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Research Article

Is Precision Viticulture Beneficial for the High-Yielding Lambrusco (*Vitis vinifera* L.) Grapevine District?

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Abstract: The best Lambrusco wines are often obtained by blending a representative of the Lambrusco family (i.e. Lambrusco Salamino) with a smaller fraction of Ancellotta, a teinturier variety possessing an extraordinary quality of accumulating color. Due to the economic importance of the Lambrusco business and the rising interest in precision viticulture, a two-year trial was carried out in seven vineyard plots growing both the named varieties. A RapidEye satellite image taken on 9 August 2018, led to vigor maps based on unfiltered normalized difference vegetation index (NDVI). In both the years, ground truthing was performed on the test vines chosen within each vigor area for soil features, vegetative growth, yield, grape, and final wine composition. For data pooled over sites and years, Ancellotta showed a very clear response to NDVA-based vigor mapping as low vigor areas always achieved improved ripening in terms of higher total soluble solids (+1.24 Brix), color and phenols (+0.36 mg/kg and + 0.44mg/kg, respectively), and lower malate (-1.79 g/L) vs high vigor. Such a behavior was shown even in those cases where NDVI of different vigor levels and pruning weight were not closely correlated and, most notably, low vigor matched with a slightly higher yield as compared to high vigor plots. Overall, the high yielding Lambrusco Salamino was less responsive in terms of vine performance and grape composition versus intra-vineyard variability. This study highlights that, in Ancellotta, adjusting the vine balance toward ostensible lower

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vigor (i.e pruning weight ≤ 1 kg/m) would result in a superior choice in terms of improved ripening and wine profiles would not be detrimentally impacted by the yield level which, in fact, increased in some cases.

Key words: grape composition, remote sensing, satellite imagery, spatial variability, vine capacity, yield

Introduction

The essence of applying precision agriculture is that it takes into account in-field variability (McBratney et al. 2005, Schieffer and Dillon 2014, Wolfert et al. 2017). Its characterization is left to a spatial and temporal mapping of crop status, vegetative growth, yield, and fruit quality variables and paves the way to the enticing prospect that the general negative traits usually bound to "variability" might turn into an unexpectedly profitable scenario (Rudd et al. 2017, Shafi et al. 2019). In fact, once proper spatial in-field variability is described and quantified the same can either be exploited through selective management operations (Bramley et al. 2005) or by balancing it towards the most rewarding status through the adoption, for instance, of variable rate technologies (Gatti et al. 2020).

The range of spectral, spatial, and temporal resolution now offered by combining the four main categories of available sensors *viz.*, commercial off-the-shelf RGB (red-green-blue), multispectral, hyperspectral, and thermal cameras and the flexibility allowed by main acquisition platforms, i.e. satellite, aircraft, unmanned aerial vehicles, and proximal (i.e. tractor mounted) offer an already huge and still rising array of possible precision agriculture applications (Maes and Steppe 2019, Matese et al. 2015). These embrace drought stress, pathogen and wind detection, nutrient status, vegetative growth and vigor, and yield prediction. Indeed, difficulties and opportunities related to the precision agriculture approach might drastically change depending on having, for instance, a field crop forming a continuous green cover or an orchard system typically featuring a discontinuous canopy where the rows alternate soil strips. Thus, it is not surprising that a very high number of precision agriculture applications pertain to the vineyard ecosystem (Hall et al. 2002, Matese et al. 2015) with the normalized difference vegetation index (NDVI) being the most often used. When compared to the orchards of other fruit trees that also show a discontinuous green cover, a vineyard is more prone to show intra-parcel variability for several reasons, which are as follows: i) it is a high-value crop grown under a wide range of latitudes, altitudes, and slopes that foster differential growth according to micro- or meso-climate variations and soil heterogeneity; ii)

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variability in vigor is favored by the plasticity of the species that due to long and flexible canes can be arranged under many different canopy geometries and trained to a multitude of training systems, and iii) as shown in several previous studies, intra-vineyard spatial variability seems to be quite stable over time (Kazmierski et al. 2011, Taylor and Bates 2013) and is mostly related to the patchiness in the soil's physico-chemical features affecting water holding capacity, water infiltration rats, nutrient availability, uptake, etc.

Despite the above, when comparing the array of current precision viticulture applications and the number of cases showing standard adoption of such techniques, the gap, at least in Italy, seems huge. Among the several factors contributing to this, it is apparent that growers still do not have a complete perception of the added value that precision viticulture or site-specific management can bring to their businesses. A recent survey conducted among the grape growers of the Emilia-Romagna Region (A. Ulrici, personal communication, 2020) and the collection of 353 responses to a submitted questionnaire has shown that precision techniques were regarded as a priority topic by only 51 responders, whereas aspects such as adaptation to climate change, new techniques for pest control, and automation/mechanization were preferred by more than 100 growers. Part of the problem is that, despite a large number of applications and subsequent vast publication activity on the subject (Bramley 2010, Matese et al. 2015), the mapping derived from image acquisition is not always associated with proper ground truthing. This means that the agronomic performance of vines falling in the vineyard parcels having different degrees of vigor and yield potential need to be properly and carefully substantiated. A quite common mismatch is that a given vigor level described as "high," "medium," or "low" might result in an agronomic counterpart that is negating that meaning. A case in point, among several, is the one reported by Fiorillo et al. (2012) who mapped a Sangiovese vineyard in Tuscany and reported an average one-year-old pruning weight of 498 g/m of cordon length for the high vigor (HV) plots that, indeed, according to a robust literature (Kliewer and Dokoozlian 2005, Smart 1985) cannot be regarded as an expression of HV or excessive vegetative capacity. Then, it was not surprising that the HV vines performed better than low vigor (LV) vines in the Tuscany experiment having only 250 g of pruning weight/m. This assumption gains support also from a 4-year study conducted by Bonilla et al. (2015) on cv. Tempranillo grown in the warm area of La Rioja in Spain. It indicates that an NDVI-based HV vineyard parcel delivered notably improved grape composition, especially as to anthocyanin concentration, over that of LV vines. The above findings suggest that the labeling of vigor areas without site-specific ground truthing can lead to meaningless or even deceiving information.

Another item deserving clarification is assessing when intra-vineyard spatial variability is high enough to warrant some forms of exploitation (i.e., selective harvesting) or correction (i.e., adopting variable rate applications to let convergence towards the most desired vigor or yield level. Evidence has been provided (Schaepman-Strub et al. 2006, Tanda and Chiarabini 2019) that absolute values of NDVI cannot be directly used to infer vigor simply because at the same NDVI value, quite different levels of vigor can be found due to the interference of several factors such as ground resolution, modalities of image acquisition (i.e., zenital vs inclined), composition of mixels (a pixel having a varying contribution of canopy and soil reflection patterns), floor management, pruning type, and row orientation.

An ideal and still unexplored wine district to be assessed in terms of spatial variability by satellite imagery is the Lambrusco area, extending for about 15,590 ha primarily in the Provinces of Modena and Reggio Emilia in the Emilia-Romagna Region, mostly established on flat terrains. Lambrusco is a fairly unique product and is renowned as a crisp, vividly colored, and sparkling red wine. Currently, it is the most sold wine in large-scale retail trade and the HORECA channel in Italy and also boasts of increasing export trends to South America, Russia, and Canada (as found in http://www.inumeridelvino.it).

The purpose of this study was the following: i) to provide ground truthing, on a two-year basis, of NDVI-based vigor maps created from satellite imagery in three different farms growing Lambrusco Salamino, one of the best representative cultivars of the Lambrusco family and Ancellotta.; and ii) to determine if and how assessed and ground truthed intra-vineyard variability should lead to a change in the current cultural practices.

Materials and Methods

Plant material and experimental layout. The experiment was carried out in 2018 and 2019 in three farms located in the middle of the Po River Valley (Province of Reggio Emilia, Emilia-Romagna Region). For each of them, two different red skin grape varieties of *Vitis vinifera* L., Ancellotta and Lambrusco Salamino were chosen for a total of seven test parcels (three plots for Lambrusco Salamino and four plots for Ancellotta). While general features of each vineyard are reported in Table 1, attention was given to Ancellotta and Lambrusco Salamino due to their high acreage (4,635 and 4,085 ha for Lambrusco Salamino and Ancellotta, respectively). Ancellotta and Lambrusco Salamino nicely complement each other in the

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"Reggiano", "Lambrusco Salamino di Santa Croce," and "Lambrusco di Modena" DOC appellations where Ancellotta is allowed up to 15%. Ancellotta is a well-known, deeply-colored complementary variety bringing more color, structure, and roundness to the wine smoothing down the high acidity of the Lambrusco Salamino grapes. Mapped vineyards ranged from 0.4 ha to 1.3 ha in size and were all vertically shoot positioned (VSP) types (Table 1). However, pruning systems were different ranging from VSP spur-pruned cordon at Pignagnoli to a traditional Sylvoz trellis at Sabbattini ending with a Casarsa system at the Robuschi site. At Robuschi, data collection is limited to 2018 as very severe hail damage prevented gathering reliable harvest data in 2019.

The minimum, mean, and maximum daily air temperature (°C) and daily rainfall (mm) from April 1 to September 30 were measured in each season by a nearby weather station.

Vigor mapping and soil sampling. A multispectral remote image was taken on 9 August 2018, using a satellite belonging to the RapidEye constellation and equipped with a 5 m ground resolution sensor. The NDVI index was consequently calculated and vigor maps built according to the ”equal area” algorithm applied by the engineering company Studio TerraDat (Paderno Dugnano, Italy) resulting in the breakdown of each parcel into three vigor classes corresponding to HV, MV, and LV (Figures 1 and 2). The 'equal area' criterion was preferred in maps segmentation due to its intrinsic ability to describe more effectively rapid and/or irregular changes in natural data and phenomena (Zhou et al. 2007). Absolute values of NDVI ranges for each parcel and vigor level are reported in the captions of Figures 1 and 2 for both the cultivars. The NDVI utilizes only two reflectance values, taken at the same time and for the same target area, according to the equation NDVI = $(\rho_{NIR} - \rho_R) / (\rho_{NIR} + \rho_R)$, where ρ is the spectral reflectance of the target and the subscripts NIR and R denote the near-infrared (760–850 nm) and the red (630–685 nm) satellite's spectral bands, respectively. The NDVI is a number ranging between -1 and +1 and quantifies the relative difference between the near-infrared reflectance ”peak” and the red reflectance ”trough” in the spectral signature. For the highly vegetated targets, the vigor level is high and the NDVI value is close to unity, while for the non-vegetated targets, the vigor level is low and the NDVI value is close to zero (negative values rarely occur in natural targets).

For each cultivar x farm x vigor level combination (2 x 3 x 4 to yield 18 cases in total), a soil sample down to 120 cm depth was taken with a Dutch auger in the central part of a given vigor area and the mid-row alley on June 26 and 27, 2019. Each sampling point was geolocalized according to standard Datum WGS, projection UTM, and fuse 32. Each soil observation was then classified based on the soil taxonomy

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to the family level (Soil Survey Staff 2014). Soil subsamples from 0–40 cm depth were then taken at ten different positions around six of the 18 drilled holes and then reunited in a single composed sample per position. These soil samples were then processed for standard chemical-physical analyses as reported in Table 1S.

Vine assessment. Each vigor zone was divided into three blocks. For each block x vigor combination four vines were randomly chosen (36 vines in total for each vineyard, 12 vines for each vigor class) to collect data for ground truthing assessment. Each season, at the time of harvest, cluster number, and yield per vine were recorded for each individually tagged vine and the mean cluster weight was calculated accordingly. At the time of winter pruning, the total cane number per vine was taken and cane fruitfulness was calculated. In November 2018, before performing winter pruning, the node number for every vine left on the two-year-old wood was taken and, after pruning, the same counting was made of the newly maintained spurs or canes.

Each season, the harvest was done when the Brix concentration in grapes was higher than 20 and 18 Ancellotta and Lambrusco Salamino, respectively. At that time, a 200 berry sample was taken from each tagged vine assuring that variability due to the cluster position within the plant and the berry position within the cluster were represented. After weighing the whole sample, a 50-berry subsample was used to measure the concentration of total anthocyanins and phenols after Iland (1988), and the final data were expressed as mg/g of fresh berry mass. The remainder of each whole sample was crushed and the resulting musts were immediately analyzed for Brix, pH, and titratable acidity (TA). Brix concentration was determined using a temperature-compensating refractometer (RX-5000 ATAGO U.S.A., Bellevue, WA), pH was assessed with a pH-meter CRISON GLP 22 (Crison, Barcelona, Spain), and TA was measured by titration with 0.1 N NaOH to a pH 8.2 endpoint and expressed as g/L of tartaric acid equivalents.

The quantification of organic acids was performed injecting musts into HPLC after filtering through a 0.22µm polypropylene filter. The identification was performed by external calibration with standards and concentration was calculated measuring the peak area and expressed in g/L. For this analysis, an Allure Organic Acid Column, 300 × 4.6 mm, 5µm (Restek, Bellefonte, PA) was used. The separation was performed in isocratic conditions using water, pH adjusted at 2.5 by adding ortho-phosphoric acid. The column temperature was maintained at 30 ± 0.1 °C, 15µl of the sample was injected. The elution was monitored at 200–700 nm and detected by UV–Vis absorption with DAD at 210 nm.

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When the leaf fall was completed, the total cane number per vine was taken and the fresh weight of the 1-year old wood was removed with pruning and recorded for both the main and lateral canes. Thereafter, the vine fruitfulness was calculated as the clusters/cane ratio, whereas the Ravaz index was calculated as the total yield-to-total pruning weight ratio (kg/kg).

Microvinifications. In two selected vineyards (LSSAB and ASAB2), 300 kg of grapes from HV and LV blocks were harvested each year to conduct microvinifications in triplicate of single 100 kg batches at the ASTRA laboratory (Tebano, Ravenna, Italy). After destemming and crushing, each batch was added with sulfur dioxide (50 mg/L), ammonium phosphate (180 mg/L of nitrogen), and a suitable trade strain (30 g/100 Kg). The samples were then placed in a thermo-conditioned room (15–20°C) for the fermentation/skin maceration phases and surveyed through the daily recording of the sugar content (Babo) and temperature (°C). At 8–9% of alcohol content, the maceration was followed by sieving the solid part (macerated peels and seeds) from the liquid phase (fermenting must). The raw wines were then racked at the end of the fermentation process and added with sulfur dioxide (100 mg/L), gelatine (10 g/100 Kg), and bentonite (40 g/100 Kg). The wines were then stored at -5°C for not less than 3 weeks to achieve tartaric stabilization. At the end of this phase, the stabilized wines were racked and newly added with sulfur dioxide up to the maximum legal limit of 150 mg/L. Finally, the wines were filtered using capsules of different materials and with different porosity of the membranes (up to 0.65 µm) to obtain a limpid/shiny product.

Statistical analysis. Data were analyzed by a two-way analysis of variance (ANOVA) using Sigma Stat 3.5 (Systat Software Inc., San Josè, CA). The comparison of treatments was performed by Student–Neuman–Keuls test at $P \leq 0.05$. Year × treatment interaction was partitioned only in the case of F test significance.

Results

The weather course registered over 2018 and 2019 (Figure S1) provided a good example of variability over years. The year 2018 was quite standard for the area with a total GDD of about 2,000 °C from April 1 to September 30, moderate cumulative rainfall (276 mm) over the same period, and a quite long, hot, and rainless period in summer until harvest. On the other hand, the year 2019 was un-seasonally cold and wet until the end of May. Several rainstorms occurred also during the summer providing a remarkable 542 mm of total precipitation between April 1 and September 30.

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Composite soil samples taken at 6 positions over different sites to represent either cultivar and vigor level variability showed that although soils sampled at Sabbattini had overall higher sand fraction than the other two sites, all of the samples shared features of no apparent limiting factors for root development, abundant organic matter, and adequate total nitrogen availability (Table S1). Table S2 has the details about soil horizon depths and the structures of eight out of 16 deep soil trenches that, at a preliminary visual assessment, showed some kind of variation along the vertical profile. Most notably, in both cultivars, the soil humidity status that was checked at the time of sampling indicated a humidity status closer to the 1 (dry) category in the LV plots, whereas, in the HV plots, it approximated the 2 (slightly humid) category with the status of “humid” (rank 3) scored at position 12 and a depth of 110–120 cm.

Despite large differences in retained bud load, cluster number and yield/ m of the row due to different pruning system (spur-pruned cordons vs. long hanging canes held on a Casarsa trellis), the different vigor zones mapped through NDVI calculation at Pignagnoli and Robuschi did not result in any significant difference in terms of pruning weight, yield components, and the Ravaz index (Table 2). At Pignagnoli, no significant year x vigor interactions occurred either. Despite the vigor results being quite well balanced across the two sites (PW ranged from 630 to 800 g/m of cordon length), the high node fruitfulness of Ancellotta explains tendentially high Ravaz index values.

A different scenario occurred at Sabbattini’s locations where, in parcel 1, NDVI corresponded with pruning weight that was significantly improved in the MV and HV treatments with both exceeding the 1.5 kg/m threshold. Interestingly though, some yield components followed a somewhat unrelated or inverse relationship, whereby the yield/m was not related to NDVI, and the cluster weight decreased linearly moving from LV to HV. Consequently, the Ravaz index was the highest in LV (8.36 kg/kg) and the lowest in HV (5.47 kg/kg).

At Sabbattini 2, a relationship between yield/m and NDVI was observed as in the HV vines the yield/m was 40% lower than the level in LV vines that was set at 5.64 kg/m (data averaged over the two seasons). The specific yield components involved in such a response were cane fruitfulness and, in turn, the cluster number/m that in HV was quite lower (31) than in MV and HV (44 and 46, respectively). Pruning weight did not vary with NDVI levels; however, a significant year x vigor interaction occurred for this variable (Figure 3) indicating that, in 2018, pruning weight of HV (1.4 kg/m) largely exceeded values recorded in MV and LV in both settings at about 1 kg/m. The Ravaz index variation also matched the mapped vigor levels as it ranged from a maximum of 6.45 kg/kg in LV to a minimum of 3.15 in HV (Table 2). In terms of year effects, it was quite evident that at the Sabbattini site, 2018 was a sort of a responsive season and 2019 a nonresponsive season.

Fruit composition variables vs NDVI based vigor levels at the different sites for the Ancellotta cultivar indicates that, in general and regardless of the specific location, causal relationships were higher in number and magnitude (Table 3) as compared to vegetative and yield variables.

At Pignagnoli, despite cane pruning weight and yield showing no apparent correlation with NDVI, LV vines had higher Brix, tartrate/malate ratio and phenols than HV, and conversely lower TA and malic acid. Overall, MV vines behaved quite similarly to HV vines. There were also significant year x vigor interactions for TA, pH, and malic acid (Figure 3), showing that while in the quite dry 2018 season (Figure S1) these variables had scant variation across vigor levels, in the overall cool and rainy 2019, HV vines retained considerably higher TA, and especially malic acid, as compared to both MV and LV.

Albeit limited to a single season (2018), the outcome from Robuschi's plot mirrored what was reported for Pignagnoli, as lack of any relationship between cane pruning weights and yield vs NDVI did not prevent LV vines from reaching better maturity than either MV or HV, including total anthocyanins (Table 3). Must composition at harvest at Sabbattini site 1 had an overall good correspondence with the higher cane pruning weights measured in HV plots. Although Brix was not significantly affected, HV had higher TA and malic acid, as well as lower total phenols than MV and LV. A quite similar response was seen at Sabbattini site 2 where, for data pooled over the two seasons, HV vines originated decidedly less mature grapes for most of the fruit ripening variables, including also total anthocyanins and phenols concentration. TA showed a significant year x vigor interaction, confirming that in the wet and cooler 2019, TA of HV stayed above the 12 g/L threshold (Table 3).

Despite large variability in bud load/m, cluster number/m, yield/m, and Ravaz index, in no case were there differences among NDVI-based vigor levels for vegetative and yield variables in the Lambrusco Salamino cultivar (Table S3). At Pignagnoli, must composition at harvest was somewhat more responsive to vigor levels, and interestingly, HV concurrently had higher TA and total anthocyanins than MV and LV (Table 4). Single-year data (2018) of must composition at harvest available at Robuschi did not indicate any consistent difference in ripening, whereas at Sabbattini differences were limited to lower Brix in HV vs MV and LV and a reduced tartrate/malate ratio, primarily driven by slightly higher malic acid retained in HV (Table 4).

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Final wines composition for grapes taken from Sabbattini vineyards and representative of LV and HV is reported in Table 5. The responsiveness of Ancellotta to the described intra-vineyard variability was confirmed, overall. In both vintages and regardless of the quite sharp differences in the weather course of each season, the true final alcohol content in LV was 1.22 and 1.56 Brix higher than that measured in HV vines, and most importantly, highly desirable traits such as total anthocyanins and color intensity were associated with lower vigor zones. Similar effects, although lower in magnitude, were seen for the wine variables of Lambrusco Salamino.

Discussion

NDVI interval calculated over different sites and cultivar was between 0.160 and 0.325, i.e. quite far from saturation. Similar to the case presented in Ledderhof et al. (2016) we have worked in vineyards having grassed interrows at the time of image acquisition and ground resolution used (5 m) indeed included both vine and soil pixels. Though, our NDVI ranges were very close to those calculated by the above authors on 3 x 3 m and 5 x 5 m resampled images that were also cleaned to isolate pure vine pixels only. Likely reason is that NDVI disturbance due to grassed inter-rows is high when the vineyard floor is covered with dense vegetation, whereas under our operational condition vegetation was quite weak with several yellow spots.

Over cultivars, out of seven tested vineyard plots, in only one case (Sabbattini 1 – Ancellotta) did NDVI based vigor levels reflect a significant variation in one-year-old pruning mass. This outcome feeds two possible hypotheses; either that “low”, “medium”, and “high” were overall representative of a scant whole plot variability, or conversely that pruning weight might not be sensitive enough to detect vigor differences.

About the first hypothesis, soil samples taken at different vigor plots showed, within each cultivar, mild variation in terms of texture, nutritional status, and chemical variables (Table S1). However, in both cultivars, soil profile investigated until 120 cm depth and classified for the status of the different horizons showed that, in HV plots, soils were slightly deeper and more humid at the time sampling was made, therefore potentially accounting for a somewhat different vine vegetative expression (Table S2).

With regard to pruning weight being a good predictor of vine vigor and/or vegetative capacity, older work (Bates 2008) has shown, in Concord, a close correlation between pruning weight and total leaf area. However, when it comes to the correlation between NDVI and pruning weight, the literature is anything but unanimous. Indeed, previous work showing a high correlation between NDVI levels and pruning weight has been reported (Gatti et al. 2017, 2018, Vélez et al. 2019), although somewhat opposite results were also published, showing poor correlation or no correlation (Ferrer et al. 2020, Ortega-Blu and Molina-Roco 2016), or other vegetative indices having higher correlation (i.e., trunk circumference as reported by Trought and Bramley (2011). It has also been proposed (Bramley et al. 2019) that reliability of a given vigor parameter might depend upon the pruning type and especially bud load. In theory, moving from a low to high bud load, the latter being representative of either mechanical or minimal pruning, due to the increasing number of either main and lateral canes, wood maturation might get worse, leading to significant self-pruning before the record of winter pruning is actually taken. An additional error is also caused by the fact that, quite typically, the removed pruning mass does not take into account shoot mass previously removed with trimming, which usually has a stronger impact in severely pruned training systems that are conducive to high vigor of individual shoots. However, such a rationale is not confirmed in our study, since the three chosen vineyards adopt different pruning systems covering a large variation either for pruning length (short in spur-pruned cordons and long in Sylvoz and Casarsa trellises) and bud load (Table 1). Moreover, in all the experimental sites considered as part of this study, canopy trimming was performed several times over the season, leading to a much more standardized canopy shape and volume at the end of the growing season, and especially at veraison when satellite imagery was acquired. According to Taylor et al. (2013) this evidence suggests that bigger differences in plant growth and vigor within the selected sites might be registered by mapping vineyards at different phenological phases, such as before fruit-set or before trimming. Though, it should also be considered that even a nadir NDVI determination performed at canopy growth completion on a VSP trellis still offers room to accommodate variation in vine size mostly due to canopy thickness and, depending upon degree of laterals emission after last trimming, colonization of some interrow spacing. Conversely, it is unlikely that variation is due to canopy function as the image targets to top canopy section representing also the youngest canopy part whose senescence process has not likely commenced yet.

On the other hand, despite pruning weight measurement being a quite straightforward procedure, it is time consuming, and it could also be that sample size is not adequate to represent whole block variability (Panten and Bramley 2012). The issue could be overcome by using on-the-go proximal imaging acquisition to estimate pruning weight (Kicherer et al. 2017, Millan et al. 2019) , for comparison with NDVI images taken at full canopy earlier the same season. Previous work (Taylor et al. 2013) had confirmed the

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soundness of this approach although it was apparent that proximal sensing focused on the supporting wire of the trellis led to saturation problems which diminished when the target was a canopy area featuring still growing shoots.

A quite peculiar aspect of our work when considering the response of Ancellotta was that, though the NDVI derived vigor levels had, with few exceptions, poor correlation with either pruning weight or yield, the overall grape composition response was, regardless of training systems, pruning type, and bud load, in favor of the low vigor status. In fact in LV, Brix, malic acid, tartaric/malate ratio, total anthocyanins and phenols in all cases showed a relative change in terms of "improved" ripening as compared to HV (i.e., higher TSS, color, phenols, and tartare/malate ratio and lower malic), and in 18 cases out of 20 paired comparisons (4 locations x 5 variables), such difference was significant. Pooling Ancellotta data over different locations revealed that, to promote maturity, the Ravaz index should stay around 9-10 kg/kg and pruning weight should not exceed 1 kg/m of cordon length.

However, the response observed on LV- Ancellotta is quite different from that of other studies where low vigor was likewise associated with enhanced maturity. This has been reported for several conditions and varieties, including for Barbera (Ferrer et al. 2020, Gatti et al. 2018, Kotsaki et al. 2020, Song et al. 2014), although in these studies low vigor also paralleled considerably lower yield. Our data show that—in terms of grand means over sites—LV- Ancellotta had a yield of 7.47 ± 1.19 kg/m vs. 6.91 ± 1.05 kg/m and 5.98 ± 1.15 in MV and HV, respectively. These data look extremely promising for local growers, especially in terms of the economic sustainability of a precision approach; improving maturity under no change, or even a slight increase in yield, is a very desirable outcome and represents a very good example of how intra-vineyard variability could be profitably exploited. No doubt the growing and ripening features of Ancellotta would favor such a response: Ancellotta has been demonstrated to be a quite flexible genotype in terms of variation of fruit composition variables vs. increasing yield: yield vs Brix were not correlated ($R^2 = 0.02$) despite yield/m ranging between 3.4 and 9.6 kg/m, and the same applied to the relationship of yield/m vs total anthocyanins ($R^2 = 0.02$).

The batch of data gathered on Ancellotta also sheds light on the usefulness of ground truthing for a vigor level defined as "high" on an NDVI mapping assessment. Expected agronomic responses to "high" vigor combine with higher yield and delayed or incomplete ripening, as several previous studies have shown in detail (Gatti et al. 2017, King et al. 2014, Ledderhof et al. 2017, Song et al. 2014); however, the literature also reports cases where high vigor achieved the best quality. This happened, for instance, in a

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remote sensing application to a Riesling vineyard in the Niagara Peninsula (Marciniak 2015), where vines with higher NDVI during average-to-dry years had enhanced fruit maturity (higher Brix and lower TA). Similarly, in the hot climate of la Rioja Region (Bonilla et al. 2015), a four-year survey on NDVI-based mapping in a Tempranillo vineyard showed that berry pigmentation was consistently enhanced under HV, likely as a result of better microclimate conditions for color accumulation (Mori et al. 2007). The response of HV Ancellotta vines observed in our study, though, still seems different from the two reported ones. While it was ascertained that NDVI based high vigor led to inferior grape composition, the same high vigor was decoupled from a yield response, and the highest yield levels were found on low vigor vines. This behavior was seen at both Sabbattini sites, albeit under two probably different mechanisms; in Sabbattini 1 the inverse relationship between NDVI based vigor level and cluster weight suggests, on a two-year basis, that cluster weight was limited by lower fruit-set due to competition exerted by excessive vegetative growth (May 2004) at either MV or HV. Indirect confirmation is that neither shoot fruitfulness nor berry weight was affected by vigor, and calculated berry numbers/clusters varied from a maximum of 128 in LV to a minimum of 93 berries/cluster in HV. At the other Sabbattini site, a different mechanism is envisaged to involve a likely biannual bearing pattern. In the year 2018, which had the features of a responsive year in terms of yield, bud initiation conditions were likely less favorable due to a competitive vigorous growth in HV (PW at 1.42 kg/m, Figure 3), that resulted in a lower actual shoot fruitfulness the next season (Table 3).

Despite vineyard design and cultural practices not being changed as a function of cultivar, overall Lambrusco Salamino response to intra-vineyard variability was mild, and differences were much less at both grape and wine compositional levels. The hypothesis that can be made to explain such differential behavior hints at its different agronomic traits and the role that Lambrusco Salamino is expected to play in a Lambrusco wine type. Lambrusco Salamino is historically considered the “yield” builder in such a context, and older Lambrusco Salamino vineyards trained to the traditional Raggi Bellussi system or the more recently introduced GDC quite easily reach 40 t/ha (Intrieri and Poni 1995). In the specific context of our study, Lambrusco Salamino vine balance assessed over different sites and vigor levels was quite different from Ancellotta; vigor is overall lower (0.65-0.70 kg/m range), the yield is much higher (9.4-10.3 kg/m range), and remarkably, Ravaz index is astonishingly constant around 18 kg/kg, suggesting a sort of permanent over-cropping status. Under such high crop load status, it is also probable that vines are less responsive to any factor that is able to alter vigor. Lambrusco Salamino proved to be extremely insensitive in terms of Brix response vs yield, showing essentially no change within the interval of 6.9 – 14.1 kg/m (R^2 = 0.06).

Data need to be discussed also in terms of modifications to vineyard management that the Lambrusco district could consider in light of the presented results. Due to the responsiveness of Ancellotta in terms of the capacity of low vigor plots to improve either grape or wine composition without altering or even slightly increasing yield, such an attitude should be exploited and managed. While the target is not to exceed 1 kg/ PW/m of cordon length, a step forward would be to estimate pending pruning weight through a proximal sensing approach (Millan et al. 2019) that could quickly estimate PW amounts at the ground level. On a more general basis, confirming previous work done on Barbera vineyards of limited size (Gatti et al. 2017), the 5m ground resolution granted by RapidEye image acquisition seems anyway accurate enough to detect intra-vineyard variability, confirming what has been previously shown in studies comparing acquisition platforms at varying ground resolution (Breunig et al. 2020, Matese et al. 2015, Pádua et al. 2020, Sozzi et al. 2020). In this study, the reliability of the RapidEye images might have benefitted from the fact that at the timing that images were captured mid rows in all cases were grassed, thereby minimizing the interference of mixels where soil contribution is significant.

Conclusions

NDVI based vigor mapping conducted, for two seasons, in three sites encompassing two cultivars (Ancellotta and Lambrusco Salamino) and different pruning systems showed higher responsiveness by the highly colored Ancellotta than the Lambrusco Salamino, marked by very high yield/m and Ravaz index levels. The behavior observed in the “low vigor” Ancellotta plots allows foreseeing a vast improvement in vineyard efficiency, as enhanced grape and wine composition was achieved without any significant change in yield, which rather manifested an increasing trend. Ancellotta is currently grown across an area of about 4,100 ha and producers are many, quite small in size, mostly delivering their grapes to large cooperative wineries. This seems an ideal condition for running a large-scale mid-resolution satellite image acquisition and then quickly confirming, through proximal sensing aimed at providing an almost real-time estimation of pruning weight, areas where urgent correction of unbalanced vigor is needed.

Conversely, Lambrusco Salamino, despite being grown in nearby parcels and trained to the same training system, did not show significant vine performance differences across different NDVI based vigor

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levels, proving that ground truthing remains a necessary procedure to assess convenience for intra-vineyard variability exploitation or correction.

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Table 1 Main vineyards features of each farm with specification of soil management (SM), irrigation system (if present) and day of harvest for each season (2018 and 2019).

Farm	Vineyard code	Grape variety	Training system	In-the row and between row vine spacing (m)	Mid-row SM	Within-row SM	Irrigation system	Geographic coordinates	Area (ha)	Day of harvest (2018)	Day of harvest (2019)
Sabbattini	ASAB1	Ancellotta	Sylvoz	1.60 x 3.00	native grass	herbicides	not present	44°47'34.91" N 10° 48' 2.19" E	0.7	14.09	24.09
	ASAB2	Ancellotta	Sylvoz	1.60 x 2.50	native grass	herbicides	not present	44° 47' 35.07" N 10° 47' 21.21" E	0.4	13.09	24.09
	LSSAB	Lambrusco Salamino	Sylvoz	1.60 x 3.00	native grass	herbicides	not present	44° 47' 35.85" N 10° 48' 2.19" E	0.9	13.09	27.09
Pignagnoli	APIGN	Ancellotta	Spur-pruned cordon	1.25 x 3.00	native grass	herbicides + tillage	not present	44° 50' 22.09" N 10° 46' 21.05" E	1.2	06.09	13.09
	LSPIGN	Lambrusco Salamino	Spur-pruned cordon	1.25 x 3.00	native grass	herbicides + tillage	not present	44° 50' 22.09" N 10° 46' 21.05" E	1.3	14.09	25.09
Robuschi	AROB	Ancellotta	Casarsa	1.50 x 2.85	native grass with tillage in autumn	herbicides	sub-irrigation	44° 48' 31.36" N 10° 48' 0.26" E	1.1	14.09	-
	LSROB	Lambrusco Salamino	Casarsa	1.50 x 2.85	native grass with tillage in autumn	herbicides	sub-irrigation	44° 48' 30.83" N 10° 44' 9.71" E	1.0	25.09	-

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Table 2 Pruning weight (PW), yield components, shoot fruitfulness and yield-to-pruning weight ratio (Ravaz index as kg/kg) measured in 2018-2019 seasons on twelve vines of Ancellotta in the three identified vigor classes (HV = high; MV = medium and LV = low) at Pignagnoli, Robuschi and Sabbattini vineyards.

		Pignagnoli (APIGN)								Robuschi (AROB)							
		PW (kg/m)	**Nodes (n/m)**	**Yield (kg/m)**	**Clusters (n/m)**	**Cluster weight (g)**	**Berry weight (g)**	**Fruitfulness (clusters/ shoot)**	**Ravaz index (kg/kg)**	**PW (kg/m)**	**Nodes (n/m)**	**Yield (kg/m)**	**Clusters (n/m)**	**Cluster weight (g)**	**Berry weight (g)**	**Fruitfulness (clusters/ shoot)**	**Ravaz index (kg/kg)**
Vigor (V)	LV	0.70	13	5.18	28	179	1.51	1.9	9.0	0.73	40	9.58	92	107	1.53	2.6	13.8
	MV	0.80	12	5.19	26	191	1.55	1.9	7.9	0.63	43	8.65	83	104	1.57	2.5	14.6
	HV	0.79	14	4.68	27	170	1.45	1.9	6.5	0.77	39	7.82	84	94	1.53	2.6	10.6
Year (Y)	2018	0.92	13	3.49	23	154	1.45	1.7	4.1	0.70	41	8.58	85	101	1.55	2.6	13.1
	2019	0.61	13	6.55	32	206	1.56	2.2	11.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	V	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
	Y	***	ns	***	***	***	**	***	***	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	V x Y	ns	ns	ns	ns	ns	ns	ns	ns	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Sabbattini 1 (ASAB1)								Sabbattini 2 (ASAB2)							
		PW (kg/m)	**Nodes (n/m)**	**Yield (kg/m)**	**Clusters (n/m)**	**Cluster weight (g)**	**Berry weight (g)**	**Fruitfulness (clusters/ shoot)**	**Ravaz index (kg/kg)**	**PW (kg/m)**	**Nodes (n/m)**	**Yield (kg/m)**	**Clusters (n/m)**	**Cluster weight (g)**	**Berry weight (g)**	**Fruitfulness (clusters/ shoot)**	**Ravaz index (kg/kg)**
Vigor (V)	LV	1.24b	28b	9.50	54	183 a	1.43b	2.4	8.4a	0.94	29	5.64a	46a	119	1.49a	2.4	6.4a
	MV	1.51a	29b	8.81	57	160 b	1.55a	2.3	6.0b	0.98	27	4.99a	44a	110	1.46a	2.5	5.2b
	HV	1.59a	33a	8.05	58	139 c	1.50ab	2.4	5.5b	1.15	29	3.38b	31b	111	1.38b	1.8	3.1c
Year (Y)	2018	1.54	26	11.40	77	148	1.59	3.5	7.8	1.13	24	6.47	53	129	1.52	3.2	6.6
	2019	1.35	34	6.17	36	173	1.40	1.3	5.4	0.92	32	2.87	29	98	1.36	1.3	3.3
	V	*	*	ns	ns	*	*	ns	***	ns	ns	***	**	ns	**	*	***
	Y	ns	***	***	***	***	***	***	**	**	***	***	***	***	ns	***	***
	V x Y	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns

In case of significance of F test, mean separation within columns and year factor was performed using the Student-Newman Keuls (SNK) test or t-test, respectively:* $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant.

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Table 3 Grape composition ad total soluble solids (TSS), titratable acidity (TA), pH, tartaric and malic acid concentration, total anthocyanins and phenols comcentration, measured at 2018-2019 harvests on twelve vines of Ancellotta in each of the three identified vigor classes (HV = high; MV = medium and LV = low) at Pignagnoli, Robuschi and Sabbattini vineyards. T/M = tartrate-to-malate concentration ratio.

		Pignagnoli (APIGN)								Robuschi (AROB)							
		TSS (Brix)	**TA (g/L)**	**pH**	**Tartrate (g/L)**	**Malate (g/L)**	**T/M ratio**	**Anth. (g/kg)**	**Phenols (g/kg)**	**TSS (Brix)**	**TA (g/L)**	**pH**	**Tartrate (g/L)**	**Malate (g/L)**	**T/M ratio**	**Anth. (g/kg)**	**Phenols (g/kg)**
Vigor (V)	LV	21.19a	8.02b	3.34	9.08	3.65c	2.92a	2.32	3.27a	21.41a	6.21b	3.38a	8.54b	2.66b	3.21a	2.62a	3.68a
	MV	20.43b	7.94b	3.38	8.66	4.38b	2.37b	2.09	2.90b	19.71b	6.87a	3.40b	9.67a	3.54a	2.78b	2.11b	3.17b
	HV	19.74b	9.46a	3.36	8.15	6.14a	1.85c	2.02	2.78b	19.98b	7.13a	3.30b	8.45b	3.71a	2.34b	2.56a	3.25b
Year (Y)	2018	22.26	6.61	3.47	9.16	2.83	3.37	3.06	4.22	20.18	6.81	3.31	9.01	3.41	2.73	2.27	3.32
	2019	18.65	10.33	3.25	8.10	6.62	1.38	1.23	1.74	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	V	**	***	ns	ns	***	***	ns	**	*	*	*	*	*	***	*	*
	Y	***	***	***	***	***	***	***	***	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	V x Y	ns	**	***	ns	***	ns	ns	ns	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

		Sabbattini 1 (ASAB1)								Sabbattini 2 (ASAB2)							
		TSS (Brix)	**TA (g/L)**	**pH**	**Tartrate (g/L)**	**Malate (g/L)**	**T/M ratio**	**Anth. (g/kg)**	**Phenols (g/kg)**	**TSS (Brix)**	**TA (g/L)**	**pH**	**Tartrate (g/L)**	**Malate (g/L)**	**T/M ratio**	**Anth. (g/kg)**	**Phenols (g/kg)**
Vigor (V)	LV	20.33	7.00c	3.42a	7.70	3.20b	3.43a	2.37	3.61a	20.76a	7.40c	3.40	7.95	2.86c	3.06a	2.94a	4.15ab
	MV	20.27	7.70b	3.43a	8.23	3.60b	2.71b	2.32	3.60a	20.76a	8.94b	3.40	8.54	3.95b	2.40b	2.56a	4.36a
	HV	19.68	8.75a	3.37b	8.80	4.22a	2.46b	2.07	3.17b	19.31b	10.42a	3.44	7.97	5.46a	1.64c	2.16b	3.69b
Year (Y)	2018	21.19	6.40	3.48	8.20	2.21	3.94	2.51	3.47	20.98	7.34	3.45	9.67	3.72	3.08	2.60	4.07
	2019	19.00	9.23	3.33	8.96	5.14	180	2.00	3.45	19.57	10.21	3.47	6.63	4.46	1.65	2.21	4.07
	V	ns	***	*	ns	***	***	ns	*	***	***	ns	ns	*	***	*	*
	Y	***	***	***	*	***	***	***	ns	***	***	***	***	***	***	**	ns
	V x Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns

In case of significance of F test, mean separation within columns and year factor was performed using the Student-Newman Keuls (SNK) test or t-test, respectively:* $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant.

Table 4 Grape composition as total soluble solids (TSS), titratable acidity (TA), pH, tartaric and malic acid concentration, total anthocyanins and phenols concentration, measured at 2018-2019 harvests on twelve vines of Lambrusco Salamino in each of the three identified vigor classes (HV = high; MV = medium and LV = low) at Pignagnoli, Robuschi and Sabbattini vineyards.

Pignagnoli (LSPIGN)

		TSS (Brix)	TA (g/L)	pH	Tartrate (g/L)	Malate (g/L)	T/M ratio	Anth. (g/kg)	Phenols (g/kg)
Vigor	LV	18.23	10.54b	3.19a	9.64	6.10b	1.71a	1.30b	4.30
	MV	18.65	10.92b	3.17a	10.39	7.03ab	1.61a	1.34b	4.17
	HV	19.07	11.94a	3.13b	9.83	7.61a	1.34b	1.65a	4.55
Year	2018	19.66	9.03	3.26	10.32	5.79	188	1.44	4.50
	2019	17.63	13.24	3.06	9.59	8.04	1.22	1.41	4.18
	V	ns	*	*	ns	*	**	**	ns
	Y	***	***	***	ns	***	***	ns	ns
	V x Y	ns	ns	ns	ns	ns	ns	ns	ns

Robuschi (LSROB)

		TSS (Brix)	TA (g/L)	pH	Tartrate (g/L)	Malate (g/L)	T/M ratio	Anth. (g/kg)	Phenols (g/kg)
Vigor	LV	19.44	9.98	3.01	9.17	5.58	1.67	1.22	3.44
	MV	18.60	10.19	3.04	8.79	5.98	1.50	1.04	3.21
	HV	18.36	10.13	3.00	9.70	6.00	1.64	1.08	3.29
Year	2018	18.78	10.09	3.01	9.32	5.85	1.62	1.12	3.32
	2019	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	V	ns	ns	ns	ns	ns	ns	ns	ns
	Y	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	V x Y	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Sabbattini (LSSAB)

		TSS (Brix)	TA (g/L)	pH	Tartrate (g/L)	Malate (g/L)	T/M ratio	Anth. (g/kg)	Phenols (g/kg)
Vigor	LV	18.30a	12.73	3.06	10.42	9.04	1.29a	1.32	3.57
	MV	18.14a	13.68	3.08	10.54	9.66	1.14ab	1.32	3.60
	HV	17.42b	13.35	3.06	10.59	10.29	1.08b	1.28	3.49
Year	2018	18.65	10.88	3.08	10.21	7.41	1.41	1.31	3.31
	2019	17.26	15.62	3.06	10.83	11.92	0.94	1.31	3.79
	V	*	ns	ns	ns	ns	**	ns	ns
	Y	***	***	ns	ns	***	***	ns	**
	V x Y	ns	ns	ns	ns	ns	ns	ns	ns

In case of significance of F test, mean separation within columns and year factor was performed using the Student-Newman Keuls (SNK) test.:* $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant.

Table 5 Composition of experimental wines derived from grapes harvested in high vigor (HV) and low vigor (LV) plots at LSSAB and ASAB2 in 2018-2019 seasons. Within row, year and vigor level, significance of paired comparison was assessed by t-test at P ≤ 0.04 (n=3).

	Ancellotta				Lambrusco Salamino			
	2018		2019		2018		2019	
Parameters	**LV**	**HV**	**LV**	**HV**	**LV**	**HV**	**LV**	**HV**
Total alcohol (vol%)	12.36a	11.14b	10.84a	9.30b	10.42a	9.70b	9.11	8.53
Total sugars (g/L)	1.33	1.40	2.71	2.77	1.35a	1.10b	1.65	1.58
Total dry extract (g/L)	33.10	34.55	32.47	31.25	29.75	27.25	31.40	32.45
pH	3.94b	4.09a	3.86b	4.01a	3.60	3.64	3.37b	3.44a
Total acidity (g/L)	4.48a	3.91b	5.38a	4.20b	6.34	6.80	9.41	9.80
Volatile acidity (g/L)	0.42)	0.46	0.23b	0.54a	0.25	0.24	0.19	0.24
Tartaric acid (g/L)	1.31b	1.58a	1.43b	1.70a	1.77	1.62	1.90a	1.56b
Malic acid (g/L)	0.38b	0.55a	1.26a	0.54b	2.23b	3.32a	5.69b	6.70°
Lactic acid (g/L)	3.83	4.11	4.33	3.92	<0.2	<0.2	0.10	0.19
Citric acid (g/L)	0.42a	<0.1b	0.22a	0.08b	0.59	0.65	0.68	0.74
Phenols (mg/L)	4457a	3584b	3150a	2642b	3647a	3359b	1998a	1753b
Anthocyanins (mg/L)	705a	556b	664a	531b	323a	263b	330	312
OD 420 nm	7.00a	5.05b	4.92a	3.01b	3.26a	2.59b	2.12	1.73
OD 520 nm	10.58a	6.54b	8.45a	4.19b	5.39a	4.01b)	4.64	3.39
Intensity	17.58a	11.59b	13.37a	7.20b)	8.64a	6.60b	6.75	5.12
Tonality	0.67	0.77	0.59	0.72	0.61	0.65	0.46	0.51

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Supplemental Table 1 Main physico-chemical soil features of vineyards in high and low vigor areas of each farm. Numbers in brackets are the code of soil sample as reported in Figures 1 and 2 and the corresponding vigor level.

		Ancellotta			Lambrusco Salamino		
		APIGN (13 - LV)	**AROB** (3-HV)	**ASAB2** (17 - MV)	**LSPIGN** (12 - HV)	**LSROB** (4 - LV)	**LSSAB** (7 - HV)
Sand	**%**	16	19	43	20	12	42
Silt	**%**	44	39	30	54	42	35
Clay	**%**	40	42	27	26	46	23
Texture		silty clay loam	clay	loam	silty loam	silty clay	loam
pH		7.90	7.7	7.90	7.80	7.6	7.8
Electrical conductivity	**mS/cm**	0.24	0.30	0.24	0.26	0.34	0.23
Total carbonate	**%**	15.80	10.60	15.10	16.40	12.00	17.00
Active carbonate	**%**	9.80	8.30	5.80	9.50	8.80	4.80
Organic matter	**%**	2.94	3.76	2.87	2.94	4.59	2.68
Total nitrogen	**%**	0.15	0.20	0.15	0.16	0.23	0.14
Phosphorus (ass)	**mg/L**	65	19.00	20	44	32	32
Iron (ass.)	**mg/L**	16.20	21.00	7.00	18.20	19.20	22.2
Manganese (ass.)	**mg/L**	13.80	11.40	7.8	13.60	13.40	6.40
Copper (ass.)	**mg/L**	32.20	35.80	60.60	50.20	63.20	52.80
Zinc	**mg/L**	3.20	4.40	6.00	4.40	9.6	7.00
Calcium	**mg/L**	3950	4300	3050	3850	4300	3350
Magnesium	**mg/L**	320	420	200	340	560	176
Potassium	**mg/L**	420	420	360	440	640	320
Sodium	**mg/L**	82	54	66	72	56	48
C.E.C./100 g	**meq**	23.85	26.30	18.13	23.52	28.05	19.25
Calcium	**%**	82.80	81.70	84.10	81.90	76.70	87.00
Magnesium	**%**	11.20	13.30	9.20	12.00	16.60	7.60
Potassium	**%**	4.50	4.10	5.10	4.80	5.80	4.30
Sodium	**%**	1.50	0.90	1.60	1.30	0.90	1.10
B.C.S.R.	**%**	100	100	100	100	100	100

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Supplemental Table 2 Main features of most representative soil profiles for high vigor (HV) vs low vigor (LV) levels and grapevine cultivar. Soil profiles are described following the methodologies used by the Regional Soil Agency (Tarocco 2002).

Vigor class	Cultivar	Drilling code	Soil horizons[a]	Depth of horizon layers (cm)	Humidity[b]	Main color[c]	Oxigen availability
HV	Ancellotta	1	Ap1	0-40	1	2.5 YR 5/2	Moderate
			Ap2	40-70	2	2.5 YR 5/2	
			Bk1	70-110	2	2.5 YR 5/3	
			Bk2	110-120	2	2.5 YR 5/3	
		16	Ap1	0-40	1	2.5YR 4/3	Good
			Ap2	40-85	1	2.5YR 4/3	
			Bw	85-110	2	2.5YR 5/4	
			Bk	110-120	2	2.5YR 5/3	
	Lambrusco Salamino	6	Ap	0-50	2	2.5 YR 5/2	Moderate
			Bw	50-95	2	2.5 YR 5/2	
			Bk	95-120	2	2.5 YR 5/2	
		12	Ap1	0-40	1	2.5YR 4/3	Moderate
			Ap2	40-85	2	2.5YR 4/3	
			Bw	85-110	2	2.5YR 5/3	
			Bg	110-120	3	2.5YR 5/2	
LV	Ancellotta	13	Ap1	0-40	1	2.5YR 4/3	Moderate
			Ap2	40-75	2	2.5YR 4/3	
			Bk1	75-110	2	2.5YR 5/3	
			Bk2	110-120	1	2.5YR 5/3	
		18	Ap	0-40	1	2.5YR 4/3	Good
			Bk	40-70	1	2.5YR 4/4	
	Lambrusco Salamino	9	Ap	0-40	1	2.5YR 5/3	Good
			Bw1	40-90	1	2.5YR 5/4	
			Bw2	90-120	1	2.5YR 5/4	
		11	Ap	0-50	1	2.5YR 4/3	Moderate
			Bw	50-105	2	2.5YR 4/3	
			Bl	105-110	2	2.5YR 5/4	

[a]Soil horizons are described according to Word Reference Base (WRB) international standard for soil classification (Soil Survey Staff 2014) ;[b] 1= dry; 2= slightly humid; 3=humid; 4=strongly humid; 5=wet (no free water); 6=wet (free water) (Tarocco 2002); [c] colors classified according to Munsell Color System (Munsell 1915).

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Supplemental Table 3 Pruning weight (PW), yield components, shoot fruitfulness and yield-to-pruning weight ratio (Ravaz index as kg/kg) measured in 2018-2019 seasons on twelve vines of Lambusco Salamino in each of the three identified vigor classes (HV = high; MV = medium and LV = low) at Pignagnoli, Robuschi and Sabbattini vineyards.

Pignagnoli (LSPIGN)

		PW (kg/m)	**Nodes (n/m)**	**Yield (kg/m)**	**Clusters (n/m)**	**Cluster weight (g)**	**Berry weight (g)**	**Fruitfulness (clusters/ shoot)**	**Ravaz index (kg/kg)**
Vigor (V)	LV	0.53	14a	6.91	31	237	1.69	2.3b	15.3
	MV	0.66	10b	7.25	34	226	1.68	2.8ab	14.0
	HV	0.62	9b	6.97	34	220	1.68	3.0a	12.4
Year (	2018	0.75	8	8.34	25	275	1.76	2.6	9.5
	2019	0.46	14	9.27	41	180	1.60	2.7	18.3
	V	ns	***	ns	ns	ns	ns	*	ns
	Y	**	***	*	***	***	***	ns	***
	V x Y	ns	***	ns	ns	ns	ns	ns	ns

Robuschi (LSROB)

		PW (kg/m)	**Nodes (n/m)**	**Yield (kg/m)**	**Clusters (n/m)**	**Cluster weight (g)**	**Berry weight (g)**	**Fruitfulness (clusters/ shoots)**	**Ravaz index (kg/kg)**
Vigor (V)	LV	0.46	46	13.18	111	120	1.63	2.9	30.6
	MV	0.39	45	14.13	117	123	1.54	3.4	37.5
	HV	0.46	45	13.32	118	113	1.57	3.2	30.2
Year (	2018	0.44	45	13.45	116	118	1.58	3.13	32.0
	2019	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	V	ns	ns	ns	ns	ns	ns	ns	ns
	Y	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	V x Y	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Sabbattini (LSSAB)

		PW (kg/m)	**Nodes (n°/m)**	**Yield (kg/m)**	**Clusters (n/m)**	**Cluster weight (g)**	**Berry weight (g)**	**Fruitfulness (clusters/ shoots)**	**Ravaz index (kg/kg)**
Vigor (V)	LV	1.04	26	8.17	50	173	1.63	2.4	9.6
	MV	1.08	27	9.40	56	173	1.60	2.5	9.6
	HV	1.07	28	8.79	57	157	1.61	2.4	10.2
Year (	2018	0.88	24	13.45	83	162	1.66	3.7	16.1
	2019	1.24	30	4.12	26	174	1.57	1.1	3.5
	V	ns	ns	ns	ns	ns	ns	ns	ns
	Y	***	**	***	***	ns	*	***	***
	V x Y	ns	ns	ns	ns	ns	ns	ns	ns

In case of significance of F test, mean separation within columns and year factor was performed using the Student-Newman Keuls (SNK) test or t-test, respectively:* $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant.

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Figure 1 Maps of normalized difference vegetation index (NDVI) derived from the multispectral images taken on 9 August 2018 by the RapidEye constellation in Ancellotta vineyards (**A**) PIGN, (**B**) ROB, (**C**) SAB1, and (**D**) SAB2. Colors indicate different vigor levels: green corresponds to high vigor (HV), yellow corresponds to medium vigor (MV), and red is for low vigor (LV). Absolute values (min/max) of NDVI for each class are: (**A**) LV: 0.215/ 0.239; MV: 0.239/0.263; HV: 0.263/0.286; (**B**) LV: 0.221/0.238; MV: 0.238/0.255; HV: 0.255/0.272; (**C**) LV: 0.239/0.251; MV: 0.251/0.263; HV: 0.263/0.276; (**D**) LV: 0.261/0.281; MV: 0.281/0.301; HV: 0.301/0.322. The white triangles (Δ) on the maps indicate the spots where only deep soil drilling was carried out, whereas light blue dots (●) indicate the areas where both deep soil drilling and composite soil sampling were done. Soil samples were not taken in SAB1 (**C**).

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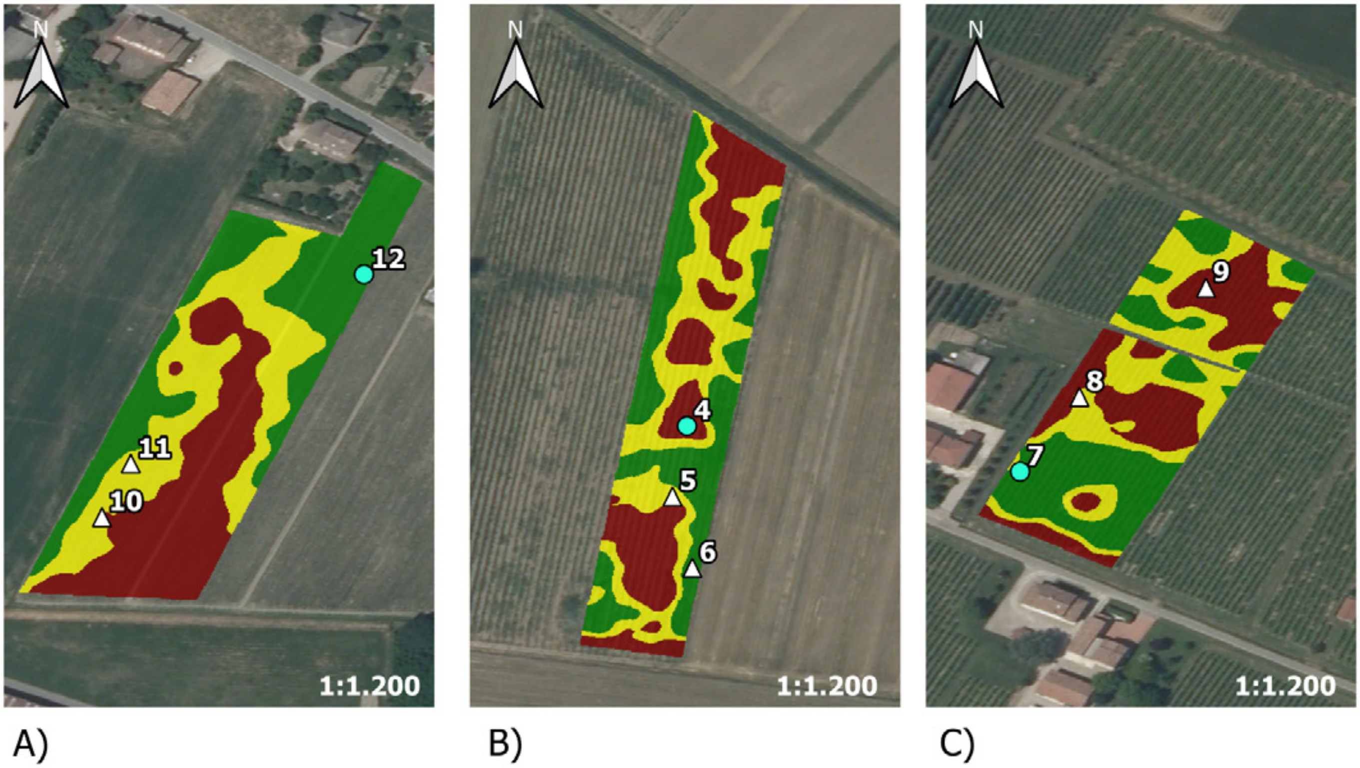

Figure 2 Maps of normalized difference vegetation index (NDVI) derived from the multispectral images taken on 9 August 2018 by the RapidEye constellation in Lambrusco Salamino (LS) vineyards (**A**) PIGN, (**B**) ROB, (**C**) SAB1, and (D) SAB2. Colors indicate different vigor levels: green corresponds to high vigor (HV), yellow corresponds to medium vigor (MV), and red is for low vigor (LV). Absolute values (min/max) of NDVI for each class area) (**A**) LV: 0.160/0.188; MV: 0.188/0.216; HV: 0.216/0.244; (**B**) LV: 0.215/0.225; MV: 0.225/0.235; HV: 0.235/0.246; (**C**) LV: 0.226/0.238; MV: 0.238/0.249; HV: 0.249/0.261. The white triangles (Δ) on the maps indicate the spots where only deep soil drilling was done, whereas light blue dots (●) indicate the areas where both deep soil drilling and composite soil sampling were carried out.

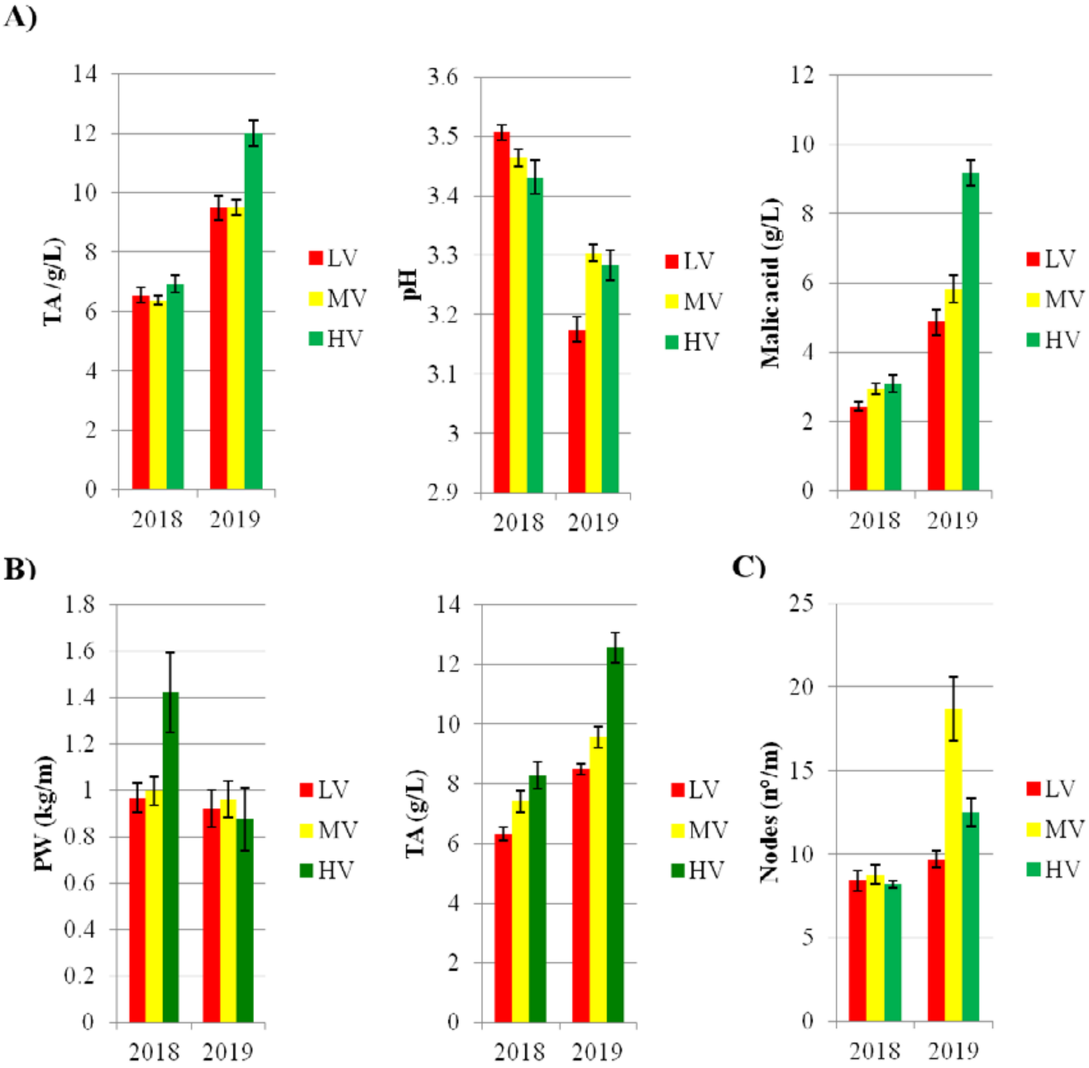

Figure 3 Partitioning of interactive vigor x year (V x Y) effects found at Pignagnoli for TA, pH, and malic acid of Ancellotta (**A**); at Sabbattini for PW and TA of Ancellotta (**B**); and at Pignagnoli for nodes/m in the "Lambrusco Salamino" vineyard (**C**). Histograms represent means (n = 12) of each treatment combination ± standard error for each vigor class (HV = high vigor, MV = medium vigor, and LV = low vigor).

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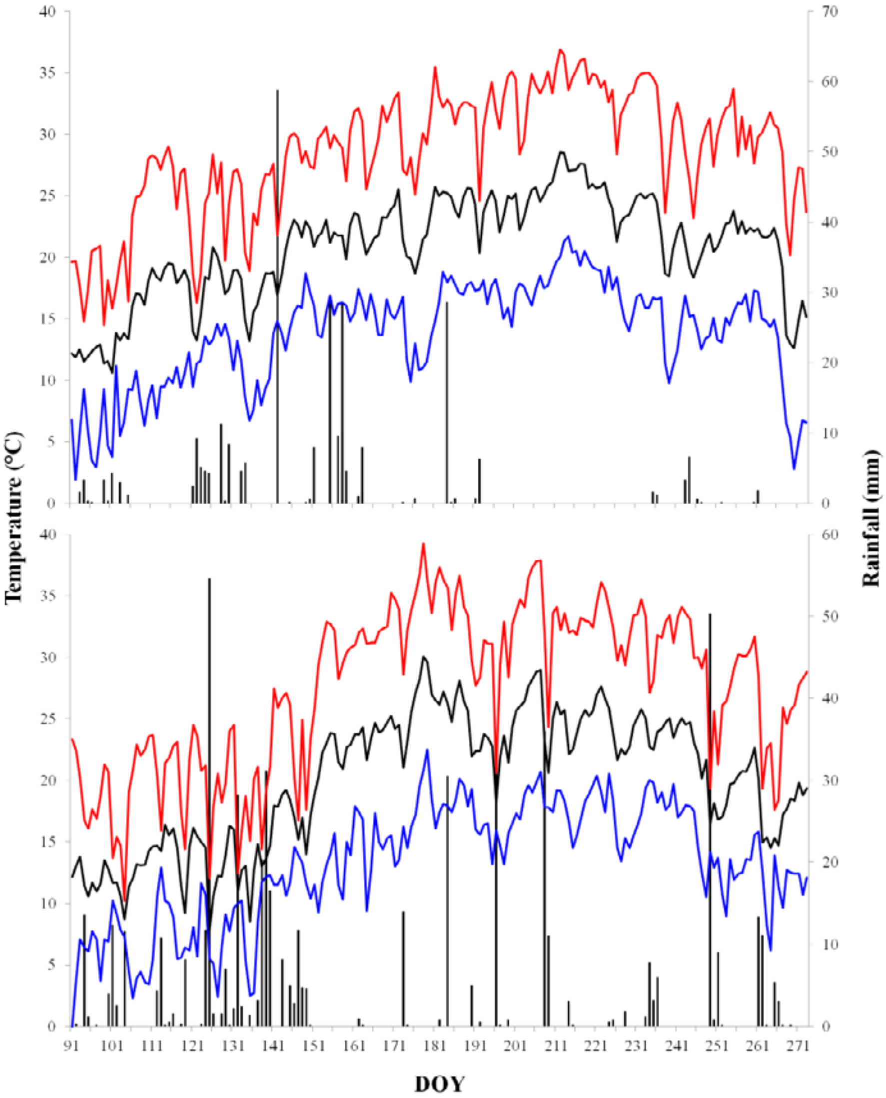

Supplemental Figure 1 Weather trends recorded at Correggio (Reggio Emilia) a nearby weather station to the experimental logged to the Emilia Romagna weather monitoring network) in 2018 (top panel) and 2019 (bottom panel) from April to September (DOY = Day of Year from 01/04 to 30/09). Data are daily maximum temperature (red line), daily mean temperature (black line), daily minimum temperature (blue line) and daily rainfall (black bars). In the considered period cumulated Growing Degree Days (GDD) were 19828 and 1836 in 2018 and 2019 , respectively , whereas while cumulated rainfall (mm) was 277 in 2018 and 542 in 2019.