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Monitoring vinasse fertigation using Sentinel optical and radar imagery applied to sugarcane production

Monitoramento da fertirrigação com vinhaça por imagens ópticas e de radar Sentinel aplicado à produção de cana-de-açúcar

Monitoreo de la fertirrigación con vinaza mediante imágenes ópticas y de radar Sentinel aplicado a la producción de caña de azúcar

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Abstract:
Remote sensing has expanded the possibilities for agricultural monitoring, and in this study we evaluate the use of Sentinel-2 and Sentinel-1 imagery to monitor vinasse fertigation in sugarcane production areas. Vinasse, a by-product of ethanol and sugar manufacturing, is rich in organic matter and nutrients and can supply water and fertilizers to the crop after harvesting, particularly during the dry season. However, insufficient, excessive, or uneven application can impair sugarcane development and reduce yield. On one farm analyzed, the Sentinel-2 image from April 2019 made it possible to identify effects associated with insufficient and uneven vinasse application, affecting approximately 21% of the evaluated area, or about 100 ha. For this area, an impact of 1,869 tonnes of sugarcane was estimated, equivalent to R$ 747,600.00, according to the economic parameters adopted in the study. Retrospective analysis of a Sentinel-2 image from July 2018 indicated sectors with no apparent application and pronounced spatial unevenness. The presence or absence of vinasse was perceptible in the visible bands, whereas differences in crop growth and stress were more clearly related to the red-edge and near-infrared bands in the April 2019 image, when the sugarcane was at an advanced development stage. A Sentinel-1 radar image from April 2019 was also analyzed. In that image, the absence of vinasse was not directly identified, although its effects on crop growth could be interpreted. The evaluation was extended to other agricultural fields and indicated a correlation coefficient of approximately −0.7 between the number of harvests and the SAVI index, while also identifying vinasse application failures in 52 fields. Based on these results, we propose a systematic approach to monitoring vinasse distribution and sugarcane development using Sentinel-2 and Sentinel-1 imagery, aiming to improve the operational efficiency, control, and sustainability of the process.

Keywords: sugarcane; fertigation; vinasse; remote sensing; Sentinel-2; Sentinel-1; SAVI; NDWI.

Resumo:
O sensoriamento remoto tem ampliado as possibilidades de monitoramento agrícola e, neste estudo, avaliamos a aplicação de imagens Sentinel-2 e Sentinel-1 no acompanhamento da fertirrigação com vinhaça em áreas de produção de cana-de-açúcar. A vinhaça, subproduto da fabricação de etanol e açúcar, é rica em matéria orgânica e nutrientes e pode fornecer água e fertilizantes à cultura após a colheita, especialmente durante o período seco. Entretanto, a aplicação insuficiente, excessiva ou desuniforme pode comprometer o desenvolvimento da cana e reduzir a produtividade. Em uma fazenda analisada, a imagem Sentinel-2 de abril de 2019 permitiu identificar efeitos associados à aplicação insuficiente e desuniforme da vinhaça,

correspondentes a aproximadamente 21% da área avaliada, ou cerca de 100 ha. Para essa área, estimou-se um impacto de 1.869 toneladas de cana, equivalente a R$ 747.600,00, conforme os parâmetros econômicos adotados no estudo. A análise retrospectiva de uma imagem Sentinel-2 de julho de 2018 indicou setores sem aplicação aparente e elevada desuniformidade espacial. A ocorrência ou ausência de vinhaça foi perceptível nas bandas do visível, enquanto as diferenças de crescimento e estresse da cultura apresentaram relação mais evidente com as bandas de borda vermelha e do infravermelho próximo na imagem de abril de 2019, quando a cana se encontrava em estágio avançado de desenvolvimento. Uma imagem de radar Sentinel-1 de abril de 2019 também foi analisada. Nela, a ausência de vinhaça não foi identificada diretamente, embora seus efeitos sobre o crescimento da cultura pudessem ser interpretados. A avaliação foi ampliada para outros talhões agrícolas e indicou coeficiente de correlação de aproximadamente −0,7 entre o número de colheitas e o índice SAVI, além de identificar falhas de aplicação de vinhaça em 52 talhões. Com base nesses resultados, propomos uma abordagem sistemática de monitoramento da distribuição da vinhaça e do desenvolvimento da cana-de-açúcar por meio de imagens Sentinel-2 e Sentinel-1, com o objetivo de ampliar a eficiência operacional, o controle e a sustentabilidade do processo.

Palavras-chave: cana-de-açúcar; fertirrigação; vinhaça; sensoriamento remoto; Sentinel-2; Sentinel-1; SAVI; NDWI.

Resumen:
La teledetección ha ampliado las posibilidades de monitoreo agrícola y, en este estudio, evaluamos la aplicación de imágenes Sentinel-2 y Sentinel-1 en el seguimiento de la fertirrigación con vinaza en áreas de producción de caña de azúcar. La vinaza, subproducto de la fabricación de etanol y azúcar, es rica en materia orgánica y nutrientes y puede aportar agua y fertilizantes al cultivo después de la cosecha, especialmente durante el período seco. Sin embargo, una aplicación insuficiente, excesiva o desigual puede comprometer el desarrollo de la caña y reducir la productividad. En una de las fincas analizadas, la imagen Sentinel-2 de abril de 2019 permitió identificar efectos asociados a la aplicación insuficiente y desigual de vinaza, correspondientes a aproximadamente el 21% del área evaluada, o cerca de 100 ha. Para esta área, se estimó un impacto de 1.869 toneladas de caña, equivalente a R$ 747.600,00, según los parámetros económicos adoptados en el estudio. El análisis retrospectivo de una imagen Sentinel-2 de julio de 2018 indicó sectores sin aplicación aparente y una elevada falta de uniformidad espacial. La presencia o ausencia de vinaza fue perceptible en las bandas del visible, mientras que las diferencias de crecimiento y estrés del cultivo mostraron una relación más evidente con las bandas del borde rojo y del infrarrojo cercano en la imagen de abril de 2019, cuando la caña se encontraba en una etapa avanzada de desarrollo. También se analizó una imagen de radar Sentinel-1 de abril de 2019. En ella, la ausencia de vinaza no se identificó directamente, aunque pudieron interpretarse sus efectos sobre el crecimiento del cultivo. La evaluación se amplió a otras parcelas agrícolas e indicó un coeficiente de correlación de aproximadamente −0,7 entre el número de cosechas y el índice SAVI, además de identificar fallas de aplicación de vinaza en 52 parcelas. A partir de estos resultados, proponemos un enfoque sistemático de monitoreo de la distribución de vinaza y del desarrollo de la caña de azúcar mediante imágenes Sentinel-2 y Sentinel-1, con el objetivo de mejorar la eficiencia operativa, el control y la sostenibilidad del proceso.

Palabras clave: caña de azúcar; fertirrigación; vinaza; teledetección; Sentinel-2; Sentinel-1; SAVI; NDWI.

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1. Introduction

Sugarcane (Saccharum spp., hybrid) is a perennial plant adapted to tropical regions, with a high capacity to produce and store sucrose [1]. Brazil holds a prominent position in global production of this crop. In the 2019/2020 season, national production exceeded 650 million tonnes [2], corresponding to more than 40% of the global total. The raw material is primarily used to manufacture sugar and ethanol. For decades, the production system was associated with preharvest burning of sugarcane fields, a practice with significant environmental impacts. The expansion of mechanized harvesting reduced this practice and changed the management of the resulting residues. These include fibrous bagasse and vinasse, a liquid effluent with a high organic load.

In the study area, the production process begins with the leasing of properties suitable for sugarcane cultivation. This is followed by soil preparation and land leveling, planting, fertilizer and pesticide application, irrigation, harvesting, transportation, and industrial processing to produce ethanol, sugar, and electricity.

At the industrial facility, harvested sugarcane is crushed, and the solid fibrous fraction, known as bagasse, is separated from the juice. After fermentation and distillation, vinasse is produced as a liquid residue. Considering the estimated production of 29 billion liters of ethanol in the 2020/2021 season and the ratio adopted in the study, approximately 319 billion liters of vinasse would be generated. Rather than being discarded, vinasse can be reapplied to agricultural areas as a source of water and nutrients for the next cycle. Experimental processes also exist for its use in biogas production. The agricultural application of vinasse as a fertilizer and water source is called fertigation. Its composition includes nutrients of agronomic interest, as presented in Table 1.

Table 1. Main parameters of the chemical composition of vinasse (Source: Embrapa).

Parameter	**Range**
pH	4.4–4.6
Temperature	80–100 °C
Oxygen demand	19,800 mg/L
Nitrogen (N)	480–710 mg/L
Phosphorus (P_2O_5)	9–200 mg/L
Potassium (K_2O)	3,340–4,600 mg/L
Calcium (CaO)	1,330–4,570 mg/L
Magnesium (MgO)	580–700 mg/L

Parameter	Range
Sulfate (SO_4)	3,700–3,730 mg/L
Carbon (C)	8,700–12,100 mg/L
Organic matter	3,800 mg/L

Vinasse fertigation is carried out shortly after harvesting, preferably within 20 days, to encourage ratoon regrowth and reduce the risk of bud damage. Under suitable conditions, the same sugarcane stand can be harvested for approximately five cycles and, in specific situations, undergo as many as ten cuts.

However, subsequent harvests tend to show declining yields, estimated in this study at approximately 10% per cycle, although this behavior may vary with the production environment and management practices.

Vinasse is transported to agricultural areas through open channels, pipelines, or trucks. In areas served by channels, self-reeling equipment, known as hydro-roll systems, is used to distribute the effluent over the sugarcane fields, as illustrated in Figure 1. Monitoring this process is complex and may vary between properties, although this stage directly affects field yields. In a 20 ha area, for example, the hydro-roll can be repositioned every 60 m to fertigate a strip approximately 350 m long, corresponding to the length of the automatically reeled pipeline. Gaps in distribution can reduce yields and, in more severe situations, threaten plant survival.

Sugarcane yields are also influenced by pests, diseases, soil conditions, and the quality of land preparation. Nevertheless, during the dry season and especially after harvesting, vinasse fertigation plays an important role. Failure to apply it, or delayed application, can intensify crop stress and reduce yield potential.

The fertigation system can operate continuously after harvesting and requires coordination between vinasse generation, transportation, and application. Inadequate application rates can cause accumulation or overflow in the channels and increase the risk of environmental impacts, including effects on watercourses and groundwater.

1.1 Remote sensing applied to sugarcane management

Remote sensing has been used in precision agriculture for sugarcane since the late 1970s [4], [5]. The Landsat series is one of the most widely used sources of satellite data in this context [5], with applications reported in Brazil, Australia, South Africa, and Thailand. SPOT (Système Probatoire pour l'Observation de la Terre) imagery, offering better spatial resolution than other

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sensors available at the time, was also used, particularly in Australia, South Africa, and India [6]. MODIS data, with lower spatial resolution ranging from 250 to 1,000 m, were employed to classify sugarcane areas in Brazil and Mozambique. However, despite their high revisit frequency, these data showed limitations such as spectral confusion with pastures.



(a) (b) (c)

Figure 1. Diagram of vinasse application: transport through the channel (a), conveyance to the hydro-roll (b), and distribution in the field (c).

With a spatial resolution of approximately 1,000 m, Duveiller et al. [7] used the Fraction of Absorbed Photosynthetically Active Radiation (FPAR), calculated from SPOT VEGETATION data, to estimate agricultural yields in the state of São Paulo, Brazil. Other studies investigated SAR (Synthetic Aperture Radar) data for mapping and monitoring sugarcane fields. Johnson and Kinsey-Henderson [8], for example, combined SPOT and ERS-1 data to map land use in an extensive sugarcane-producing region in Australia.

SAR data are frequently cited as an alternative to optical imagery when cloud cover limits surface observation, particularly during the rainy season. Baghdadi et al. [9] evaluated the potential of TerraSAR-X, ASAR/ENVISAT, and PALSAR/ALOS sensors to monitor sugarcane fields on Reunion Island using multitemporal approaches. The authors related the SAR backscatter coefficient (σ^0) to NDVI, plant height, and harvesting. Among their main results, they found that: 1) harvested fields can be identified; 2) plant height showed a stronger relationship with data acquired at larger incidence angles; 3) HV or VH cross-polarizations were slightly better than HH or VV co-polarizations for characterizing crop condition; and 4) the X band appeared potentially less sensitive to soil roughness than the L and C bands. Despite these advances, relatively few studies address SAR applications in sugarcane.

The reviews by Moran et al. [4] and Abdel-Rahman and Ahmed [5] identified various applications of remote sensing in sugarcane management. The following list summarizes these applications:

No.	Application
1	Sugarcane field classification
2	Mapping of area extent

No.	Application
3	Identification and maturity age
4	Varietal discrimination
5	Point measurements
6	Harvest yield forecasting
7	Soil variability
8	Crop monitoring
9	Identification of the causes of yield variation
10	Mapping of climatic conditions
11	Topographic assessment
12	Identification of operational periods

Items 6, 7, 8, 9, and 12 in this summary are directly or indirectly related to monitoring vinasse fertigation, the central topic of this article. The launches of Sentinel-1 in 2014 and Sentinel-2 in 2015 expanded the possibilities for multitemporal observation of sugarcane fields. In this context, this study aims to evaluate the usefulness of Sentinel-2 and Sentinel-1 data for identifying and quantifying the effects associated with inadequate vinasse distribution in sugarcane areas. To this end, we combine multitemporal Sentinel image series with field yield data. Ultimately, we seek to propose an image analysis method capable of supporting the monitoring of vinasse application and crop development.

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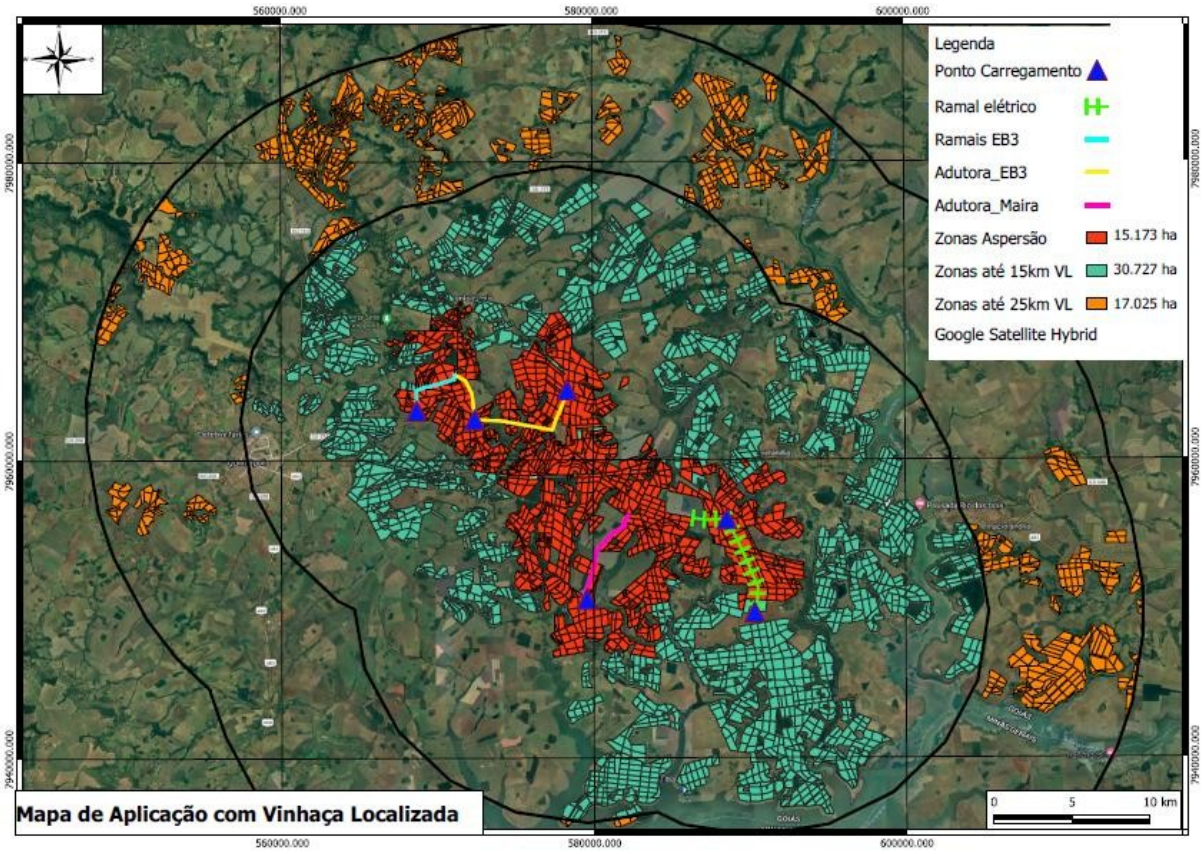

Figure 2. Location of the study area, sugarcane fields, and vinasse application zones. The area of interest corresponds to the sector fertigated by sprinklers.

Map labels: Legend; Loading point; Electric branch; EB3 branches; EB3 main pipeline; Maira main pipeline; Sprinkler zones; Zones up to 15 km VL; Zones up to 25 km VL; Google Satellite Hybrid; Map of localized vinasse application.

2. Methodology

2.1 Study area

The study area is located in the far south of the state of Goiás, near the municipality of Quirinópolis and the border with Minas Gerais (Figure 2), within the Paraná River basin. The analyzed dataset comprises 768 fields, shown in yellow in Figure 2, with an average area of approximately 16 ha. These fields form part of the production area of São João Cargill, SJC Bioenergia, the company that supplied the data used in this study. According to the available data, the operation encompassed approximately 150,000 ha of sugarcane and production of about 15 million tonnes.

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The region has annual rainfall of approximately 1,500 mm, concentrated mainly between October and April, and a mean temperature of around 25 °C. The terrain is gently undulating, with slopes of up to 6%. Soil textures range from sandy to clay loam.

2.2 Auxiliary data

Auxiliary data were supplied by SJC Bioenergia and consisted of control spreadsheets organized by field, with areas ranging from 12 to 60 ha. These records contained descriptive information used to select sampling units, according to the criteria presented below.

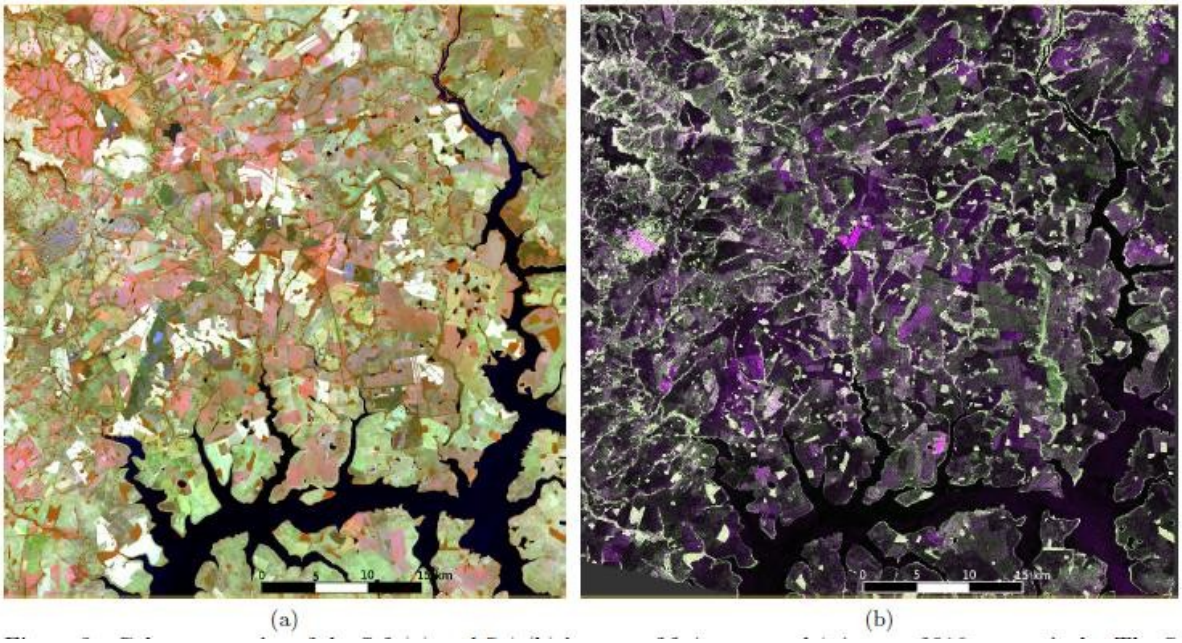

Figure 3. Color composites of Sentinel-2 imagery (a), from August 2, 2018, and Sentinel-1 imagery (b), from August 1, 2018. The Sentinel-2 composite corresponds to the “Healthy vegetation” enhancement available in SNAP, with infrared displayed in red, SWIR in green, and blue in blue. The Sentinel-1 composite uses VV in red, VH in green, and the VV − VH difference in blue.

Production fields were required to:

• be located in the area served by the vinasse distribution system using pumps and long pipelines, excluding areas without application or served by other methods, mainly trucks;

• be in the fourth or fifth harvest cycle; and

• have complete descriptive data.

In this study, the fourth and fifth cycles correspond to the fourth and fifth years of cultivation of the same sugarcane stand. This criterion was adopted because yields tend to decrease over successive cuts, with an estimated average reduction of approximately 10% per cycle. After a certain number of cuts, which may reach eight or nine depending on cultivation conditions, the sugarcane field is renewed and a new stand is established.

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2.3 Imagery and image processing

Sentinel-1 and Sentinel-2 images were obtained from the European Space Agency's Sentinel Data Hub for the period from 2018 to 2019, to represent different crop development stages and allow comparison with the 2019 harvest data. A single scene covered the entire study area. The acquisition dates used in the analyses are presented in Tables 2 and 3.

Sentinel-2 images were processed in SNAP software using reflectance products. The sensor has 13 spectral bands with spatial resolutions of 10, 20, and 60 m. The three 60 m bands have specific applications: coastal aerosols (B1), water vapor (B9), and cirrus cloud detection (B10).

These three bands were not used. Images with low cloud interference over the area of interest were selected. The four 10 m bands were retained at their original resolution, while the 20 m bands were resampled to 10 m using the bilinear method. The images were then cropped to the extent of the polygons of the evaluated fields. Figure 3 presents the August 2018 images as color composites, with the selected polygons overlaid.

SNAP was also used to calculate spectral indices. Following visual evaluation of the products, considering fields with previously known problems, SAVI (Soil-Adjusted Vegetation Index) and NDWI (Normalized Difference Water Index) were selected because they provided better discrimination of portions with possible uneven vinasse application.

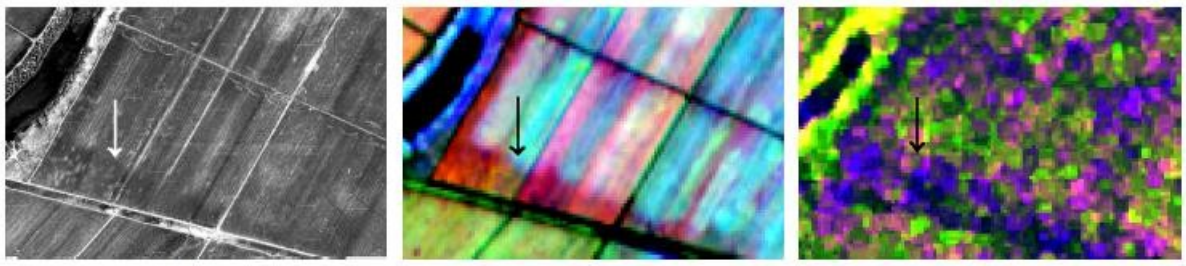

Figure 4. Example of possible nutritional stress associated with irregular vinasse distribution in sugarcane fields: (a) Google Earth image with a slight tonal difference; (b) multitemporal SAVI composite obtained from Sentinel-2 images from August, September, and November 2018; and (c) Sentinel-1 color composite using VV, VH, and the VV/VH ratio.

Sentinel-1 images were also processed in SNAP. The workflow included thermal noise removal, radiometric calibration, Range-Doppler terrain geometric correction, and Refined Lee speckle filtering. The products contained VV and VH polarizations, and the VV/VH ratio was added as a third variable. As with the Sentinel-2 images, the data were cropped to the study area.

Processing primarily consisted of extracting statistics by field. For each polygon, the mean, standard deviation, median, minimum, and maximum were calculated. This step was performed with the Objects Radiometric Statistics tool from Orfeo ToolBox (OTB; CNES, 2002–2018), using the vector file of the selected fields.

Image processing primarily consisted of extracting statistical parameters from the images of each stand. The following variables were extracted for each field: mean, standard deviation, median, minimum value, and maximum value. This operation was performed using "ObjectsRadiometricStatistics" from Orpheo Tool Box (OTB, Copyright © 2002–2018 CNES) and a shapefile of the selected fields.

2.4 Statistical testing

Because the objective was to define an approach that would facilitate the identification of fertigation problems, three limitations were considered. The first concerns the harvesting period, which extends from April to November and requires several images to represent the different crop stages. The second arises from the number of sugarcane cuts: because yields tend to decline over successive harvests, tonnage cannot be interpreted in isolation as a dependent variable. The third, and most relevant, concerns the scale at which yield was recorded, being available by farm rather than by field. This aggregation may hinder the identification of localized fertigation failures, because the same farm may contain fields with and without application problems.

To reduce these limitations, fields showing indications of fertigation problems, characterized by spatial heterogeneity on the observed dates, and fields with apparently homogeneous vinasse distribution were visually identified. These sets formed two comparison groups. Figure 4 presents examples of areas with visual signs of unevenness in a Google Earth image, a multitemporal Sentinel-2 composite, and a multipolarized Sentinel-1 composite.

Two statistical approaches were evaluated: 1) Pearson correlation between sugarcane tonnage per hectare (TCH) and the bands and indices derived from Sentinel-2, as well as the polarizations and polarization ratio from Sentinel-1; and 2) analysis of variance (ANOVA) to determine whether fields with indications of fertigation problems had different means from those observed in fields without such indications, and to identify the bands, polarizations, and indices with the greatest capacity to separate the groups.

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3. Results and discussion

Table 2 presents the Pearson correlations between sugarcane tonnage per hectare (TCH), the number of harvests (NH), and the individual bands of three Sentinel-2 images.

Table 2. Pearson correlation between sugarcane tonnage per hectare (TCH), the number of harvests (NH), and the individual Sentinel-2 bands.
The coefficients highlighted in bold are greater than 0.2 or less than −0.2 and are statistically significant at $p < 0.01$.
Table 2. Pearson correlation between sugarcane tonnage per hectare (TCH), the number of harvests (NH), and the individual Sentinel-2 bands.

S-2 band	Spectral range	04-04-2018 TCH	04-04-2018 NH	09-11-2018 TCH	09-11-2018 NH	18-04-2019 TCH	18-04-2019 NH
2	Blue	-0.01	-0.06	**-0.21**	0.09	0.04	**0.25**
3	Green	-0.06	0.03	**-0.22**	0.11	0.05	**0.24**
4	Red	-0.03	-0.12	**-0.26**	0.08	-0.02	**0.32**
5	Red edge 1	-0.04	-0.03	**-0.27**	0.08	-0.05	**0.33**
6	Red edge 2	-0.03	0.12	0.10	0.08	**0.41**	**-0.39**
7	Red edge 3	0.06	0.09	0.19	0.09	**0.41**	**-0.46**
8	NIR	0.04	0.10	0.17	0.11	**0.40**	**-0.45**
11	SWIR 1	-0.03	-0.01	**-0.23**	0.18	0.01	**0.33**
12	SWIR 2	0.02	-0.09	**-0.23**	0.15	-0.04	**0.35**

All numbers in bold are above 0.2 or below −0.2 and are significant at $p < 0.01$.

In the first image, acquired on April 4, 2018, no band showed a relevant correlation, greater than 0.2 or less than −0.2, with TCH or NH. This result may be associated with the fact that many fields had not yet been harvested and therefore reflected the effects of the previous cycle. In the second image, from November 9, 2018, significant but weak to moderate correlations, between −0.20 and −0.27, were observed in the visible, red-edge, and shortwave infrared bands. Although most fields had probably already been harvested, differences in their development stages may have reduced the expression of the effect under investigation. In the April 18, 2019 image, moderate correlations of around 0.40 were observed between TCH and red-edge bands 2 and 3 and the near-infrared band. The bands also showed correlations with the number of harvests, consistent with the tendency for yields to decline over successive cuts.

Table 3 presents Pearson correlations between TCH, NH, the NDWI and SAVI indices derived from Sentinel-2 images, and the polarizations and polarization ratio of Sentinel-1 images. Overall, NDWI showed significant results more frequently, whereas SAVI achieved correlations of greater magnitude, especially in the April 18, 2019 image, corresponding to a more advanced crop development stage. The positive correlation between TCH and SAVI suggests that the index responds to vegetative vigor and may help estimate relative yields.

Conversely, the negative correlation between NH and SAVI indicates decreasing vigor as the number of cuts increases. On the July and August 2018 dates, the signs of the correlations may also have been influenced by differences in harvest dates and the ratoon regrowth stages of the fields.

Table 4 presents the results of the analysis of variance used to test the null hypothesis of equal means between the groups with and without visual indications of fertigation problems. For NDWI, the null hypothesis was rejected on two of the six dates, September 30, 2018 and April 18, 2019, at the 5% significance level, with p = 0.036 and p = 0.046, respectively. For SAVI, the difference was significant only on September 30, 2018, with p = 0.038.

Table 4 presents the results of the analysis of variance used to test the null hypothesis of equal means between the groups with and without visual indications of fertigation problems. For NDWI, the null hypothesis was rejected on two of the six dates, September 30, 2018 and April 18, 2019, at the 5% significance level, with p = 0.036 and p = 0.046, respectively. For SAVI, the difference was significant only on September 30, 2018, with p = 0.038.

4. Conclusion

Nutritional stress associated with irregular or partial vinasse application in sugarcane areas proved visually identifiable in Sentinel imagery, particularly in Sentinel-2 optical products. However, the wide harvesting window makes it difficult to establish a systematic monitoring procedure. Variables such as the number of cuts may mask the effect of fertigation when analysis is restricted to field radiometric means. Visual interpretation simultaneously incorporates aspects related to tone, color, shape, size, spatial context, and temporal evolution. Another limitation concerns the availability of yield data at farm scale rather than field scale, which reduced the ability to directly relate local application failures to production outcomes.

Table 3. Pearson correlation between sugarcane tonnage per hectare (TCH), the number of harvests (NH), the SAVI and NDWI indices, and variables derived from Sentinel-1.

S-2 image date	TCH-NDWI	TCH-SAVI	NH-NDWI	NH-SAVI
04-04-2018	-0.04	0.11	-0.04	0.11
12-07-2018	-0.17	-0.17	-0.17	**0.37**
01-08-2018	-0.20**	**-0.28***	-0.20**	**0.33****
30-09-2018	-0.05	0.08	-0.05	0.13
09-11-2018	0.31**	**0.36****	**0.31**	-0.11
18-04-2019	0.16	**0.56****	0.16	**-0.73****

S-1 image date	VV TCH	VV NH	VH TCH	VH NH	VV/VH TCH	VV/VH NH
07-09-2018	0.20**	-0.17**	0.04	0.12**	**0.22****	**-0.34****
23-04-2019	0.19**	**-0.36****	0.11**	-0.20**	0.15**	**-0.32****

The coefficients highlighted in bold are greater than 0.2 or less than −0.2. * significant at 95%; ** significant at 99%.

Table 4. Analysis of variance between fields with and without visual indications of fertigation problems, considering the SAVI and NDWI indices on six Sentinel-2 image dates.

S-2 image date	NDWI F test	NDWI Significance (p)	SAVI F test	SAVI Significance (p)
04-04-2018	1.42	0.24	1.74	0.19
12-07-2018	0.43	0.51	0.29	0.59
01-08-2018	0.38	0.54	0.80	0.37
30-09-2018	4.58	0.036*	4.44	0.038*
09-11-2018	2.28	0.14	3.23	0.08
18-04-2019	4.12	0.046*	3.47	0.07

* significant at 95%.

Despite these limitations, the results highlight four main aspects: 1) the optical Sentinel-2 showed a greater capacity to identify fertigation problems than Sentinel-1, although SAR data remain relevant during periods of cloud cover; 2) the SAVI and NDWI indices better summarized the effects associated with crop condition than the bands analyzed individually; 3) images acquired at the end of the cycle, shortly before harvesting, tended to show the accumulated effects of irregular application more clearly, although identification may occur too late for operational correction; and 4) factors such as soil preparation, pests, weeds, and partial replanting may produce similar patterns and should be considered in interpretation.

To improve the process, it is recommended that field records be organized by field and linked to the respective harvest and vinasse application dates.

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