

## Temporal monitoring of the soybean cycle using Sentinel-2 images and NDVI analysis

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### Abstract

This study aims to monitor the temporal dynamics of soybean crop development using Sentinel-2 multispectral imagery and the Normalized Difference Vegetation Index (NDVI). Five image acquisition dates were selected to represent key phenological stages of the crop: emergence, early vegetative stage, flowering, pod formation, and maturation. NDVI maps and difference analyses between consecutive dates were employed to assess changes in vegetation vigor over time. The results showed characteristic pattern for irrigated soybean: NDVI values increased during early growth and peaked during flowering, followed by a gradual decline toward maturation, consistent with the typical spectral responses across crop phenological stages. The spatial resolution of the images allowed the identification of field-level variations, including planting row differences and the effects of machinery tracks on plant development. A key contribution of this study is the establishment of a reference multitemporal NDVI pattern for soybean under irrigated conditions. This reference can serve as a baseline for comparing non-irrigated fields, supporting the detection of anomalies caused by stress factors such as water scarcity, pests, or diseases. The method stands out for being low-cost, accessible, and user-friendly, which makes it valuable for both large-scale and smallholder farmers. Although NDVI is effective in identifying variations in plant vigor, it does not indicate the health loss of plants compared to a good health one and should be complemented with additional agronomic information. The approach presented here reinforces the potential of NDVI-based temporal analysis as a practical tool for crop monitoring and precision agriculture.

### 1. Introduction

The revenue from exports of Brazil's soybean agro-industrial complex exceeds ten billion dollars, accounting for approximately 8% of the country's total exports (Embrapa, 2021). One out of every four dollars exported by the Brazilian agro-industrial sector comes from soybeans. Over the last 47 years, soybean production in Brazil has increased approximately 262 times, triggering a series of transformative changes in Brazilian agriculture (Embrapa, 2021). Alongside wheat, soybeans were instrumental in establishing commercial agriculture in the country. They played a key role in advancing the mechanization of agricultural practices, modernizing transportation infrastructure, expanding the agricultural frontier, and boosting both professionalization and international trade. Furthermore, soybeans contributed significantly to the decentralization of the national agro-industry and stimulated the growth of pork and poultry production (Embrapa, 2021).

Both increasing soybean production and adopting more modern methods for monitoring crop development are current objectives in agriculture. Monitoring plays a vital role for farmers and, depending on the technique applied, can provide multiple advantages with minimal investment. Remote sensing techniques have proven to be effective for such applications, as the shift from conventional to digital agriculture shows that different production areas should not be treated uniformly in terms of variable measurement (Possebon et al., 2023).

In recent years, remote sensing technologies have provided an efficient, large-scale, and non-invasive solution for monitoring crop health. The use of orbital images in agriculture is a viable

and low-cost alternative for crop monitoring and temporal analysis (Judith et al., 2025). Depending on the platform used, it is possible to obtain spatial, temporal and spectral resolutions suitable for applications such as vegetation monitoring, growth stage identification, and productivity estimation. For instance, the Sentinel-2 constellation, part of the *Copernicus* Program, provides free access to multispectral imagery with 10-to-20-meter spatial resolution and a revisit time of 5 days, making it highly appropriate for monitoring agricultural areas (Drusch et al., 2012).

The use of multispectral imagery enables the generation of vegetation indices aimed at assessing crop conditions. One of the most widely used is the Normalized Difference Vegetation Index (NDVI), which is based on the spectral behavior of vegetation—specifically, its high reflectance in the near-infrared band and strong absorption in the red band (Rouse et al., 1973). NDVI can quickly delineate vegetated areas and detect plant stress, making it highly applicable in commercial agriculture and land-use studies. It is widely used to improve the analysis of remote sensing data for estimating productivity, biomass, vegetation type differentiation, and identifying crop stress (Huang et al., 2021).

Given this context, the objective of this study is to evaluate the temporal development of a soybean crop by generating NDVI maps from multispectral orbital images and analyzing their variation across different vegetative stages. Specifically, the study aims to generate NDVI values for different dates and assess the variation between them as a means of characterizing crop vigor and development throughout the growth cycle.

Additionally, the study seeks to establish a reference NDVI pattern for soybean grown under irrigated conditions, where water availability is not a limiting factor. This reference is particularly relevant for the region under study, which is characterized by unpredictable summer rainfall. The temporal NDVI behavior in this well-managed environment can serve as a baseline for comparison with non-irrigated areas, allowing the detection of deviations potentially caused by water stress, pests, diseases, or other constraints affecting crop development

## 2. Materials and Methods

### 2.1 Study area

To meet the objectives of this study, it was essential to select a location where soybean cultivation had been carried out and its full growth cycle completed. The chosen study area provided reliable information on crop type and approximate sowing date, allowing the selection of satellite image acquisition dates that corresponded to the main phenological stages of the soybean cycle.

The soybean field under study is located in the municipality of Santo Anastácio, state of São Paulo, more specifically at the Fazenda Modelo from the Grupo Facholi, as shown in Figure 1. The region's climate is classified as Aw—tropical with dry winters—according to the Köppen-Geiger system. Annual temperatures typically range from 15 °C to 32 °C, with extremes rarely dipping below 10 °C. Rainfall is concentrated in the summer months, with January being the wettest, averaging 190 mm, while July marks the driest period, with approximately 30 mm of precipitation. The predominant soil type is a shallow Red-Yellow Argisol, characterized by a moderate to weak A horizon and a medium sandy texture (Rossi, 2017), commonly found in areas with undulating to gently undulating relief.

The largest center pivot irrigation field, which was the focus of this study, is located at 422914.170 E and 7554010.760 N (UTM, zone 22S), referenced to the SIRGAS 2000 reference frame, with an average altitude of 376 m above sea level.

All center pivot irrigation fields within the study area contained soybean crops during at least one of the observed dates. However,

due to differences in planting times between the pivots, the crops were not synchronized in terms of phenological stage throughout the acquisition period. This heterogeneity could compromise the interpretation of the NDVI curves if all pivots were analyzed together.

For this reason, the temporal analysis was intentionally restricted to the largest center pivot irrigation field, for which the selected acquisition dates adequately represented the main phenological stages of the soybean development cycle: emergence, vegetative growth, flowering, pod formation, and maturation. Keeping the analyses focused on a single pivot is important to better relate the spectral responses to the phenological stages of the cultivar, allowing the identification of the characteristic vegetation index pattern throughout the crop cycle. This reference curve can be used for monitoring future cycles or for comparative analyses with non-irrigated areas. Even so, the other pivots were kept within the image frame to enable qualitative visual comparison of spectral responses at different stages, further illustrating the temporal variability captured by NDVI.

### 2.2 Sensor Selection Criteria and Processing Level

In monitoring and temporal analysis applications, the selection of a sensor must take into account its various resolutions. The spatial resolution is selected based on the size of the study area and the desired level of detail. The temporal resolution varies depending on the orbital platform and is a key factor in determining the appropriate revisit interval for tracking the target or phenomenon. Additionally, depending on the specific research question, certain regions of the electromagnetic spectrum may be more suitable for capturing relevant surface characteristics. Therefore, spectral resolution also becomes a criterion, requiring that the sensor includes bands that address the spectral needs of the analysis. Based on these concepts, the Sentinel-2 platform was selected for this study, as it offers spatial, temporal, and spectral resolutions compatible with the research objectives.

Sentinel-2 is a European Earth observation mission that uses high-resolution, wide-swath multispectral sensors. The mission supports a variety of operational applications, with emphasis on the monitoring of vegetation, soil, and water cover. The Multispectral Instrument (MSI) onboard Sentinel-2 features 13

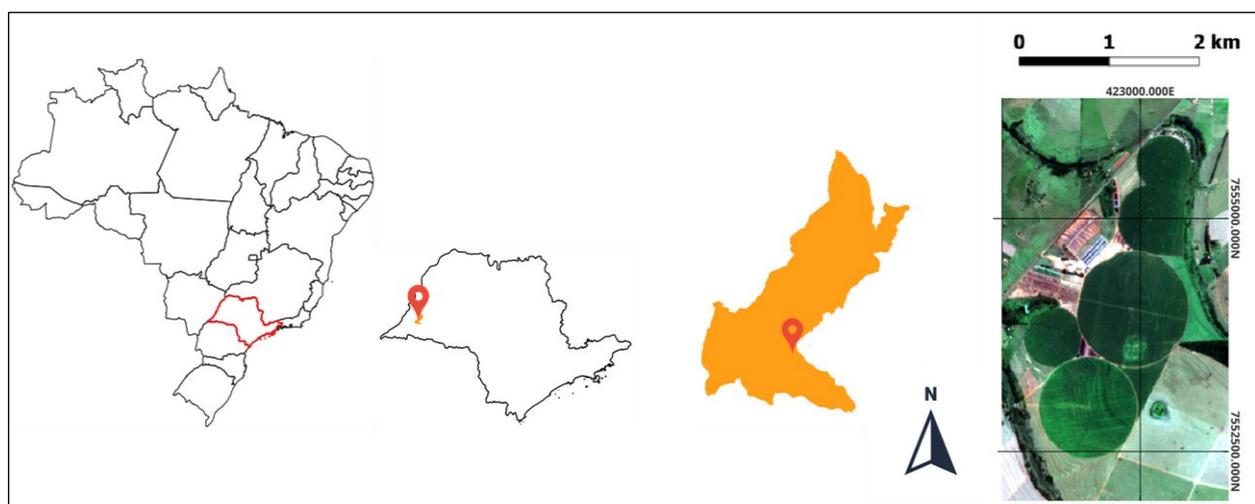


Figure 1. Location of the study area at different spatial scales and Sentinel-2 RGB (Red = B4, Green = B3, Blue = B2) orbital image.

spectral bands, four of which have a spatial resolution of 10 meters, considered suitable for the scale of the study area used in this research. Among the products available from the *Copernicus* Open Access Hub for Sentinel-2, two commonly used processing levels can be found:

- **S2MSI1C (Level-1C):** Top-of-atmosphere (TOA) reflectance, ortho-rectified and geocoded in the UTM projection, with sub-pixel multispectral and multitemporal registration.
- **S2MSI2A (Level-2A):** Surface reflectance (Bottom-of-atmosphere – BOA), ortho-rectified and UTM-geocoded. Additional outputs include Aerosol Optical Thickness (AOT) maps, Water Vapor (WV) maps, Scene Classification (SCL) maps, and quality indicators for each pixel.

### 2.3 Selection of dates for image acquisition and pre-processing

The images used in this study were acquired free of charge from the *Copernicus* Open Access Hub (<https://scihub.copernicus.eu/>). The soybean cycle typically ranges from 100 to 130 days, depending on cultivar and environmental conditions (EOSDA, 2022). Five acquisition dates were selected to allow temporal analysis of the crop during different developmental stages of the soybean cycle:

- **1st Date:** March 6, 2023 – Emergence stage
- **2nd Date:** March 21, 2023 – Early vegetative stage
- **3rd Date:** April 22, 2023 – Flowering
- **4th Date:** May 25, 2023 – Pod formation
- **5th Date:** June 9, 2023 – Maturation

All five images are Level-2A products, meaning they were atmospherically corrected and provide surface reflectance values. This correction minimizes the influence of atmospheric effects, resulting in more accurate and consistent data for temporal analysis.

Image preprocessing steps, such as clipping the study area and visualizing spectral bands, were performed using software Quantum GIS (QGIS), version 3.40.5-Bratislava (QGIS Development Team, 2023), an open-source geographic information system widely used for spatial data analysis and remote sensing applications.

### 2.4 NDVI Calculation and Spectral Band Selection

The NDVI widespread adoption in agricultural monitoring is due to its simplicity and effectiveness. It is particularly sensitive to chlorophyll activity and vegetation density, making it well-suited for identifying temporal variations in crop vigor. The spectral region between 700 nm and 1,300 nm exhibits high reflectance and low absorbance due to the internal structure of healthy green leaves. In contrast, the red region presents low reflectance values due to strong absorption by chlorophyll. According to Rouse et al. (1973), the NDVI is calculated as follows:

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \quad (1)$$

where:

$\rho_{NIR}$  = Reflectance in the Near Infrared band.

$\rho_{RED}$  = Reflectance in the Red band.

The spectral bands used in this study are presented in Table 1, with Bands 4 (red) and 8 (near-infrared) highlighted in red, as they are the ones used to calculate the NDVI — an essential index for assessing vegetation vigor throughout the crop cycle. NDVI maps were generated using the raster calculator tool available in QGIS.

Band ID	Wavelength (nm)	Spatial Resolution (m)
2	493	10
3	560	10
4	665	10
8	833	10

Table 1. Spatial resolution and central wavelength of the Sentinel-2 MSI visible-NIR spectral bands, highlighting in red those used in the NDVI calculation.

In order to more easily assess the variation in vegetation index throughout the crop cycle, the differences between NDVI values on consecutive dates were calculated. The calculation consisted of subtracting the NDVI value of the previous stage from that of the current stage. Since five dates were used in the study, corresponding to distinct soybean growth stages, a total of four NDVI differences were obtained. In this approach, positive values indicate an increase in NDVI, while negative values indicate a decrease.

## 3. Results and Analysis

As shown in Figure 2, each image acquired on a different date presents a distinct spectral response in the red and near-infrared bands, which directly influences the resulting NDVI maps. NDVI values range from -1 to 1. Negative values typically correspond to non-vegetated surfaces, such as water, bare soil, or built-up areas. Positive values indicate the presence of vegetation, with values close to 1 representing dense and healthy plant cover. Typically, vegetation indices above 0.6 indicate robust, thriving plant growth, whereas values below 0.4 suggest either early developmental stages or significant environmental stress, such as drought or poor soil conditions.

The NDVI images effectively represent the crop development stages in the area surrounding the largest irrigation pivot. During the emergence stage, low positive values dominate, reflecting bare soil. As the crop progresses through stages C and D, vegetation vigor increases, leading to a corresponding rise in NDVI values, culminating in the maturation stage (E).

Variation in NDVI occur when the plant's spectral characteristics change, often due to environmental stress factors such as water deficiency or excess, pests, diseases, or soil conditions. These factors tend to cause a decrease in near-infrared reflectance and an increase in red reflectance, which directly impacts the index values.

Furthermore, in Figure 2 it is possible to observe how the criterion of spatial resolution selection directly impacts the quality and detail of the generated NDVI maps. Since the images used have a spatial resolution of 10 meters, certain features within the central pivot become distinguishable. For example, in some dates, differences between planting rows are noticeable, as well as tracks left by agricultural machinery, where soil compaction appears to have affected crop development.

Although soybean was planted on different dates across the individual pivots, planting within each pivot occurred on the same day. Therefore, differences in crop development between pivots are related to planting dates, whereas the lack of spatial

uniformity within each pivot is likely associated with variations in soil properties, microtopography, or other local factors that influence plant growth.

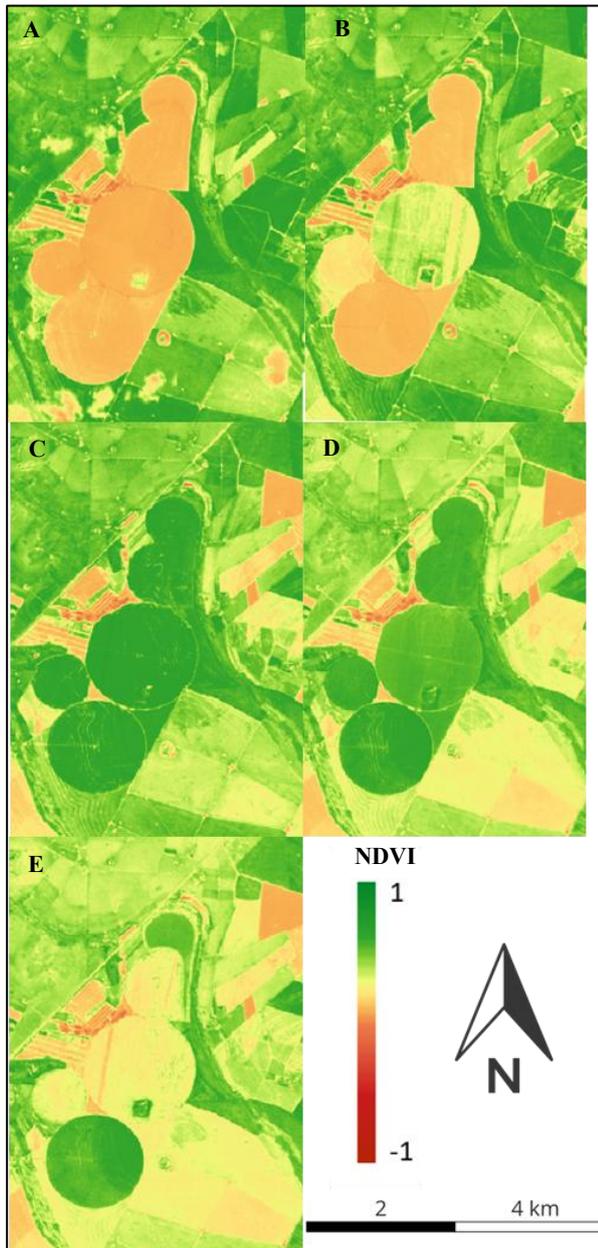


Figure 2. NDVI images for the acquisition dates. A: March 6 (Emergence); B: March 21 (Early vegetative); C: April 22 (Flowering); D: May 25 (Pod formation); E: June 9 (Maturation).

Within the main pivot, which is the focus of this study, a small region in the southern portion consistently exhibited a different spectral behavior from the rest of the area throughout the soybean cycle. Based on its spectral response, it is also identified as vegetation, but its distinct temporal pattern clearly indicates that it is not soybean. The spectral behavior of this area indicates that it corresponds to a different type of vegetative cover, which reinforces the usefulness of temporal analysis for distinguishing crop types within the same field.

To prevent this anomaly from affecting the analysis of vegetation indices, it was excluded from the clipped area of the studied

pivot. Nevertheless, it serves as a clear example of the potential of remote sensing in agriculture, as the anomaly was easily identified within a center pivot over one kilometer in diameter, without the need for field inspection. To evaluate the NDVI values at each stage, the mean values within the main pivot were calculated using the “Raster Information” tool in QGIS, excluding the anomalous area from the analysis. The mean values were plotted on the graph in Figure 3.

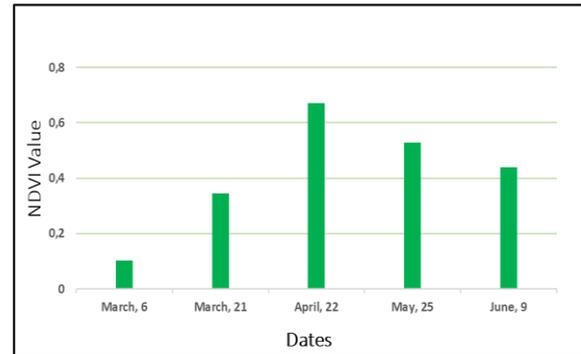


Figure 3. Mean NDVI values by date in the central irrigation pivot.

As shown in Figure 3, NDVI values change throughout the soybean growth cycle. In the first two dates, the mean NDVI values are low, due to the mixed spectral response between the crop and the exposed soil, as the plants were still in early stages of development. During the flowering stage, NDVI reaches its peak, reflecting full canopy development and high photosynthetic activity. After this stage, the plant begins to redirect its energy toward grain formation, and the leaf structure starts to degrade, leading to a gradual decline in NDVI values.

To complement the analysis, Figure 4 presents the NDVI differences calculated between consecutive acquisition dates, highlighting the variation in vegetation vigor across soybean growth stages. Four difference maps were generated, each representing the change in NDVI from one stage to the next.

Although NDVI is one of the most widely used vegetation indices due to its simplicity and strong relationship with photosynthetically active biomass, it presents some well-known limitations. The index tends to saturate in areas with dense vegetation canopy, where increases in leaf area index (LAI) no longer result in significant NDVI changes. In addition, NDVI can be affected by soil background reflectance in areas with partial canopy cover, as well as by atmospheric conditions and sensor viewing geometry (Meneses et al., 2019). These factors must be considered when interpreting NDVI time series, particularly when comparing different fields or cultivars under variable environmental conditions.

To overcome some of these limitations, other vegetation indices derived from Sentinel-2 data can be employed to emphasize specific biophysical parameters of crops. For instance, the Normalized Difference Red Edge Index (NDRE) exploits red-edge bands to remain sensitive to chlorophyll content even in high LAI conditions, while the Soil-Adjusted Vegetation Index (SAVI) minimizes soil brightness effects, improving estimates in sparse canopies. The Enhanced Vegetation Index (EVI) is also commonly used for crop monitoring because it reduces atmospheric and background influences, providing better sensitivity to canopy structure in densely vegetated areas. Integrating NDVI with these complementary indices can provide

a more robust and comprehensive assessment of crop status throughout the growing season (Meneses et al., 2019).

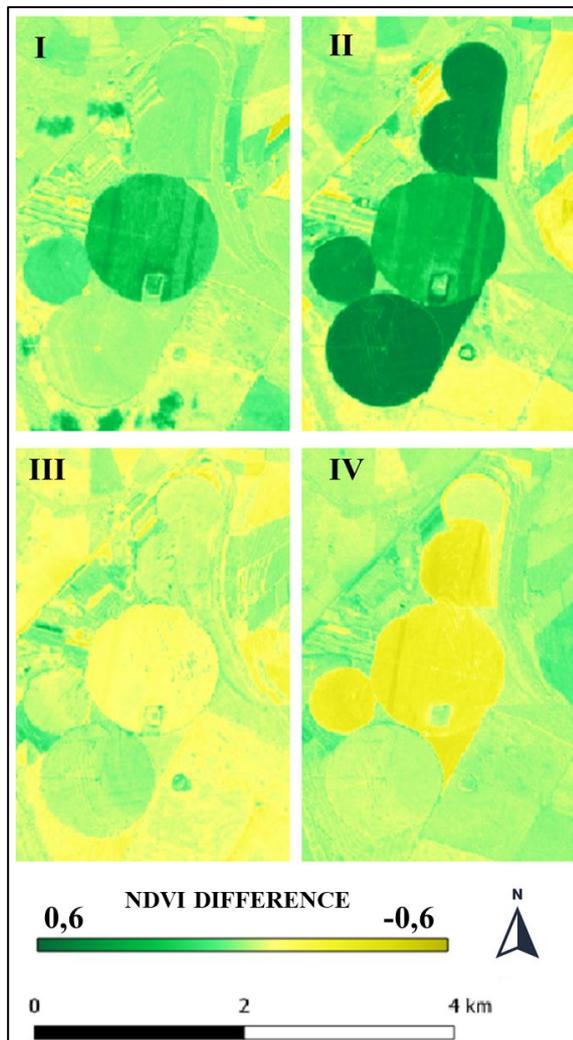


Figure 4. NDVI differences between consecutive vegetation stages. I: Emergence to Early vegetative; II: Early vegetative to Flowering; III: Flowering to Pod formation; IV Pod formation to Maturation.

Figure 4 illustrates the NDVI transitions over time. The first two periods (March 6–21 and March 21–April 22) show positive differences, indicating increased plant vigor during early development and flowering. Conversely, the final two intervals (April 22–May 25 and May 25–June 9) exhibit negative NDVI differences, reflecting a gradual decline in vegetative activity as the crop progresses from flowering to pod formation and, ultimately, maturation. Rather than focusing solely on the dynamics of the cycle, these difference maps aim to establish a reference NDVI pattern for irrigated soybean fields, which can support future comparisons and monitoring in non-irrigated areas under similar environmental conditions.

#### 4. Conclusion

This study demonstrated the effectiveness of using Sentinel-2 multispectral imagery and the NDVI index for the temporal monitoring of soybean crop development. The temporal evolution of NDVI followed an expected pattern for irrigated fields: initially low values during early growth stages, a peak

during flowering, and a gradual decline during the maturation phase, which is consistent with the spectral response of crops across their phenological stages, where canopy closure and chlorophyll content reach their maximum near flowering and progressively decrease during senescence (Meneses et al., 2019). The analysis of NDVI differences between consecutive dates reinforced this pattern and highlighted the index's sensitivity to phenological changes in the crop.

This study also proposes a reference NDVI pattern for soybean grown under favorable, irrigated conditions. Given the region's climatic variability, this pattern can serve as a baseline for monitoring non-irrigated areas and detecting anomalies that may indicate water stress, pests, diseases, or other limiting factors. In addition to being technically effective, the method is low-cost, accessible, and easy to interpret, making it useful for both large-scale and smallholder producers in supporting field decisions. To further this research, the same procedures should be applied to a non-irrigated area, allowing comparison of results and assessment of environmental impacts on crop development.

However, although NDVI is a powerful tool for detecting changes in vegetation vigor, it has limitations. The index is not capable of indicating the crop stress level, serving only as an alert to changes in plant condition. Therefore, NDVI should be used along with other agronomic information and sensing tools for a more comprehensive analysis.

Additionally, it is important to note that the NDVI pattern presented in this study reflects the response of the specific soybean cultivar grown under irrigated conditions. Variations in cultivar genetics, management practices, and environmental conditions may result in different NDVI dynamics, meaning that the pattern should be recalibrated before being applied to other soybean varieties or regions (Possebon et al., 2023; Huang et al., 2021).

Future works may also benefit from the inclusion of other spectral indices derived from Sentinel-2 data, such as the Normalized Difference Water Index (NDWI) to evaluate crop water status, or the Soil-Adjusted Vegetation Index (SAVI) to minimize the influence of soil background. The integration of multiple indices could provide a more comprehensive characterization of crop health and environmental stress factors.

Finally, this study reinforces the potential of low-cost and freely available remote sensing data, such as that provided by the Sentinel-2 mission, as an accessible tool for crop monitoring. When combined with basic field information, these methods can support decision-making in both large-scale and smallholder agriculture, improving management efficiency and resilience to climate variability.

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