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Spatial variability management using a simplified approach of precision viticulture: a case study in a hilly vineyard of Prosecco DOCG

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Abstract: In viticulture, spatial variability of vine vigour may lead to differences in yield component and grape composition. In hilly landscapes, spatial variability is typically stronger due to soil and nutrient erosion, different water availability, and vine planting operation. Variable-rate fertilizer application may be used to manage such spatial variability aiming to provide different amounts of fertilizer according to the vine's needs, reducing the vine's spatial variability. The objective of this work was to evaluate the effects of variable-rate fertilizer application on vines' vigour, yield components, and grape composition spatial variability. A block of 8.5 hectares in a hilly landscape was chosen for this study. Variable-rate fertilizer application was performed by using a proximal spectral sensor (GreenSeeker) to directly control the fertilizer spread (on-the-go configuration) in a 2-year trial. According to the results, variable-rate fertilizer application significantly reduced the spatial variability in yield components, while the grape composition was slightly influenced. Furthermore, geostatistical analysis performed on the spectral sensor data confirmed a reduction of the total variability (Sill) by 55% and the percentage of erratic variance (nugget effect) by 39%. This latter consideration represents an important advantage of on-the-go variable-rate fertilizer application since even small variability (4 vines) can be managed.

Keywords: simplified precision viticulture; within-vineyard variability; vineyard fertilization; variable-rate technology; grape quality; smart agriculture; Vitis vinifera L..

1. Introduction

In viticulture, yield, berry composition, and the final wine style obtained by separate winemaking processes may be spatially variable within the same block [1]. In this sense, natural spatial variability is present in blocks caused by soil profiles and topography [2]. In this regard, field arrangements before the vineyard establishment are among the main factors affecting soil characteristics and terroir expression. As a matter of fact, modern viticulture requires an appropriate field layout, especially in hilly areas, to make mechanization feasible in order to reduce operational costs and face the human labour shortage, also avoiding at the same time possible soil erosion [3,4]. Field levelling, excavation or earth-moving operations are usually performed in hilly areas in order to allow suitable vine canopy exposure and water management leading to a landscape modification [5]. Vine rows and water channels can be realized in the direction or perpendicularly to the line of the maximum slope, leading to a different water flow and different levels of erosion. This soil preparation implies the remixing of soil layers which negatively impacts soil fertility and could create a remarkable spatial variability with zones inappropriate for vine development [3,6].

The vine terroir expression is reached when vine physiology is positively influenced by soil, water availability, climate, training systems, human labour and field management operations [7,8]. The remixing of soil fertility layers in this sense can inevitably result in a poor expression of terroir characteristics due to nutritional imbalances and different soil water retention properties that could lead to root asphyxia, soil compactness or altered soil microbiology, which costs a negative impact on homogeneity in terms of grape yield and, particularly, fruit characteristics [9]. In the particular case of the Conegliano-Valdobbiadene Prosecco Superiore DOCG (protected denomination of origin, located in North-east Italy) wine region, where the micro-zone characteristics inside the Consortium particularly influence the wine profile, the within-field homogeneity of vineyard growth status is essential to achieve the high-quality standards required by this denomination in its 19 micro-zones [10,11]. In fact, *Vitis vinifera L.* cv. Glera, the primary grape used for the production of this vine, is particularly influenced by the factors mentioned previously and the reply of this cultivar on limiting factors, such as altered soil characteristics, water shortages, costs of low yield and unappropriated macro-constituents (sugar, acidity and pH) profiles for the oenological purposes [12,13]. Therefore, the winegrower usually adopts agronomic and operational decisions to achieve the within-field homogeneity of the vineyard [14]. According to the traditional practices, these actions can be translated into different pruning interventions with, for e.g., the control of buds number per plant [15], fertilisations, soil in-row tillage, and application of cover crops, topping or irrigation [11]. All these operations influence grape physiology and growth, but when a condition of in-field spatial variability caused by vineyards arrangement is emphasized, the application of these operations and inputs in a fixed rate cannot give the expected result results [16].

In this regard, the solution for winegrowers aimed to reduce the within-field variability is identified in the precision viticulture (PV) approach, which relies on the accounting of spatial and temporal variability in field management. PV consists of applying precision agriculture (PA) concepts to vineyard management. PA strategy is based on the collection and analysis of spatial and temporal data, which are combined together and processed to obtain valuable information that can be used to improve resource use efficiency and sustainability of agricultural systems. PV tools were applied to identify spatial variability of yield components and phenolic composition of berries [17], and sensors developed for PV application were used for non-destructive estimation of grape composition [18]. Several monitoring tools are used in PV to perform spatial variability assessment, such as satellites, unmanned aerial vehicles, portable spectrometers, and wireless sensor networks. In order to further improve the PV adoption rate, low-cost tools were proposed [19], while the reliability of low-cost platforms was assessed [20], highlighting the need for straightforward and affordable tools. Among the operations manageable with PV, fertilisation is one of the most important with direct influences on quantitative and qualitative performances of the vineyard and impacts in terms of economic, energetic, and environmental sustainability of the farm [21–24]. The distribution of fertiliser depending on the plant's needing and zone potential allows to reach an improved efficiency of the fertiliser nutritional effects reducing at the same time wastes of this input [25]. In this regard, in the last few years, the technologies have evolved quickly, providing solutions able to account for the spatial variability in terms of spectral indexes that describes the plant vigour or health [26], soil texture or humidity content with georesistivimeter or electromagnetic sensors [27] or the vineyard yield and quality mapping [28]. This information helps delineate homogeneous zones and provides prescription maps of the variable rate application depending on zone potential and needs.

Although all these steps can guarantee to reach a high accuracy of the prescription, this methodology is time consuming and often difficult to apply for the winegrower since it requires specific data-science and analytics skills or important investments in terms of equipment for its application not always applicable, especially in realities characterized by small farm size such as the Prosecco Conegliano Valdobbiadene area. In this sense, the market has provided "simplified" solutions for the variable rate application of fertilizers based on on-the-go systems able to detect in real-time the field variability according to the plant health status (e.g. NDVI) and elaborate fertilizer rate application automatically without the needing of prescription maps or GNSS systems mounted in the tractor [29,30]. As a result, a straightforward approach for the winegrower to PV application is provided with benefits on the timing of this operation. Therefore, a futuristic vision, where the spread of this "simplified" system is reached among wineries, would be desirable in order to improve the fertilisation efficiency and sustainability. To do so, research that could verify the effects of the aforementioned system is necessary since in the literature, a poor number of studies can be found, especially concerning viticulture.

This work aims to assess the capacity to reduce the spatial variability of nutritional imbalances caused by field arrangements in terms of plant vigour, yield, and quality of a simplified PV system for the fertilisation of vineyards. In particular, two-year of variable-rate fertilisation was applied on a block characterized by a spatially structured variability, taking advantage of a real-time sensor-driven fertiliser spreader for variable rate application (VRA). Such an approach is pointed out as an economic solution able to be integrated into the farm machinery [31] to provide an immediate impact in terms of sustainability on the wine production chain. Furthermore, the proposed approach represents a case study of within-field variability reduction using simplified technological solutions which can be used in wine regions characterized by low within-field homogeneity.

2. Materials and Methods

2.1. Study area description and climatic profiles of the experimental site

The study was carried out in 8.5-hectare commercial vineyard located in the Conegliano Valdobbiadene Prosecco Superiore DOCG wine region (45.935789 N, 12.255311 E, Vittorio Veneto, Italy – Figure 1). The vineyard was planted with *Vitis vinifera L.* cv. Glera in 2011 with a row spacing of 3.0 m and a vine spacing of 1.1 m, with a North-West/South-East orientation. The vines were trained in vertical shoot positioning (VSP), specifically the Sylvoz training system. An average slope of 10% characterized the vineyard, and vines were planted perpendicularly to the slope direction. Field levelling was carried out before planting, causing spatial variability in the topsoil. The vineyard is equipped with an underground irrigation system used for emergency irrigation (around 5 days/year).

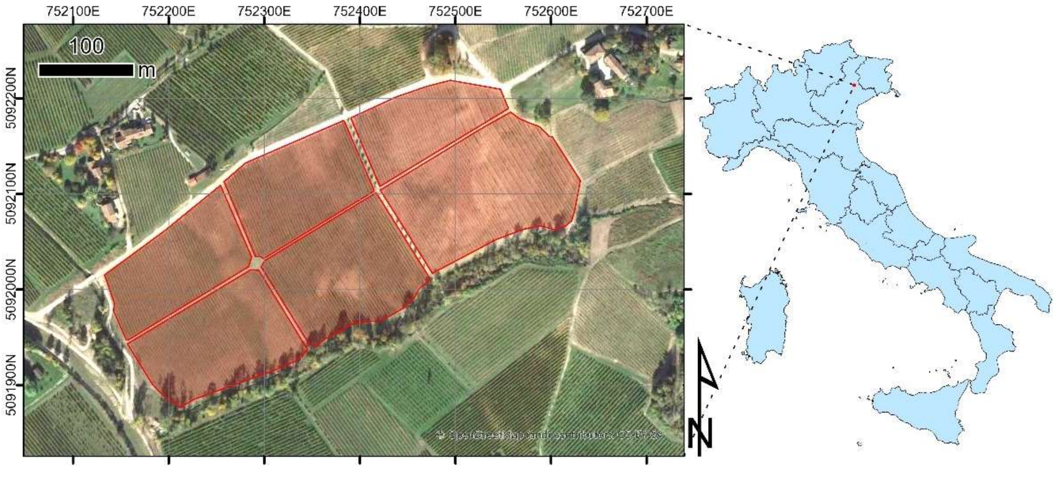


Figure 1. The vineyard was located in the Northeast of Italy in the Conegliano Valdobbiadene Prosecco DOCG consortium area.

The study area consists of an area classified as humid subtropical climate (Cfa) by Köppen and Geiger. In this regard, the environmental profiles elaborated from a weather station close to the experimental field of the two vintages subjected to this work are summarized in Table 1. The data shows an average temperature during the growing cycle (April-September) of 20,6 °C with an average rainfall of 797,3 mm. An increment in the average temperatures in the studied years and an increment in the average total rainfall occurred compared with historical data (1980-2018). In addition, the average temperature range, which is an indicator for the grape quality profiles (influencing especially colour, flavour and malic acid respiration) [32], calculated from August to September (which consists of the period from veraison to the commercial maturity of grape), indicates a higher temperature in the year 2020 than 2019. However, compared with historical data, this data is lower, suggesting that faster ripening of the vines characterises the area compared to the past. In addition, the Huglin heat sum index [33] was calculated between 1980 and 2020 (Figure 2). The Huglin Index was 2457°C in 2020, showing an increase of over 15% compared to 1980. Such an increase identifies the climate change consequence at the field scale, which could indicate the future vine-growth conditions, identifying the need for more efficient and sustainable agricultural practices.

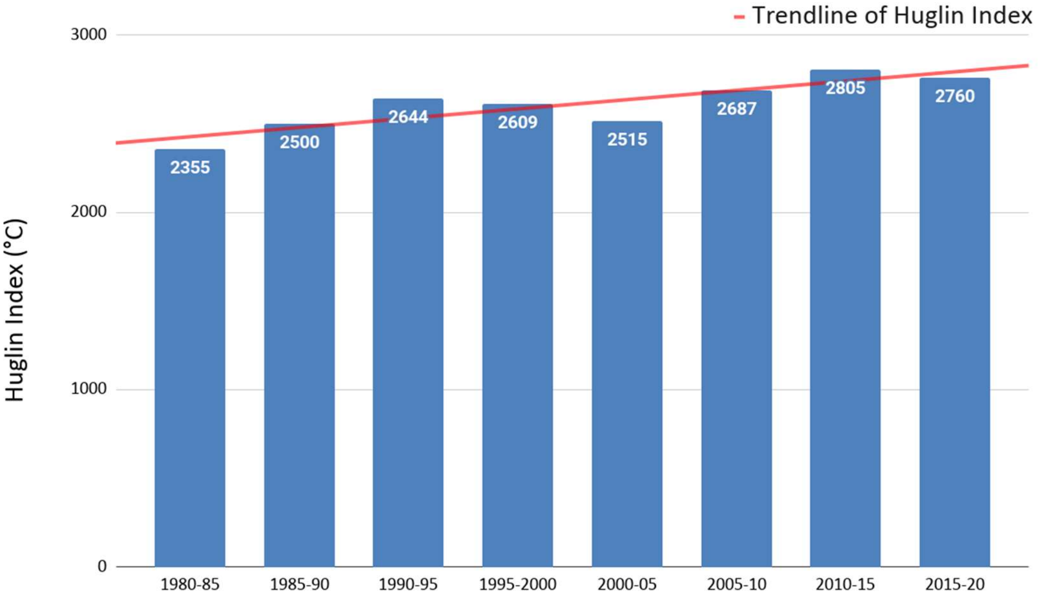


Figure 2. Five-year average Huglin index of the Conegliano (6.4 km from the study area) meteorological station (45.88132477 N, 12.28232702 E). Over the last 40 years, the Huglin index has increased by more than 15%.

Table 1: Environmental profiles of the vine growth cycles in terms of average temperature, rainfall and average temperature range of the vintages considered in the study in comparison with average long-term data (1980-2018)

Year	Average temperature (April-September) °C	Rainfall (April-September) mm	Average temperature (August-September) °C	Rainfall (August-September) mm	Average temperature range (August-September) °C
Average 1980-2018	19,9	673,6	21,4	348,5	10,9
Average 2019-2020	20,6	797,3	22,6	168,1	9,5
2019	20,7	827,2	22,6	178,0	9,2
2020	20,6	767,4	22,7	158,2	9,8

2.2. Fertilizer management and experimental design

The selected block was uniformly managed until the end of the 2019 growing season. This uniform management relies on a fixed-rate application of fertilizer of 60 kgN ha^{-1}, 20 kgP ha^{-1}, and 80 kgK ha^{-1} divided between two fertilizer applications in pre-blooming (BBCH 55) and after harvest (BBCH 91). At the end of the 2019 growing season, a survey with the Greenseeker sensor (Trimble Inc., Sunnydale, USA) was performed before harvest. The Greenseeker is an active spectral sensor which measures canopy reflectance at 656 nm and 774 nm and retrieves the NDVI [34], which was used by several authors to provide information related to yield spatial variability, plant vigour, and pruning weight [35]. Table 2 summarizes sensor surveys and fertilizer application during the experimentation. Following the obtained NDVI map, 10-sampling points were selected based on the measured NDVI values. In these points, a group of three vines were manually harvested to obtain a reference point before variable-rate management introduction. Fertilizer was applied according to the vigour level after the harvesting in 2019 and 2020 (BBCH 91). In early 2020, 30 t ha^{-1} of manure was applied only in low and medium vigour areas, while in 2020, 50-100-150 kg ha^{-1} of a complex fertilizer were applied for HV, MV, and LV, respectively. The pre-blooming fertilizer application was performed using a sensor-driven variable-rate spreader for 2020 and 2021 vintages, spreading 50-100-150 kg ha-1 of a complex fertilizer for HV, MV, and LV. The fertilizer applications were carried out with a New Holland T4.110F tractor (CNH Industrial N.V., Amsterdam, The Netherlands) and a Kuhn MDS 12.1 Q fertilizer spreader (Kuhn SAS, Severe, France).

Table 2. Timesheet of surveys and fertilizer application

	Action	Strategy	Rate	Fertilizer	Stages
09-2019	NDVI survey				BBCH89
01-2020	Fertilizer application	Low – Medium NDVI areas	30 t ha^{-1}	manure	BBCH00
05-2020	Fertilizer application	Real-time VRA based on NDVI	50-100-150 kg ha^{-1}	NPK 15-5-20	BBCH55
09-2020	NDVI survey				BBCH89
10-2020	Fertilizer application	Prescription map VRA based on previous NDVI	50-100-150 kg ha^{-1}	NPK 15-5-20	BBCH91
06-2021	Fertilizer application	Real time VRA based on NDVI	50-100-150 kg ha^{-1}	NPK 15-5-20	BBCH57

2.2.1. Real-time (on-the-go) variable rate fertilizer application procedure

The fertilizer was applied using a real-time methodology (on-the-go) at the pre-blooming in 2020 and 2021 by taking advantage of the Greenseeker sensor and the variable rate spreader. Two Greenseeker sensors were mounted on a metal chassis in front of the tractor while the rear linkage was carrying the fertilizer spreader (Figure 3). Sensors and fertilizer spreader were equipped with their respective control units, which were wired with a display located in the tractor cab (FM1000, Trimble Inc.). First, the relation between the NDVI value and the fertilizer rate was manually defined according to the NDVI value measured beforehand in the 10-sampling points with different vigour levels. Then the average NDVI values for each vigour zone (HV, MV, and LV) were entered into the display in the tractor cab with the corresponding levels of fertilizer (50-100-150 kg ha^{-1}, respectively). Finally, the amount of fertilizer was chosen in order to re-balance the vine vigour.

(**a**) (**b**)

Figure 3. Working configuration during the fertilizer application: (a) The Greenseeker sensor system; (b) The fertilizer spreader.

2.3. *Yield components and grape composition*

The 10-sampling points previously selected according to the first NDVI survey were chosen for experimental purposes since they were representative of each vigour area. A group of 9 vines was divided into three blocks and manually harvested at the ripening stage. The resulting grapes were weighted to obtain the average yield per vine. After that, grape juice was extracted using a manual grape crusher, and then the juice was analysed for the main quality components (sugar contents, titratable acidity, pH). The total soluble sugars were quantified by means of a digital refractometer (PR-32, ATAGO CO., LTD., Tokyo, Japan) and expressed in Brix%; in the same samples, the titratable acidity was measured using an automatic titrator (Crison micro TT 2022, Danaher Corporation, Washington, USA) using 1N sodium hydroxide reagent (Honeywell International, Inc., Morristown, NJ, USA). Finally, the pH was measured with a FlushTrode P/N 238060/80 probe (Hamilton, Reno, NV, USA).

2.4. *Statistical analysis*

K-Clustering unsupervised classification algorithm [36] has been used to classify three different clusters according to the information gained in each of the 10 monitored points. After that, normality and homoscedasticity of the data were checked (Shapiro-Wilk and Levene test), and a factorial ANOVA with the non-parametric test of Tukey HSD was performed to check the intra-variability of the data and among groups. All these analyses have been performed with R software [37]. The latter analysis involved yield components (yield per plant, number of clusters per plant, and cluster weight), grape composition (sugar content, titratable acidity, and pH), and NDVI in pre-harvest. Spatial variability was analysed by considering different indexes to estimate the dispersion of the data. Coefficient of variation (CV) was calculated for yield components, grape composition parameters, and NDVI, according to equation (1) for 2019 and 2020.

$$CV(\%) = \frac{\sigma}{\mu} \tag{1}$$

The evaluation of spatial variability relies on geostatistical analysis to evaluate the variation of variables according to spatial features. The NDVI retrieved by the GreenSeeker in each of the four surveys (Table 2) was used to define the specific experimental variogram. These variograms were used to extract spatial specific parameters such as Nugget, Sill and Range. The sill describes the maximum variance achieved by the NDVI at a specific distance (the range). On the other hand, the nugget describes the variance at a null distance, summarizing the not spatially organized variance [38]. Nugget, sill and range can be used to calculate specific indexes describing the spatial structure of the given variables. Experimental variograms were calculated with R software [35], using the autofitVariogram function of Automap packages with spherical models.

Data extracted from the NDVI experimental variogram were used to calculate the Nugget Effect Index (NE) [39] according to equation (2) and the Mean Correlation Distance (MCD) [40] according to equation (3). These indexes were then used to compare the spatial variability after the variable-rate fertilizer application in 2019 and 2020.

$$NE\ (\%) = \frac{nugget}{sill} \tag{2}$$

$$MCD\ (m) = \frac{3}{8} \times \frac{nugget}{sill} \times range \tag{3}$$

According to Cambardella and Karlen [41], NE indicates how the data are spatially arranged. Specifically, a NE <25% describes a strong spatial dependence and small erratic variance; a NE between 25% and 75% describes a moderate spatial dependence, while a NE <75% stands for random spatial distribution. MCD estimates at which distance NDVI and spatially structured factors (e.g., soil) are highly related while accounting for the nugget variability.

3. Results

3.1 Yield components and grape composition

Data obtained in the ten sampling points examined in the two experimental years have been clustered in three groups per each year using a k-clustering algorithm (unsupervised classification) in order to determinate homogeneous zones profiles representative of 3 class of vine vigour based on the pre-harvest NDVI values: low, medium and high. Results concerning the yield and quality components of the sampling are depicted in Table 3a and 3b, respectively.

Table 3a: Average yield components classified in 3 different zones depending on Pre-Harvest NDVI investigation

	Yield per plant (kg)	**N° of clusters per plant**	**Cluster weight (g)**	**Pre-harvest NDVI**
2019				
Low Vigor	2,64 ± 0,55	26,96 ± 2,74	98,79 ± 21,69	0,76 ± 0,04
Medium vigor	4,52 ± 0,55	30,93 ± 3,33	147,34 ± 19,19	0,79 ± 0,05
High vigor	7,56 ± 1,79	39,19 ± 6,22	192,45 ± 22,46	0,85 ± 0,02
Average	***4,91 ± 0,85***	***32,36 ± 4,09***	***146,19 ± 21,11***	***0,80 ± 0,04***
2020				
Low Vigor	3,17 ± 0,99	14,19 ± 3,50	224,99 ± 58,96	0,78 ± 0,03
Medium vigor	5,87 ± 1,00	18,14 ± 5,05	331,47 ± 51,51	0,82 ± 0,01
High vigor	5,90 ± 1,07	14,06 ± 0,08	419,98 ± 78,92	0,86 ± 0,00
Average	***4,98 ± 1,02***	***15,46 ± 2,87***	***325,48 ± 63,13***	***0,82 ± 0,01***

Table 3b: Average yield components classified in 3 different zones depending on Pre-Harvest NDVI investigation

	Sugar (° Brix)	**Titratable acidity (g/l)**	**pH**	**Pre-harvest NDVI**
2019				
Low Vigor	19,11 ± 0,54	5,03 ± 0,51	3,40 ± 0,05	0,76 ± 0,04
Medium vigor	18,33 ± 0,58	5,52 ± 0,34	3,33 ± 0,05	0,79 ± 0,05
High vigor	17,33 ± 0,90	6,06 ± 0,25	3,30 ± 0	0,85 ± 0,02
Average	***18,24 ± 0,68***	***5,53 ± 0,36***	***3,34 ± 0,03***	***0,80 ± 0,04***
2020				
Low Vigor	19,00 ± 0,67	5,07 ± 0,38	3,28 ± 0,07	0,78 ± 0,03
Medium vigor	18,73 ± 0,61	4,62 ± 0,47	3,34 ± 0,02	0,82 ± 0,01
High vigor	16,55 ± 1,20	7,29 ± 1,54	3,28 ± 0,04	0,86 ± 0,00
Average	***18,09 ± 0,83***	***5,66 ± 0,80***	***3,30 ± 0,05***	***0,82 ± 0,01***

Conceiving the two vintages analysed, the average yield per plant is generally similar, with no significant differences. However, significant ($P<0,05$) changes can be found considering the clusters number and the cluster weight among the two vintages: in 2019, vines presented an averagely double number of clusters than in 2020, but in 2020 the lower number of clusters have been compensated by a higher cluster weight. Again, highlighting the sugar content is possible to see how this one is similar (null hypothesis acceptable) among the two vintages. The same is statable for titratable acidity and pH.

Pre-harvest NDVI affects significantly ($p<0.05$) the quantitative yield (kg/plant) of vintage 2019. Higher yields were found when higher NDVI (average 0,86) values were found, thanks to a higher cluster number and cluster weight per plant. In the vintage 2020, the effect of pre-harvest NDVI value is less marked than in 2019, although generally, the sites with the lower NDVI have the lowest yield; on the other hand, the sites with a higher NDVI (from 0,82 to 0,86) generally presents a higher and similar yield per plant, highlighting the fact that above a specific value of NDVI other physiological parameters, such as the cluster number per plant and the cluster weight, have a magnitude in the yield formation and concur with NDVI values for its determination.

The spatial variability of yield components and grape composition was evaluated using CV calculated in the 10 sample points. Figure 4 shows the differences in the latter descriptors between the 2019 and 2020 vintage. Yield per plant, number of clusters, cluster weight, and pH showed a CV reduction of 39.2%, 21.1%, 6.25, and 50.0, respectively. On the other hand, after introducing a variable-rate fertilizer application, the CV of sugar content and titrable acidity increased by 40.0% and 177%, respectively.

Considering the total amount of fertilizer used, the application of variable rate technologies reduces 50% of the total amount of Nitrogen spread. The application of different thresholds of fertilizer (50-100-150 kg ha^{-1} of NPK 15-5-20) by using different NDVI thresholds chosen according to plants allowed to move from 60 kgN ha^{-1} to 30 kgN ha^{-1} after the introduction of variable rate fertilization.

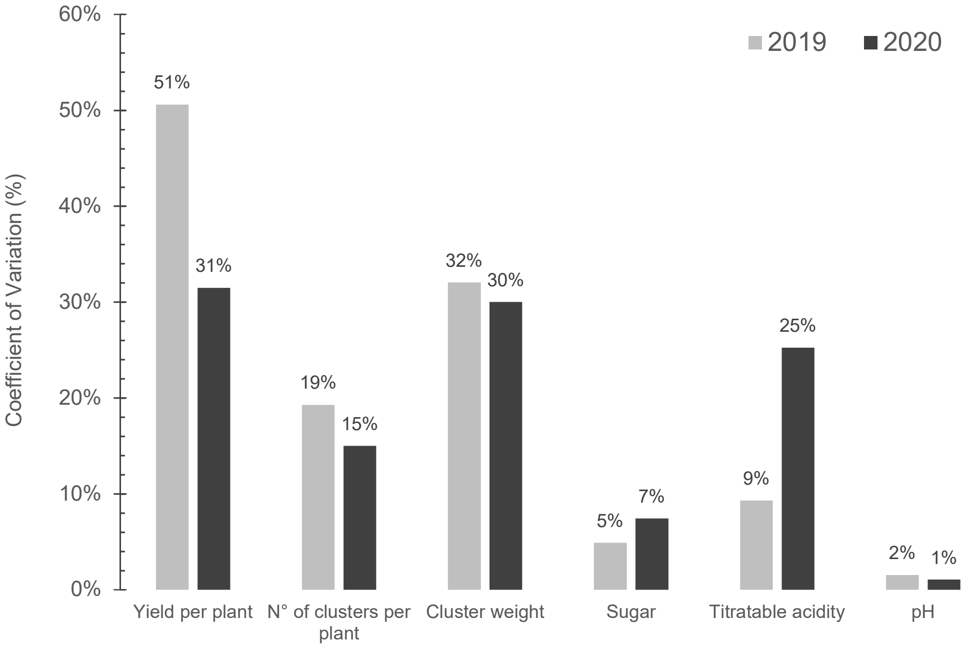
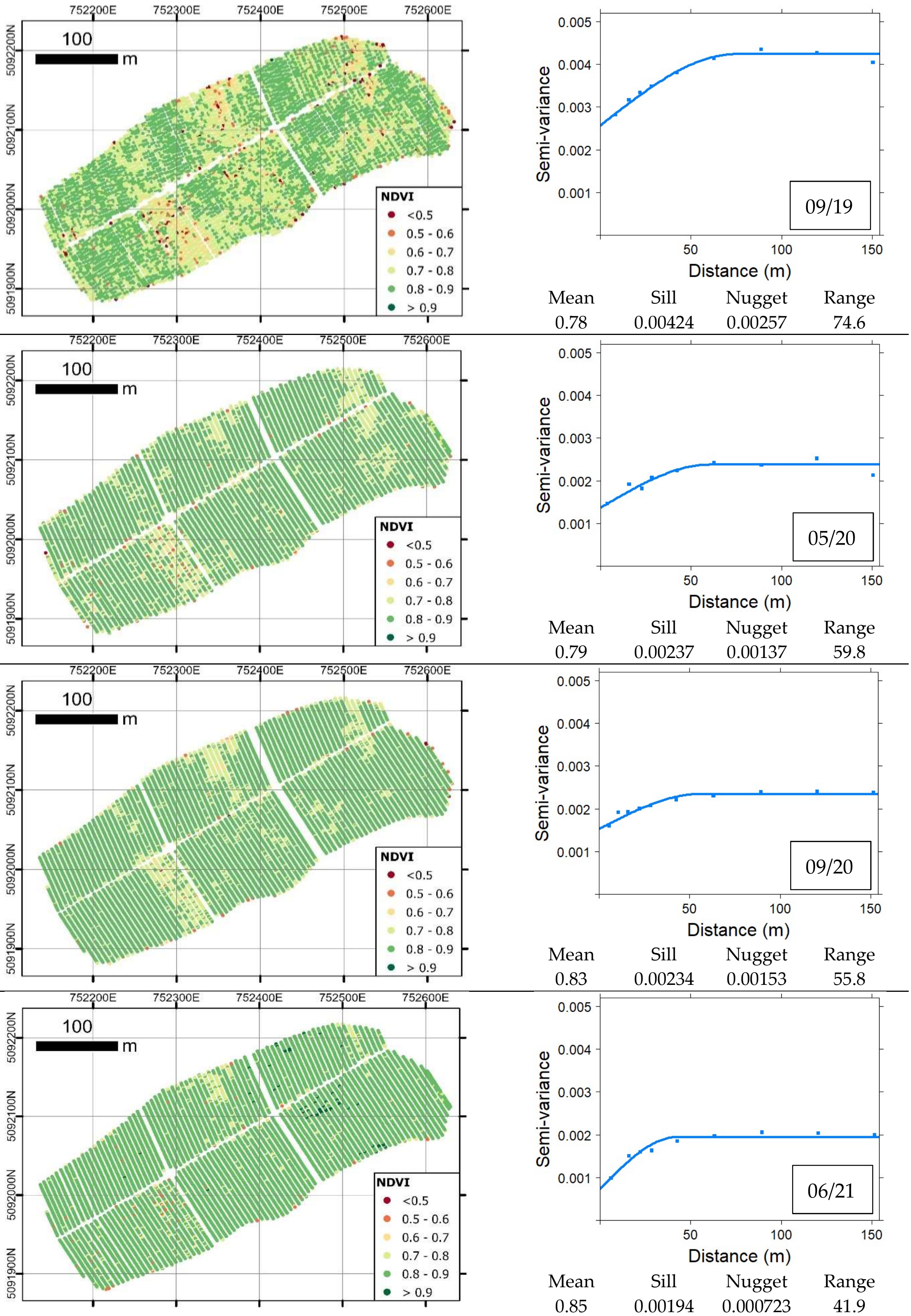


Figure 4. Comparison between Coefficient Variation for yield components and grape composition in the 2019 and 2020 vintage

3.2 Spatial structure analysis of NDVI

Experimental variograms obtained from the four NDVI surveys were analysed in nugget, sill, range, NE, MCD, and CV. NDVI maps and semi-variogram for each survey are shown in Figure 5. Figure 6 summarizes the six parameters analysed among the four NDVI surveys. The mean NDVI value increased from 0.78 in September 2019 up to 0.85 in June 2021. As shown in the maps in Figure 5, this increment of NDVI is mainly due to the reduction of points with low NDVI.

The maximum variability of the NDVI data is summarized as semi-variance in the sill graph (Figure 6a). The Sill decreased from 0.0042 to 0.0019, with the highest step between September 2019 and May 2020. Similarly, the nugget and the range (Figures 6b and 6c) showed an overall reduction at the same time. The NE (Figure 6d) showed a general decrease, and a peak can be found in September 2020 due to a higher nugget value with a similar sill. The MCD, which index includes the range compared to the NE, showed a linear reduction from 16.9 m up to 5.9 m. Finally, the CV of the NDVI decreased from 8.1% up to 5.9% between September 2019 and May 2020, then it mainly remained stable at around 5%.



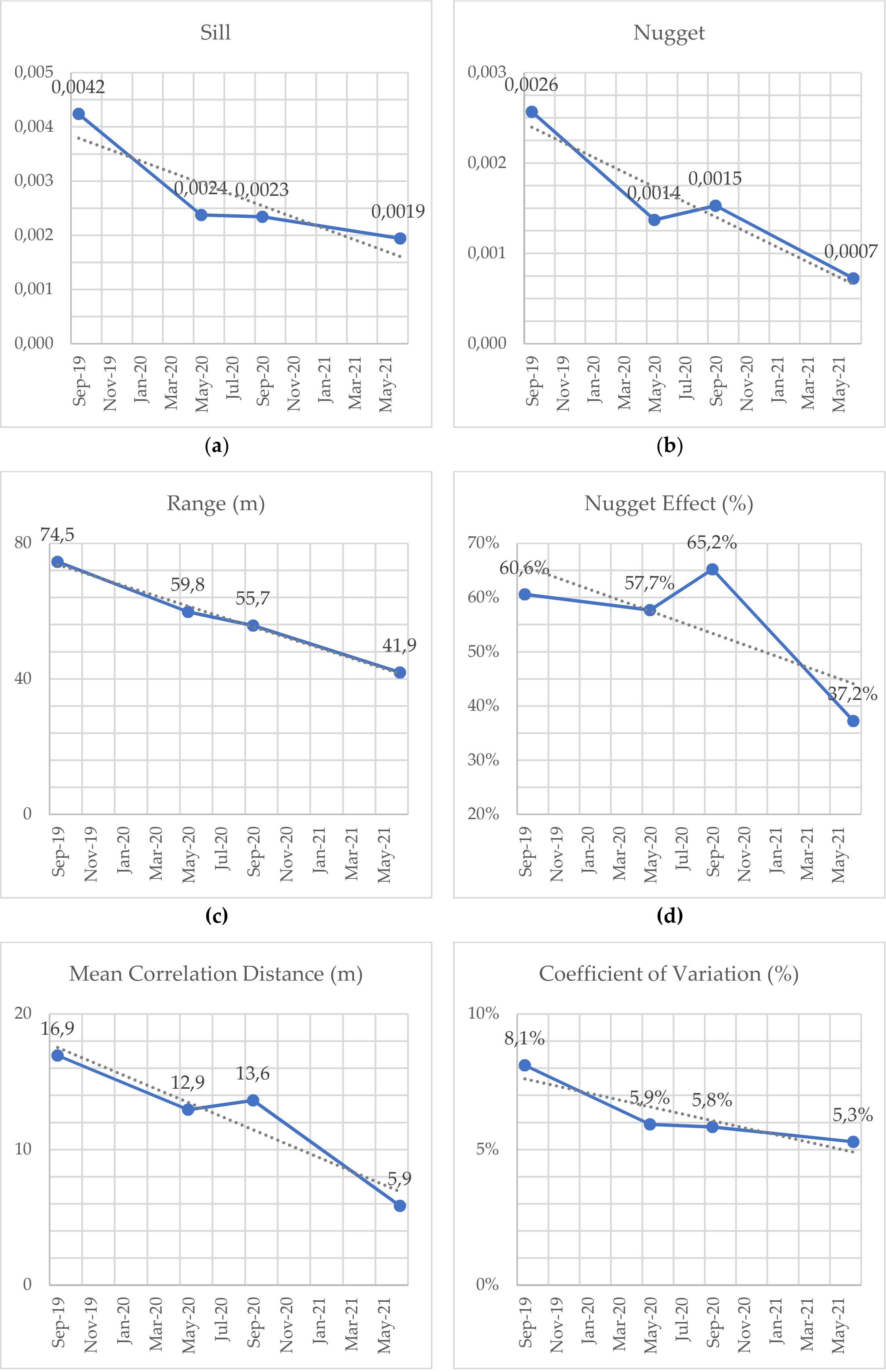
Mean	Sill	Nugget	Range
0.78	0.00424	0.00257	74.6

Mean	Sill	Nugget	Range
0.79	0.00237	0.00137	59.8

Mean	Sill	Nugget	Range
0.83	0.00234	0.00153	55.8

Mean	Sill	Nugget	Range
0.85	0.00194	0.000723	41.9

Figure 5. On the right side are shown the NDVI maps for each survey. On the left is the corresponding semi-variogram. NDVI colour ramp is constant within each map in order to highlight differences.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 6. Variation along the four NDVI surveys of Sill (a), Nugget (b), Range (c), Nugget Effect (d), Mean Correlation Distance (e) and Coefficient of Variation (f).

4. Discussion

The introduction of variable rate fertilizer application using a real-time methodology (on-the-go) on a block characterized by high spatial variability implied different considerations in yield components, grape composition, and vigour spatial variability.

The similarity in yield per plant but differences in cluster number and weight can be explained by the plasticity of Glera cv, which can regulate its production, adapting the cluster weight depending on its fertility and environmental conditions. A lighter, higher value in pH and titratable acidity can be found for 2020, probably due to a higher temperature range in that year's ripening period (Table 1). As a matter of fact, high NDVI can be correlated to a higher photosynthetic capacity of the plant, which can be easily interpreted into greater assimilation of photosynthesized ability to sustain a higher physiological activity. Conversely, the sugar contents are resulted lower where high NDVI was founded, probably due to a high yield load to sustain by the plant with a negative effect on sugar accumulation and dilution. Conversely, this effect is more marked in lower NDVI areas (average of 0.76). Nevertheless, higher plant yield positively affected the total acid's preservation, maintaining an almost 1 g/l higher concentration, which can be considered a positive parameter for the production of sparkling wines, such as the Prosecco's case. This result on yield components and grape composition confirms what was previously found by Davenport et al. [42], highlighting the positive effect of VRA on yield components and a limited effect on grape composition.

However, is it possible to state that the effect of the VRA fertilisation applied affected homogenizing yield, especially among high and medium vigour areas. Conceiving the sugar content, again, the low vigour presented the higher sugars, probably due to a concentration effect of the sugars caused by the smaller size of berries. However, the medium vigour area has also reached a similar value in the sugars. In contrast, high vigour areas highlighted a lower sugar content but a higher titratable acidity, probably a late-ripening due to a higher production to sustain. These considerations could open debates towards adopting selective harvesting strategies based on pre-harvest NDVI when a marked field variability is present to improve the oenological management of the further wine transformation. The spatial variability of yield components and grape composition calculated as the CV in the 10 sample points highlighted a reduction in yield components and a general increase in grape composition. The effects of variable rate fertilizer application showed positive effects on reducing the CV of yield components since they were characterized by a stronger variation, probably due to different vigour. According to this latter consideration, an object detection algorithm can be considered to assess the effects of VRA in viticulture by using image analysis [43]. Differently, grape composition variation was mainly due to temperature, and water availability differences during the analysed growing seasons. Similar results were found by Gatti et al. [44] using satellite NDVI and MECS-VINE proximal sensors with a reduction from 8.20% to 1.42% of CV after the introduction of VRA. The validation of this approach using remote sensing may lead to additional consideration by using the inversion of the radiative transfer model [45].

Besides the discussed effects on yield components and grape composition, variable rate fertilizer application using a real-time methodology reduced the total amount of fertilizer spread by 50%. These results were obtained since the amount of HV vines increased after every fertilizer application because the higher amount fertilizer was spread to MV and LV, and the NDVI thresholds were chosen before each application. These results are comparable to what was obtained by Balafoutis et al. [46], which stated that the introduction of precision viticulture leads to a reduction of 28.3% of product carbon footprint, where fertilizers contributed by 27.6% to this decrease.

Furthermore, the effects of variable rate fertilizer application on spatial variability were investigated using geostatistical parameters extracted from the experimental variogram. This approach should be preferred in PV studies since it includes spatial variation [47]. The total spatial variation (Sill) decreased by 54.7% after introducing variable rate fertilization. The not spatially organized variance (Nugget) decreased by 73.1%, while the effect of this variance on the total (NE) decreased by 38.6%. These results showed a reduction of the erratic variance stronger than a reduction of the spatial dependent variance. The most common approach to variable-rate application is based on the interpretation of sensor data by the definition of management zones. Management zones are usually defined by a data fusion approach that summarises different sensor data inside each zone: The prescription is then chosen uniformly for each management zone. During this process, sensor data aggregation reduces the ability to detect small variances. In this study, a real-time (on-the-go) system was used, which was able to control the fertilizer application directly. A small variance in vine vigour was detected and controlled by the spread of different amounts of fertilizer, leading to a substantial reduction of the nugget. This small variability correspond to the mean average distance of the points which was by way of example 1.82 m in the survey of May 2020. At this distance and considering the two row of vine managed by the fertilizer spreader the the presented methodology for variable-rate fertilizer application was able to manage a group of 4 vines. Similarly, the MCD showed a reduction of 65.1%, showing a reduction in spatial autocorrelation and structure.

The study of the vine vigour and its spatio-temporal variability has to consider the trellis system and the pruning methods. Indeed, different vine training systems are characterized by a different selection of buds, especially if vines are hand pruned [48]. In the spur pruning system, the number of buds can slightly change during years, while in the cane pruning system, hand pruned, the number of buds can be changed according to vine vigour to preserve grape quality. Consequently, spur-pruned vineyard vine vigour is stable during years [49]. The block described in this study is characterized by Sylvoz trellis, where the number of buds chosen during hand pruning is limited. According to this, the results of this study suggest that the reduction of vine vigour variability was mainly due to the introduction of VRA. Kazmierski et al. suggest regularly renewing spatial variability assessment in the case of VRA application [50]. By the use of proximal sensors, the vigour variability assessment can be performed during each fertilizer application.

The strong spatial dependence of vine vigour found in this study can be a consequence of slope vineyards [51]. According to the hilly landscape of the Conegliano Valdobbiadene Prosecco area, the VRA approach can provide advantages in terms of variability reduction.

5. Conclusions

Spatial variability in vine vigour may lead to differences in yield components and grape composition, affecting the following oenological procedures. In hilly areas, spatial variability may be exacerbated by field levelling and earth-moving operations usually performed before the vineyard plantation. In addition, soil and nutrient erosion may change plant vigour's spatial variability, leading concurrently to land degradation and water pollution. In the current paper, spatial vigour variability was reduced using variable-rate fertilization by using a proximal sensor that controlled the amount of fertilizer spread in real-time. According to the results, this approach reduced the spatial variability in yield components, while grape composition did not show a significant variation in terms of spatial variability.

Furthermore, the geostatistical parameters extracted from the proximal sensor data confirmed variability reduction, especially in terms of erratic variance. This reduction of non-structured variability represents a peculiarity of this on-the-go approach since the sensor and implement were able to manage small variability (4 vines) by changing the fertiliser rate. In addition, variogram paraments extracted from the proximal sensors data can be used to compare different geographic areas or production systems.

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