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Assessing the Contribution of EC_a and NDVI in the Delineation of Management Zones in a Vineyard

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Abstract: Precision fertilization implies the need to identify the variability of soil fertility, which is costly and time-consuming. Remotely measured data can be a solution. Using this strategy, a study was conducted, in a vineyard, to delineate different management zones using two indicators: apparent soil electrical conductivity (EC_a) and normalized difference vegetation index (NDVI). To understand the contribution of each indicator, three scenarios were used for zone definition: (1) using only NDVI, (2) only EC_a, or (3) using a combination of the two. Then the differences in soil fertility between these zones were assessed using simple statistical methods. The results indicate that the most beneficial strategy is the combined use of the two indicators, as it allowed the definition of three distinct zones regarding important soil variables and crop nutrients, such as soil total nitrogen, Mg^{2+} cation, exchange acidity, and effective cation exchange capacity, and some relevant cation ratios. This strategy also allowed the identification of an ionic unbalance in the soil chemistry, due to an excess of Mg^{2+}, that was harming crop health, as reported by NDVI. This also impacted EC_a and NDVI relationship, which was negative in this study. Overall, the results demonstrate the advantages of using remotely sensed data, mainly more than one type of sensing data, and suggest a high potential for differential crop fertilization and soil management in the study area.

Keywords: vineyard; precision viticulture; management zones; within-field variability; EC_a; NDVI

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1. Introduction

The current urge in the agricultural sector is to maintain high crop productivity, or even increase it due to high food demand, and simultaneously reduce the consequent emissions and other environmental impacts. Employing precision agriculture (PA) practices can directly and indirectly contribute to a decrease in greenhouse gas emissions and improve the use efficiency of agricultural inputs, optimizing crop production and economic return [1,2]. This is achieved because PA considers the inherently variable agricultural land and thus is based on the variable and precise use of inputs to match the specific site characteristics within a field and the adequate timing of application [3,4].

However, first, the site-specific characteristics of a field, i.e., the intra-variability of a field, must be known. Nowadays, the use of sensors is becoming normal to map various and relevant soil properties [5], thus reducing the number of soil samples needed to describe field variability. For instance, sensing of soil apparent electrical conductivity (EC_a) is very common and useful, being used by various researchers to map soil water content [6], top and subsoil physical properties [7], clay content and cation exchange capacity [8,9], overall soil textural classes [10,11], soil pH [12], exchangeable magnesium [13], and other soil nutrient variations [14]. These are soil properties known to mutually influence soil's electrical conductivity [15].

However, using one sensing data type alone might not be sufficient to understand yield variations. For example, in a Chilean vineyard, the use of EC_a itself was not enough to estimate the most commonly used soil variables to delineate different zones [16]. Therefore, linking soil variations, as indicated by EC_a, to crop performance differences, as indicated by vegetation indices, can help further identify the factors limiting the system yield [17].

Normalized difference vegetation index (NDVI) is the most popular vegetation index used in agriculture, dating to 1969, and is based on the spectral reflectance in certain wavelengths of crop surfaces and bare soil [16]. This index is used to map canopy changes within a field and provides information about plant morphology, vegetation's greenness, and crop yield [16–18].

This type of sensing data is the foundation for the delineation of management zones (MZs), which are sub-regions in a field with homogeneous yield-controlling features [16,19]. In the MZs, it is possible to apply variable rates of farm inputs, according to the characteristics of each zone, to attain maximum farm yield and efficiency [19]. It is also possible to differentiate practices such as pruning, shoot thinning, and harvesting [2,16,20–22]. The combination of EC_a maps and NDVI has been thoroughly studied and successfully used in vineyards to assess the variability of the field and crop conditions (e.g., [21,23–26]), and it is important because of the impact of soil on vine nutrition, water uptake, root depth, and temperature, which in turn affects vine performance and wine production [21].

However, in potato farming, the combination did not show extra benefit [27], and in a peach orchard, the combination was only beneficial in predicting fruit yield, as opposed to quality parameters which were successful using just NDVI [28]. Furthermore, this combination was useful in MZ delineation for irrigation in an olive grove [29].

The results presented here represent the extended version of a proceedings paper by Esteves et al. [30] where significant differences in soil attributes were found between zones delineated in a vineyard in a Mediterranean climate. However, in this extended version, we wanted to understand the contribution of the indicators chosen, NDVI and EC_a, and in the present specific field conditions and climate. As such, zones for differential management were delineated based on three scenarios: (1) just NDVI, (2) just EC_a, and (3) a combination of the two. The results of the soil analysis were then compared between these delineated zones, and the need for one indicator, either NDVI or EC_a, or the need for both was assessed in the identification of soil intra-variability.

2. Materials and Methods

2.1. Experimental Site

The experimental site is located in a vineyard of Tricadeira *cv*, grafted on 1103P and planted in 2003 in Montijo, Portugal (38°41′25.9″ N 8°45′40.8″ W). The selected study area has 6.77 ha; the vines are spaced 1.4 m within rows and 2.8 m between rows and are pruned as a single Guyot.

The soil is primarily classified as an Orthic Podzol, according to the World Reference Base for soil classification [31], and the region's climate is a Csa, according to the Köppen–Geiger climate classification, a temperate climate with rainy winter and dry summer [32].

The vineyard has a drip irrigation system that provides water after the fruit set up until ripening (usually from June to August, depending on the year). The crop is fertilized once a year after the dormant season, with an organic fertilizer (4.2:4.5:1 in N:P:K units; and 65% of organic matter) at a rate of 1000 kg ha^{-1}. The organic fertilizer is applied in the interrow in the shape of pellets of 4 mm at 40 cm depth. The application alternates between interrows every year to homogenize the effects of this fertilization.

2.2. Remote Measurements

2.2.1. EC_a

There are two main methods for measuring EC_a: (1) a direct contact method, where electrodes are in direct contact with the soil to inject and measure an electrical current, and

(2) an indirect contact method called electromagnetic induction (EMI) where a transmitter coil induces a magnetic field in the soil and a receiver determines the response [16,33].

The EC_a map was obtained by the means of an electromagnetic induction (EMI) sensor, the EM38-MK2 sensor [34]. This non-invasive sensor is considered very sensitive in describing the soil sublayer properties, without in-depth disturbance [20].

The sensor was positioned in the vertical dipole with the receiver separated from the transmitter by 1 m [35,36] and was mounted on a four-wheel motorcycle, which passed on every other interrow (intervals of 5.6 m). The EC_a sensing data dated from 14 May 2018, and the soil had a water content of about 75% of field capacity during measurement. The data were then kriged in QGIS version 3.16.15 [37], and, using the median values, two levels of EC_a were defined: high and low.

2.2.2. NDVI

The expression used to obtain NDVI is extensively described in the literature (e.g., [16,18,38]), where the bands from the near-infrared radiation (NIR) region (from 0.7 to 1.2 µm) and the red radiation region (from 0.6 to 0.7 µm) of the electromagnetic spectrum (EMS) are used for the computation. The indicator varies from +1 to −1, where positive values represent vegetation or high-reflective surfaces, since they have a higher reflectance of NIR radiation, and negative values indicate non-vegetation or senescent and dry vegetation, or clouds or water, as they have a lower reflectance of NIR radiation [38].

The NDVI map used here was obtained with images from the satellite Sentinel-2 [39], from the European Commission's Copernicus program. The images were downloaded directly through the DataFarming platform [40], which already provided the NDVI map. The image is from tile number T29SMC, which corresponds to continental Portugal. The date was 24 June 2018, a day without clouds, and the images had a resolution of 10 m. In the Sentinel-2 instruments, the bands 8 and 4 correspond to the NIR and red band of the EMS, respectively, and thus are used for NDVI computation. The downloaded images were then treated in QGIS to also obtain two levels of NDVI (also using the median values): high and low.

Also in QGIS, the NDVI map was used in conjunction with the EC_a map to obtain, through a factorial design, the three suggested zones, which are combinations of high and low values of NDVI and EC_a, as summarized in Figure 1.

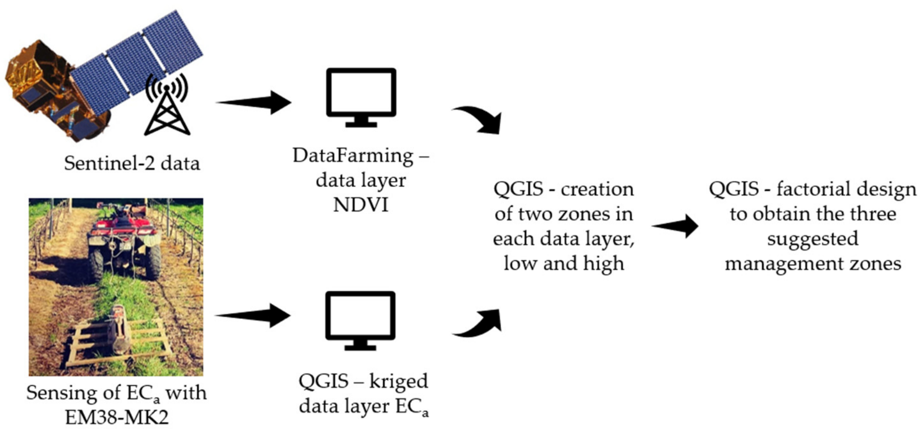

Figure 1. Summary of the procedures performed to obtain the EC_a map, the NDVI map, and the map with the three distinct zones in terms of these two indicators.

2.3. Experimental Design

Within the experimental area, zones were defined based on the low and high levels of two indicators, NDVI and EC_a. The experimental design used in the statistical analysis was based on three scenarios: (1) zoning based on NDVI, (2) zoning based on EC_a, and (3) zoning based on both indicators, NDVI + EC_a.

In the first two scenarios, only two zones were defined: high NDVI (N+) and low NDVI (N−) when using NDVI for zone delineation; high EC_a (E+) and low EC_a (E−) when using EC_a for zone delineation. In the last scenario, three zones were defined as shown in Figure 2: zone one with high levels of NDVI and low of EC_a (Z1: N+ E−), zone two with high levels of both NDVI and EC_a (Z2: N+ E+), and zone three with low NDVI and high EC_a (Z3: N− E+). High and low levels were defined based on the 50 percentile values. In each zone, 3 different plots (replicates) were randomly established. Moreover, in the study area, a zone with low NDVI and low EC_a was not detected.

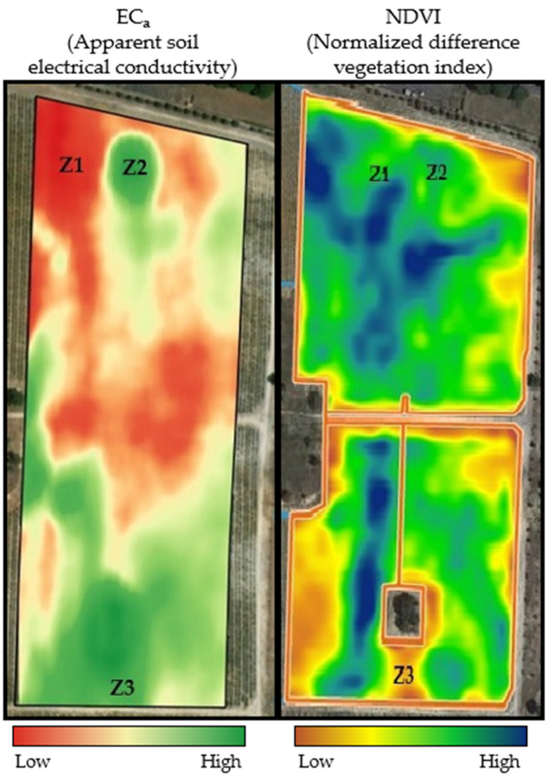

Figure 2. Satellite image of the study area (6.77 ha), with EC_a and NDVI maps and the respective legend. In the figure, it is also possible to view the three delineated zones (Z1, Z2, and Z3 as mentioned in [30]).

2.4. Soil Analysis

Using a probe, soil samples were collected from the first 0–50 cm of soil. From each plot of each zone, 13 soil samples were taken, making up a total of 117 soil samples (3 zones × 3 plots × 13 samples), that were individually analyzed. Before chemical analysis, the 117 soil samples were air-dried until constant weight and sieved through a 2 mm mesh. The variables assessed in the present study were the following: pH and laboratory-determined soil electrical conductivity ($EC_{1:2}$), soil organic carbon (SOC), total nitrogen (N), extractable phosphorus (P), exchangeable cations (potassium K^+, calcium Ca^{2+}, magnesium Mg^{2+}, and sodium Na^+), exchangeable acidity (EA), and effective cation exchange capacity (ECEC).

Soil pH and $EC_{1:2}$ were measured in a soil:water suspension (p/v) prepared with distilled water, using a 1:2.5 suspension and a potentiometer for pH measurement, and using a 1:2 suspension and an electrical conductivity meter for $EC_{1:2}$ determination, both measured at room temperature [41]. Furthermore, pH was also measured in a 1:2.5 soil:$CaCl_2$ (0.01 M) suspension [42].

Extractable P was determined using the Égner–Rhiem method and measured through the inductively coupled plasma optical emission spectroscopy (ICP-OES) technique [43];

SOC concentration was determined through the total organic carbon (TOC) method using dry combustion [44]; total N was measured using the micro-Kjeldahl method [45].

Exchangeable cations were determined by extraction with ammonium acetate (1 M at pH 7) and then quantification through the ICP-OES technique; EA was determined through KCl (1 M) extraction, followed by titration with NaOH (0.043475 M); ECEC was determined as the sum of exchangeable cations and EA. The procedures were according to Amacher et al. [46].

Particle size determination was also evaluated in the present work and was determined through the conventional pipette method to obtain the soil percentage of sand, silt, and clay [47].

2.5. Statistical Analysis

The experimental data were analyzed through a one-way variance analysis (ANOVA), using the general linear model procedure to perform the F test with a completely randomized design. Mean separation was performed using the LSD test with the significance level set at $\alpha = 0.05$. All statistical analyses were performed with the Statistix software package [48]. ANOVA was used in this context to obtain information about the statistical separation between the potential management zones in the study area, as in Li et al. [19].

3. Results and Discussion

3.1. Soil Particle Size

The results of soil particle size analysis from each zone delineated in the three scenarios are shown in Table 1. In zones delineated based on NDVI, the high NDVI levels (N+ zones) are associated with a higher percentage of sand and a lower percentage of clay in the soil, while there are no significant differences for silt. These results indicate that high NDVI is related to soils with more porosity that have better drainage and allow aeration near the root zone, which is important in healthy vine roots [49].

Table 1. Mean values of soil percentage of sand, silt, and clay according to zone and indicator used.

Zone Design	Sand	Silt	Clay
		%	
NDVI			
N+	79.25 a	7.14	13.61 b
N−	71.16 b	6.67	22.17 a
Signif.	*	ns	**
EC$_a$			
E+	72.29 b	7.62 a	20.09 a
E−	85.06 a	5.71 b	9.23 b
Signif.	***	*	***
NDVI + EC$_a$			
N+ E−	85.06 a	5.71 b	9.23 b
N+ E+	73.43 b	8.58 a	18.00 a
N− E+	71.16 b	6.67 b	22.17 a
Signif.	***	***	**

Signif.—significance level by the F test, ns—non-significant at $p < 0.05$ level, significant at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***) by the F test. In each column, values followed by the same letter do not significantly differ by the LSD test at $\alpha = 0.05$.

However, when using EC$_a$ for zone delineation, high values of the indicator (E+) correspond to a lower percentage of sand and a higher percentage of silt and clay in the soil. This result agrees with other researchers' work, which demonstrated the positive correlation between soil clay content and EC$_a$, regardless of the soil type or EC$_a$ data types [8]. In another study also performed in a vineyard, a negative correlation between EMI-based EC$_a$ and soil sand was found [25], similar to the present work findings. The same conclusions were reached by other authors, with the same EM38 sensor [10,13,29–31,50], and in a Portuguese vineyard, with the EC_a sensor Veris 3150 [51]. Given this positive relationship between EC_a and soil clay content, EC_a maps can be used for a variety of purposes, such as a base for soil fertilization and irrigation, since clay content is linked to nutrient availability and structural and hydrological properties [51].

In another study, soils with higher clay content had the highest values of NDVI [25]. The authors associated the benefits of soils with a finer texture, specifically having higher water holding capacity, better vegetative vigor, and higher NDVI. However, the results in the present work do not reflect these findings. Quite the opposite, high levels of NDVI were related to low content of clay and high content of sand.

Regarding the scenario NDVI + EC_a, the results are equivalent to scenario EC_a, where zones with high EC_a had significantly less sand in the soil and higher content of clay, regardless of the NDVI levels. It suggests that soil particle size is more related to EC_a than to NDVI. Zone delineation using EC_a as a proxy should be adequate, as the addition of NDVI did not bring any added value, as already concluded by other researchers [27].

3.2. Soil pH, EC, SOC, N, and P

3.2.1. Soil pH

Values of soil pH (H_2O) and pH ($CaCl_2$) showed significant differences between zones, but such variations rely on the scenario considered (Table 2). Using NDVI for zone delineation, only pH ($CaCl_2$) values showed significant differences between zones, while when using EC_a, only pH (H_2O) showed significant differences. In the NDVI + EC_a scenario, the differences between zones are significant, and there is a combination of the above-mentioned results, further evidencing the relationship between pH (H_2O) and EC_a and between pH ($CaCl_2$) and NDVI.

Table 2. Mean values of soil pH (extracted with H_2O and $CaCl_2$), electrical conductivity (1:2 soil:water extraction), soil organic carbon (SOC), total nitrogen (N_{tot}), and extractable phosphorus (P) according to zone and indicator used.

Zone Design	pH (H_2O)	pH ($CaCl_2$)	$EC_{1:2}$ ($\mu S\ cm^{-1}$)	SOC (%)	N_{tot} ($mg\ kg^{-1}$)	Extractable P ($mg\ kg^{-1}$)
NDVI						
N+	6.37	5.35 b	72.86 b	0.42	285.64 a	19.20 a
N−	6.51	5.70 a	161.27 a	0.42	179.85 b	8.83 b
Signif.	ns	***	***	ns	***	*
EC_a						
E+	6.49 a	5.52	121.19 a	0.42	247.91	13.69
E−	6.25 b	5.36	64.60 b	0.42	255.30	19.85
Signif.	**	ns	***	ns	ns	ns
NDVI + EC_a						
N+ E−	6.25 b	5.36 b	64.60 b	0.42	255.30 b	19.85
N+ E+	6.48 a	5.35 b	81.11 b	0.42	315.98 a	18.55
N− E+	6.51 a	5.70 a	161.27 a	0.42	179.85 c	8.83
Signif.	**	***	***	ns	***	ns

Signif.—significance level by the F test, ns—non-significant at $p < 0.05$ level, significant at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***) by the F test. In each column, values followed by the same letter do not significantly differ by the LSD test at $\alpha = 0.05$.

A positive, and significant, relationship between EC_a and pH (H_2O) was already observed in other studies [14,51]. Regarding the relationship between NDVI and pH ($CaCl_2$), there is little proof of it; however, using $CaCl_2$ to measure pH is known to be more consistent as it is less affected by environmental changes, i.e., the addition of fertilizer, whereas water extracted pH can vary without changes in exchangeable acidity [52]. As such, in the present work, pH ($CaCl_2$) is well related to NDVI since this measurement method better reflects plant response to pH variations.

Soil pH (H_2O) is quite neutral or slightly acidic in the study area, but pH ($CaCl_2$), which should be between 5.5 and 8 for optimum grapevine production [53], is slightly below the minimum threshold when NDVI is high, when EC_a is low, and when both are combined. However, pH ($CaCl_2$) is not below five, a threshold associated with stunted shoot and root growth [53].

3.2.2. Soil $EC_{1:2}$

The low values of laboratory-measured $EC_{1:2}$ indicate that there are no salinity issues in the soil [41,53]. As can be seen in Table 2, higher values of this variable are related to high EC_a, an expected outcome as $EC_{1:2}$ is a direct measurement of soil salinity, which has a great impact on EC_a measurement. This positive correlation was also observed in another study [51]. High $EC_{1:2}$ is also related to low NDVI, meaning that the high content of exchangeable cations is related to low vegetation health. Low values of NDVI indicate stressed vegetation, with less photosynthetic activity since less near-infrared radiation is reflected [54]. Thus, there might be unbalance in soil nutrient content that is affecting plant nutrition and consequently affecting photosynthetic activity and producing lower values of NDVI.

Additionally, zones with lower values of $EC_{1:2}$ coincide with zones that have larger particle sizes (higher content of sand), whereas higher values of $EC_{1:2}$ coincide with smaller particle sizes (higher content of clay), a result also found in the literature [50]. Perhaps the leaching of salts in excess, promoted by the large size of the soil particles in the zone with sandy soil, N+E−, is one of the reasons this zone has a high NDVI. The other zone with a high NDVI, N+E+, is the one with more silt percentage, as seen in Table 1. The $EC_{1:2}$ in this zone does not significantly differ from $EC_{1:2}$ in zone N+E−, with both zones having substantially less soil electrical conductivity ($EC_{1:2}$) in the soil than N−E+, the only zone with a small NDVI. This is another indication that the soil might have an excess of salts, as reported by $EC_{1:2}$, that is harming crop performance, as reported by the NDVI. However, it remains difficult to assess what has the greatest impact on NDVI: aeration near roots or the leaching of salts, or even the combination of the two.

3.2.3. Soil Organic Carbon (SOC)

SOC content, on the other hand, is very homogeneous within the experimental area since no significant differences are observed between zones, in all scenarios. A similar outcome was obtained in a study performed in a Chilean vineyard, using EC_a as an indicator for zone definition [16]. As such, organic matter added to soil, if needed, could be done uniformly across the field. However, since this characteristic is quite temporally stable in the soil, it is not expected to be a necessity in the upcoming years. Even if not observed in the present work, a small correlation between soil organic matter and EC_a has been documented in a similar condition, i.e., in a Mediterranean vineyard [51].

3.2.4. Soil Total Nitrogen (N_{tot}) and Extractable Phosphorus (P)

Concerning N_{tot}, the results reveal significant differences when using NDVI and NDVI + EC_a for zone delineation, but no differences were observed between zones when using only EC_a. High NDVI levels were related to a high content of soil N_{tot}. Here, the importance of NDVI to differentiate management zones for nitrogen fertilization is indisputable, as N_{tot} strongly influences this indicator. This correlation has been thoroughly studied in the past decades due to the importance of nitrogen to plant biomass production (e.g., recently: [55–57]).

Using EC_a in the delineation of distinct zones, regarding soil N content, was only effective when used jointly with NDVI. Nevertheless, EC_a addition proved to be very effective as the three zones, delineated in the scenario NDVI + EC_a, were substantially different from each other and thus can be managed differently.

For extractable P content, the zones were only significantly different when using NDVI for zone definition, with high values of the nutrient being related to high levels of NDVI. In the present work, using EC_a for zone definition added no value. The relationship between soil P and the indicators varies in the literature, with some studies finding no significant correlation between EC_a and soil P [14,24], whereas other researchers found a significant correlation ($R^2 = 0.61$) between Olsen P and EC_a [13]. Serrano et al. [24] found a small connection between P and NDVI ($p < 0.05$) in a vineyard. By considering the soil type, in terms of soil texture, ECEC, and humic matter, some authors have improved the correlation between this nutrient (and others) and EC_a [58].

3.3. Cation Exchange Complex

3.3.1. Exchangeable Cations

The exchangeable cation content is significantly different between zones in all three scenarios, as seen in Table 3. The high content of exchangeable cations is related to low NDVI and to high EC_a in the scenarios where only one indicator is used. This finding corroborates the hypothesis mentioned in Section 3.2.2., which stated that low vegetation health (low NDVI) may be related to a high content of salts in the soil. Aeration promoted by the larger particle soil also plays an important role in plant health; however, these results do indicate that leaching of excess salts in these soils may have a greater impact on crop health and NDVI than the aeration.

Table 3. Mean values of soil exchangeable cations, exchangeable acidity (EA), and effective cation exchange capacity (ECEC) according to zone and indicator used.

Zone Design	**Exchangeable Cations**				**EA**	**ECEC**
	K^+	**Ca^{2+}**	**Mg^{2+}**	**Na^+**		
	($cmol^+ kg^{-1}$)					
NDVI						
N+	0.19 b	1.83 b	0.76 b	0.07 b	0.22	3.07 b
N−	0.23 a	3.03 a	2.96 a	0.43 a	0.22	6.87 a
Signif.	*	***	***	***	ns	***
EC_a						
E+	0.23 a	2.52 a	2.01 a	0.26 a	0.28 a	5.31 a
E−	0.15 b	1.66 b	0.45 b	0.04 b	0.11 b	2.40 b
Signif.	***	**	***	***	***	***
NDVI + EC_a						
N+ E−	0.15 b	1.66 b	0.45 c	0.04 b	0.11 c	2.40 c
N+ E+	0.23 a	2.01 b	1.07 b	0.09 b	0.33 a	3.74 b
N− E+	0.23 a	3.03 a	2.96 a	0.43 a	0.22 b	6.87 a
Signif.	***	***	***	***	***	***

Signif.—significance level by the F test, ns—non-significant at $p < 0.05$ level, significant at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***) by the F test. In each column, values followed by the same letter do not significantly differ by the LSD test at $\alpha = 0.05$.

In the results from scenario NDVI + EC_a, the effect of K^+ on EC_a is noticeable, since high K^+ content is related to high EC_a, regardless of NDVI levels. This result is not in agreement with other results, as some have found no correlation between EC_a and K^+ [14,50]. A similar but inverse relationship was observed between Ca^{2+} and NDVI in the present work, with low Ca^{2+} related to high NDVI levels.

Concerning Mg^{2+} and Na^+, both differed at the highest significance level in all three scenarios: NDVI, EC_a, and NDVI + EC_a. Both cations are normally correlated with EC_a, but Na^+ has shown a more dominant correlation with EC_a in previous studies [14,50] as compared to the present results. In another study, Mg^{2+} was the most correlated cation with EC_a, and since it was most correlated at higher depth, the authors justified this correlation with the parent material of the soil [13]. In the present case study, both Na^+ and Mg^{2+} were also highly related to NDVI.

Additionally, the soil content of Mg^{2+} is significantly different between the three zones established in the NDVI + EC_a scenario. This is a very positive outcome because delineating zones based on two indicators, instead of just one, allowed the definition of three significantly distinct zones in terms of Mg^{2+}, which in turn, if managed differently, allows for better soil and crop fertilization, more adequate to the field intra-variability.

3.3.2. Exchangeable Acidity (EA) and Effective Cation Exchange Capacity (ECEC)

EA differed between zones delineated with EC_a, with high EC_a associated with high EA, but it did not differ when using NDVI. However, in the scenario NDVI + EC_a, the three zones were significantly different from each other, again showing the effectiveness of combining two indicators for the delineation of management zones. The differences observed in EA results are the same as the differences obtained in pH (H_2O) results, implying that EA is positively related to distilled water extracted pH, rather than calcium chloride extracted pH. Contrarily to what was previously mentioned, the variations in pH (H_2O) accompanied the EA variations in the present work conditions. The low values of EA imply that no acidity issues are expected in the soil [59].

As for ECEC, due to the content of exchangeable cations and EA, high values of ECEC correspond to low NDVI and high EC_a. Regarding ECEC, the differences between zones, and the relationship with NDVI and EC_a, are the same as those obtained for soil clay content. This result is similar to those reported in previous works [8,13,14], evidencing the influence of soil clay content on EC_a measurement [58]. This agrees with the rationale that EC_a increases with the increase in charges in the soil surfaces, e.g., an increase in clay minerals in the soil matrix, and an increase in exchangeable cations [13].

Like soil Mg^{2+}, ECEC content is substantially different between the three established zones (in scenario NDVI + EC_a), suggesting a strong influence of the nutrient in ECEC.

3.4. Ratios within the Cation Exchange Complex

The ratios between cations and the percentages of the cations within ECEC are presented in Table 4. The understanding of the exchangeable cation content in soil is very important, as they are in a plant-available form and consequently important for plant growth [13]. Equally important are the cation ratios in the soil cation exchange complex, as a disequilibrium between cation content may affect soil physical properties, such as clay dispersion due to Na excess, and nutrient availability to plants, as the excess of one cation may harm another cation's absorption (e.g., potassium and magnesium antagonism), therefore affecting root growth and development and plant performance and productivity.

As seen, high NDVI and low EC_a are related to higher values of Ca^{2+}/ECEC and K^+/ECEC and lower proportions of Mg^{2+}/ECEC and Na^+/ECEC. Hence, it is natural that they are also related to higher Ca^{2+}/Mg^{2+} and K^+/Mg^{2+} ratios.

In the scenario where both indicators are used for zone delineation, almost all ratios, except for K^+/ECEC and Na^+/ECEC, were significantly different between the three zones, again demonstrating the usefulness and effectiveness of using two indicators for zone delineation, one for soil salinity and a multitude of soil chemical and physical parameters (EC_a), and another that relates to crop response and health (NDVI).

The Ca^{2+}/Mg^{2+} ratio, which is important as it indicates the likely effect of clay dispersion consequent from Mg^{2+} excess [60], should be within the interval 2–10 for optimal vineyard production [53]. However, the ratio in zone N−, zone E+, and zone N−E+ is below the mentioned interval, which may indicate an excess of Mg^{2+} in relation to Ca^{2+}, in turn inducing clay dispersion and affecting soil structural stability. Lanyon et al. [53] suggested that this effect is induced in soils with ratios of Ca^{2+}/Mg^{2+} below 1. This is not seen in the results; however, zones N− and N−E+ have this ratio very close to 1 (1.01 as seen in Table 4). Therefore, this is something to investigate in the future as the excess of Mg^{2+} may cause soil damage and, consequently, loss of crop productivity.

Table 4. Mean values of ratios between Ca^{2+} and Mg^{2+} and K^+ and Mg^{2+} and percentages of the cations within the effective cation exchange capacity (ECEC) according to zone and indicator used. Also shown are the "suggested criteria for soil chemical status for sustainable vine health for wine grape production" [53].

Zone Design	Ca^{2+}/Mg^{2+}	K^+/Mg^{2+}	Ca^{2+}/ECEC	K^+/ECEC	Mg^{2+}/ECEC	Na^+/ECEC
			%			
NDVI						
N+	3.18 a	0.32 a	61.41 a	6.41 a	22.31 b	2.13 b
N−	1.01 b	0.08 b	41.99 b	3.59 b	44.56 a	6.22 a
Signif.	***	***	***	***	***	***
EC_a						
E+	1.62 b	0.17 b	48.32 b	4.95 b	35.59 a	4.35 a
E−	4.12 a	0.38 a	68.17 a	6.51 a	18.01 b	1.78 b
Signif.	***	***	***	***	***	***
NDVI + EC_a						
N+ E−	4.12 a	0.38 a	68.17 a	6.51 a	18.01 c	1.78 b
N+ E+	2.24 b	0.25 b	54.65 b	6.31 a	26.61 b	2.48 b
N− E+	1.01 c	0.08 c	41.99 c	3.59 b	44.56 a	6.22 a
Signif.	***	***	***	***	***	***
Reference values according to Lanyon et al. [53]	2–10	0.1–0.4	60–80	5–10	15–30	<6

Signif.—significance level by the F test, significant at $p < 0.001$ (***) by the F test. In each column, values followed by the same letter do not significantly differ by the LSD test at $\alpha = 0.05$.

Simultaneously, the K^+/Mg^{2+} ratio, which should be between 0.1 and 0.4 for optimal vine production [53], is below the minimum threshold in two of the same zones: N− and N−E+, reinforcing the hypothesis of excess Mg^{2+} and the existence of an ionic imbalance in the soil's chemical composition. The fact that the excess of Mg^{2+} happens in zones with high EC_a and low NDVI suggests that the high content of this cation is increasing soil cation concentration to a point of decreasing crop vegetation health status and, eventually, affecting crop production.

Indeed, the ratio of Mg^{2+}/ECEC is very high in these zones (30 is the maximum value for this ratio according to Lanyon et al. [53]), confirming the excess of Mg^{2+} in this case study. According to the same author, Ca^{2+}/ECEC, K^+/ECEC, and Na^+/ECEC have reference values for optimal grape production (Table 4), and as seen in the results, the zones with the Mg^{2+} disequilibrium fail to be within these intervals: Ca^{2+} is below as well as K^+, but Na^+ is slightly above. An excess of Na^+ may even aggravate clay dispersion in these zones. The unhealthy vegetation, as reported by the low NDVI, may also be due to ion antagonism as the excess of Mg^{2+} is injuring K^+ absorption. This problem can be solved by lowering pH to make the absorption of Mg^{2+} difficult, but a more successful approach is potassium fertilization [61]. The success rate does depend on various factors, such as soil lime content [62].

Thereby, the zones with high EC_a and low NDVI deserve special attention, in the matter of fertilization purposes. Furthermore, throughout the present work, the results point to a negative relationship between EC_a and NDVI, since the differences obtained between zones are somewhat opposite when using one or the other indicator, i.e., one variable is high with high levels of EC_a and low levels of NDVI. This often happens in the results, with most of the soil variables tackled in the world, which supports the idea that, in the present case, a high concentration of exchangeable cations (more precisely, Mg^{2+}) is related to low plant vigor. In a Bordeaux vineyard, this relation was positive rather than negative [25], and in an arid environment, the relationship was also negative, which was attributed to salinity [18].

The interpretation of soil analysis relative to crop yield prediction is very uncertain in a vineyard since it is a perennial plant with storage organs that temporally varies in nutrient content [53]. Nonetheless, the present soil evaluation whilst using two remote indicators (NDVI and EC_a) for soil sampling proved to be extremely important because it allowed the definition of different zones, with contrasting soil properties in the study area.

4. Conclusions

For a few of the soil variables, NDVI alone was sufficient to delineate different zones, e.g., pH ($CaCl_2$) and extractable P. For other soil variables, such as pH (H_2O), EC_a allowed an effective zone definition. However, for most of the soil variable content, the combined use of the indicators proved to be more effective, as the three delineated zones in scenario NDVI + EC_a were significantly distinct, allowing the three zones to be managed differently, which would have not been possible if only one indicator had been used. That is the case of soil N_{tot}, Mg^{2+}, EA, and ECEC and the ratios Ca^{2+}/Mg^{2+}, K^{+}/Mg^{2+}, Ca^{2+}/ECEC, and Mg^{2+}/ECEC. As such, it is concluded that the use of both indicators, NDVI and EC_a, is more beneficial than using just one and that there is a high potential for differential application of crop nutrients and soil management in the present vineyard.

It is also formulated that, in the present study conditions, plant health is related to sand content because it allowed the leaching of excess salts, in this case, excess of Mg^{2+}. The negative relationship between NDVI and EC_a (the latter impacted by the excess of Mg^{2+}) also corroborates this hypothesis. However, further analysis is needed, such as petiole analysis at flowering and veraison stage, and registration of grape production is also important.

If the soil characterization had been performed as if the 6.77 ha of vineyard were homogenous, as is conventionally done, this ionic problem would have not been identified and would remain uncorrected. Hence, the use of these technological tools, namely NDVI and EC_a, is of great relevance in today's context and if used properly, is capable of increasing food production with less environmental impact.

Nevertheless, validation of these results in other conditions, with different soil types or in different regions, is still needed.

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