The High-Yielding Lambrusco (*Vitis vinifera* L.) Grapevine District Can Benefit from Precision Viticulture

Cecilia Squeri,[1] Irene Diti,[1] Irene Pauline Rodschinka,[1] Stefano Poni,[1]* Paolo Dosso,[2] Carla Scotti,[3] and Matteo Gatti[1]

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. Because of 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 Aug 2018 led to vigor maps based on unfiltered normalized difference vegetation index (NDVI). In both 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 NDVI-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 +0.44 mg/kg, respectively), and lower malate (-1.79 g/L) versus 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 intravineyard variability. This study highlights that in Ancellotta, adjusting the vine balance toward ostensible lower 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 affected by the yield level which, in fact, increased in some cases.

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

The essence of applying precision agriculture is that it takes into account in-field variability (McBratney et al. 2005, Schieffer and Dillon 2015, 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 toward 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 red-green-blue (RGB), 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 agricultural applications (Matese et al. 2015, Maes and Steppe 2019). 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 intraparcel variability for several reasons: 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 mesoclimate variations and soil heterogeneity; ii) variability in vigor is

favored by the plasticity of the species, which because of 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, intravineyard 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 physicochemical features affecting water holding capacity, water infiltration rates, 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 grapegrowers of the Emilia-Romagna Region (A. Ulrici, personal communication, 2020) and the collection of 353 responses to a submitted questionnaire, have 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 and/or 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. An example of this 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 (PW) of 498 g/m of cordon length for the high vigor (HV) plots that, indeed, according to literature (Smart 1985, Kliewer and Dokoozlian 2005) 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 PW per meter. This assumption gains support also from a four-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 with 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 intravineyard 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 toward 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 because of the interference of several factors such as ground resolution, modalities of image acquisition (i.e., zenital versus 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 ~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 hotel-restaurant-catering (HORECA, also "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 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 intravineyard 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 because of their high acreage (4635 and 4085 ha for Lambrusco Salamino and Ancellotta, respectively). Ancellotta and Lambrusco Salamino nicely complement each other in the "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 because 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 1 April to 30 Sept were measured in each season by a nearby weather station.

Vigor mapping and soil sampling. A multispectral remote image was taken on 9 Aug 2018 using a satellite belonging to the RapidEye constellation and equipped with a 5 m ground resolution sensor. The NDVI index was then calculated and vigor maps built according to the "equal area" algorithm applied by the engineering company Studio TerraDat, resulting in the breakdown of each parcel into three vigor classes corresponding to HV, medium vigor (MV), and LV (Figures 1 and 2). The equal area criterion was preferred in map segmentation because of 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 Ancellotta and Lambrusco Salamino cultivars. The NDVI uses 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 to 850 nm) and the red (630 to 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 nonvegetated targets, the vigor level is low and the NDVI value is close to zero (negative values rarely occur in natural targets).

For each cultivar × farm × vigor level combination (2 × 3 × 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 midrow alley on 26 and 27 June 2019. Each sampling point was geolocalized according to standard Datum World Geodetic System, projection Universal Transverse Mercator, and fuse 32. Each soil observation was then classified based on the soil taxonomy to the family level (Soil Survey Staff 2014). Soil subsamples from 0 to 40 cm depth were then taken at 10 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 Supplemental Table 1.

Vine assessment. Each vigor zone was divided into three blocks. For each block × 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, 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 total soluble solids (TSS) concentration in grapes was higher than 20 and 18 in 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 were crushed and the resulting musts were immediately analyzed for TSS, pH, and titratable acidity (TA). TSS concentration was determined using a temperature-compensating refractometer (RX-5000, ATAGO U.S.A., Inc.), pH was assessed with a pH-meter CRISON GLP 22

Table 1 Main vineyard 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)	Midrow SM	Within-row SM	Irrigation system	Geographic coordinates	Area (ha)	Day of harvest (2018)	Day of harvest (2019)
Sabbattini	ASAB1	Ancellotta	Sylvoz	1.60 × 3.00	native grass	herbicides	not present	44°47′N; 10°48′E	0.7	14 Sept	24 Sept
	ASAB2	Ancellotta	Sylvoz	1.60 × 2.50	native grass	herbicides	not present	44°47′N; 10°47′E	0.4	13 Sept	24 Sept
	LSSAB	Lambrusco Salamino	Sylvoz	1.60 × 3.00	native grass	herbicides	not present	44°47′N; 10°48′E	0.9	13 Sept	27 Sept
Pignagnoli	APIGN	Ancellotta	Spur-pruned cordon	1.25 × 3.00	native grass	herbicides + tillage	not present	44°50′N; 10°46′E	1.2	06 Sept	13 Sept
	LSPIGN	Lambrusco Salamino	Spur-pruned cordon	1.25 × 3.00	native grass	herbicides + tillage	not present	44°50′N; 10°46′E	1.3	14 Sept	25 Sept
Robuschi	AROB	Ancellotta	Casarsa	1.50 × 2.85	native grass with tillage in autumn	herbicides	sub-irrigation	44°48′N; 10°48′E	1.1	14 Sept	–
	LSROB	Lambrusco Salamino	Casarsa	1.50 x 2.85	native grass with tillage in autumn	herbicides	sub-irrigation	44°48′N; 10°44′E	1.0	25 Sept	–

(Crison), 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 high-performance liquid chromatography (HPLC) after filtering through a 0.22 µm polypropylene filter. The identification was performed by external calibration with standards, and concentration was calculated by measuring the peak area and expressed in g/L. For this analysis, an Allure Organic Acid Column, 300 × 4.6 mm, 5 µm (Restek Corporation) was used. The separation was performed in isocratic conditions using water, and the pH adjusted at 2.5 by adding orthophosphoric acid. The column temperature was maintained at 30 ± 0.1°C, and 15 µL of the sample was injected. The elution was monitored at 200 to 700 nm and detected by UV-vis absorption with diode array detector at 210 nm.

When the leaf fall was completed, the total cane number per vine was taken and the fresh weight of the one-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-to-cane ratio, whereas the Ravaz index was calculated as the yield-to-total PW 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. After destemming and crushing, sulfur dioxide (50 mg/L), ammonium phosphate (180 mg/L of nitrogen), and a suitable trade strain (30 g/100 kg) were added to each batch. The samples were then placed in a thermo-conditioned room (15 to 20°C) for the fermentation/skin maceration phases and surveyed through the daily recording of the sugar content (Babo) and temperature (°C). At 8 to 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 SO_2 (100 mg/L), gelatin (10 g/100 kg), and bentonite (40 g/100 kg). The wines were then stored at -5°C for no less than three weeks to achieve tartaric stabilization. At the end of this phase, the stabilized wines were racked and newly added with SO_2 up to the maximum legal
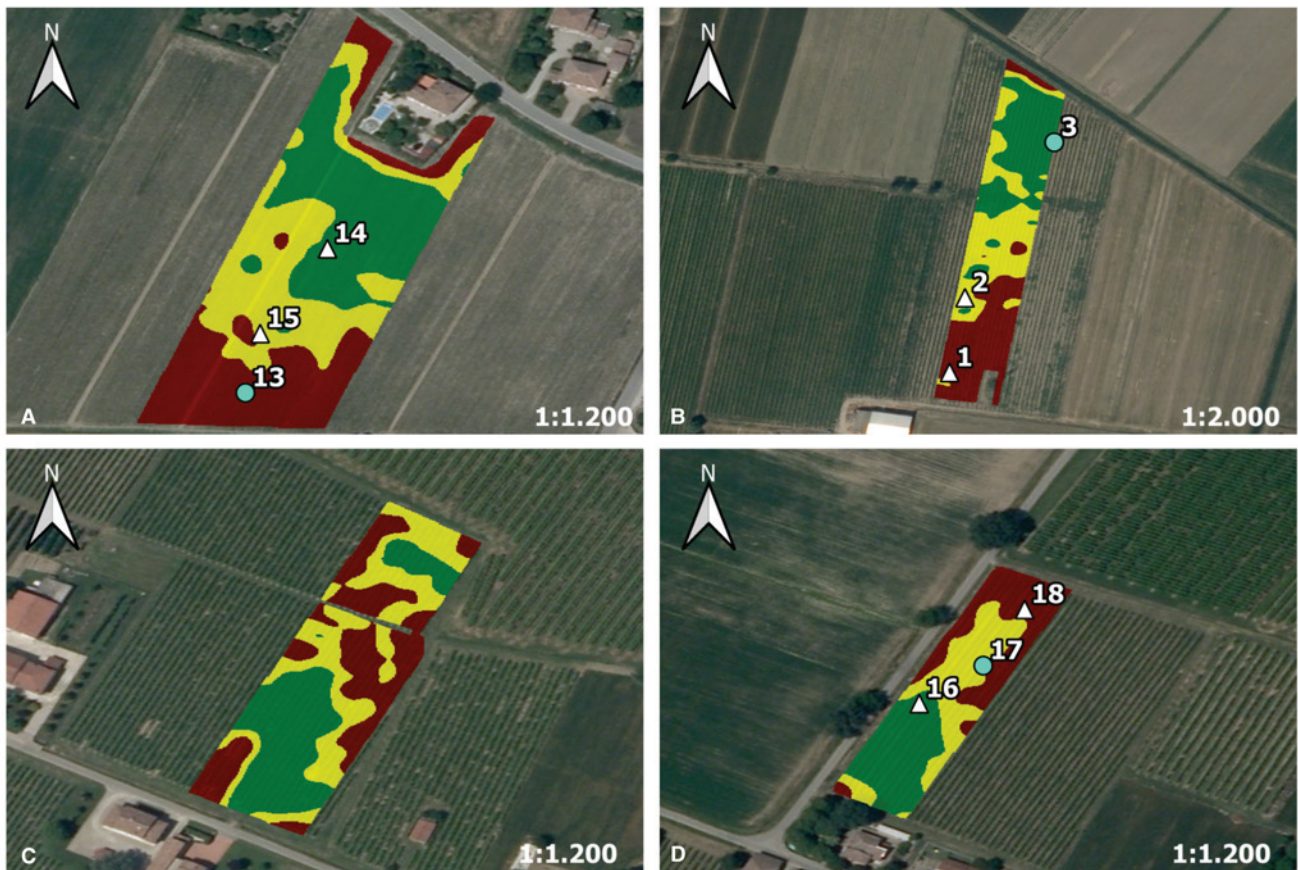
Figure 1 Maps of normalized difference vegetation index (NDVI) derived from the multispectral images taken on 9 Aug 2018 by the RapidEye constellation of satellites in Ancellotta vineyards (**A**) PIGN, (**B**) ROB, (**C**) SAB1, and (**D**) SAB2. Colors indicate different vigor levels: green corresponds 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 (△) 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**).

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 and shiny product.

Statistical analysis. Data were analyzed by a two-way analysis of variance using Sigma Stat 3.5 (Systat Software Inc.). 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 patterns registered over 2018 and 2019 (Supplemental Figure 1) provided a good example of variability over years. The year 2018 was quite standard for the area with total growing degree days (GDD) of ~2000°C from 1 April to 30 Sept, 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 unseasonably cold and wet until the end of May. Several rainstorms occurred also during the summer providing a remarkable 542 mm of total precipitation between 1 April and 30 Sept.

Composite soil samples taken at six 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 (Supplemental Table 1). Supplemental Table 2 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 to 120 cm.

Despite large differences in retained bud load, cluster number, and yield/m of the row because of different pruning systems (spur-pruned cordons versus 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 PW, yield components, and the Ravaz index (Table 2). At Pignagnoli, no significant year × 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 the high Ravaz index values.

A different scenario occurred at Sabbattini's locations where in parcel 1, NDVI corresponded with PW 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
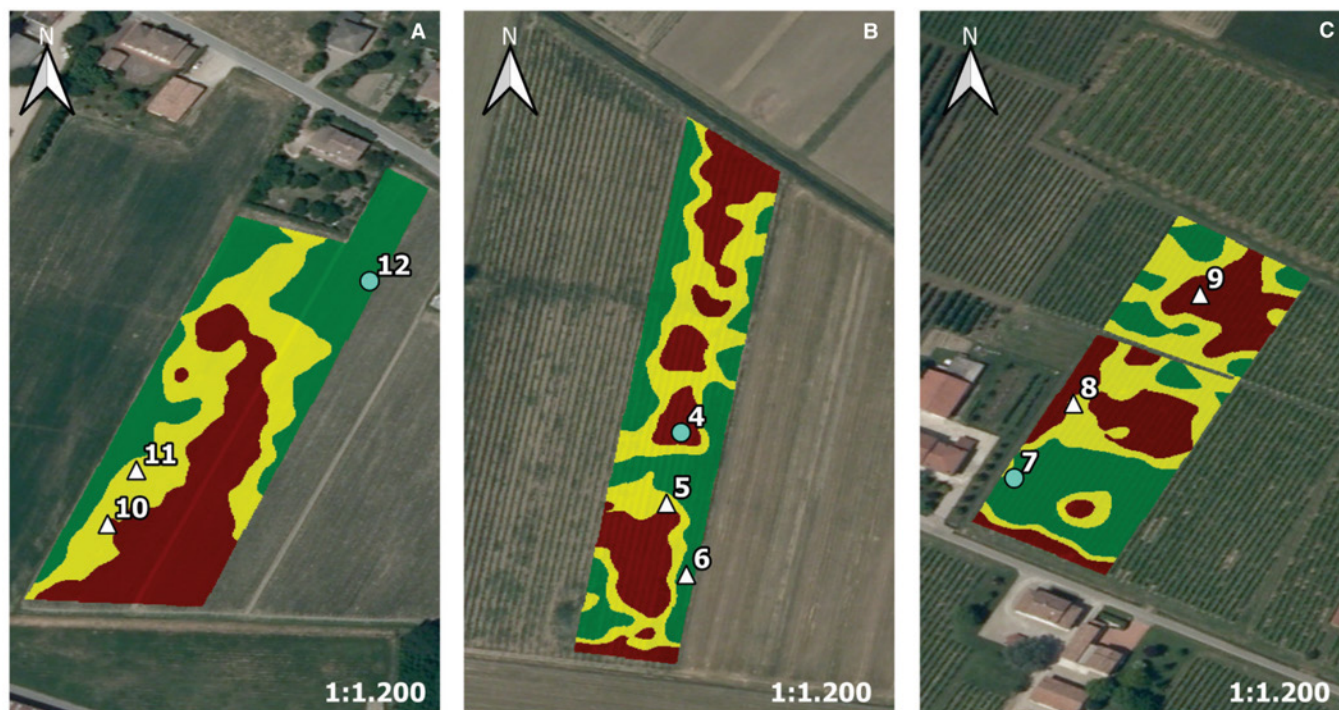
Figure 2 Maps of normalized difference vegetation index (NDVI) derived from the multispectral images taken on 9 Aug 2018 by the RapidEye constellation of satellites in Lambrusco Salamino (LS) vineyards (**A**) PIGN, (**B**) ROB, and (**C**) SAB1. Colors indicate different vigor levels: green corresponds 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: 0.160/0.188; 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 (△) 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.

Table 2 Pruning weight (PW), yield components, shoot fruitfulness, and yield-to-PW ratio (Ravaz index as kg/kg) measured in the 2018 to 2019 seasons on 12 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 wt (g)	Berry wt (g)	Fruitfulness (clusters/shoot)	Ravaz index (kg/kg)	PW (kg/m)	Nodes (n/m)	Yield (kg/m)	Clusters (n/m)	Cluster wt (g)	Berry wt (g)	Fruitfulness (clusters/shoot)	Ravaz index (kg/kg)
Vigor (V)[a]																
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)[a]																
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 × 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 wt (g)	Berry wt (g)	Fruitfulness (clusters/shoot)	Ravaz index (kg/kg)	PW (kg/m)	Nodes (n/m)	Yield (kg/m)	Clusters (n/m)	Cluster wt (g)	Berry wt (g)	Fruitfulness (clusters/shoot)	Ravaz index (kg/kg)
Vigor (V)[a]																
LV	1.24 b[b]	28 b	9.50	54	183 a	1.43 b	2.4	8.4 a	0.94	29	5.64 a	46 a	119	1.49 a	2.4	6.4 a
MV	1.51 a	29 b	8.81	57	160 b	1.55 a	2.3	6.0 b	0.98	27	4.99 a	44 a	110	1.46 a	2.5	5.2 b
HV	1.59 a	33 a	8.05	58	139 c	1.50 ab	2.4	5.5 b	1.15	29	3.38 b	31 b	111	1.38 b	1.8	3.1 c
Year (Y)[a]																
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 × Y	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	***

[a] In case of significance of F test, mean separation within columns and year factor was performed using the Student-Newman-Keuls test or t-test, respectively. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant; NA: not available.
[b] Different lowercase letters indicate pair-wise mean differences.

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, and 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 per meter (number/m) that in HV was quite lower (31) than in MV and HV (44 and 46, respectively). PW did not vary with NDVI levels; however, a significant year × vigor interaction occurred for this variable (Figure 3) indicating that in 2018, PW of HV (1.4 kg/m) largely exceeded values recorded in MV and LV in both settings at ~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 kg/kg in HV (Table 2). In terms of year effects, it was quite evident that at the Sabbattini site, 2018 was a responsive season and 2019 a nonresponsive season.

Fruit composition variables versus 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 PW and yield showing no apparent correlation with NDVI, LV vines had higher TSS, tartrate-to-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 × vigor interactions for TA, pH, and malic acid (Figure 3), showing that while in the quite dry 2018 season (Supplemental Figure 1) 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, because a lack of any relationship between cane PWs and yield versus 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 PWs measured

in HV plots. Although TSS 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, which also included total anthocyanins and phenols concentration. TA showed a significant year × 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 (Supplemental Table 3). 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 TSS in HV versus MV and

LV, and a reduced tartrate-to-malate ratio, primarily driven by slightly higher malic acid retained in HV (Table 4).

Final wine 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) included both vine and soil pixels. Although our NDVI
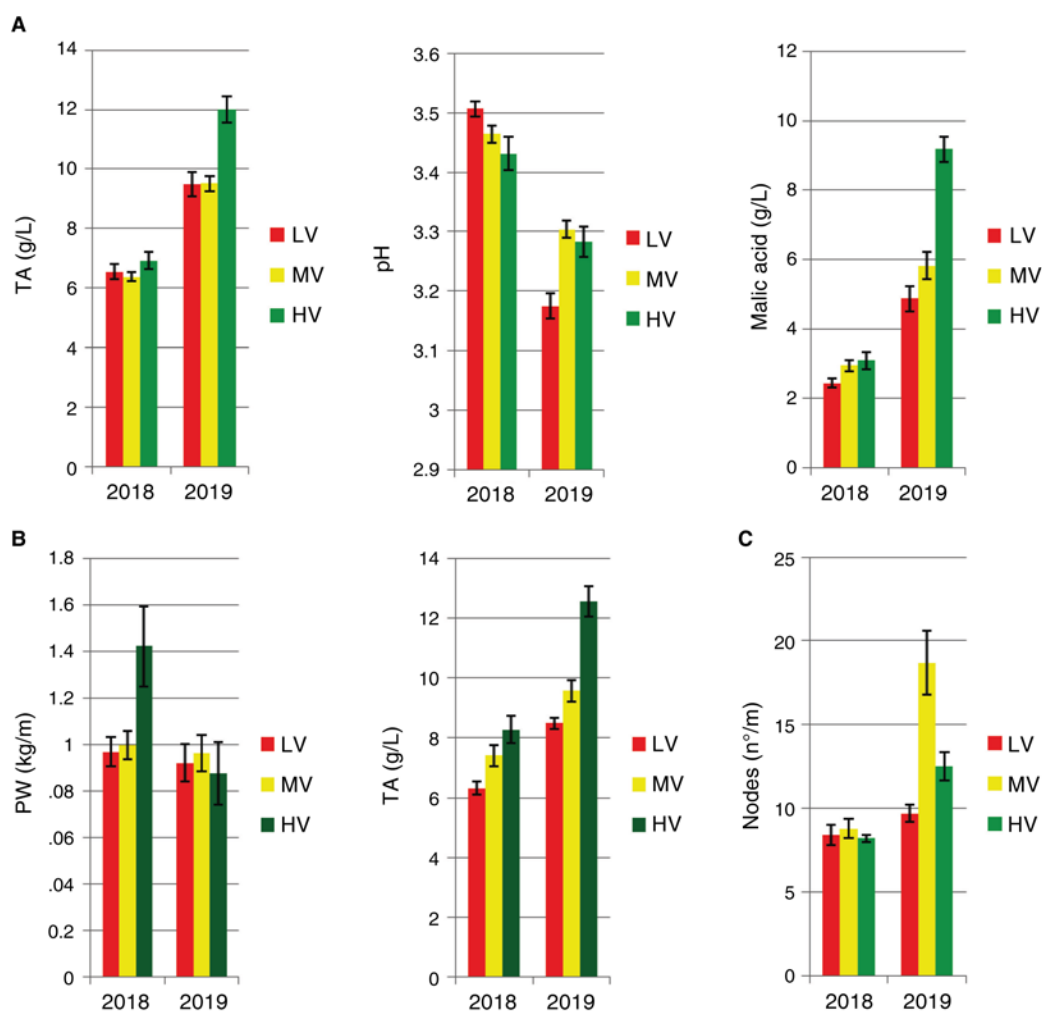
Figure 3 Partitioning of interactive vigor × year (V × Y) effects found (**A**) at Pignagnoli for titratable acidity (TA), pH, and malic acid of Ancellotta; (**B**) at Sabbattini for pruning weight (PW) and TA of Ancellotta; and (**C**) at Pignagnoli for nodes/m in the "Lambrusco Salamino" vineyard. 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).

Table 3 Grape composition as total soluble solids (TSS), titratable acidity (TA), pH, tartaric and malic acid concentration, total anthocyanins, and phenols concentration, measured at 2018 to 2019 harvests on 12 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)[a]																
LV	21.19 a[b]	8.02 b	3.34	9.08	3.65 c	2.92 a	2.32	3.27 a	21.41 b	6.21 b	3.38 a	8.54 b	2.66 b	3.21 a	2.62 a	3.68 a
MV	20.43 b	7.94 b	3.38	8.66	4.38 b	2.37 b	2.09	2.90 b	19.71 b	6.87 a	3.40 b	9.67 a	3.54 a	2.78 b	2.11 b	3.17 b
HV	19.74 b	9.46 a	3.36	8.15	6.14 a	1.85 c	2.02	2.78 b	19.98 b	7.13 a	3.30 b	8.45 b	3.71 a	2.34 b	2.56 a	3.25 b
Year (Y)[a]																
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 × 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)[a]																
LV	20.33	7.00 c	3.42 a	7.70	3.20 b	3.43 a	2.37	3.61 a	20.76 a	7.40 c	3.40	7.95	2.86 c	3.06 a	2.94 a	4.15 ab
MV	20.27	7.70 b	3.43 a	8.23	3.60 b	2.71 b	2.32	3.60 a	20.76 a	8.94 b	3.40	8.54	3.95 b	2.40 b	2.56 a	4.36 a
HV	19.68	8.75 a	3.37 b	8.80	4.22 a	2.46 b	2.07	3.17 b	19.31 b	10.42 a	3.44	7.97	5.46 a	1.64 c	2.16 b	3.69 b
Year (Y)[a]																
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	***	***	***	ns
Y	***	***	***	*	***	***	***	ns	***	***	***	*	*	***	**	ns
V × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	*	***	ns	ns

[a]In case of significance of F test, mean separation within columns and year factor was performed using the Student-Newman-Keuls test or t-test, respectively. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant; NA: not available.
[b]Different lowercase letters indicate pair-wise mean differences.

ranges were very close to those calculated by the above authors, 3 × 3 m and 5 × 5 m resampled images were also cleaned to isolate pure vine pixels only. The likely reason is that NDVI disturbance because of grassed interrows 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: i) either that "low," "medium," and "high" were overall representative of a scant whole-plot variability, or conversely that (ii) PW might not be sensitive enough to detect vigor differences.

Regarding 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 (Supplemental Table 1). However, in both cultivars, analysis of different soil horizons until 120 cm depth 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 (Supplemental Table 2).

With regard to PW being a good predictor of vine vigor and/or vegetative capacity, previous work (Bates 2008) has shown a close correlation between PW and total leaf area in Concord. However, when it comes to the correlation between NDVI and PW, the literature is anything but unanimous. Indeed, previous work showing a high correlation between NDVI levels and PW 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 (Ortega-Blu and Molina-Roco 2016, Ferrer et al. 2020), 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 on 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; this usually has a stronger effect in severely pruned training systems that are conducive to high vigor of individual shoots. However, such a rationale is not confirmed in our study because the three chosen vineyards adopted 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 because of 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 because the image includes only the top, hence the youngest, canopy section, whose senescence process has not likely yet commenced.

On the other hand, despite PW 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 PW (Kicherer et al. 2017, Millan et al. 2019) for comparison with NDVI images taken at full canopy earlier

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 to 2019 harvests on 12 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. T/M = tartrate-to-malate concentration ratio.

	TSS (Brix)	TA (g/L)	pH	Tartrate (g/L)	Malate (g/L)	T/M ratio	Anth. (g/kg)	Phenols (g/kg)
Pignagnoli (LSPIGN)								
Vigor (V)[a]								
LV	18.23	10.54 b[b]	3.19 a	9.64	6.10 b	1.71 a	1.30 b	4.30
MV	18.65	10.92 b	3.17 a	10.39	7.03 ab	1.61 a	1.34 b	4.17
HV	19.07	11.94 a	3.13 b	9.83	7.61 a	1.34 b	1.65 a	4.55
Year (Y)[a]								
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 × Y	ns	ns	ns	ns	ns	ns	ns	ns
Robuschi (LSROB)								
Vigor (V)[a]								
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 (Y)[a]								
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 × Y	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sabbattini (LSSAB)								
Vigor (V)[a]								
LV	18.30 a	12.73	3.06	10.42	9.04	1.29 a	1.32	3.57
MV	18.14 a	13.68	3.08	10.54	9.66	1.14 ab	1.32	3.60
HV	17.42 b	13.35	3.06	10.59	10.29	1.08 b	1.28	3.49
Year (Y)[a]								
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 × Y	ns	ns	ns	ns	ns	ns	ns	ns

[a]In case of significance of F test, mean separation within columns and year factor was performed using the Student-Newman-Keuls test or t-test, respectively. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant; NA: not available.
[b]Different lowercase letters indicate pair-wise mean differences.

the same season. Previous work (Taylor et al. 2013) had confirmed the soundness of this approach, although it was apparent that proximal sensing focused on the supporting wire trellis that led to saturation problems, which diminished when the target was a canopy area featuring still-growing shoots.

A very peculiar aspect of our work when considering the response of Ancellotta was that although the NDVI-derived vigor levels had, with few exceptions, poor correlation with either PW 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, all cases of LV, TSS, malic acid, tartrate-to-malate ratio, total anthocyanins, and phenols showed a relative change in terms of "improved" ripening as compared to HV (i.e., higher TSS, color, phenols, and tartrate-to-malate ratio and lower malic acid), and in 18 cases out of 20 paired comparisons (4 locations × 5 variables), such difference was significant. Pooling Ancellotta data over different locations revealed that to promote maturity the Ravaz index should stay ~9 to 10 kg/kg and PW 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 (Song et al. 2014, Gatti et al. 2018, Ferrer et al. 2020, Kotsaki et al. 2020), 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 versus 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 intravineyard 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 versus increasing yield: yield versus TSS 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 versus 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 (King et al. 2014, Song et al. 2014, Gatti et al. 2017, Ledderhof et al. 2017); however, the literature also reports cases where high vigor achieved the best quality. This happened, for instance, in a 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 TSS 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

Table 5 Composition of experimental wines derived from grapes harvested in high vigor (HV) and low vigor (LV) plots at LSSAB and ASAB2 in the 2018 to 2019 seasons. Within row, year, and vigor level, significance of paired comparison was assessed by t-test at $p \leq 0.05$ (n = 3). OD, optical density.

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

[a]The significance of paired comparison was assessed by t-test at $p \leq 0.05$ (n = 3), shown as different lowercase letters.

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 because of 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 Sabbattini 2, a different mechanism is envisaged to involve a likely biannual bearing pattern. In 2018, which had the features of a responsive year in terms of yield, bud initiation conditions were likely less favorable because of a competitive vigorous growth in HV (PW at 1.42 kg/m, Figure 3), which 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 intravineyard 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 Geneva Double Curtain, 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 to 0.70 kg/m range), the yield is much higher (9.4 to 10.3 kg/m range), and remarkably, Ravaz index is astonishingly constant ~18 kg/kg, suggesting a sort of permanent overcropping status. Under such high crop load status, it is also probable that vines are less responsive to any factor able to alter vigor. Lambrusco Salamino proved to be extremely insensitive in terms of TSS response versus yield, showing essentially no change within the interval of 6.9 to 14.1 kg/m ($r^2 = 0.06$).

Data need to be discussed also in terms of modifications to vineyard management, which the Lambrusco district could consider in light of the presented results. Because of 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 PW through a proximal sensing approach (Millan et al. 2019), which 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 5 m ground resolution granted by RapidEye image acquisition seems accurate enough to detect intravineyard variability, confirming what has been previously shown in studies comparing acquisition platforms at varying ground resolution (Matese et al. 2015, Breunig et al. 2020, Pádua et al. 2020, Sozzi et al. 2020). In this study, the reliability of the RapidEye images might have benefited from the fact that at the time the images were captured, midrows in all cases were grassed, thereby minimizing the interference of mixels where soil contribution is significant.

Conclusions

For two seasons, NDVI-based vigor mapping was conducted in three sites encompassing two cultivars (Ancellotta and Lambrusco Salamino) and different pruning systems. The vigor mapping showed higher responsiveness by the highly colored Ancellotta than the Lambrusco Salamino, as indicated by very high yield/m and Ravaz index levels. The behavior observed in the "low-vigor" Ancellotta plots allows improvement in vineyard efficiency, as enhanced grape and wine composition was achieved without any significant change in yield, which manifested an increasing trend. Ancellotta is currently grown across an area of ~4100 ha and while there are many producers, they are quite small in size, mostly delivering their grapes to large cooperative wineries. This seems an ideal condition for running a large-scale midresolution satellite image acquisition and then quickly confirming, through proximal sensing aimed at providing an almost real-time estimation of PW, 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 levels, proving that ground truthing remains a necessary procedure to assess convenience for intravineyard variability exploitation or correction.

Literature Cited

Bates T. 2008. Pruning level affects growth and yield of New York Concord on two training systems. Am J Enol Vitic 59:276-286.

Bonilla I, de Toda FM and Martínez-Casasnovas JA. 2015. Vine vigor, yield and grape quality assessment by airborne remote sensing over three years: Analysis of unexpected relationships in cv. Tempranillo. Span J Agric Res 13:e0903.

Bramley RGV. 2010. Precision Viticulture: Managing vineyard variability for improved quality outcomes. *In* Managing Wine Quality: Viticulture and Wine Quality. Reynolds AG (ed.), pp. 445-480. Woodhead Publishing Limited, Cambridge.

Bramley RGV, Proffitt APB, Hinze CJ, Pearse B and Hamilton RP. 2005. Generating benefits from precision viticulture through selective harvesting. *In* Precision Agriculture 2005, 5th European Conference on Precision Agriculture.JV Stafford (ed.), pp. 891-898. Wageningen Academic Publishers, Netherlands.

Bramley RGV, Ouzman J, Trought MCT, Neal SM and Bennett JS. 2019. Spatio-temporal variability in vine vigour and yield in a Marlborough Sauvignon Blanc vineyard. Aust J Grape Wine Res 25:430-438.

Breunig FM, Galvão LS, Dalagnol R, Santi AL, Della Flora DP and Chen S. 2020. Assessing the effect of spatial resolution on the delineation of management zones for smallholder farming in southern Brazil. Remote Sensing Applications: Society and Environment 19:100325.

Ferrer M, Echeverría G, Pereyra G, Gonzalez-Neves G, Pan D and Mirás-Avalos JM. 2020. Mapping vineyard vigor using airborne remote sensing: Relations with yield, berry composition and sanitary status under humid climate conditions. Precis Agric 21:178-197.

Fiorillo E, Crisci A, De Filippis T, Di Gennaro SF, Di Blasi S, Matese A, Primicerio J, Vaccari FP and Genesio L. 2012. Airborne high-resolution images for grape classification: Changes in correlation between technological and late maturity in a Sangiovese vineyard in Central Italy. Aust J Grape Wine Res 18:80-90.

Gatti M, Garavani A, Vercesi A and Poni S. 2017. Ground-truthing of remotely sensed within-field variability in a cv. Barbera plot for improving vineyard management. Aust J Grape Wine Res 23:399-408.

Gatti M, Squeri C, Garavani A, Vercesi A, Dosso P, Diti I and Poni S. 2018. Effects of variable rate nitrogen application on cv. Barbera performance: Vegetative growth and leaf nutritional status. Am J Enol Vitic 69:196-209.

Gatti M, Schippa M, Garavani A, Squeri C, Frioni T, Dosso P and Poni S. 2020. High potential of variable rate fertilization combined with a controlled released nitrogen form at affecting cv. Barbera vines behavior. Eur J Agron 112:125949.

Hall A, Lamb DW, Holzapfel B and Louis J. 2002. Optical remote sensing applications in viticulture – A review. Aust J Grape Wine Res 8:36-47.

Iland PG. 1988. Leaf removal effects on fruit composition. *In* Proceedings of the Second International Symposium for Cool Climate Viticulture and Oenology. Smart RE et al. (eds.), pp.137-138. Auckland, New Zealand.

Intrieri C and Poni S. 1995. Integrated evolution of trellis training systems and machines to improve grape quality and vintage quality of mechanized Italian vineyards. Am J Enol Vitic 46:116-127.

Kazmierski M, Glémas P, Rousseau J and Tisseyre B. 2011. Temporal stability of within-field patterns of NDVI in non irrigated Mediterranean vineyards. J Int Sci Vigne Vin 45:61-73.

Kicherer A, Klodt M, Sharifzadeh S, Cremers D, Töpfer R and Herzog K. 2017. Automatic image-based determination of pruning mass as a determinant for yield potential in grapevine management and breeding. Aust J Grape Wine Res 23:120-124.

King PD, Smart RE and Mcclellan DJ. 2014. Within-vineyard variability in vine vegetative growth, yield, and fruit and wine composition of Cabernet Sauvignon in Hawke's Bay, New Zealand. Aust J Grape Wine Res 20:234-246.

Kliewer WM and Dokoozlian NK. 2005. Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. Am J Enol Vitic 56:170-181.

Kotsaki E, Reynolds AG, Brown R, Lee HS and Jollineau M. 2020. Spatial variability in soil and vine water status in Ontario vineyards: Relationships to yield and berry composition. Am J Enol Vitic 71:132-148.

Ledderhof D, Brown R, Reynolds A and Jollineau M. 2016. Using remote sensing to understand Pinot noir vineyard variability in Ontario. Can J Plant Sci 96:89-108.

Ledderhof D, Reynolds AG, Brown R, Jollineau M and Kotsaki E. 2017. Spatial variability in Ontario Pinot noir vineyards: Use of geomatics and implications for precision viticulture. Am J Enol Vitic 68:151-168.

Maes WH and Steppe K. 2019. Perspectives for remote sensing with unmanned aerial vehicles in precision agriculture. Trends Plant Sci 24:152-164.

Marciniak M, Brown R, Reynolds AG and Jollineau M. 2015. Use of remote sensing to understand the terroir of the Niagara Peninsula. Applications in a Riesling vineyard. J Int Sci Vigne Vin 49:1-26.

Matese A et al. 2015. Intercomparison of UAV, aircraft and satellite remote sensing platforms for precision viticulture. Remote Sens 7:2971-2990.

May P. 2004. Development after fertilization. *In* Flowering and Fruitset in Grapevines. pp. 69-72. Lythrum Press, Adelaide, Australia.

McBratney A, Whelan B, Ancev T and Bouma J. 2005. Future directions of precision agriculture. Precis Agric 6:7-23.

Millan B, Diago MP, Aquino A, Palacios F and Tardaguila J. 2019. Vineyard pruning weight assessment by machine vision: Towards an on-the-go measurement system. OENO One 53:307-319.

Mori K, Goto-Yamamoto N, Kitayama M and Hashizume K. 2007. Loss of anthocyanins in red-wine grape under high temperature. J Exp Bot 58:1935-1945.

Ortega-Blu R and Molina-Roco M. 2016. Evaluation of vegetation indices and apparent soil electrical conductivity for site-specific vineyard management in Chile. Precis Agric 17:434-450.

Pádua L, Guimarães N, Adão T, Sousa A, Peres E and Sousa JJ. 2020. Effectiveness of Sentinel-2 in multi-temporal post-fire monitoring when compared with UAV Imagery. ISPRS Int J Geo-Inf 9:225.

Panten K and Bramley RGV. 2012. Whole-of-block experimentation for evaluating a change to canopy management intended to enhance wine quality. Aust J Grape Wine Res 18:147-157.

Rudd JD, Roberson GT and Classen JJ. 2017. Application of satellite, unmanned aircraft system, and ground-based sensor data for precision agriculture: A review. *In* 2017 ASABE Annual International Meeting. Spokane, WA.

Schaepman-Strub G, Schaepman ME, Painter TH, Dangel S and Martonchik JV. 2006. Reflectance quantities in optical remote sensing—definitions and case studies. Remote Sens Environ 103:27-42.

Schieffer J and Dillon C. 2015. The economic and environmental impacts of precision agriculture and interactions with agro-environmental policy. Precis Agric 16:46-61.

Shafi U, Mumtaz R, García-Nieto J, Hassan SA, Zaidi SAR and Iqbal N. 2019. Precision agriculture techniques and practices: From considerations to applications. Sensors 19:3796.

Smart RE. 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality. A review. Am J Enol Vitic 36:230-239.

Soil Survey Staff. 2014. Keys to soil taxonomy, 12th ed. USDA–Natural Resources Conservation Service, Washington, DC.

Song J, Smart RE, Dambergs RG, Sparrow AM, Wells RB, Wang H and Qian MC. 2014. Pinot Noir wine composition from different vine vigour zones classified by remote imaging technology. Food Chem 153:52-59.

Sozzi M, Kayad A, Marinello F, Taylor J and Tisseyre B. 2020. Comparing vineyard imagery acquired from Sentinel-2 and unmanned aerial vehicle (UAV) platform. OENO One 54:189-197.

Tanda G and Chiarabini V. 2019. Use of multispectral and thermal imagery in precision viticulture. J Phys: Conf Ser 1224:012034.

Taylor JA and Bates TR. 2013. Temporal and spatial relationships of vine pruning mass in Concord grapes. Aust J Grape Wine Res 19:401-408.

Taylor JA, Nuske S, Singh S, Hoffman JS and Bates TR. 2013. Temporal evolution of within-season vineyard canopy response from a proximal sensing system. *In* Precision Agriculture 2013 – Papers Presented at the 9th European Conference on Precision Agriculture, ECPA 2013. Stafford JV (ed.), pp. 659-665. Wageningen Academic Publishers, Wageningen, The Netherlands.

Trought MCT and Bramley RGV. 2011. Vineyard variability in Marlborough, New Zealand: Characterising spatial and temporal changes in fruit composition and juice quality in the vineyard. Aust J Grape Wine Res 17:79-89.

Vélez S, Rubio JA, Andrés MI and Barajas E. 2019. Agronomic classification between vineyards ('Verdejo') using NDVI and Sentinel-2 and evaluation of their wines. Vitis 58:33-38.

Wolfert S, Ge L, Verdouw C and Bogaardt MJ. 2017. Big data in smart farming – A review. Agr Syst 153:69-80.

Zhou CH, Ou Y, Yang L and Qin B. 2007. An equal area conversion model for rasterization of vector polygons. Sci China Ser D 50:169-175.