



Seasonal interactions between spatial and temporal variability in a steep Barbera vineyard

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Abstract

Purpose A three-year study was carried out in a steep vineyard to study inter-annual and within-season vigor variability by proximal sensing.

Methods Each season, vigor maps were obtained around veraison when a full canopy status was achieved; in 2021 and 2022, within-season vigor variability was assessed at 9 and 8 dates. Every year, main yield components, grape composition and pruning weight were determined. In 2022, dynamic in vegetative growth, canopy density, leaf gas exchange and water status, soil temperature and water status were also performed.

Results Mostly due to more rapid soil warming, vines growing in low vigor (LV) plots had fostered leaf area development and shoot growth over the first three dates of measurements before high vigor (HV) fully made up at pre-flowering. From flowering onward, vine growth in LV was totally checked and the gap versus the HV kept widening. Over summer, in LV, leaf water potential assessed pre-dawn and midday reached the quite limiting thresholds of -0.6 and -1.4 MPa, whereas in HV water stress was rather moderate. Gas exchange limitations in LV essentially mirrored the above with stomatal conductance decreased to $0.03 \text{ mmol m}^{-2} \text{ s}^{-1}$ at pre-veraison. Final vine size and yield were severely curtailed in LV (-49% and -62% as compared to HV, respectively) which, on the other hand, achieved much better and complete grape maturity.

Conclusion This trial confirms that even within a tiny and steep vineyard, spatial variability between vigor zones evaluated at full canopy tends to be maintained over years, thus justifying, for instance, a selective harvesting approach. However, it is quite meaningful that, in both 2021 and 2022, the ultimately defined LV vigor initially developed bigger canopy, balanced with HV at pre-flowering and then re-entered in their standard classification of “low vigor” plots. This behavior is relevant anytime a variable management strategy is planned. Indeed, early season fertilization should be adjusted with a logic opposite to that applicable to a “low vigor” level while, real-time canopy spray is recommended.

Keywords *Vitis vinifera* · Vigor maps · Soil water potential · Yield · Canopy microclimate · Management zones

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Introduction

Since the advent of precision agriculture, an endless number of applications have followed on horticultural crops (Bazzi et al., 2022; Longchamps et al., 2022; Zude-Sasse et al., 2016). Among the latter category, grapevine boasts by far the highest number of published work inherently demonstrating its role as a leading crop case study (Bramley, 2022; Ferro & Catania, 2023; Matese & Di Gennaro, 2015; Santesteban, 2019; Singh et al., 2022). If one of the primary goals of precision viticulture is to describe and eventually exploit intra-vineyard variability, reasons for this interest can be easily listed as it follows: (i) on the side of studying spatial within-field variability the grapevine is an ideal case as vineyard size can notoriously span from fraction of an hectare to several hectares rendering the study of spatial variation of vine performance especially challenging (Bramley, 2022; Fiorillo et al., 2012; Gatti et al., 2017); (ii) vineyards show a typical year-to-year variability usually due to a complex interaction between climate and anthropogenic factors (Bernizzoni et al., 2009); (iii) vineyards also characterize for a consistent “within season” variability due, for instance, to varying climate conditions between key phenological stages (Jones et al., 2012); (iv) if it is widely shared that “vigor” is the main expression of intra-vineyard variability, then the grapevine has a great attitude to manifest different vigor levels which is also favored by the plasticity of the vine canopy where the presence of long and flexible canes allows a great variety of shapes, geometries and arrangements (Del Zozzo & Poni, 2024; Kliewer & Dokoozlian, 2005).

A major achievement from intensive research on precision viticulture is that, regardless of vineyard size and, thus, even in the case of tiny (e.g. less than 1 hectare) plots, the extent of spatial variability in vine vigor is often quite significant (Baluja et al., 2013; Garavani et al., 2023; Gatti et al., 2022; Jasse et al., 2021). Several authors described temporal patterns of remotely assessed vineyard vigor across grapevine phenology identifying as vegetation indices can be subject to significant interannual variation. NDVI values are low at the beginning of the season, reflecting limited photosynthetically active biomass, and linearly increase until blooming. Although vineyard management practices, such as floor management or canopy trimming, can alter canopy structure and introduce variability in vegetation indices, the highest NDVI values are generally observed between fruit set and veraison, corresponding to a full canopy status. Thereafter, NDVI tends to decline as the canopy ages and leaf senescence advances (Kazmierski et al., 2011; Pádua et al., 2020; Zanchin et al., 2024). Once each vigor level is properly described and validated with ground truthing (Bramley et al., 2011; Gatti et al., 2017; Poni et al., 2013), the resulting yield and quality performances might result “different” enough to advise for an enological differentiation of the final product (Bramley, 2022; Ozdemir et al., 2017). Indeed, ground truthing is necessary as a Normalized Difference Vegetation Index (NDVI) based high vigor level is not necessarily associated with an expected yield increase and likely quality impairment. It has been already shown that high vigor can actually lead to lower yield through limited fruit set (Squeri et al., 2021a), whereas quality can unexpectedly benefit from a consistent increase in the leaf area to yield ratio (Bonilla et al., 2014; Bramley et al., 2005).

On top of the above, there is already one merit that the realm of precision viticulture can be credited of: capability to transform a negatively perceived trait such as “variability” into a valuable unexpected resource which can be used or corrected to the benefits of the growers. In this matter several examples dealing with selective operations (the natural product

of vigor, yield or quality variability assessment) or variable rate applications (e.g. modifying the vine balance towards the desired equilibrium by adjusting, for instance, water and nutrients supply) are available in literature (Gatti et al., 2019; Kang et al., 2023; Llorens et al., 2010; Tardaguila et al., 2021).

However, reality seems to be not very permeable to the challenges launched by precision viticulture and, despite objective consistent spatial variability, most of the time viticultural practices are uniform within the same vineyard. Skepticism and investments costs play a role in such a context (Beber et al., 2023; Grander et al., 2021; Tongrod et al., 2009); however, transferability of precision viticulture approaches is still hindered from uncertainty about its stability over short and long time space, hence introducing the item of temporal variability.

Long-term temporal variability refers to year-to-year variation which, hopefully, should be evaluated at least over a 5-year span to accommodate some climatic variability among vintages. Overall, there is consensus that vegetative vigor differences among management zones identified within a vineyard tend to be relatively stable over time (Bramley & Hamilton, 2004; Gatti et al., 2017; Johnson, 2003; Kazmierski et al., 2011; Tisseyre et al., 2008). Such stability links to a strong controlling factor that is often associated with soil heterogeneity which, in turn, leads to significant differences in the amount of plant available water and, albeit to a lesser extent, in soil organic matter and salinity (Trought et al., 2008; Bramley et al., 2011; Tardaguila et al., 2011; Gatti et al., 2022). A good question is if such inter-annual temporal stability is consistently maintained when considering different vine performance parameters such as yield or some key grape composition factors such as sugars and phenolics.

As far as yield is concerned, a sharable conclusion is that, yes, relative differences in yield among different vigor levels are overall maintained (Gatti et al., 2022) although, as clearly pointed out by (Bramley & Hamilton, 2004), substantial inter-annual differences in mean annual yield (up to tenfold, i.e. 2 to 20 t/ha) might occur. Remotely sensed vegetative vigor is frequently and positively related to yield; numerous recent studies report linear or strongly predictive relationships between vigor indices and seasonal yield. Accordingly, UAV-based multispectral imaging shown strong vigor–yield correlations across seasons (Ferro et al., 2023), pruning weight was correlated with yield components in vigor-delineated zones (Gatti et al., 2017), and canopy vigor quantified even before bloom has been identified as a robust predictor of final yield (Taylor et al., 2023). However, in some relevant cases, variation in yield and its components does not appear to be linearly associated with variation in vine vigor or, by inference, variation in soil texture. This happened in a long term (14 years) trials conducted on cane-pruned Sauvignon blanc grapevines grown in the Marlborough region (Bramley et al., 2019) where “extra size” vines did not achieve any yield increase as compared to small size vines and also in a three year trial performed in the Lambrusco area in Italy where the highest vigor led to the lowest yield due to excessive competition versus fruit set and berry growth (Squeri et al., 2021a). A further complication arises when trying to correlate the spatial distribution of key ripening parameters such as TSS, TA and total phenolics and anthocyanins with the spatial yield distribution patterns. If it is assumed that a “medium vigor” status is associated to balanced vine condition corresponding to a pruning weight of about 500 g m^{-1} of row, any “high vigor” should lead to higher yield and retarded or even incomplete ripening, whereas a “low vigor” should likely lower yield hence fostering full or even anticipated harvesting (Arnó et al., 2012; Poni et al.,

2018). However, the relationship between vigor and agronomic performance is not linear and case studies moving into a somewhat opposite direction are at one hand: Fiorillo et al. (2012) and Bonilla et al. (2013) analyzed vigor maps of Sangiovese and Tempranillo in Tuscany (Italy) and La Rioja (Spain), respectively. Both papers reported that the so called “high vigor” plots declared as such on a pruning weight basis were also the ones reaching best grape quality especially as total anthocyanins at harvest. The explanation given was that both environments experience hot summers with several heat spells conducive to berry overheating and sunburn. Under such conditions, a high vigor status is more favorable to cluster protection from direct radiation, having well known positive effects on color synthesis while also limiting degradation of already formed color, which is largely enhanced at air temperatures above 35 °C (Mori et al., 2007). Moreover, despite significant variability in crop levels, a more recent study conducted in a Sangiovese vineyard in Central Italy reported similar anthocyanin concentrations in both high- and low-vigor zones, highlighting the role of interactions between vigor and canopy microclimate in shaping anthocyanin and phenolic maturity in grapes (Romboli et al., 2017).

A much less investigated item in precision viticulture is stability of vine parameters bound to a given vigor level within the same growing season. A legitimate question is: does an NDVI based high vigor zone hold such status across the various phenological stages? This question is also fed by a quite standard methodological approach tending to depict canopy growth around veraison when growth is supposed to be almost completed (Johnson, 2003; Sun et al., 2017; Pañitur-De la Fuente et al., 2020). As a matter of fact, phenological stage affects absolute values of most remotely sensed vegetation indices. Indeed, NDVI changes dramatically across phenology showing initial increases during canopy growth, and peaks before declining because of canopy management and senescence (García-Gutiérrez & Meza, 2023; Matese & Di Gennaro, 2021). So while relative ranking among zones may be stable, absolute NDVI values associated to “high” vs “low” vigor may vary across phenology. Temporal stability of within-field patterns of grapevine vigor can be influenced by external factors (water stress, soil moisture fluctuations, etc.) that can expand or make narrow initial vigor zones as well as by cultural practices such as fertilization, irrigation and floor management (Gatti et al., 2018; Sanchez et al., 2017). Though, different authors found that zones are stable only if major changes are avoided (Deidda et al., 2024; Kazmierski et al., 2011) as key physical-chemical properties such as soil depth, soil organic carbon (SOC), bulk density (BD), and soil penetration resistance (SPR) not only exert a strong influence on vegetative growth but also contribute to the temporal consistency of vigor patterns across years (Catania et al., 2025; Gatti et al., 2022). However, it has also been demonstrated that both the timing of image acquisition and canopy size and growth affect direction and strength of correlation with fruit composition and yield. Hall et al. (2011) showed that canopy descriptors derived from NDVI values on a Cabernet Sauvignon vineyard on nine occasions over a two-year span had the lowest and most inconsistent correlation with TSS; moreover, polarity of correlations between canopy density and yield often reversed during the season being negative early in the season and becoming positive late in the season. More reassuring results were shown from (Verdugo-Vásquez et al., 2018) reporting in four cultivar grown in Chile that TSS maps obtained 40 days before harvest maintained an almost unaltered ripening spatial pattern until harvest.

While several studies have examined spatial variability (i.e. yield mapping, NDVI zoning, etc.) and others have addressed temporal variability separately, our work aims to com-

bine both spatial and temporal dimensions to provide a comprehensive framework. This dual perspective aims at identifying stable patterns and transient dynamics of vegetative vigor, offering methodological advances for site-specific management. The current study had therefore the following objectives: (i) assess and validate the inter-annual stability of different vigor zones in a small Barbera vineyard through image acquisition and subsequent ground truthing; (ii) provide, for a single season, a rigorous and detailed assessment of changes in vegetative growth, canopy structure and microclimate, soil water status and leaf physiology across progressing phenology, and (iii) derive more targeted guidelines for growers.

Materials and methods

Plant material and experimental layout

This research was conducted during the growing seasons 2020–2022 in a vineyard of 1.31 hectares, owned by the “Società Agricola Tenuta Villa Tavernago” estate and sited in Pianello Val Tidone (44°56′10.99″; 9°27′01.07″), Colli Piacentini wine district (Emilia-Romagna, Italy). The vineyard was planted in 2015 with *Vitis vinifera* L. cv. Barbera clone AT84 grafted on 420A rootstock, at a vine spacing of 2.5 m x 1 m (inter- and intra-row, respectively), leading to a density of 4000 vines/ha. Based on previous studies, the plant material (cv. Barbera grafted on *Vitis berlandieri* x *Vitis riparia* rootstock) was selected as good candidate for the study because of being highly responsive to available water in soil, nitrogen and soil organic matter (Garavani et al., 2023; Gatti et al., 2020, 2022), with fruit composition reflecting vine balance and crop load (Gatti et al., 2017). The vineyard insists on a North-West (NW) facing versant at an altitude of around 265–325 m a.s.l. and a mean slope of approximately 30%. Vines are pruned to a unilateral renewed cane (Guyot) training system, featuring main wire at 0.8 m above the ground and three upper foliage wires to reach about 2.2–2.4 m in total canopy height. The vineyard was consistently managed according to organic viticulture protocols, with copper and sulphur sprayed for broad fungal control, and no irrigation or fertilization applied throughout the experiment. Resident vegetation in the alleys was mowed twice per year, while every second row was tilled before blooming and again before veraison. In tandem, the under-vine strip was tilled using a horizontal blade weeder. Each season, climate data as daily minimum, mean and maximum air temperature and daily rainfall were recorded with a weather station sited nearby the vineyard.

The experimental layout was a randomized block design, distinguishing between areas of high and low vigor (HV and LV, respectively). From South to North the vineyard was divided into 4 blocks, each containing the HV and LV levels. For each vigor × block combination, 4 vines were identified as representative of the area, with 16 vines sampled per vigor class. Vigor classes were initially defined based on vigor maps acquired through high resolution proximal sensing since August 2020 and described hereafter; accordingly, the initially identified LV and HV zones were mostly located in the upper and lower portions of the versant, respectively. Measurements were taken on the same tagged vines over the trial period, while early in the season they were determined to be healthy and able to fill space along the support wire.

Per each vigor \times block combination soil profiles were analyzed in 2021 by I.TER (Soc Coop, Bologna, Italy) to derive information that could have explained spatial variability of the soil, and whether soil depth and texture would exert any significant influence on vine vigor. Soil characterization was performed through 8 sampling points randomly located within the LV and HV areas as shown in Fig. S1 by following the guidelines reported into the regional protocol for soil description (Regione Emilia-Romagna, 2002). On the same occasion 16 composite soil samples were taken to represent four replicates of the following vigor \times depth combinations: LV-30 and HV-30 collected down to 0.3 m depth, LV-60 and HV-60 representing the 0.3–0.6 m depth layer (Orgiazzi et al., 2018). An aliquot of each composite sample was then processed in the lab for texture (fraction of sand, silt and clay), total nitrogen (N), soil organic matter (SOM), pH, extractable P (P_{2O_5}) and exchangeable K (K_2O).

Vigor mapping by proximal sensing

A vigor map encompassing the whole Barbera vineyard was generated on 25 August 2020, while additional 10 and 9 vigor maps were acquired in 2021 and 2022, respectively. Accordingly, maps were collected on 7 and 27 May, 4, 18 and 29 June, 7, 13, 21 and 30 July and 6 August 2021, and on 17, 27 May, 3, 10, 17 and 23 June, 1, 14 and 29 July 2022 by MECS-VINE® sensor (Micro Environment and Canopy Sensor, VINE version, TEAM, Italy) concurrently with real-time variable-rate canopy spray operations conducted from when shoots were longer than 0.1 m until pre-veraison (D'Ambrosio et al., 2023). MECS-VINE is a multi-parameter, tractor-mounted sensor specifically developed for characterizing canopy vigor in hedge-trained vineyards (Gatti et al., 2016). Under a bilateral configuration including two sensing heads left and right facing with a bottom-up orientation allowing image acquisition free of vineyard floor interference, MECS-VINE combines a GPS antenna, an RGB camera, a thermal sensor and an ultrasonic sensor. MECS-VINE allows to record the following parameters: Canopy Index (CI), ambient temperature, canopy surface temperature, and distance from the target vine. CI is a dimensionless vigor index ranging between 0 and 1000 quantifying the mass of vegetation at 3 Hz acquisition frequency resulting in a 1.3 m ground resolution (Squeri et al., 2021b). As part of the study, per each acquisition date, CI values have been partitioned into ten classes according to an equal area algorithm and values were reported on vigor maps. In 2022, the study on temporal variability was performed considering only three vigor classes as low (LV), medium (MV) and high vigor (HV) corresponding to the 0–30, 31–70, 71–100 percentile intervals, respectively.

Leaf gas exchange, soil and vine water status

Single leaf gas exchange measurements were carried out on the cloudless days of 16 June, 7 July and 4 August 2022 to include the progressive occurrence of water stress across phenological stages such as berry pea size, berry touch and veraison. Readings were taken under ambient conditions when photosynthetically active radiation (PAR) rates exceeded the saturation point, between 10:30 and 12:30, on two mid-shoot (nodes 5–9) sunlit leaves per vine chosen on the South-facing side of the row. Equipment was a LCi Portable Photosynthesis System (ADC BioScientific Ltd., Hoddesdon, Herts, UK) fitted with a standard 6.25 cm² broad leaf chamber. Air flow was set at 300 mL min⁻¹ and readings were taken at

ambient CO₂ concentration. Leaf assimilation (A), leaf transpiration (E) and leaf stomatal conductance (g_s) rates were then calculated from the in-built processor based on air flow and amount of leaf area enclosed in the chamber (Long and Hallgren 1985). The instantaneous water use efficiency (WUE) was therefore calculated as the A/E ratio.

In 2022, soil water potential (Ψ_{SOIL}) and soil temperature (T_{SOIL}) were measured on average every ten days from 14 February to 20 October in the morning hours (9–11am) by sixteen TERS 21 (Meter Group, Inc., Pullman, WA) sensors. The sensors were installed on 10 February 2021 in each vigor x block combination (Figure S1) and buried at 0.3 m and 0.6 m depths in holes dug along the row in close proximity to the four tagged vines. Results from soil analysis and vigor maps were used to optimize location of soil water potential and temperature probes as a function of spatial differences in soil traits. As a result, eight sensors were placed in HV zones and eight in LV zones.

Pre-dawn and midday leaf water potentials (Ψ_{PD} and Ψ_{MD} respectively) were determined three times during the 2022 growing season (June 16, July 7 and August 4) with a Pump-Up Chamber (PMS Instrument Company, Albany, OR, USA). Ψ_{MD} was swiftly taken on the two leaves per vine previously sampled for gas exchange, whereas the two leaves sampled for Ψ_{PD} were taken from shoots arising either from the head of the vine or the proximal portion of the fruiting cane.

Phenology and vegetative growth

BBCH scale was used to define phenological progression (Lorenz et al., 1995). Bud burst was assessed on all the count-nodes per cane of each tagged vine. Per each test vine, two shoots arising from nodes 3–4 and from the second to last node on each cane (designated as L1 and L2 respectively) were chosen and tagged for subsequent canopy growth determinations (Fig. S1). Shoot length of L1 and L2 was measured weekly and shoot growth rate calculated. Total leaf area for both LV and HV vines from budburst to trimming was estimated by fully defoliating three shoots per block x vigor combination at two timings during the season, May 31 (post flowering) and June 14 (berry pea size). Total length of the 24 collected shoots was immediately taken and main and lateral leaf area (LA) per shoot measured with a leaf area meter (LI-3000, LI-COR Biosciences, Lincoln, NE, USA). Afterwards, actual total LA per vine was estimated depending on the equations reported in Figure S2 and adjusted to the total shoot number per vine.

Canopy microclimate and density

Canopy microclimate data were collected using Temperature/RH MX data loggers (HOBO, Onset, USA) installed inside the canopy at a height of about 1.5 m above the ground corresponding to the midpoint of the canopy wall, which recorded air temperature (T_{air}) and relative humidity (RH) at hourly intervals. A total of 8 sensors were distributed throughout the vineyard, one per block in both LV and HV zones essentially superimposing with the position of the TERS sensors. These data were used to calculate the growing degree days (GDD) accumulation (base 10 °C) from April 1st (DOY 91) to October 31st (DOY 304) according to the following equation $\text{GDD} = (T_{\text{mean}} - T_{\text{base}})$. GDDs were calculated depending on vigor zone under the advantage of closer proximity to the canopy as compared to those derived from a nearby located weather station.

Canopy structure and density of eight vines per vigor class (two vines per treatment per block) were scored through a Point Quadrat Analysis (PQA) according to the protocol presented by Smart & Robinson (1991). PQA was performed on four dates as 23 May (pre-flowering), 14 June (berry pea size), 12 July (berry touch) and 28 July (veraison). An H-shaped plastic frame having a width including the entire processed canopy was used; a horizontal plastic pipeline having 15 holes drilled 0.1 m apart was progressively moved from the lowest position (about 0.05 m above fruiting cane) to the top of the canopy (about 1.15 m from the fruiting cane). At each horizontal position, a rigid tin rod was inserted through the different holes into the canopy yielding about 110 readings per vine. If the rod did not touch anything, the region was identified as a canopy gap (CG), whereas the first and last contact with a leaf was classified as an “exterior” contact whereas any further leaf within the same path was recorded as “interior”. This protocol allowed to calculate leaf layer number (LLN), canopy gaps percentage (%CG) and fraction of interior leaves (%IL) according to the specifications reported in Smart & Robinson (1991). PQA variables were therefore expressed depending on the distance (n expressed in cm) from the fruiting cane (C) identifying $C+n$ canopy positions.

Yield components, grape composition and pruning weight

Harvest was performed on 23, 23 and 19 September in 2020, 2021 and 2022, respectively, targeting total soluble solids (TSS) around 22 Brix and titratable acidity $< 10 \text{ g L}^{-1}$, corresponding to suitable sugar-to-acidity ratio for the target wine style. From each vine all clusters were counted, and their total weight immediately recorded using a portable scale and mean cluster weight calculated accordingly. Biochemical and morphological assessment was then undertaken on three representative clusters per tagged vine, that were individually weighed and rachis length measured to calculate a compactness index (Tello et al., 2016) which is given as total berry fresh mass/rachis plus main shoulder length ratio (g cm^{-1}). From each sample, a 50-berry subset was used for determining total anthocyanins and phenolics concentration (Iland et al., 1996) and data were given as mg g^{-1} of fresh berry mass. Remaining grapes were crushed and the resulting juice was immediately processed for the determination of TSS through a temperature-compensating refractometer (RX-5000 ATAGO U.S.A., Bellevue, WA, USA), must pH with a pH-meter CRISON GLP 22 (Crison, Barcelona, Spain), and titratable acidity (TA) by titration with 0.1 N NaOH to a pH 8.2 endpoint and expressed as g L^{-1} of tartaric acid equivalents. Tartrate and malate concentration was determined by chromatography (Savi et al., 2019) while yeast available nitrogen concentration (YAN) was measured through the formol titration method after Gump et al. (2001).

As an estimate of vine vigor, in each season, at winter pruning, removed one-year-old pruning mass was quantified on each tagged vine with a portable field-scale by keeping separate main canes and lateral canes. In parallel, crop load per vine was assessed as the yield-to-pruning mass ratio also known as Ravaz Index (Ravaz, 1911).

Statistical analysis was conducted using a mixed-model with the SPSS software (IBM SPSS Statistics 27.0). A two-way analysis of variance (ANOVA) was performed assuming vigor as a fixed factor and year as a random factor; in case of significant Fisher test, mean separation was performed according to the Student Newman Keuls (SNK) test at $p \leq 0.05$. Year \times treatment interaction was partitioned only in case of F test significance and mean

values compared by standard error. Repeated measurements of the same parameters (Ψ_{SOIL} , T_{SOIL} , shoot growth) taken at different time points during each season were analyzed using the Repeated Measure ANOVA procedure in the XLSTAT software package (Addinsoft, New York, NY, USA). Multiple comparisons within dates were conducted using the least-squared mean method at $p < 0.05$. Regression analyses and R^2 calculations were also performed using the same XLSTAT package.

Results

Soil characteristics and weather trends

HV spots showed predominantly Virola (VIR) soils, known to be present in cultivated irregular slopes ranging from 35 to 55% inclinations (Table S1). Their superficial horizons are generally about 0.1 m thick, moderately or weakly acidic, with a loose, pebbly texture, whereas the deeper horizons tend to be slightly acidic or neutral, with a very pebbly, frank texture, and are approximately 0.3 m thick. LV sites mainly characterized by Tavernelle (TVN) soils, which are also known to be in ridges of convex, steep slopes ranging from 20 to 35%. TVN soils are moderately deep and stratified on marls and perlites. Their superficial horizons are about 0.20 to 0.40 m thick with loose silty or clay-silt textures in which gravel is uncommon. The deeper horizon is 0.20 to 0.40 m thick and contains a loose loamy or loam-clay texture with gravel. In general, TVN soils are considered pedologically young. The A-horizon, or the topsoil, is a mineral horizon which typically forms at the surface and integrates decomposed organic matter (OM) into its mineral fraction. As shown in Table S1, the soils of the studied vineyard lack the O and E-horizons, made up of OM and minerals, respectively. Soil depth was also determined to be predominantly shallower (≤ 0.7 m) at the top of the slope where the LV vines resided due to the shallower rocky C horizon, limiting root extension due to the TVN nature of the soil, whereas it was deeper (> 0.7 m) at the bottom of the slope where the HV vines were located because of the larger B horizon in the VIR soil.

When soil hydrological constants and namely wilting point and field capacity were calculated from soil texture and organic matter content (Table 1) after (Saxton & Rawls, 2006) the resulting fraction of available water (AW) was quite similar across soil types and depths: it resulted to be 160 mm m^{-1} for both HV and LV at the same depth (0.3 m), whereas at 0.6 m AW was slightly higher in HV (160 mm m^{-1}) as compared to LV (150 mm m^{-1}). According to the USDA Soil Classification System the low vigor plots featured a loam soil, whilst a silt–clay–loam characterized the high vigor patches.

Table 1 Physical–chemical composition of soil samples taken at two different depths (0.3 and 0.6 m) in the high vigor (HV) and low vigor (LV) plots

Treatment	Sand (%)	Loam (%)	Clay (%)	pH	Total lime (%)	Active lime (%)	SOM (%)	N (g kg^{-1})	P_2O_5 (ppm)	K_2O (ppm)
LV-30	30	47	23	7.93	10	5.3	0.68	0.47	11	192
HV-30	20	47	33	7.81	6	4.9	1.41	0.94	9	233
LV-60	34	45	21	7.90	11	5.2	0.84	0.58	9	178
HV-60	16	51	33	7.73	3	2.7	1.37	0.96	7	188

SOM soil organic matter

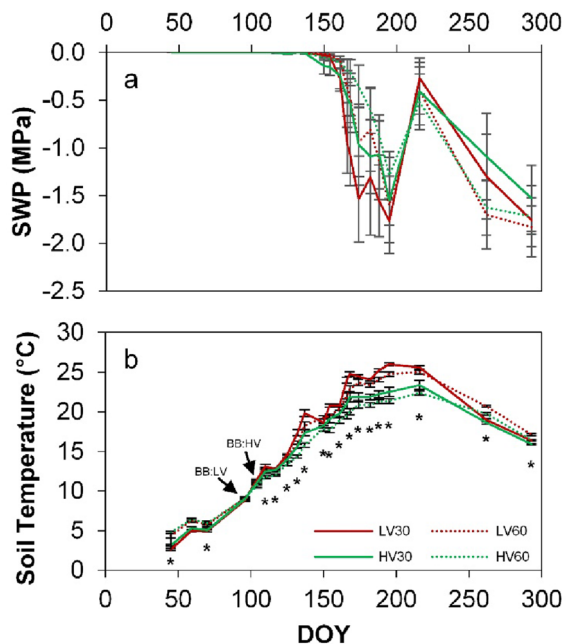
In 2020, the Winkler Index (WI) calculated as the cumulated growing degree days (GDD) from April to October on a 10 °C base temperature was 1919 °C and the annual precipitation was 705 mm (Fig. S3). The 2021 season was cooler and much drier as compared to the previous year as the WI was slightly lower than 1900 °C and annual precipitation was 596 mm. 2022 resulted as the warmest and driest season of the three-year period with WI summing up to 2436 °C and annual rainfall limited to 546 mm. In 2021 the seasonal precipitation from April to September was limited to 165 mm with only 68 mm registered between June and September, while seasonal distribution of rainfall was almost similar in 2020 and in 2022 (274 mm on average). However, if following a relatively dry spring a peak of rainfall was registered in August 2020, a more regular distribution of rainfall was registered from April to September in 2022 even if coupled to very high thermal regimes being maximum air temperature higher than 35 °C in 21 days between June and August.

Soil temperature and water status

Figure 1a shows the seasonal variation of mean Ψ_{SOIL} measured with the TEROS probes at 0.3 m and 0.60 m soil depths in each block of high and low vigor areas. Although between the time period comprised between DOY 180 and 185 and between DOY 206 and 210 some heavy rain occurred (21 and 60 mm, respectively) one tendency was having, at each soil depth, more negative Ψ_{SOIL} in LV against HV. Data were characterized from a fairly high variability and, upon the performed repeated measure analysis (RMA) both between-subjects (i.e. vigor levels) and within subject effects (i.e. time \times treatment interaction) resulted to be non-significant ($\text{Pr} > F = 0.144$ and 0.214 , respectively).

Vice versa, RMA analysis conducted on seasonal soil temperature showed significant differences between and within subject effects. Since the start of measurements in winter until the end of March (DOY 96) T_{SOIL} did not differ among the four treatments (Fig. 1b).

Fig. 1 Seasonal variation recorded in 2022 from 14 February (DOY 47) until 20 October (DOY 293) of soil water potential (–MPa, panel a) and soil temperature (°C, panel b) by TEROS 21 sensors. Readings were taken in the low vigor (LV) and high vigor (HV) plots at 0.3 and 0.6 m soil depths. Data are reported as means \pm standard error (SE). In a) repeated measure analysis (RMA) of variance resulted to be non-significant and mean separation within each date is not reported. In b) RMA was significant for between treatment effects ($F = 18.70$, $\text{Pr} > F = 0.001$) and for time \times treatment interaction ($F = 2.63$, $\text{Pr} > F = 0.001$). Within each date, presence of an asterisk indicates significant differences among treatments at $P = 0.05$. Arrows indicate the occurrence of budburst (BB) in grapevines from LV and HV plots



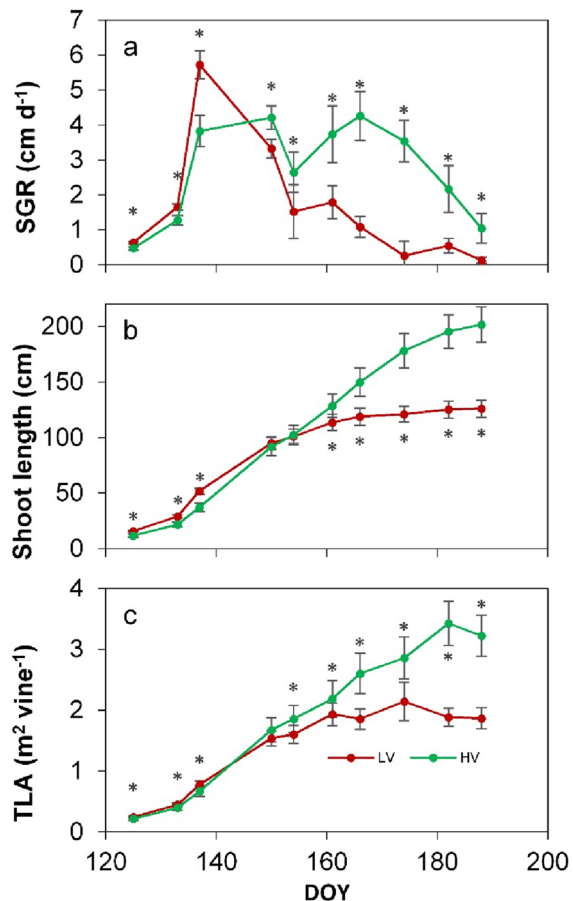
Thereafter, BV plots started to be warmer than AV plots with AV-30 being the warmest; the highest magnitude of such difference was reached on DOY 168 when BV-30 was 4.8 °C warmer than AV-60. Differences between the four treatment combinations tended to become milder during the two final late season readings.

Phenology, vegetative growth and canopy structure

According to BBCH scale, bud-burst was 4-day delayed in the HV plots vs LV (Fig. 1b). Such delay was fully compensated at BBCH 65 (50% of flower hoods fallen, on DOY 158) and at BBCH 79 (berry touch, on DOY 188).

The three vegetative growth parameters shown in Fig. 2a–c all showed a significant time x treatment interaction at RMA analysis over a measuring period comprised between May 5, when shoots were about 12–15 cm long, until 7 July (DOY 188). Since the very first measurement (Fig. 2a, b), LV plots had longer shoots (15.7 cm versus 11.7 cm recorded in LV) and a significant difference was maintained until end of May (DOY 150). Hereafter, HV took over and beginning from DOY 161 (10 June) the gap between the two treatments widened with LV having an almost totally checked shoot growth and HV showing further

Fig. 2 Seasonal variation recorded in 2022 from 5 May until last pre-trimming date (7 July) of shoot growth rate (cm day⁻¹, panel a), shoot length (cm, panel b) and total vine leaf area (m², panel c) in the low vigor (LV) and high vigor (HV) plots. Data are reported as means ± standard error (SE). RMA analysis was significant for all variables for either between-treatments and time x treatment interactions. In more details: in a) $F=16.80$, $Pr>F=0.001$ and $F=6.70$ and $Pr>F=0.001$, respectively; in b) $F=5.41$, $Pr>F=0.027$ and $F=17.52$, $Pr>F=0.001$, respectively; in c) $F=5.73$, $Pr>F=0.023$ and $F=13.26$, $Pr>F=0.001$. Within each date, presence of an asterisk indicates significant differences among treatments at $P=0.05$. SGR data reported on first sampling date is calculated as instantaneous shoot length divided by number of days elapsed since bud burst



elongation with a final difference of +72 cm as compared to LV (Figure S4). Growth speed (i.e. the derivative of the primary elongation curve given as cm day^{-1}) emphasized the fast shoot growth in spring in the LV plots with a remarkable 5.7 cm day^{-1} touched at pre-flowering – and the rapid growth fading hereafter (Fig. 2a). Since DOY 154 and onward HV had a sustained shoot growth speed comprised between 2 and 4 cm day^{-1} until the end of measurements.

Unsurprisingly, total leaf area (TLA) per vine at the start of measurements (May 5, DOY 125) was slightly greater for LV vines than HV vines, with a difference reaching 0.1227 m^2 (Fig. 2c). Beyond DOY150, TLA vine^{-1} of HV vines overtook that of LV vines, whose growth levelled off as HV vine leaf area continued to increase to reach a final differential gap of 1.2194 m^2 ($p=0.01$). When evaluation of vine vigor was extended to the three-year data set, total final pruning weight and its two main components (main and lateral canes) were consistently higher in HV, scoring 96.7% more as per total pruning weight versus LV (Table 2). No significant interaction with the factor year was found for these variables.

Correlating total shoot lengths recorded in the two vigor plots with the cumulated growing degree days (GDD) derived from the within canopy temperature readings yielded in both cases a tight exponential relationship (Fig. 3a) which, in LV, showed a saturation threshold already at about 550 GDD whereas in HV a full plateau was never reached. Then, same correlations were calculated for the time periods before (Fig. 3b) and after (Fig. 3c) DOY 154 in fact dictating the switch between LV and HV. For the time window before DOY 154 the two variables showed a very close linear fit ($R^2=0.99$ in both vigor levels), with no differences in slope yet with an higher intercept value in LV (Fig. 3b); post DOY154 the log model fitted to HV was still very accurate ($R^2=0.98$) whereas a looser ($R^2=0.66$), albeit significant, linear relationship between GDD and total shoot length was found in LV (Fig. 3c).

Correlations between Ψ_{SOIL} and soil temperature (T_{SOIL}) versus total shoot length were also run in LV and HV for data pooled over depths (Fig. 4). All correlations drawn for Ψ_{SOIL} and shoot length fitted to a log model with R^2 ranging between 0.72 and 0.84 (Fig. 4a). In LV plots, regardless of soil depth, shoot growth was almost arrested at about -0.22 MPa ,

Table 2 Vegetative growth, yield components, and vine balance recorded over three years (2020–2022) on field-grown cv. Barbera grapevines growing in different vigor zones (HV high vigor, LV low vigor)

	Main pruning weight (g vine^{-1})	Lateral pruning weight (g vine^{-1})	Total pruning weight (g vine^{-1})	Clusters vine^{-1}	Cluster weight (g)	Berry weight (g)	Yield/vine (kg)	Cluster compactness (g cm^{-1})	Ravaz index (kg kg^{-1})
Vigor (V)									
HV	655.3	60.0	668.9	21.7	206.6	2.22	4.47	16.3	6.9
LV	373.2	16.9	340.2	19.0	91.0	1.51	1.71	12.9	5.3
F-prob	***	***	***	*	***	***	***	**	**
Year (Y)									
2020	523.6b	42.9	507.5b	26.4a	160.1a	1.92a	3.82a	15.5a	7.60a
2021	601.7a	45.0	595.6a	22.8b	162.4a	1.73b	3.31a	16.4a	5.9b
2022	446.9b	28.2	410.7c	18.5c	123.9b	1.66b	2.13b	12.0b	4.9b
F-prob	***	n.s	***	***	**	**	***	**	***
V x Y	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s

In case of significance of the F test, within column mean separation was performed by SNK test. * = $p < 0.05$, ** $p < 0.01$, *** = $p < 0.001$, ns = not significant

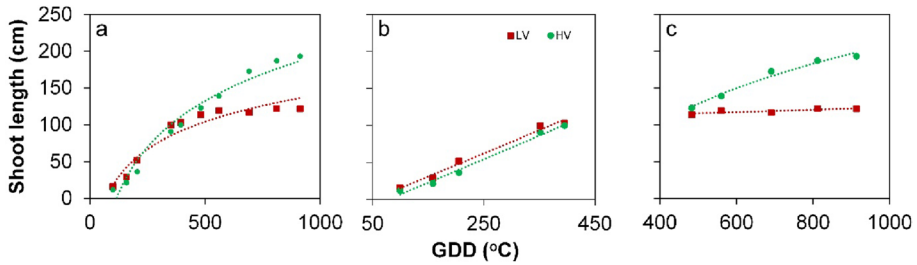
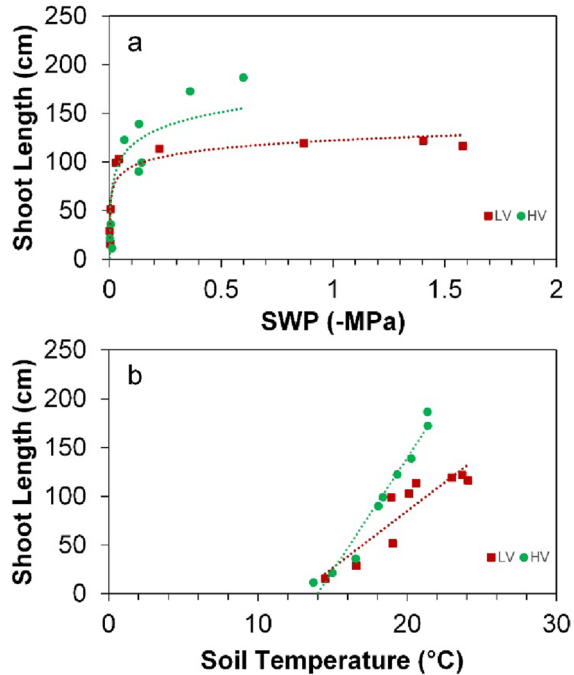


Fig. 3 Correlations between growing degree days (GDD as °C) and total shoot length for the LV and HV levels plotted for the whole measuring period (a), for the time between first measurement and DOY 154 (b), and for the time between DOY 154 and last pre-trimming measurements. DOY 154 synchronizes with the moment of vigor switch. In a) non linear equations fitted to the data were: $y=90.36\ln(x) - 429.37$, $R^2=0.96$ (HV) and $y=53.68\ln(x) - 229.78$, $R^2=0.93$ (LV); in b) linear models fitted to the data were: $y=0.3174x - 25.008$, $R^2=0.99$ (HV) and $y=0.313x - 16.063$, $R^2=0.99$ (LV). In c) the following non linear model was fitted to the HV data: $y=116.02\ln(x) - 592.74$, $R^2=0.97$; instead, a linear model was fitted to the LV data: $y=0.016x + 107.35$, $R^2=0.66$. GDD were calculated from a thermo-hygrometer recording data every hour at 1.5 m canopy height

Fig. 4 Correlations between soil water potential (-MPa) and total shoot length obtained by pooling seasonal readings over the two soil depths (0.3 and 0.6 m) (a); equations fitted to the data were: $y=21.27\ln(x) + 165.84$, $R^2=0.72$ (HV) and $y=11.76\ln(x) + 121.98$, $R^2=0.84$ (LV). Correlations between soil temperature (°C) and total shoot length obtained by pooling seasonal readings over the two soil depths (0.3 and 0.6 m) (b); linear equations were: $y=23.199x - 324.89$, $R^2=0.96$ (HV) and $y=11.666x + 148.6$, $R^2=0.82$ (LV)



whereas shoot elongation appeared to continue in HV plot even at the lowest Ψ_{SOIL} of -0.6 MPa.

When same correlations were analyzed by replacing Ψ_{SOIL} with the T_{SOIL} all data closely fitted to a linear model (R^2 varying from 0.82 and 0.96) (Fig. 4b). The Fig. 4b shared two features: fitted lines had significantly different slopes and a cross-over temperature was

apparent. Within the LV vs HV comparison HV started to show increasingly longer shoots when T_{SOIL} exceeded about 16 °C; within LV, the cross-over T_{SOIL} was about 18 °C.

Point quadrat analysis (PQA) results referred to the LV and HV levels are shown in Fig. 5 for four dates. Regardless of vigor level, it is quite expected that CG (%) increased from the bottom to the top of the canopy due to both short shoots not able to reach the upper foliage wires and to the diminishing leaf size moving from basal to apical nodes positions. At pre-flowering, CG was higher in HV up to 0.50 m above the cane, while resulting similar between vigor levels at berry pea size (Fig. 5a, d). PQA made a month ahead fully reversed this pattern, as HV vines had lower CG at any canopy levels with the exception of C+5 and C+15 where full leaf occlusion occurred in both treatments (Fig. 5g). LLN trends are a somewhat direct reflection of the CG patterns as early in the season HV had a less dense canopy up until 0.4 m from the fruiting cane (Fig. 5b); at berry pea size HV still retained a slightly looser canopy at the cluster level (C+5–C+25), whereas a month later, starting from the C+15 level and onward HV had a decidedly higher LLN peaking at 3.5 at fruit

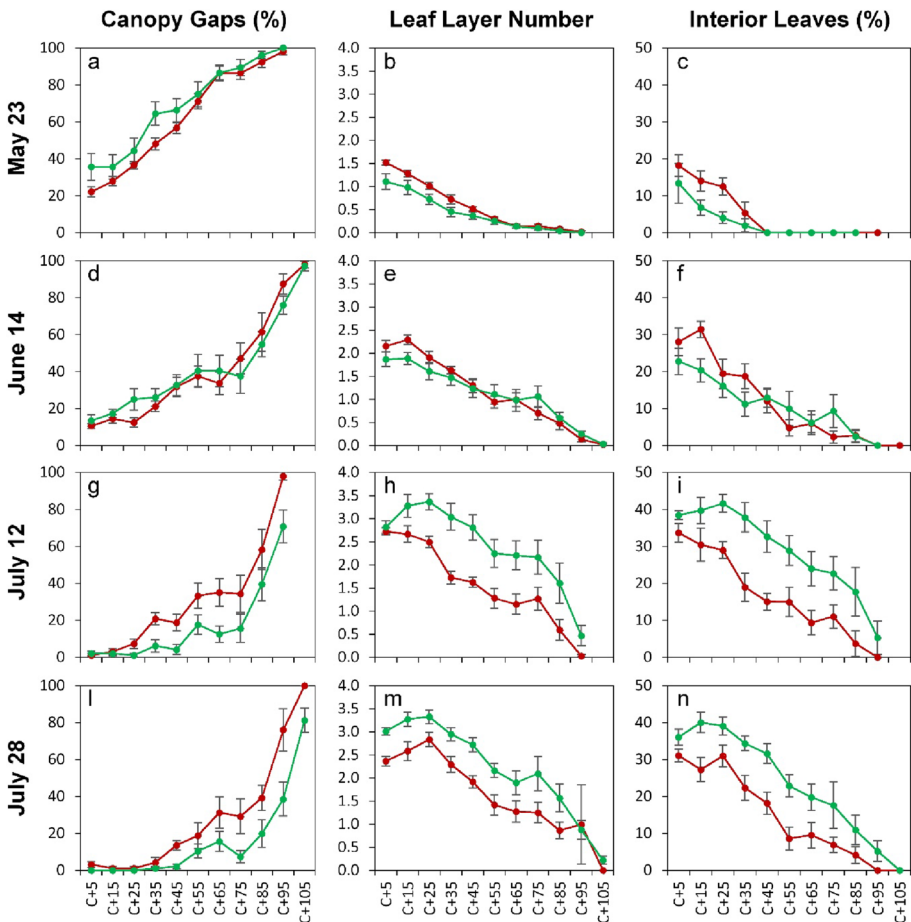


Fig. 5 Seasonal progression fraction of canopy gaps (%), leaf layer number and fraction of interior leaves estimated according to a Point Quadrat method in vines growing from LV and HV plots. X axis show increasing distance (cm) from the cane level. Data are reported as means±standard error (SE)

level (Fig. 5e, h). Overall, the same comments can be extended to the results achieved in terms of fraction of interior leaves, reaching the highest value (42%) in HV at the pre-veraison sampling for the C+25 canopy level (Fig. 5c, f, i, n). At veraison, differences among vigor classes were still consistent for all the assessed parameters (Fig. 5l, m, n).

Vigor mapping by proximal sensing

CI-based vigor maps acquired in 2022 at eight dates from 17 May until 29 July show that spatial distribution of canopy levels given as CI index progressively shifts positions over time (Fig. 6). A trend being consistent with data from 2021 despite, over that season, only two proximal acquisitions were displayed in Fig. 6 (7 May vs 21 September). Notably, localization of LV zones as described at the end of 2020 growing season are confirmed at the end of the following seasons. However, in both 2021 and 2022, LV zones appear as more vigorous around pre-flowering and thereafter HV gradually takes over. The CI increased along the season, following grapevine development. The maximum CI observed throughout the experiment in 2022 was 519, whereas the minimum was 80. Excluding the first sampling date, the smallest variation in the CI range was on 3 June, or DOY 154, around the vigor inversion. The most prominent difference was found on 10 June.

Leaf gas exchange, soil and leaf water status

Soil and leaf water status assessed as pre-dawn (Ψ_{PD}) and midday (Ψ_{MD}) water potential, respectively, were measured in 2022 on June 16, July 6 and August 8 in vines pertaining to either low and high vigor plots (Fig. 7). At any time, HV had less negative Ψ_{PD} and Ψ_{MD} . According to the literature reviewed by Rienh and Scholasch (2019), HV showed moderately stressful conditions (most negative Ψ_{PD} and Ψ_{MD} were -0.34 and -0.84 MPa, respectively) whereas LV was more stressed with Ψ_{PD} approaching -0.6 MPa and Ψ_{MD} setting close to -1.5 MPa on two dates out of three (Fig. 7a, b). Leaf A rates in HV never decreased below $10 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Fig. 7c) and, correspondingly, leaf E and gs rates were also never severely limited (Fig. 7d, e). Vice-versa, in LV, an increasing stomatal limitation in turn leading to lower leaf E rates was seen along the season, although on 8 August, despite the lowest gs, A rates in LV did not differ from those recorded a month before. Interestingly, on 8 August, instantaneous WUE significantly improved in LV vines as compared to HV (Fig. 7f).

Yield components and grape composition

When total yield per vine and the relative main components were pooled over the three years (2020–2022) it was apparent that LV suffered a drastic reduction in vine cropping (1.71 kg corresponding to 6.8 t/hectare) when compared to HV reaching 4.47 kg vine⁻¹ to be equivalent to 17.9 t/hectare (Table 2). Ultimately productivity was 161% higher in HV vs LV. Any yield components contributed to this yield gap, although the largest reduction was seen in cluster weight (127% higher in HV) and berry weight (47% higher in HV). LV achieved looser cluster while vine balance assessed as the crop weight-to-pruning weight ratio (Ravaz Index) highlighted close to optimal values for both treatments under a tendency

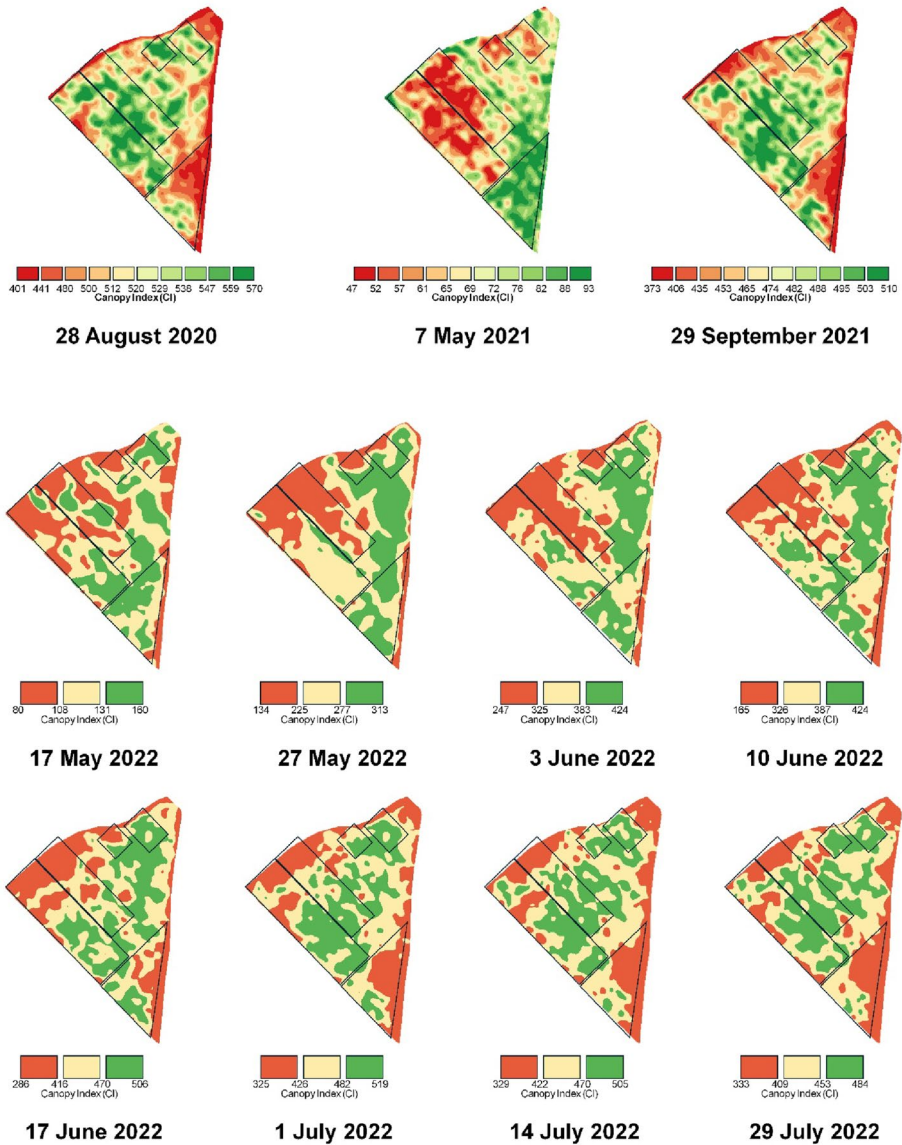


Fig. 6 Canopy Index (CI) vigor maps obtained at different dates in 2020, 2021 and 2022 with a MECS-VINE® sensor mounted in front of a tractor. Polygons show the areas where vigor inversion mostly occurred

for HV to show higher attitude toward the reproductive phase (Kliewer & Dokoozlian, 2005).

Grape composition at harvest was markedly affected by vigor and a significant year x treatment interaction occurred for TSS, pH, TA, malate, total anthocyanins and phenolics (Table 3 and Fig. 8). Overall, LV grapes showed a TSS concentration that was 1.7°Brix higher than HV, a titratable acidity of around 8 g L⁻¹, and less than half the malate con-

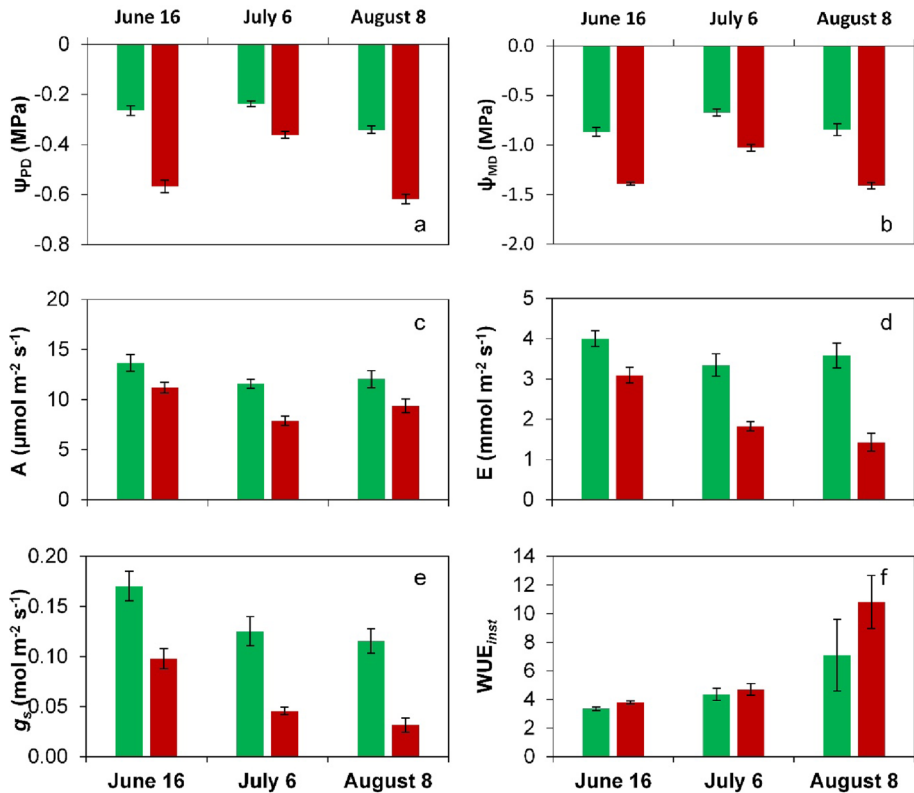


Fig. 7 Pre-dawn leaf water potential (a), midday leaf water potential (b), leaf assimilation (c), leaf transpiration (d), leaf stomatal conductance (e) and instantaneous water use efficiency (f) recorded at three dates in 2022 on the low vigor (LV, red bars) and high vigor (HV, green bars) vines. Data are reported as means \pm standard error (SE)

Table 3 Grape composition recorded over three years (2020–2022) on field grown cv. Barbera grapevines growing in different vigor zones (HV high vigor, LV low vigor)

	TSS (°Brix)	pH	TA (g L ⁻¹)	Tartrate (g L ⁻¹)	Malate (g L ⁻¹)	Antho- cyanins (mg g ⁻¹)	Phenolics (mg g ⁻¹)	YAN (mg L ⁻¹)
Vigor (V)								
HV	21.15	3.16	10.84	8.94	3.86	0.866	1.814	122.6
LV	22.85	3.26	8.24	10.13	1.52	1.405	2.753	118.0
F-prob	***	***	***	***	***	***	***	n.s
Year (Y)								
2020	20.92b	3.09c	10.74	11.48a	3.31a	0.858b	1.820b	185.9a
2021	20.24b	3.18b	11.38	10.61a	3.05a	1.328a	2.458a	110.1b
2022	24.85a	3.34a	8.05	8.72b	1.71b	1.219a	2.573a	108.7b
F-prob	***	***	***	***	***	***	***	***
V x Y	*	**	***	n.s	***	**	**	n.s

In case of significance of the F test, within column mean separation was performed by SNK test. * = $p < 0.05$, ** $p < 0.01$, *** = $p < 0.001$, ns not significant

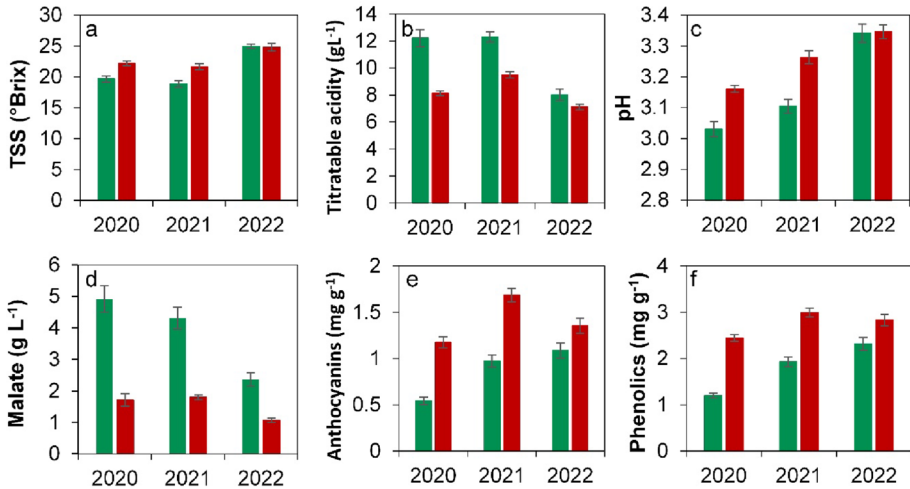


Fig. 8 Partitioning of the year \times treatment significant interactions highlighted in Table 3 for total soluble solids (a), titratable acidity (b), pH (c), malate (d), total anthocyanins (e) and total phenolics (f). Data are means for each year \times treatment combination \pm interactive SE. LV red bars, HV green bars

centration compared to HV (1.52 vs. 3.86 g L⁻¹ in LV and HV, respectively). In addition, LV grapes contained higher levels of both anthocyanins and total phenolics (1.405 and 2.753 mg g⁻¹, respectively) compared to grapes from more vigorous plots. In no cases, the interaction was of a cross over type, meaning that, within each year, consistent relative differences between HV and LV were maintained. In LV, a more advanced maturity stage than HV was reached as higher TSS, pH, total anthocyanins and phenolics and, concurrently, as lower TA and malate. The quite hot and dry 2022 season likely contributed to offset the differences between vigor levels for TSS and pH (Fig. 8a, c).

Discussion

Data presented in this study include a 3-year ground truthing of vine performance assessed for high vigor and low vigor zones insisting on the same relatively small vineyard and fostered by either a changing longitudinal slope and variation in physical and chemical soil properties. While differences in soil texture led in turn to minor variation in soil available water among soil types and depths, differences due to either soil fertility and soil depth which might hypothetically be colonized by roots are the primary determinants of the observed vigor levels. In terms of ground truthing, inter-annual variation assessed over three years (2020–2022) confirms a strong temporal stability of spatial differences in vine vigor and, consequently, vine performances. It is relevant that for either pruning weight and yield components no interaction with year was found indicating that relative differences are maintained across a range of environmental conditions. The quite low yield per vine recorded in LV (1.71 kg) rather than being an expression of under cropping is a sign of a general low vigor status which also includes limited pruning weight and especially small clusters and berries. Trends of grape composition over years is, in fact, further confirma-

tory of a strong link between vine vigor and final quality. Despite several year \times treatment interactions were found, none of them showed a cross over type (Landsheer et al., 2006), meaning that depending from the level of a given factor (i.e. year), level of expression of the other factors can be reversed. This never happened in our study indicating that ripening traits of low vigor areas vs high vigor areas were overall mildly affected by seasonal climatic conditions. Inter-annual stability and magnitude of vine performance variables recorded in the two soil types highlight suitable conditions for implementing a precision management approach directed to fertilization, irrigation, harvest and some summer pruning operations such as leaf removal. Notably, this happened in a quite small sized vineyard (1.31 hectares) emphasizing the usefulness of a high-resolution proximal sensing approach for intra-vineyard detection of spatial variability (Gatti et al., 2016; Henry et al., 2019; Moreno & Andújar, 2023).

A second important feature that has been confirmed in our study on a biennial basis (2021 and 2022) by proximal canopy scanning performed at different timings during the growing season is that early shoot and canopy growth are typically enhanced in the ultimately defined “low vigor” plots. End of flowering sets the timing when the two vigor levels become the most similar and, hereafter, high vigor vines consistently show further canopy development which is instead fully checked in LV. In parallel the scenario that can be drawn in terms of physiological behavior of the two vigor classes is definitely in favor of HV, always showing a higher resilience to a progressively lower soil water availability and higher evaporative demand. The effectiveness of remote sensing technologies in detecting temporal variations in vineyard vigor has been well documented through studies employing satellite imagery and drone-based approaches (Kazmierski et al., 2011; Pádua et al., 2020; Zanchin et al., 2024). However, the potential of the MECS-VINE sensor to describe seasonal patterns of vineyard variability has never been directly compared with more conventional technologies. We therefore assume that other remote sensing approaches at around 2 m ground resolution may result in comparable results, because of the good correlations between specific vigor indices (i.e. NDVI and CI) and agronomic data reported by Squeri et al. (2021b).

Indeed, the first conclusion which can be drawn from the above is that, despite the alternance in terms of specific vigor level at a specific timing during the season between HV and LV, the former maintained, at harvest, higher vigor and productivity and, concurrently, incomplete or retarded berry maturity as compared to LV (Table 3 and Fig. 8). While the consistent outcome observed at each harvest reassures growers about what it might eventually be expected, under the specific cultural condition, from a high vigor status, the within-season change in vine balance is something that needs to be discussed as it might affect either when and how a given cultural practice should be applied as well as how more or less tolerance to biotic or abiotic stress factors can be pursued.

Taking first into consideration within-season patterns of vine balance and physiology observed in the LV plots, both positive and negative features can be highlighted; among the positives (i) earlier canopy filling and optimal LLN (about 1.0 to 1.5) at the basal nodes are good premises for good photosynthetic potential when climatic factors are unlikely to be limiting and for non-limited bud induction for next year cropping, respectively; (ii) despite faster canopy filling, vegetative growth is fully checked at beginning of fruit-set with an expected fostering of the ripening process due to lack of competition; (iii) under quite severe water stress LV was able to significantly improve leaf WUE; (iv) regardless of soil depths (0.3 vs 0.6 m) higher soil warming recorded from bud burst until lag phase in LV might

facilitate micro-biological soil activities as well as affecting readiness and efficiency in nutrient uptake; (v) overall low vigor is a good yield regulator and a booster of final grape quality and prospect wines. Concurrently, LV manifested several weaknesses as it follows: (i) an earlier budbreak is a trait that inherently increases the risk of spring frost damage (Poni et al., 2022); (ii) shoot growth rate peaking at about 6 cm day⁻¹ late in May (Fig. 2a) might hinder the ongoing bud induction process with a negative impact on next year productivity; (iii) moderate water stress recorded on July 16 and July 7 (Fig. 7) certainly overlaps with green phase of berry growth and might contribute to reduced final berry size and yield.

When the same analysis is carried on the HV vines the somewhat delayed budbreak due to the cooler soil and slower reactivity to cumulated GDD until about 200 °C represents a positive trait; likewise, HV vines, despite their higher final leaf area development (hence expected higher water use) showed to be more resilient to water stress, a quite important feature for a rainfed vineyard in a global warming scenario. Such higher resilience does not seem to be due to higher water availability due to soil characteristics insisting in the HV plot as the estimated fraction of AW was similar to LV at both depts. Rather, due to a lower sand fraction, HV plots likely had slower water percolation rates whereas soil profile also allowed root colonization of deeper soil layers potentially down to about 1 m. As a result, HV vines showed a mostly non-limited leaf water status and gas exchange over the whole summer season.

Potential weaknesses shown by HV is a ripening lag as compared to LV and a canopy density in the fruiting zone (up to 3.5 LLN) which, in case of a wet season might enhance the incidence and severity of cluster rots. However, the same fairly high foliage density in the cluster area might be a warrant, in hot and dry seasons, against early basal leaf drop which might then trigger a condition of excessive cluster exposure and subsequent overheating and sunburn (Haselgrove et al., 2000; Poni et al., 2018).

A literature review about temporal stability of within season vine performance offers a limited amount of information as many papers either describe inter-annual temporal stability without reporting about within-season changes to spatial variability (Baluja et al., 2012; Bramley & Hamilton, 2004; Bramley et al., 2011; Gatti et al., 2017; Tisseyre et al., 2008) or lack at defining different vigor levels within the same vineyard (Jasse et al., 2021; Verdugo-Vásquez et al., 2015). Instead, work done by Bahat et al. (2021) about in-season interactions between vine vigor, water status and wine quality in terrain-based management zones of an irrigated Cabernet Sauvignon vineyard in Israel is an ideal term of comparison. Their LV zone, spatially defined as such in terms of topographic wetness index, soil electrical conductivity and soil depth confirmed lower total leaf area, lower yield and cluster weight, better grape maturity and higher susceptibility to a seasonal water deficit scored through stem water potential readings vs a HV zone. To differ from us, no in-season switch for vigor was detected validating the assumption that management zones can be rather static as also pointed out by Ohana-Levi et al. (2020) and Priori et al. (2013). Vice versa, in agreement with our study, a significant change in the dynamic of within season spatial variability was reported (Hall et al., 2011) in a two-year study on Cabernet Sauvignon where vine vigor was assessed through NDVI at high spatial resolution (0.25 m). Canopy density grew faster in the western part of their block until flowering, became similar to that of the eastern part by veraison and took gradually over toward maturity. Main consequence of such a pattern was that correlations calculated between NDVI at a given growth stage vs yield and grape composition variables change dramatically in sign and accuracy.

Guidelines that can be proposed to growers to opt for any given vigor level must certainly include the sought wine types as well as the best compromise between environmental and economic sustainability. Indeed, the switch in vigor observed in our study suggests, for instance, real-time adjustments of timing and volume of canopy spray for a reduced use of chemicals and more efficient deposition of plant protection products (D'Ambrosio et al., 2023; Gil & Escolà, 2009). Likewise, the earlier canopy formation observed in LV might require adjustments in the timing and amount of spring nitrogen fertilization (e.g. depletion of N stored in the permanent organs might be faster therefore requiring prompter supply). Conversely, starting at fruit set, LV areas, due to soil type and positioning on top of the steep slope, become likely candidates for progressive water deficit leading to severe limitations in leaf functions. Under such circumstances, the recourse to precision irrigation seems to be a viable solution (Bellvert et al., 2021; Sanchez et al., 2017).

An alternative approach is trying to correct and/or modify spatial-temporal patterns of intra-vineyard vine vigor variability. A good use case is represented by variable rate (VR) fertilization where LV and HV vigor can be adjusted towards a uniform intermediate medium vigor class or even reversed (Gatti et al., 2019, 2020; Sozzi et al., 2020). However, vine vigor correction through VR fertilization is more likely to be successful when the soil induced vigor patches refer to a flat or a moderate slope parcel. When a significant slope component is also present (i.e. our study) interactions between soil slope and surface water runoff and rate of precipitation water infiltration into deeper layers might result in a quite confounding response. In fact if a shift from low to high vigor is usually obtained by providing higher amounts of a fertilizer earlier in the season (Gatti et al., 2020), under our circumstances this approach could lead to a somewhat opposite result as LV already starts with faster shoot growth which could be additionally pushed by additional nutrient availability and favorable condition for root uptake (warmer soil in LV vs cooler soil in HV early in the season).

Under the experimental context, a consistent differentiation among vigor zones has been described in terms of fruit chemistry achieved at harvest. According to previous studies performed within the region when comparing “Vicobarone” (HV) vs. “Montalbo” (LV) soils (Gatti et al., 2017, 2022), our experiment resulted in a very consistent pattern of fruit ripening allowing to consistently separate the enological potential of less ripe grapes from “Virola” (HV) soil to those associated to the “Tavernelle” (LV) soil characterized by a more pronounced aptitude for producing full bodied long aging wines (Table 3). Overall, if the LV vines behavior is taken as a whole and both interannual and in-season vigor variability are considered, the LV status can be deemed to be quite risky under the specific pedoclimatic conditions. In more details, higher exposure to frost damage and multiple summer stresses (Pallioti et al., 2015) seem to be a defeating perspective. It could be argued that LV consistently reaches the most complete grape maturity; once again, though, shift in consumer's behavior hinting to higher appreciation for more moderate final alcohol content (Ristic et al., 2016) and serious risk for excessively early ripening or overripening fruits (Poni et al., 2018) are real concerns.

In conclusion, the study clarifies the interactions between spatial and temporal variability in steep vineyards, offering new insights into vineyard management. By rigorously ground-truthing patterns of variability in terms of vegetative growth, canopy structure, microclimate, soil water status, and leaf physiology across phenological stages, it provides a basis for more targeted management guidelines that can improve the efficiency and sustainability of

viticulture. Despite the trade-off between spatial and temporal variability in a steep vineyard has been widely described under experimental conditions, the findings of this study should be validated over different conditions as they are potentially affected by the vineyard's size as well as by the specific topographic and geological context. Moreover, more consistent results should be validated across different grapevine varieties and training systems, while the use of remote sensing and high-resolution drone technologies should be further tested to address spatial and temporal variability under diverse operational contexts.

Conclusions

Our study confirms that, despite a small vineyard size, end of season spatial separation of low vigor and high vigor zones is quite constant over a three-year span indicating large differences in terms of yield performance and final grape composition which could eventually justify a selective harvesting approach. Different vigor levels accounted for variability in soil fertility and depth, rather than in soil available water. In two seasons out of three and in greater detail in 2022, the same dynamic for vigor zones was shown within each season. Initially, and for about three weeks after budburst, LV plots had higher and faster vegetative growth than HV; thereafter, around pre-flowering, the two vigor levels tended to equalize before having HV to take over for the remainder of the season. While the initial higher growth push in LV is due to faster soil warming and higher reactivity to accumulated heat, the vigor switch takes place mostly due to higher sensitivity of LV to summer water stress. As a result, a significant vigor inversion affecting the pattern of vineyard variability is described across progressing phenology.

The switch between the two vigor levels warrants caution when variable vineyard management is planned to be performed. Initial early season higher vigor in LV would advise for variable spraying and fertilization which should be calibrated opposite way to a standard LV plots; conversely, since the switch point onward, vine performance in LV plots should be sustained, for instance, through a precision irrigation strategy, or any other technique which limits the incidence of summer water stresses.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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Ethical approval The authors comply with the Journal's Ethics guidelines confirming to respect third parties rights such as copyright and/or moral rights.

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