV zone in all three study years. These differences were due to a higher presence of mineral nitrogen (NO_3^- and NH_4^+) and to a higher potential mineralisation of the O.M (greater soil depth, slightly higher O.M. content) in the HV zone (p-value < 0.05).

Leaf N (Nl) and K (Kl) contents were globally higher in the HV zone than in the LV zones in most years (p-value < 0.05) (Table 1). Over the period 2015 to 2020, %Nl varied between 0.63 and 1.87 % in the plot. %Nl was significantly higher in the HV zone in 2016, 2017 and 2020. K values ranged from 0.34 to 0.76 % over the period 2015 to 2016 and they were also higher in the HV zone in 2015.

3. Water, nitrogen and root distribution for the representative vigour plants

The trunk diameter (TD_{10}) of the plants chosen for root and soil exploration was nearly the same as the mean TD_{10} for HV (58 mm) and LV (35 mm). Trunk diameter correlated with NDVI and other soil (TAW, CEC) and plant variables (ELA, Y) (Supplement 2). At dormancy (in 2020), the distribution

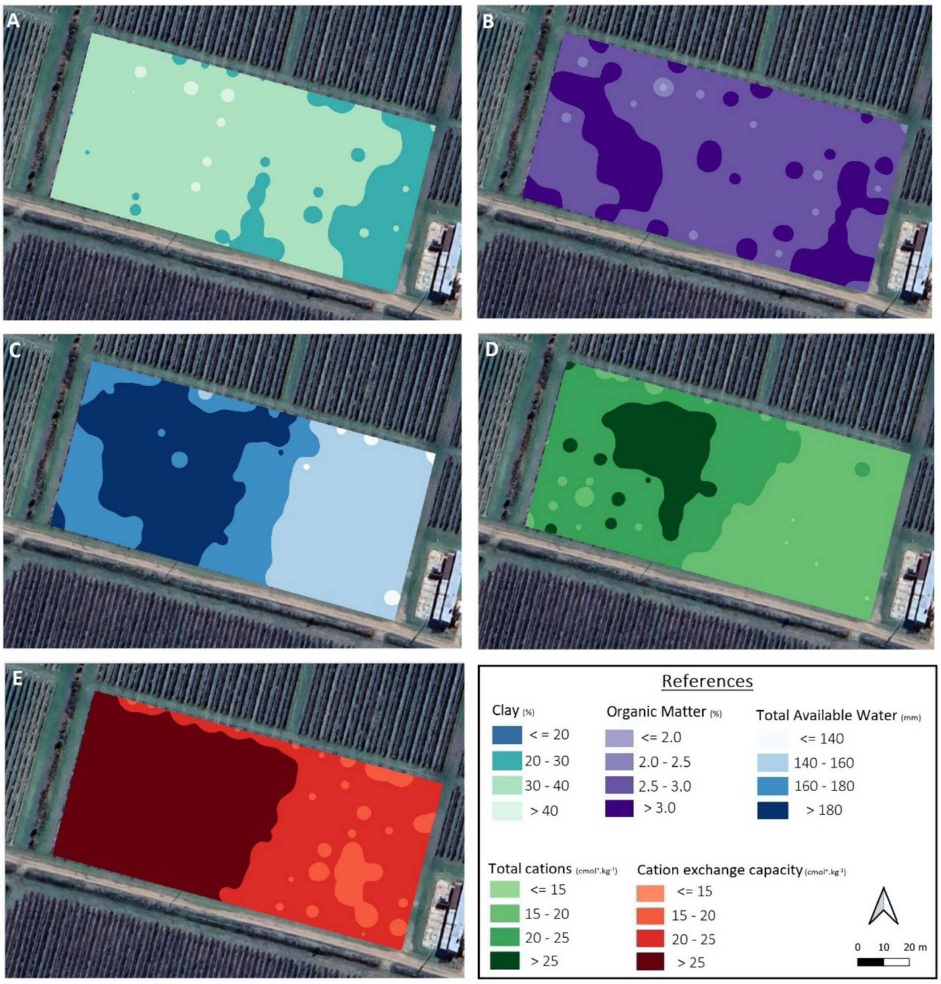

FIGURE 3. Maps representing soil variability for different soil parameters.

A- Clay (%) at 0-20 cm. B- Organic matter (OM, %) at 0-20 cm. C- Total Available Water (mm) over the soil depth explored by roots (0-90 cm for High Vigour; 0-60 cm for Low Vigour; see Figure 6). D- Total cations (cmol$^+$.kg^{-1}) at 0-20 cm. E- Cation exchange capacity (CEC, cmol$^+$.kg^{-1}) at 0-20 cm. The maps were built from the soil physico-chemical measurements carried out in August 2015 from the soil sampling points presented in Figure 1B.

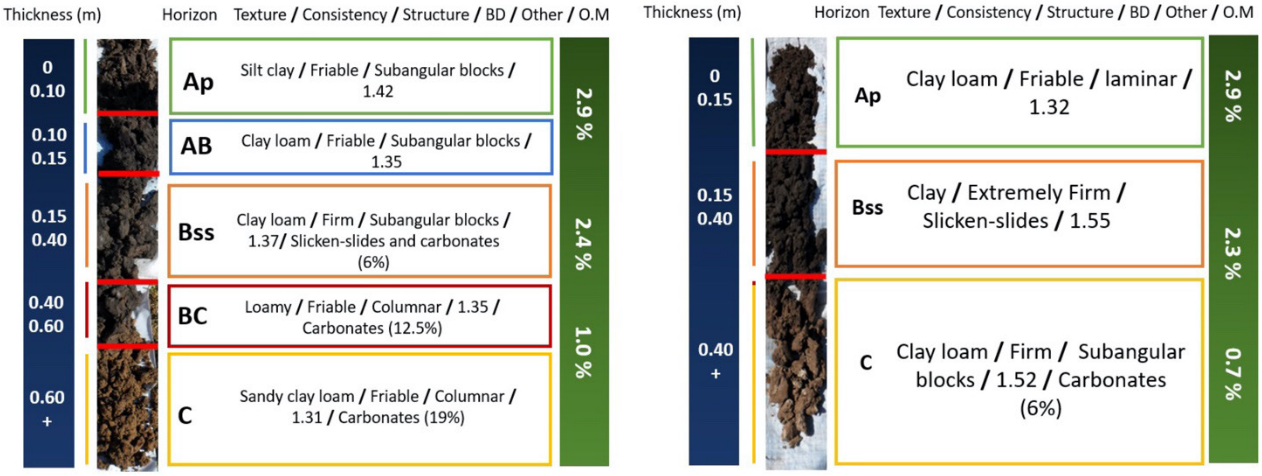

FIGURE 4. Soil profiles for the High and Low vigor zones.

The main soil parameters evaluated were: soil depth, texture, consistency, structure, bulk density (BD) and organic matter. The vigor zones were defined from the NDVI and trunk diameter values. High vigor: NDVI 0.57-0.61 and trunk diameter: 58.0 mm. Low vigor: NDVI 0.48-0.57 and trunk diameter 36.0 mm. Images and description collected in winter 2019.

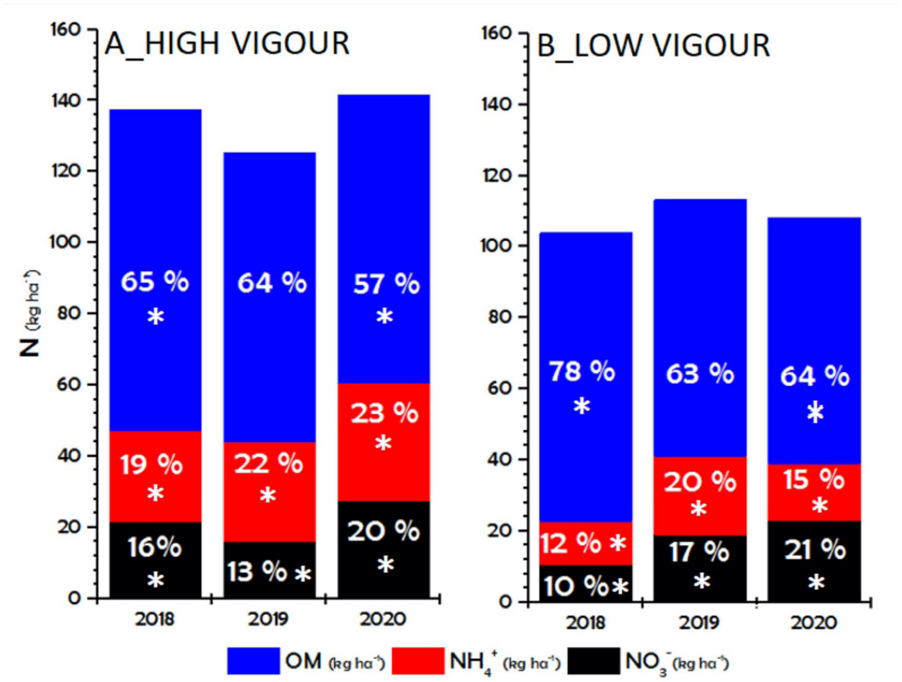

FIGURE 5. Changes in the N stock (absolute values and percentages) from 2018 to 2020 in the High and Low vigour zones.

A- High Vigour; B- Low Vigour. Black: NO$_3^-$ (kg ha^{-1}); Red: NH$_4^+$(kg ha^{-1}); Blue: N potentially mineralized from organic matter (kg ha^{-1}) calculated with the same mineralization rate (2 %) in the two vigor zones. Asterisks indicate significant differences according to Fisher (p-value < 0.05) between vigor conditions for each year evaluated. The vigour zones were defined from the NDVI and trunk diameter values. High vigour: NDVI 0.57-0.61 and trunk diameter: 58.0 mm. Low vigour: NDVI 0.48-0.57 and trunk diameter 36.0 mm.

of soil moisture along the 1m deep soil profile (0.5m from both sides of the vine) differed depending on the vigour zone (Figure 6A). In the HV zone, higher % moisture values were observed (38 % to 68 %) throughout the soil profile and with a more uniform distribution than in the LV zone (25 % to 55 %).

Soil N concentration at dormancy (in 2020) was higher in the HV zone than in the LV zone (Figure 6B): up to 50 mg/ kg in the first 30 cm of soil and greater than 20 mg/kg until 80 cm depth. By contrast, in the LV zone, concentrations of N higher than 20 mg/kg were only observed in soil above a depth of 0.50 m and did not exceed 40 mg/kg.

The root exploration maps showed differences at dormancy (2020) depending on the vigour zone (Figure 6C). HV plants had greater root density than LV plants, and the roots reached a greater depth (roots were detected down to 0.9 m) than LV plants (absence of roots below 0.6 m). Moreover, the roots were spread over a wider area in the HV zone than in the LV zone (Supplement 5), thus allowing them to colonise a greater volume of soil. The number and distribution of roots thinner than 2 mm differed between the HV and LV zones (Figure 6C). In the HV zone, these were more numerous than in the LV zone, occupying a larger area and volume above the depth of 0.7 m, compared to just a depth of 0.4 m in the LV zone. Root growth in the inter-row (0.3 m from the plant)

TABLE 1. Leaf concentration of N (%) and K (%) according to year and vigor condition.

Year/Vigor	Nl (% of dry matter)		Kl (% of dry matter)	
	High vigor	Low Vigor	H. Vigor	L. Vigor
2015	1.64 ± 0.07	1.53 ± 0.07	0.56 ± 0.03*	0.36 ± 0.02*
2016	1.70 ± 0.04 *	1.39 ± 0.09 *	0.75 ± 0.06	0.67 ± 0.05
2017	1.66 ± 0.09 *	0.69 ± 0.07 *	n.d.	n.d.
2018	n.d	n.d.	n.d.	n.d.
2019	1.58 ± 0.15	1.42 ± 0.18	n.d.	n.d.
2020	1.79 ± 0.08 *	1.28 ± 0.11 *	n.d.	n.d.

Mean and standard deviation. Values expressed as percentage of dry matter. Leaf nitrogen (%Nl) and potassium (%Kl) evaluated from a sample composed of 20 healthy and exposed leaves collected at veraison of each season. * Asterisks indicate significant differences according to the Fisher test (p-value < 0.05). n.d. No data available. n = 3.

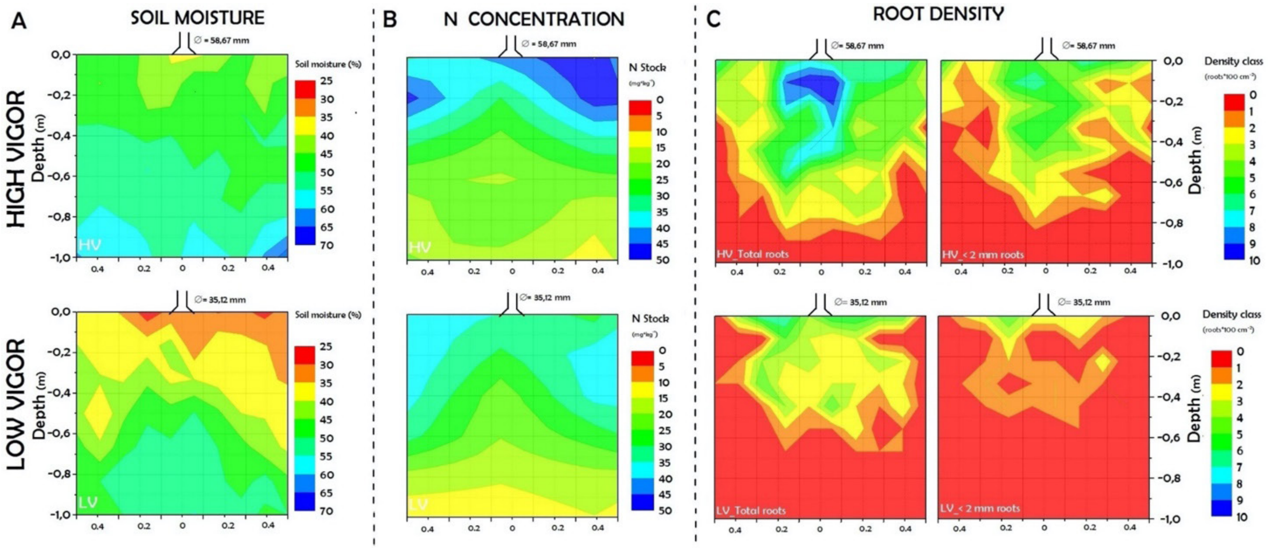

FIGURE 6. Soil moisture, nitrogen and root distribution in soil profile according to the vigor condition.

Maps in the area of influence of the vine (1.0 m depth, 0.5 m both sides of the vine). The plants chosen were representative for each vigor zone in terms of trunk diameter. The evaluations were carried out in winter 2020. Maps above represent the high vigor zone. Maps below represent the low vigor zone. A- Volumetric soil moisture (%) contour lines. B- Nitrogen concentration contour lines (mg kg^{-1}). C- Root density maps (number of roots 0.01 m^{-2}). The observations were made 5 cm apart from the plant. Maps on the left represented the total density of roots, and maps on the right represented the roots with a diameter lower than 2 mm.

was also evaluated. A greater root density (of all the classes, including those thinner than 2 mm) was found in the HV zone (Supplement 5).

4. Temporal and spatial variation of plant vigour and yield

Plant variables such as pruning weight, exposed leaf area, yield and concentration of berry anthocyanins (PW, ELA, Y and ApH1) varied highly over time depending on the vigour zone (Figure 7, Supplement 6 and 7). The HV zone systematically showed higher pruning weight (0.4 to 0.7 kg/ vine), exposed leaf area (1.2 to 2.3 m^2/vine) and yield 5.1 to 8.0 kg/vine) than the LV zone (pruning weight: 0.1 to 0.4 kg/vine; exposed leaf area: 0.8 to 2.0 m^2 /vine; yield: 3.9 to 6.8 kg/vine) ($p\text{-value} < 0.05$), except in 2014 when the yield was affected by sanitary conditions. The higher bunch size (Bz) and Bw values explain the higher yields obtained in HV compared to LV. In both zones (Supplementary Data 6), PW and ELA were the highest in years 2014, 2015, 2017 and 2019. The years 2015, 2016, 2017 and 2018 were characterised by the highest yields in both vigour zones. The lowest yields were observed in 2014 and 2019 in the HV zone, and in 2014 and 2021 in the LV zone. Total anthocyanin concentrations also varied at plot level (ranging from 773 to 2345 mg/l); however, this variable was not clearly associated with vigour. Total anthocyanin concentration was alternatively higher in the HV or LV zone, depending on the year.

An exploratory analysis (Correspondance Factor Analysis, ACF) on all plant, soil and weather variables and climate variables was conducted for all the years (Figure 8). The first two axes on the ACF explain 77.3 % of total inertia (Axis 1: 48.0 %; Axis 2: 29.3 %). The two vigour zones (HV/LV) are on opposing ends of axis 1. The HV zone can be seen to be highly associated with soil variables Total Available Water (TAW), stock of nitrogen (N stock) and clay content (%), and, to a lower extent, to cation exchange capacity (CEC) and total cations (TC). By contrast, the LV zone is opposite these soil variables. Plant variables related to vegetative development (RI, ELA and PW), leaf nitrogen content (%Nl), and the production variables (Y and Bw) were associated with the HV zone. However, vine fertility (B/v) was more closely associated with the LV zone than with the HV zone. The LV zone was also associated with higher total phenol (Tp) concentrations. Micro-climatic variables such as maximum temperature in the canopy at veraison (TMv) and soil temperature (Ts) were found to be associated with the HV zone, while the number of days with temperature above 30 ºC (ND30) in the canopy were found to be more closely associated with the LV zone. On the second axis, the years are distributed on both sides of the diagram, with the most extreme and opposing years being 2014 and 2018. Rainfall variables (RRff and RRrip) were positively correlated with the wet years (2014, 2015 and 2019) and negatively correlated with the dry years (2016, 2018 and 2020). The intermediate years (2017 and 2021) are close to the centre of this axis. The rainy years were associated with high berry Acidity, pH, Bw and %Nl. Dry years were associated with high canopy temperature (TMv, TMh and ND30), and high sugar and total anthocyanins (Brix, ApH1).

Lastly, a multiple regression was performed on a set of 12 variables related to plant vigour, yield components and berry composition to determine which soil variables had the most influence on spatial variations at plot level. Significant regressions were obtained for only 8 of the 12 variables: NDVI, Leaf area, Pruning Weight, Yield, Berry weight,

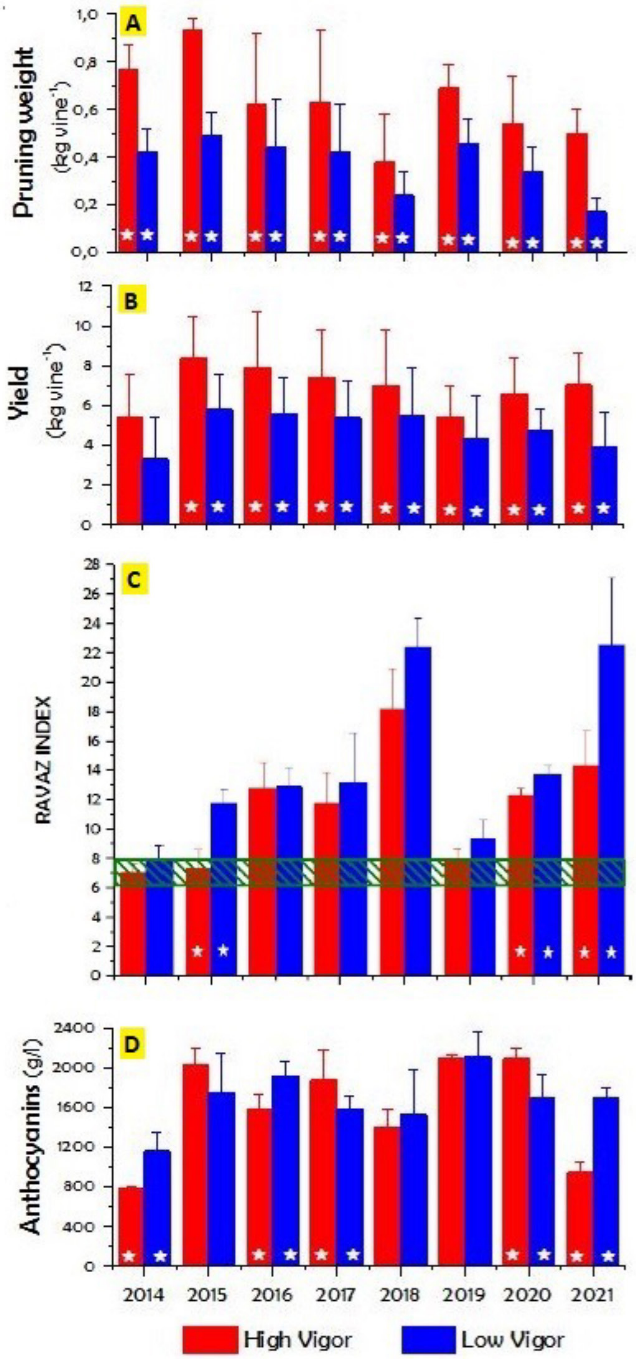

FIGURE 7. Average values for the yield, pruning weight, Ravaz Index and total anthocyanins content according to the vigour level during each studied year.

The vigour zones were defined from the NDVI and trunk diameter values. High vigour: NDVI 0.57-0.61 and trunk diameter: 58.0 mm. Low vigour: NDVI 0.48-0.57 and trunk diameter 36.0 mm. The bars represent the average value, and the error bars represent the standard deviation. Green rectangle indicates optimum Ravaz Index values for Tannat (6-8).

Pruning weight (PW) in kg vine-1 (n = 63); Yield (Y) in kg vine-1 (n = 63) and Anthocyanins in g/l (n = 3). The asterisks indicate significant differences according to the Fisher test (p-value < 0.05).

Brix, Total anthocyanin and Total Phenol concentrations (Table 2). In general, total available water (TAW), soil temperature (Ts), organic matter (OM) and stock N were the soil parameters that were the most closely correlated with plant response. The climatic variables that were the most closely associated with the plant variables were maximum temperature at veraison (TMv), cumulative rainfall from flowering to fruit set (RRff) and cumulative rainfall during ripening (RRrip). Vegetative variables (NDVI, ELA and PW) were positively correlated with edaphic parameters, such as TAW, Stock N and O.M. and with climate variables such as RRff and RRrip. Similarly, yield (Y) and berry weight (Bw)

FIGURE 8. Correspondence factor analysis (ACF) for soil, climate and plant variables (from 2014 to 2021).

HV: High Vigour; LV: Low Vigour. Soil parameters: CEC: Cation exchange capacity; Stock N: Stock nitrogen (kg ha-1); OM: organic matter (%); Cl: Clay (%); TAW: Totally Available Water (mm); TC: total cations and Ts: soil temperature (°C). Climate variables: RRff: cumulated rainfall from flowering to fruit set; RRrip: cumulated rainfall during ripening; TMv: maximum temperature at veraison: TMh: maximum temperature at harvest; ND30: numbers of days with temperatures above 30° C from flowering to harvest. Plant parameters: RI: Rooting index; Y: Yield (kg vine-1); Bw: Berry weight (g); B/v: bunch/vine; ELA: Exposed leaf surface (m2 ha-1); PW: Pruning weight (kg vine-1); %NI: Leaf nitrogen (%); Brix (°); Acidity (g H2SO4/L); ApH1: Total anthocyanins (g/l) and Tp: Total phenols index.

TABLE 2. Multiple regression analysis for the vegetative, yield and berry composition variables as a function of soil parameters in 2015 and climate condition (2014-2021).

Response variable	Model	R^2	p-value
NDVI	-1.69 + 0.02 (Cl) + 2.8 x 10^{-3}(TAW) + 1.3 x 10^{-3} (RRrip) + 8.5 (Ts)	0.74	< 0.01
Exposed leaf area (ELA; m^2 ha^{-1})	-5.58 + 0.01 (Stock N) + 0.40 (OM) + 0.01 (TAW) + 9.2 x 10^{-4} (RRff) + 0.13 (TMv)	0.64	< 0.05
Cane Production (CP; kg $vine^{-1}$)	-0.93 + 0.01 (Stock N) + 3.7 x 10^{-4} (RRff) + 0.01 (TAW) + 1.1 x 10^{-3} (CEC)	0.77	< 0.01
Yield (Y; kg $vine^{-1}$)	6.27 + 0.03 (TAW) + 0.50 (Stock N) + 1.6 x 10^{-3} (Ts) + 0.34 (TMv)	0.63	< 0.10
Berry weight (Bw, g)	2.50+ 0.11 (TAW) + 1.2 x10^{-3} (RRff) + 4.9 x 10^{-4} (RRrip) + 0.01 (Stock N) - 0.07 (TMv)	0.78	< 0.05
Brix (°)	53.88 – 2.09 (TMv) + 0.98 (TMh) - 0.01 (RRrip) + 1.07 (OM) + 0.04 (TAW)	0.67	< 0.01
Total anthocyanins (ApH1; g/l)	3046 + 0.57 (Ts) - 564 (OM) + 240 (TMh) – 104 (TMv)	0.61	< 0.10
Total Phenols (Tp; %)	103 - 0.01 (Ts) + 1.76 (TC) + 0.66 (ND30) + 0.01 (RRff) +2.47 (TMv)	0.55	< 0.01

Abbreviations: TAW: Total Available Water; OM: Organic matter; Cl: clay %; Ts: soil temperature; CEC: cation exchange capacity; TC: total cations; RRff: cumulated rainfall from flowering to fruit set; RRrip: cumulated rainfall during ripening; TMv: maximum temperature at veraison.

were positively correlated with TAW, Stock N, RRff, RRrip and TMv. Yield was also positively correlated with soil temperature (Ts). Primary and secondary berry metabolisms (brix, ApH1, Tp) were more closely correlated with climatic variables. The edaphoclimatic variables that were the most closely associated with grape composition parameters were TMv, TMh, RRrip, RRff, O.M. and Ts (Table 2).

DISCUSSION

1. The variability of soil and root density between high and low vigour zones

The HV zone has a high natural fertility (CEC >20 $cmol^+/kg$), while the LV zone has medium natural fertility (CEC 10-20 $cmol^+/kg$) (Silva *et al.,* 2018). This difference in CEC between zones is related to contrasting percentages of clay and of the type of clay (Pereyra *et al.,* 2022a). When applying a decomposition rule, the clay types are 28 % montmorillonite and 7 % illite in the HV zone, and 10.2 % montmorillonite, 18 % illite and 1.8 % kaolinite in the LV zone. Assuming typical values of CEC for montmorillonite (90 $cmol^+/kg$), illite (30 $cmol^+/kg$) and kaolinite (10 $cmol^+/kg$), the CEC (clay) are 27.3 and 14.8 $cmol^+/kg$ in the HV and LV zones respectively. These values are superior to the OM contribution to CEC, particularly in the HV zone. With a CEC for OM of around 250 cmol+/kg and 2.7 % OM, we find a contribution of OM to CEC that is less than 7 cmol+/kg. The differing amounts and types of clay depending on the vigour zone may explain the soil water retention in the HV zone as compared to the LV zone (van Leeuwen and Seguin, 2006; Tardáguila *et al.,* 2011). Soils containing a higher amount of montmorillonite have a greater expansion capacity (Brady and Weyl 2008), which may be responsible for the lower bulk density (BD) calculated for the HV zone. The swelling properties of montmorillonite is linked to changes in the hydration of calcium (Sun *et al*., 2015) when the soil becomes wet. The clay-humic association is then subject to strong geometric constraints, which could explain why the humus of mollisol is called soft humus (Brady and Weyl, 2008). In the LV zone, the higher density at deeper soil layers is probably a result of some internal processes linked to soil evolution. As the soil contains less calcium, it is possible that acidification in the root zone progressively reduced the positive effect of calcium carbonate, leading to soil degradation.

The differences in root development in the vigour zones were associated with the physical and chemical properties of the soil. Total available water, aeration, soil depth, penetration resistance, bulk density and cultivation practices are known to affect root development (Morlat and Jacquet, 1993; Callejas-Rodríguez *et al.,* 2012; Gatti *et al.,* 2020). Deeper soil, greater water reserve capacity, higher cation exchange and lower bulk density (Figure 3 and 4), as found in the HV zone, lead to greater root development (Figure 6) with a higher abundance of fine roots (higher RI). The presence of calcium carbonates in the HV zone may have been favourable for the formation of bigger textural aggregates (Ubalde *et al.,* 2011), facilitating root development in deep layers. Moreover, because of the (medium) tolerance of rootstock SO_4 to carbonates, no iron deficiency symptoms were observed during this trial. Due to the greater soil compaction (higher bulk density and extremely firm consistency) in LV zone, 70 % of the roots thinner than 2 mm were located in the top 0.30 m-deep layer of soil, and no roots were observed below 0.5 m (Figure 6C). In addition to soil water availability, soil temperature influences the development of fine roots that have an important role in water and nutrient uptake (Mahmud *et al.,* 2019). Soil temperature directly affects the root system by impacting root metabolism, root growth, nutrient and water uptake (Clarke *et al.,* 2015; de Souza *et al.,* 2022; Mezzatesta *et al.,* 2022) and indirectly affects it by conditioning N mineralisation rates (Zogg *et al.,* 1996; Verdenal *et al.,* 2021). These factors, especially Ts and TAW, could explain the heterogeneity in soil nitrogen availability and root development between HV and LV zones (Figures 5 and 6). Indeed, the areas with higher fine root density in both the HV and LV zones were associated with soil zones containing higher soil moisture content and available N (Figure 6). Insufficient resources (water and N) in the zone of influence of the LV plants (Figure 6-A, 6-B) could explain the observed low root density. Under similar conditions, plants have been found to apply a nitrogen/carbohydrate “saving” strategy by reducing the synthesis of new roots and extending the lifespan of existing roots (de Souza *et al.,* 2022). This situation would lead to negative feedback in the long term due to a reduction in water and nutrient uptake capacity (Centinari *et al.,* 2016) as root age increases.

2. Canopy and berry development responses to soil and climate

Zones of differing vigour within a vineyard tend to be stable over time (Bramley and Hamilton, 2004; Gatti *et al.,* 2022) - even up to 6 years (Tisseyre *et al.,* 2008). In this study, the NDVI maps from 2015 to 2017 were corroborated in 2020 by measuring trunk diameter (Figure 1 D; Supplement Data 2). The leaf area (ELA, NDVI), pruning weight (PW) and yield (Y, Bw and Bz) were higher in the HV zone than in the LV zone, regardless of the climatic conditions of the years (Figure 7 and 8). The stability of the vigour zones over time was mostly associated with edaphic factors, as reported in other studies (Priori *et al.,* 2019, Gatti *et al.,* 2022;). In turn, soil factors such as Cl, O.M, SD, conditioned soil water availability (TAW) and were strongly associated with the abovementioned productive factors (ELA, NDVI, PW, Y; Table 2). This indicates that soil characteristics play a dominant role in vigour establishment and can mitigate or enhance the effects of weather. The root system has the ability to adapt to different edaphic situations, thus impacting vegetative growth, production and grape quality (Tomasi *et al.,* 2015). Higher TAW, Ts in the HV zone resulted in higher soil N concentration and higher %Nl (Figure 6; Table 1). The limitation of water content in the LV zone may have decreased plant N availability by negatively impacting microbial activity, and N mobility and uptake. In addition, a high soil bulk density also limits root elongation and decreases N uptake. The lower %Nl values reflected such a limitation in the LV zone, which was more marked in the drier years (2016, 2017 and 2020) (Table 1, Figure 2), thus making it possible to conclude that Nl may be an indicator of vine vigour (Balachandra *et al.,* 2009; Gatti *et al.,* 2022).

The ability of HV and LV vines to provide a constant supply of water and nutrients for vegetative development, yield and grape quality was determined by the differing root distribution and density depending on the physical and chemical properties of the soil (Morlat and Jacquet, 2003; van Leeuwen *et al.,* 2009). In addition, climatic variables, such as water supply (RRff, RRrip) and temperature (Tmv), also impacted those plant variables (Table 2). Rainy and intermediate years (high RRff and RRrip) were favourable for vegetative growth in both zones (Figure 2 and 7). Yield tended to be lower when rainfall during the month prior to harvest (RRrip) increased in the HV zone (e.g., in 2014) because of higher susceptibility to bunch rot (Figure 7 and 8); this has also been observed in other studies (Filippetti *et al.,* 2013; Ferrer *et al.,* 2020b). The higher soil water content (during rainfall) in the HV zone than in the LV zone can be attributed to the swelling properties of montmorillonite and higher humus levels. Such characteristics buffered the effects of water deficit (in dryer years), with less impact on plant growth and yield in the HV zone than in the LV zone, as was also reported by Tomasi *et al.* (2015). The plants in the HV zone achieved a better production/vegetative balance (Figure 7) than those in the LV zone, as expressed using the Ravaz index (11.5 vs. 14.2). In the rainy years, the plants reached the optimum Ravaz index value (6-8) reported for Tannat. Bud fertility was higher in the LV zone than in the HV zone, and the canopy microclimate (ND30) tended to be warmer (Figure 8). The lower ELA in the LV zone may have allowed greater exposure of the buds to light which explains the higher number of clusters per plant (Sánchez and Dookozlian, 2005).

In this trial, the harvest date was set according to the evolution of pH, Brix and Bw in each year. These parameters showed a coefficient of variation of less than 10 % (data not shown) between the vigour zones. Our results indicate that the inter-annual variability in pH and Brix were poorly linked to soil properties (Figure 8; Table 2; Supplement 7). The concentrations of variables linked to berry composition (sugar and acidity) mostly depended on air and canopy temperature in both zones and on precipitation in the LV zone (due to its low water reserve capacity). Tisseyre *et al.* (2008) and Gatti *et al.* (2022) reported less intra-annual variation in Brix and pH than in berry anthocyanin content. Although the secondary metabolism variables (ApH1 and Tp) showed significant variations between the HV and LV zones, the differences were not consistent from one year to another.

Anthocyanin and phenol concentrations in berries are known to depend highly on soil properties and climatic characteristics of the year (van Leeuwen *et al*., 2004). Our results show that the concentrations of these variables depended highly on the climatic and microclimatic conditions of a given year, tending to be higher in the dry years (Figure 7 and 8, Table 2). The more open canopies of the LV zone increased light interception in the cluster zone, thus increasing anthocyanin content when temperature was not excessive (< 35 °C) (Haselgrove *et al.,* 2000; Mori *et al.,* 2007). Indeed, the concentrations of berry secondary metabolites (ApH1 and TP) were shown to be associated with temperature parameters (Ts, TMV, TMh and ND30, Table 2). These results are in line with Ryu *et al.* (2020), who reported that high berry temperatures around the onset of ripening (veraison) inhibited anthocyanin synthesis. In addition, high spring rainfall (2016, 2019 and 2021), which was an important factor influencing vine vigour in the LV zone, had a positive impact on ApH1 in the same zone (Figure 7, Supplement 7). Sams *et al.* (2022) reported that the spatial variability of phenolic compounds was fairly consistent with that predicted by remote sensing data, such as NDVI and the canopy temperature index. Canopy temperature relies on energy balance and plant water status and also affect grape composition (Brillante *et al.,* 2016; Sams *et al.,* 2022).

3. Site-specific management

This study showed that the variation in yield and vigour at the plot level was mainly determined by the heterogeneity of the soil and exacerbated by weather conditions. As mentioned previously, the stability over time of plant vigour and yield gradients related to soil heterogeneity will allow differential management zones to be established within the same plot (Bramley and Hamilton, 2004). A strategy that could be applied is the division of the vineyard into homogeneous zones to take advantage of this variability and generate wines of different qualities (Bramley and Lamb, 2003; Gatti *et al.,* 2022).

Alternatively, the site-specific management of the vineyard comprising different uses of inputs, could help to lower heterogeneity in plant vigour (Tisseyre *et al.,* 2008; McClymont *et al.,* 2012). Since the distribution of vigor zones was consistent in this trial, it would be possible to establish two differentiated site-specific management zones. We recently reported the impact of site-specific management following this approach (Pereyra *et al.,* 2022b). In the HV zone, a reduction in nitrogen fertilisation could be an option to reduce vine vigour (Pereyra *et al.,* 2022b), but the accumulation of reserves in the medium- and long-term must be considered. In addition, favouring the growth of cover crops in the inter-row would decrease grapevine growth (Celette *et al.,* 2009; Coniberti *et al.,* 2018). However, cover crops must be carefully managed, for example the variability of rainfall in Uruguay (enhanced under climate change) could lead to excessive competition, even in the HV zone, during dry years. Lastly, the improvement of the microclimate in the bunch zone via leaf removal could be necessary to increase berry secondary metabolism and reduce pest pressure in the HV zone (Filippetti *et al.,* 2013). Pre-flowering leaf removal at high vigour in the vineyard of this study improved grape quality (sugars and anthocyanins) and reduced the incidence of bunch rot without any sunburn damage (Pereyra *et al.,* 2022b).

In the LV zone, a different irrigation strategy and/or supplementary fertiliation would help overcome water and nitrogen deficits resulting from certain soil characteristics (TAW, depth and nutrients) and increase vine vigour. Working on Shiraz, McClymont *et al.* (2012) managed to increase yield and water use efficiency by implementing differential irrigation according to vigour conditions. Supplementary irrigation during the flowering and fruit set periods is also a possibility (Table 2). In the LV zone, the cover crop should be controlled. More exhaustive maintenance through periodic mowing and the use of less competitive species would improve water availability for the vine.

Other management levers could be proposed in the future when planting in new vineyards to reduce vine heterogeneity. Our results suggest that the vines can support more shoots and produce a higher yield than was the case in the HV zone. Therefore, increasing bud number per plant and adopting open canopy trellis/training systems may be a way of reducing vine vigour while improving the microclimate in the cluster zone (Gladstone and Dokoozlian, 2003); however, this would require vine density to be decreased accordingly. Furthermore, it may be necessary to evaluate the adaptation of rootstocks to specific soil characteristics (Ollat *et al.,* 2015). Field phenotyping approaches still need to be improved to characterise and select grapevine rootstocks and varieties better adapted to heterogeneous soil conditions (Carvalho *et al.,* 2021). Finally, based on the results, the soil water reserve could be used as a criterion for plot delimitation in future plantations. Plots of similar TAW would result in the homogenisation of vigour.

CONCLUSIONS

This work has provided new information on soil-plant-environment interactions. The variability in soil characteristics (clay type and content, TAW, O.M, SD and Stock N) at the vineyard level conditioned plant response, generating two well-defined zones according to vigour (HV, LV). Compared with the LV zone, the HV zone was characterised by greater soil water and nitrogen availability and better vine root exploration, which enabled higher wood production and yield. The predominance of montmorillonite over illite was an important factor contributing to soil fertility in the HV zone, which is compatible with the use of cover crops between the vine rows. The gradient of vine vigour and yield in both zones was stable over the years, regardless of weather conditions. These results suggest that the differences found in the soil properties in the HV zone attenuated the effects of the climatic conditions, which did not occur in the LV zone. However, no consistent grape composition in either zone was observed. Secondary metabolite concentrations (anthocyanins and phenols) were mainly affected by the climatic and micro-climatic conditions in a given year, highlighting the complexity of the interactions of these compounds in the soil-plant-atmosphere system. Defining vigour zones (by remote sensing) within a plot would be required for more precise soil and crop management and for more sustainable vineyard management and berry production.

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