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Remote sensing of apparent soil electrical conductivity (EC_{ap}) and NDVI to delineate different zones in a vineyard for precision fertilization†

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Abstract: The intensification of agriculture has greatly enhanced crop productivity but so its potential environmental impact. Nutrients recycling and increase of resource use efficiency are the key points to keep production at high level with minimum impact. The present work's goal was to provide new insight on the spatial variability of soil chemical properties in a vineyard. For this, three different zones were identified in a 6,77 ha parcel, according to remote sensing of apparent soil electrical conductivity (EC_{ap}) and normalized difference vegetation index (NDVI). Soil samples from specific locations were then collected and chemically described, and the resulting data statistically analyzed. EC_{ap} and NDVI appeared as efficient tools in the definition different zones within the vineyard, with most of the soil chemical properties varying at the highest significance level (p<0.001) by the F test, except for extractable phosphorus (Égner-Rhiem) and organic carbon (TOC method). Overall, our results revealed potential for the implementation of site-specific soil fertilization and soil quality management.

Keywords: apparent soil electrical conductivity; normalized difference vegetation index; soil sampling; precision fertilization; vineyard

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1. Introduction

Intensification of agricultural systems with the sole purpose of increasing crop's productivity is no longer viable nor sustainable. The technologies that are being developed and have emerged in the last two or three decades has allowed the modernization of food production systems, capable of maintaining high productive crops whilst reducing consequent environmental impacts. That is the case of Precision Agriculture (PA), a food production system based on the variable and precise use of inputs, to match the specific site characteristics within a field and the adequate timing of application, i.e., can adjust the amount of input material used and achieve optimal yield [1,2].

As a result, resource use efficiency is improved by generating less losses to the environment with more economic benefits in contrast to the conventional uniform management [2-4]. Consequently, there is an opportunity of PA practices in tackling climate change, since the amount of production inputs responsible for greenhouse gas emissions, e.g., fertilizers, pesticides, irrigation, is reduced [2]. When PA technologies are applied for fertilization purposes, crop productivity and quality is expected to be higher, and yield is more stable [5].

However, the delineation of homogenous fertility zones within a field, which allows site-specific management of production inputs, remains difficult to implement due to the complex relationships between soil nutrients and the vast spatial variability of soil chemical and physical properties, being responsible for crop production variations [6]. And so, the within-field variability must be known or quantified, which can be achieved through the mapping of relevant variables or attributes [7], for instance, soil physical and chemical properties.

To identify such attributes, the current paper presents there two examples. The first, field-scale apparent EC_{ap} maps are used to measure various characteristic, such as soil salinity, soil water content, clay content, organic matter, and many other properties that are known to mutually influence soil electrical conductivity [6,8]. Altogether, interpretation of EC_{ap} maps is a very complex process, requiring expertise and ground-truth soil samples, however, it is a fundamental economic tool to strategy sampling locations, reducing the number of samples needed to describe spatial variability of soil physical and chemical properties [8], which otherwise would be very time and cost consuming.

Second, NDVI which is also a very common and well-recognized in PA, is correlated to several crop parameters, such as plant physiology, crop yield and production biomass [9]. The indicator is obtained from the expression (1) [10,11], where Band4 is the reflectance of near infrared (NIR) radiation and Band3 is the reflectance of red radiation, also known as visible radiation. The indicator varies from +1 to -1, where positive values represent vegetation or high-reflective surfaces, since they have higher reflectance of NIR radiation, and negative values indicate non-vegetation or senescent and dry vegetation, or clouds and water, with less reflectance of NIR radiation [11].

$$NDVI = (Band4 – Band3) / (Band4 – Band3), \quad (1)$$

In the present work, these two indicators were used in combination to selec zones within a vineyard. Three different zones were selected, and soil samples were collected in specific locations and later analysed. Afterwards, statistical analysis was made to determine if 1) these tools were effective in the delineation of different zones within a field and 2) if there is a potential for the implementation of precision fertilization within the vineyard.

2. Materials and Methods

2.1. Experimental site

The experimental site is located in a vineyard of *Vitis vinifera* L in Montijo, Portugal (38°41'25.9"N 8°45'40.8"W). The selected study area has 6,77 ha, with the vines spaced by 1,4 m x 2,8 m.

The soil was primarily classified as an Orthic Podzol, according to the World Reference Base for soil classification, a soil with low nutrient status, low moisture content and low pH, and is common to present aluminium (Al) toxicity and phosphorus (P) deficiency issues [12]. The region's climate is a Csa, according to the Köppen-Geiger climate classification, a temperate climate with rainy winter and dry summer [13].

The vineyard has drip irrigation system that provides water during the months of June and July, over berry formation. The vineyard soil is fertilized, once a year after the dormant season, with an organic fertilizer (4.2:4.5:1; 65% organic matter content) at a rate of 1000 kg ha^{-1}. The organic fertiliser is applied in the shape of pellets of 4 mm at 40 cm depth in alternated inter-row.

2.2. Experimental design

Three different potential management zones were selected within the experimental area, according to the remote measurements of EC_{ap} and NDVI, as follows: zone one (Z1) has high levels of NDVI and low EC_{ap}, zone two (Z2) has high levels of NDVI and EC_{ap} and zone three (Z3) has low NDVI and high EC_{ap}.

2.3. Remote sensing

The EC_{ap} map was obtained with the EM38-MK2 sensor [14], mounted on a four-wheel motorcycle, and NDVI was obtained from Copernicus Sentinel-2 [15].

2.4. Soil analysis

Soil samples were collected in the summer of 2019, from the first 0-50 cm of arable soil, using a probe. Prior to be chemically analysed, soil samples were air-dried until constant weight, and sieved through a 2-mm mesh. The chemical properties assessed in the present study were the following: pH and laboratory determined soil electrical conductivity ($EC_{1:2,5}$), soil organic carbon (SOC), total nitrogen (N), extractable P and potassium (K), exchangeable cations K^+, Ca^{2+}, Mg^{2+} and Na^+, exchangeable acidity (EA), sum of bases (SB), base saturation percentage (BSP), and cation exchange capacity (CEC). The last-mentioned properties were calculated from the following expressions (2):

$$SB = K^+ + Ca^{2+} + Mg^{2+} + Na^+, \qquad CEC = SB + EA, \qquad BSP = SB / CEC, \tag{2}$$

Both pH and $EC_{1:2,5}$ were measured in a 1:2.5 soil:water suspension prepared with distilled water, using a potentiometer, and an electrical conductivity meter at room temperature, respectively. Furthermore, pH was also measured in a 1:2.5 soil:$CaCl_2$ (0.01 M) suspension.

Extractable P and K were determined using the Égner-Rhiem method and measured through Inductively Coupled Plasma (ICP-OES) technique; SOC concentration was determined through total organic carbon (TOC) method using dry combustion; total N was measured using Kjeldahl method. Exchangeable cations were determined by extraction with ammonium acetate and then quantification through ICP-OES technique; EA was determined through KCl (1 M) extraction, followed by titration with NaOH (0.043475 M).

Particle size determination was also evaluated in the present work, and was measured through the conventional Pipette Method to obtain soil percentage of sand, silt, and clay.

2.5. Statistical analysis

The experimental data were analysed through analysis of variance, using the General Linear Model (GLM) procedure for factorial design and F-test. Means separation was performed using the LSD test with significance level set at α =0,05. All statistical analysis was achieved through the Statistix software package [16].

3. Results and discussion

Statistical analysis revealed that most of the selected soil properties significantly varied between zones, with a high significance level (p<0.001) by the F test (Table 1 and 2). However, SOC and extractable P did not significantly change with zones. In fact, SOC values observed here are relatively low, as expected in an aged vineyard [17], and very homogeneous in the present vineyard. Therefore, in the event of organic matter supplementation, it should be homogeneous in the entire field area.

The differences observed in this data suggests that zones are different between each other, in turn indicating a potential for differential soil fertility management, and simultaneously showing the efficiency of EC_{ap} and NDVI in selecting different zones within the vineyard. Indicators EC_{ap} (Geonics EM38®) and NDVI had already been successfully used before to delineate management zones in vineyards [18]. In another case, EC_{ap} (Veris 3100®) used exclusively, was highly correlated with pH (1:2,5 soil:water ratio extraction), soil organic matter content and electrical conductivity (extract) but was not correlated with P content (Bray & Kurtz method) [19]. The author's result is similar to the present results, regarding pH and EC, and also with the lack of P variations with the selected zones and selecting method, even adding the NDVI indicator, which also confirms the difficulty of identifying homogenous zones within a field.

Additionally, there is a tendency of higher soil N_{tot} content in zones with high NDVI values, as Z2 and Z1 (zones with high NDVI) presented the highest N_{tot} content, in that order. The correlation of NDVI with soil N content has been extensively studied (e.g., [20]), and so the outcome was to be expected. Nevertheless, NDVI was a vital component in the delineation of zones within the vineyard and showed the potential for differential N fertilization in the present vineyard.

Table 1. Effect of zone on soil pH (extracted with H_2O and with $CaCl_2$), soil electrical conductivity extracted in a 1:2,5 soil:water proportion ($EC_{1:2,5}$), soil organic carbon (SOC), total N, and extractable P and K.

Zones	**pH**	**pH**	**$EC_{1:2,5}$**	**SOC**	**N_{tot}**	**Extractable**	
						P	**K**
	(H_2O)	($CaCl_2$)	(µS cm^{-1})	(%)		(mg kg^{-1})	
Signif.	**	***	***	*ns*	***	*ns*	***
Z1	6,25 b	5,36 b	64,60 b	0,42	255,30 b	19,85	56,90 b
Z2	6,48 a	5,35 b	81,11 b	0,42	315,98 a	18,55	91,50 a
Z3	6,51 a	5,70 a	161,27 a	0,42	179,85 c	8,83	90,33 a

Signif. – significance level by the F test, ns – non-significant at $p<0.05$ level, significant at $p<0.05$(*), at $p<0.01$(**) and 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 $\alpha=0.05$.

Table 2. Effect of zone on selected soil exchangeable cations, exchange acidity (EA), cation exchange capacity (CEC), sum of bases (SB) and base saturation percentage (BSP).

Zones	**Exchangeable cations**				**EA**	**CEC**	**SB**	**BSP**
	K^+	**Ca^{2+}**	**Mg^{2+}**	**Na^+**				
				($cmol^+ kg^{-1}$)				%
Signif.	***	***	***	***	***	***	***	***
Z1	0,15 b	1,66 b	0,45 c	0,04 b	0,11 c	2,40 c	2,30 c	94,46 a
Z2	0,23 a	2,01 b	1,07 b	0,09 b	0,33 a	3,74 b	3,41 b	90,04 b
Z3	0,23 a	3,03 a	2,96 a	0,43 a	0,22 b	6,87 a	6,65 a	96,35 a

Signif. – significance level by the F test, ns – non-significant at $p<0.05$ level, significant at $p<0.05$(*), at $p<0.01$(**) and 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 $\alpha=0.05$.

In respect to $EC_{1:2,5}$, Z3 presented the highest value registered, twice as high as Z2, even though these zones both have high EC_{ap} levels. Regarding pH extracted with water, Z3 and Z2, zones with high EC_{ap}, both had high pH results when compared to Z1, zone with low EC_{ap}. However, pH extracted with $CaCl_2$ was highest only for Z3. In relation to exchangeable cations, Z3 presented the highest concentration of K^+, Ca^{2+}, Mg^{2+} and Na^+, as seen in Table 2, although K^+ was also high in Z2. Again, Z3 presented the highest value of CEC, SB and BSP; the latter was also high in Z1, due to the calculation of low SB divided by low CEC.

Regarding soil percentage of sand, silt, and clay, as shown in Table 3, the results revealed that Z2 and Z3, presented higher content of clay and less of sand, significantly contrasting with Z1.

Soil electrical conductance has three pathways: 1) liquid phase, 2) solid-liquid and 3) a solid pathway, and the key contributors for these pathways are clay content and type, CEC, and organic matter for several reasons, such as the exchange surfaces in clay minerals and organic matter who "provide a solid-liquid phase pathway primarily via exchangeable cations" [21]. And so, soils with high clay content are expected to have higher CEC, due to the exchange surfaces in clay mineral that adsorb exchangeable cations and consequently higher count of exchangeable cations, an effect observed in the present study. Another author confirms the strong correlations of EC_{ap} (Geonics EM38®) with clay content and CEC, and regarding all types of EC_{ap} data used in the study [22]. Other research found that EC_{ap} well explained extractable Na^+, Mg^{2+} and sand and clay content, particularly in a vineyard in California [23].

Ultimately, EC_{ap} allowed the definition of three different zones within the current vineyard regarding soil texture, and simultaneously, regarding soil pH, exchangeable cations, acidity, sum of bases and base saturation percentage.

Table 3. Effect of zone on percentage of sand, silt, and clay in soil samples.

Zones	Sand	Silt	Clay
		%	
Signif	***	***	**
Z1	85,06 a	5,71 b	9,23 b
Z2	73,43 b	8,58 a	18,00 a
Z3	71,16 b	6,67 b	22,17 a

Signif. – significance level by the F test, ns – non-significant at $p<0.05$ level, significant at $p<0.05$(*), at $p<0.01$(**) and 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 $\alpha=0.05$.

5. Conclusions

The results showed the efficiency of combining the indicators EC_{ap} and NDVI in the delimitation of three distinct zones within the vineyard in respect to all the assessed soil properties, except for SOC and extractable P. As such, the study area did show potential for site-specific management of soil fertilization and soil health management, however, not in the case of P fertilization.

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