SPATIAL VARIABILITY OF VEGETATION INDICES (SENTINEL-2) FOR COFFEE CROP MONITORING ON SMALL FARM

C.R. Grego[1], C. A.G. Rodrigues[2], A Luchiari Jr[3], G. C. Rodrigues [4], C. F. Quartaroli[5], A. Pereira[6], V.F. Melo[7], F. Fagundes[8]

[1] Embrapa Digital Agriculture, Av. Dr. André Tosello, 209 - Cidade Universitária, Campinas - SP, 13083-886, celia.grego@embrapa.br
[2] Embrapa Territorial, Av. Soldado Passarinho, nº 303, Fazenda Jardim Chapadão CEP: 13070-115 - Campinas - SP, cristina.rodrigues@embrapa.br
[3] Embrapa Digital Agriculture, Av. Dr. André Tosello, 209 - Cidade Universitária, Campinas - SP, 13083-886, ariovaldo.luchiari@embrapa.br
[4] Embrapa Digital Agriculture, Av. Dr. André Tosello, 209 - Cidade Universitária, Campinas - SP, 13083-886, Gustavo.rodrigues@embrapa.br
[5] Embrapa Territorial, Av. Soldado Passarinho, nº 303, Fazenda Jardim Chapadão CEP: 13070-115 - Campinas - SP, carlos.quartaroli@embrapa.br
[6] Caconde Rural Union , R. Benedito de Oliveira Santos, 64 - Centro, Caconde - SP, 13770-000 ,ademarpereira.caconde@hotmail.com
[7] Sebrae SP, R. Benedito de Oliveira Santos, 64 - Centro, Caconde - SP, 13770-000 complete address, valeriafmelo38@gmail.com
[8] Caconde Rural Union , R. Benedito de Oliveira Santos, 64 - Centro, Caconde - SP, 13770-000 , fabriciofagundes48@gmail.com

Abstract: Monitoring the development of coffee crops on small farm with steep slopes is facilitated by resources like high-spatial-resolution satellite imagery, such as that obtained by Sentinel-2A. From this data, it's possible to derive NDVI (Normalized Difference Vegetation Index) and NDRE (Normalized Difference Red-Edge Index). The objective of this study was to monitor the vegetative development phase of coffee crops on a smallholding in the municipality of Caconde, SP, for 5 years. Sentinel-2A images from December of 2020, 2021, 2022, 2023, and 2024 were selected and downloaded to generate NDVI and NDRE images. A total of 2,671 NDVI pixels and 671 NDRE pixels were extracted and subjected to geostatistical analysis to identify spatial variability and construct contour maps. The results from the geostatistical analysis allowed for the identification of scaled-time spatial dependence of the data for both indices. Furthermore, the maps reveal a change in vegetative pattern over the years in response to crop management carried out between these study years.

Keywords: NDVI, NDRE, geostatistical, satellite image.

VARIABILIDADE ESPACIAL DE ÍNDICES DE VEGETAÇÃO (SENTINEL-2) PARA MONITORAMENTO DA CULTURA DO CAFÉ EM PEQUENA PROPRIEDADE

Resumo: O monitoramento do desenvolvimento da lavoura de café em pequena propriedade em declive elevado é facilitado por meio de recursos como imagens de satélite de alta resolução espacial como as obtidas pelo Sentinel 2A, o qual é possível obter os índices NDVI (Indice Vegetativo de Diferença Normalizada) e NDRE (Indice de Borda Vermelho de Diferença Normalizada). O objetivo desse trabalho foi realizar o monitoramento durante 5 anos da fase de desenvolvimento vegetativo da cultura do café em pequena propriedade no município de Caconde, SP. Foram selecionadas e baixadas imagens Sentinel-2A do mês de dezembro dos anos de 2020, 2021, 2022, 2023 e 2024 para geração das imagens de NDVI e NDRE. Foram extraídos 2.671 pixels de NDVI e 671 pixels de NDRE e foram submetidos a análise geoestatística, para identificação da variabilidade espacial e construção de mapas de contorno no software ArcGis 10.7. Os resultados obtidos decorrentes da análise geoestatística permitiram identificar a dependência espacial dos dados de forma escalonada no tempo para os dois índices e pelos mapas é possível caracterizar uma mudança de padrão vegetativo no decorrer dos anos em resposta ao manejo da cultura realizado entre estes anos de estudo.

Palavras-chave: NDVI, NDRE, geoestatistica, imagem de satélite.

1. Introduction

Considered the municipality with the largest coffee production area in the state of São Paulo, Caconde is characterized by small rural farm located in hilly terrain, producing high-quality coffee. Given the importance of this agricultural activity, monitoring crop development is facilitated by resources like high-spatial-resolution satellite imagery, such as that obtained by Sentinel-2A, from which NDVI (Normalized Difference Vegetation Index) and NDRE (Normalized Difference Red-Edge Index) can be derived. The relationship between vegetation indices (VIs) and the vegetative, and consequently productive, development of plants primarily aids in crop monitoring and management for obtaining data with greater precision and speed. The NDVI is more commonly used due to its ease of acquisition and its strong correlation with crop growth and subsequent monitoring for management purposes (Shiratsuchi et al., 2014). The NDRE utilizes the transition band between visible red and near-infrared, proving to be more sensitive to chlorophyll content and leaf structure (Xie et al., 2018). The investigation of the spatial variability of these indices can be performed using geostatistical analysis tools, which can generate variability maps that are unbiased and have minimum variance. The objective of this study was to monitor the spatial variability over 5 years during the period vegetative development important of coffee crops on a small farm in the municipality of Caconde, SP.

2. Materials and Methods

The work was developed on a small coffee farm in Caconde, SP (Figure 1). The total area is approximately 25ha. The predominant soil in the region is Red-Yellow Latosol, with a humid subtropical climate (IPEF, 2014) and and sloped areas. Figure 1 also highlights three plots (A, B, and C) selected for soil fertility assessment for this 2023 coffee harvest. However, it is not the objective of this work to relate vegetation indices to fertility in these plots.

Figure 1. Sampling area with coffee crop for pixels to point index vegetation, divided into plots A (plot contorn red), B (plot contorn yellow and C (plot contorn blue), at Small Farm, Caconde, SP. Google satellite image (Qgis versão 3.34).

Sentinel-2A images from December of 2020, 2021, 2022, 2023, and 2024 were selected and downloaded, as this month represents the plants' grain-filling growth phase. The images were obtained already corrected for surface reflectance (Level 2A) from the Copernicus Browser platform of ESA (European Space Agency), accessed in July 2025. To generate the NDVI and NDRE images, ArcGIS software version 10.7 was used, applying bands B4 (Red) and B8 (NIR) for NDVI (NDVI = (B8 – B4) / (B8 + B4)), and bands B5 (Red-edge 1) and B8 for NDRE (NDRE = (B8 − B5) / (B8 + B5)), as per Fernández-Manso et al. (2016). A total of 2,671 NDVI pixels (10 m x 10 m) and 671 NDRE pixels (20 m x 20 m) were extracted, totaling 3,342 reference pixels, respectively for each of the dates in each year. The central pixel to NDVI ($100m^2$) and NDRE ($400m^2$) data for the 5 years were subjected to descriptive statistical and geostatistical analysis, including semivariance calculation, semivariogram fitting and validation, and kriging interpolation with 2m to interpolation grid. The use of geostatistics in raster data is not common, however, it was intended to improve the result of spatial dependence analysis and consequently improve map production. The geoestatistical analysis was according to the methodology described in Vieira (2000), using the GEOR program and related packages in the R Studio software environment. The interpolated data were used to construct contour maps in ArcGIS 10.7 software.

3. Results and Discussion

The descriptive statistics for the exploratory analysis of NDVI and NDRE data are presented in Table 1. It's observed that there was a gradual increase in the mean of both indices from 2020 to 2024 over time. This indicates an increase in vegetative vigor as time progressed, with pixels showing higher values.

Table 1. Descriptive statistics for NDVI and NDRE data over the five years analyzed.

Name	Num.	Mean	Variance	Std.Dev.	C.V.	Minimum	Maximum	Skewness	Kurtosis
NDVI									
2020	2671	0.6502	0.02	0.13	19.66	0.2759	0.868	-0.5143	-0.6031
2021	2671	0.6467	0.02	0.12	19.29	0.1573	0.8893	-0.9212	0.7366
2022	2671	0.7392	0.01	0.11	14.2	0.2189	0.9044	-1.657	3.815
2023	2671	0.7303	0.00	0.07	9.432	0.4054	0.904	-0.7537	1.319
2024	2671	0.807	0.00	0.07	8.133	0.4211	0.9239	-1.332	2.422
NDRE									
2020	671	0.437	0.009	0.094	21.55	0.1616	0.6074	-0.3883	-0.8229
2021	671	0.4513	0.010	0.098	21.71	0.09	0.6468	-0.9047	0.6108
2022	671	0.5354	0.006	0.077	14.3	0.1699	0.6637	-1.531	3.519
2023	671	0.5235	0.003	0.053	10.07	0.2921	0.682	-0.4939	0.9515
2024	671	0.573	0.003	0.052	9.108	0.3385	0.6922	-1.104	1.522

For the analysis of spatial dependence, scaled semivariograms were calculated and fitted for all years for both NDVI and NDRE (Figure 2). A similar pattern with strong spatial dependence was observed across the years, with a spherical model fit showing a nugget effect (0.1), parcial sill (1), and range (300)."

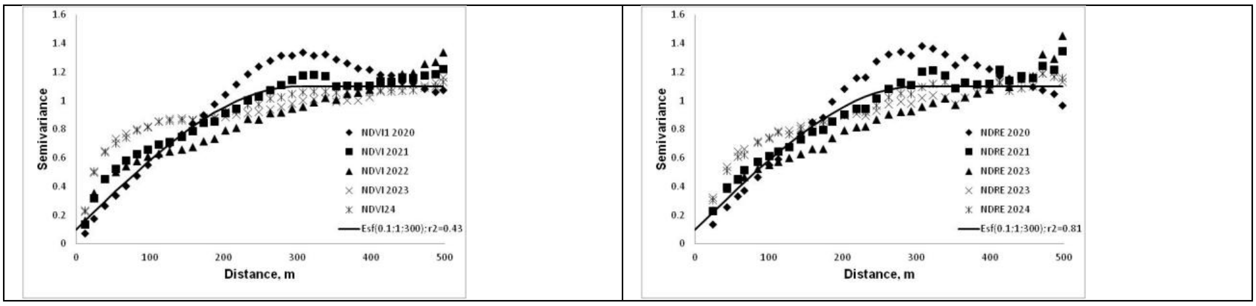
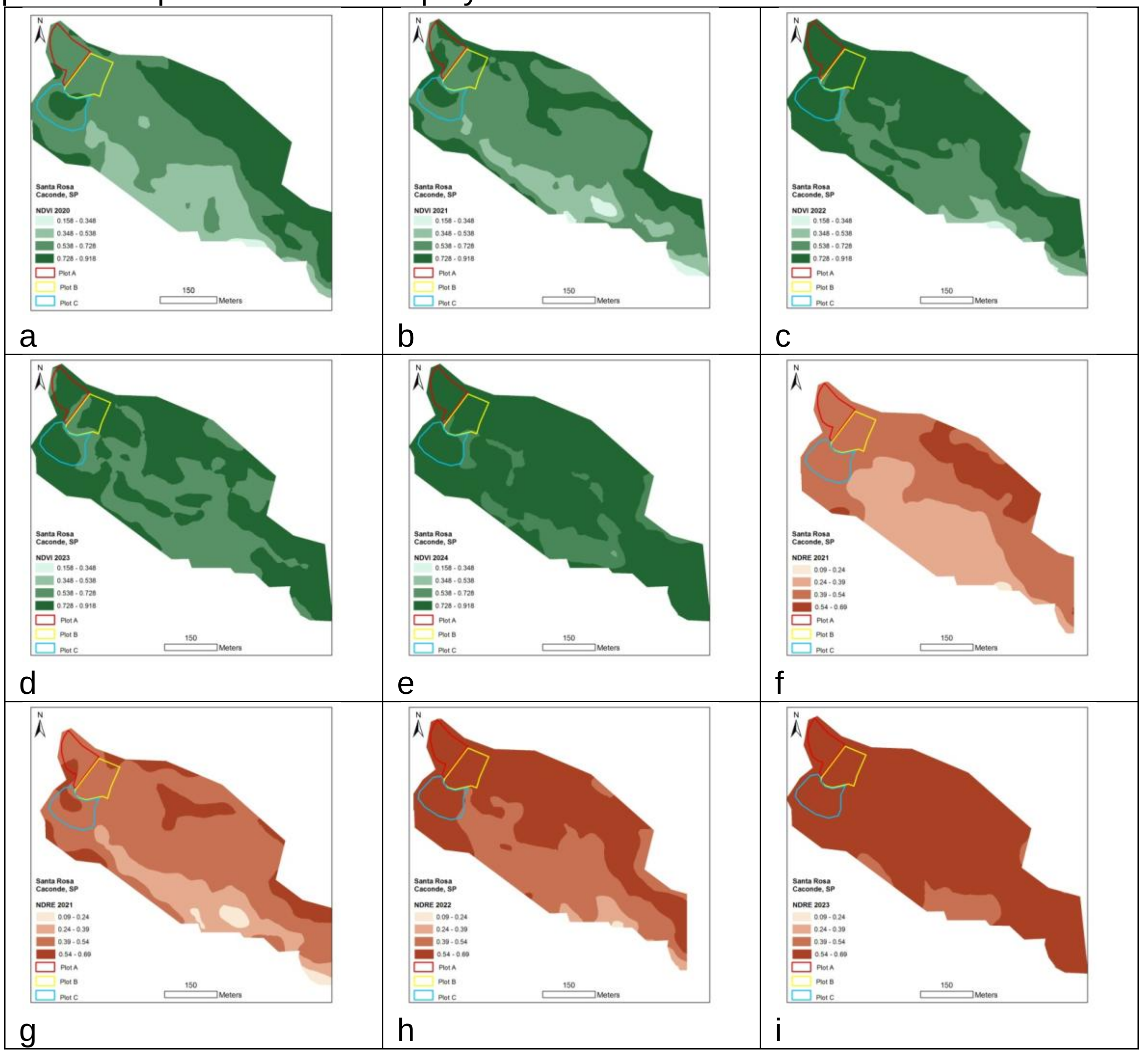


Figure 2. Scaled semivariograms fitted by the spherical model for NDVI and NDRE obtained from Sentinel-2A imagery in December from 2020 to 2024.

Contour maps were generated in ArcGIS software, using NDVI and NDRE data interpolated by ordinary kriging (Figure 3). The identified spatial dependence allowed for differentiation of changes in spatial variation over time. Larger patches with higher index values were observed in 2020, 2021, and 2022 compared to 2023 and 2024. This might reflect changes implemented by the producer regarding soil and plant management recommendations. According to Grego et al. (2024), a soil fertility assessment in the three plots (A, B, and C) of this coffee crop revealed low soil fertility and a need for canopy pruning. Therefore, fertilization and pruning management were recommended to improve the productive potential of the crop cycle.



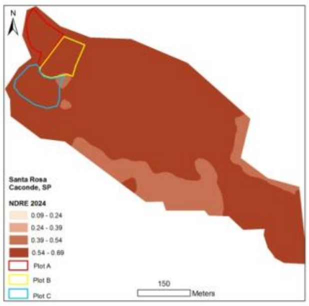


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Figure 3. Contour maps of data interpolated by kriging for NDVI (a, b, c, d, and e) and NDRE (f, g, h, i, and j) obtained from Sentinel-2 imagery in December from 2020 to 2024 on a small farm in Caconde, SP.

4. Conclusions

The high-resolution imagery from the Sentinel-2 satellite was suitable for monitoring the vegetative indices of coffee crops on small farms. NDVI and NDRE indexes were spatially dependent, allowing for the identification of variability patterns with higher values after soil and plant management in the study area. Therefore, the use of NDVI and NDRE derived from free, high-resolution images holds promise for correlation with management on small coffee farms.

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