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Papers

Analysis of the Influence of the ENSO Phenomenon on the Normalized Difference Vegetation Index (NDVI) in Soybean Fields of Jari, Rio Grande do Sul, Brazil

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Abstract
Given the expansion of soybean fields in Rio Grande do Sul (RS), it is essential to investigate the impacts caused by drought associated with climate phenomena such as the El Niño-Southern Oscillation (ENSO). This study aimed to analyze the behavior of the Normalized Difference Vegetation Index (NDVI) in response to ENSO activity in soybean fields and off-season crops in the municipality of Jari (RS) between October 2022 and March 2024. The methodology used rainfall data and NDVI images obtained through Google Earth Engine from Sentinel-2 imagery, with field validation of the data. The results indicated considerable variation in monthly precipitation relative to the historical average. In 9 of the 18 months analyzed, precipitation was below the historical monthly average. Drought associated with La Niña impaired plant development, and field observations showed the need for soybean replanting in January 2023 and the use of irrigation techniques. NDVI indicated that only 13% of the area under soybean cultivation contained plants classified as very healthy. The off-season period and the transition to a wetter period associated with El Niño showed a predominance of vegetation classified as very healthy between June and October 2023. Between January and March 2024, more than 90% of the areas were classified as very healthy, indicating that there was no water shortage. It was concluded that ENSO influenced the observed NDVI values; therefore, it is essential to develop drought mitigation and adaptation strategies in the municipality of Jari (RS).

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INTRODUCTION

In the context of agricultural expansion, soybean (Glycine max) stands out as one of the main crops, playing an important role in the transformation of land use and occupation (Anholeto; Massuquetti, 2014; Chiaravalloti *et al.*, 2022; Gass *et al.*, 2024). Currently, soybean is the world's largest source of protein for animal feed and the second-largest source of vegetable oil (Song *et al.*, 2021), playing a central role in agricultural production systems in several countries (Pagano; Miransari, 2016).

Between 2000 and 2019, the area cultivated with soybean in South America more than doubled, increasing from 26.4 Mha to 55.1 Mha (Song *et al.*, 2021). Brazil is one of the world's largest producers of the crop (Crusiol *et al.*, 2018). In the 2024/25 crop season, Rio Grande do Sul (RS) accounted for approximately 9.7% of national soybean production, with an estimated output of 16.6 million tons (Conab, 2025), and according to MapBiomas data, in 2025, approximately 24.3% of the state's territory was occupied by the crop. Between 2001 and 2020, the area devoted to soybean cultivation increased by 100.5% in Rio Grande do Sul (Torres *et al.*, 2023), with crop expansion being particularly notable in the central and southern regions of the state (Castro, 2020).

The occurrence of large-scale climate phenomena, such as the El Niño-Southern Oscillation (ENSO), exerts a significant influence on several crops, especially during the plant growth stage, because of variations in precipitation and temperature patterns (De La Casa *et al.*, 2021; Jacóbsen *et al.*, 2002; Júnior *et al.*, 2020). In this regard, the latitudinal extent of RS is conducive to the occurrence of several meteorological phenomena, including El Niño and La Niña (Cera *et al.*, 2017). Despite the increase in soybean production in recent decades, soybean yield in RS is still strongly influenced by precipitation variability associated with ENSO (Pilau *et al.*, 2022). In La Niña years, reduced precipitation may lead to water deficits, compromising crop development and yield, whereas El Niño periods tend to provide greater water availability for soybean, although excessive precipitation may also affect cultivation (Pilau *et al.*, 2022).

In this context, remote sensing has become a viable alternative for monitoring the effects of drought on plants because it enables analyses at broader temporal and spatial scales than would be possible using conventional methods (Amaral *et al.*, 2024; Crusiol *et al.*, 2018; West *et al.*, 2019). Among the various remote-sensing techniques, vegetation indices (VIs) stand out as valuable tools for studying the spectral and temporal signatures of soybean throughout its phenological cycle (Amaral *et al.*, 2024; Morlin Carneiro *et al.*, 2020). These VIs make it possible to correlate soybean development with factors that influence its growth and production, such as climate, soil, and relief (Sobrinho Neto; Danelichen, 2023).

Among the VIs most commonly used in the analysis of vegetation and agricultural crops, the Normalized Difference Vegetation Index (NDVI), proposed by Rouse *et al.* (1973), stands out. NDVI has shown promising results in identifying vegetation and monitoring vegetation stress, making it particularly relevant to commercial agriculture and land-use monitoring studies (Crusiol *et al.*, 2024; Huang *et al.*, 2021; Mantovani; Lelis, 2023). In addition, NDVI is important for drought monitoring and for assessing soybean conditions during these critical periods (Yagci *et al.*, 2015).

Given the increasing frequency of drought episodes in RS, it is essential to analyze how soybean crops respond to water scarcity in terms of biomass and plant health. This is particularly relevant in Jari (RS), where soybean cultivation has expanded mainly into areas with steeper slopes and shallower soils in recent decades (Beilfuss *et al.*, 2022). Currently, approximately 35% of soybean fields are established on Neosols. Shallow soils have shallow profiles and reduced moisture-retention capacity, increasing the risk of water stress during drought periods (Streck, 2018). The combination of shallow soils, steeper slopes, which favor surface runoff and may limit infiltration and soil water storage, and precipitation variability associated with ENSO may increase the water vulnerability of soybean fields, especially during periods of precipitation deficit.

In this context, the objective of this study was to analyze NDVI behavior in response to ENSO activity in soybean fields and off-season crops in Jari (RS) during the 2022/2023 and 2023/2024 crop seasons. The specific objectives were: (i) to characterize precipitation in Jari (RS) and ENSO activity during the period analyzed; (ii) to evaluate the effectiveness of NDVI in the context of Jari (RS), validating the results through fieldwork on three dates; and (iii) to use NDVI to monitor the behavior of soybean fields from October 2022 to March 2024.

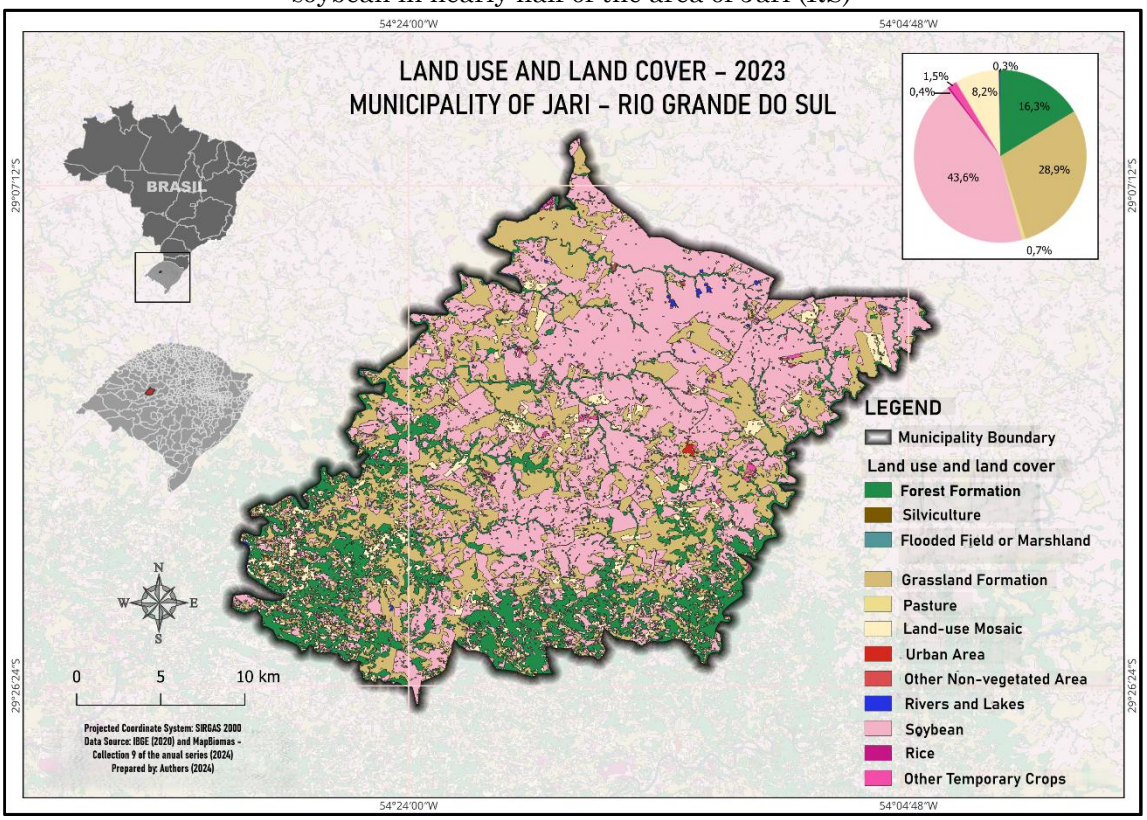
MATERIALS AND METHODS

This section presents the study area and the methodological approaches adopted in the research.

Study Area Characterization

The municipality of Jari (RS) is located between the geographic coordinates 29°08'52" and 29°46'07" S and 54°07'59" and 54°50'45" W (Figure 1), with an area of 853.080 km². According to IBGE data for 2021, Jari (RS) had a GDP per capita of R$ 135,082.01. Regarding the composition of the municipal Gross Value Added (GVA), the largest share corresponded to the agricultural sector, which totaled approximately R$ 377.84 million, representing 80.6% of the municipality's GVA (Beilfuss, 2022; Beilfuss, 2025).

Figure 1 – Location of the municipality and land use and land cover in 2023, showing the presence of soybean in nearly half of the area of Jari (RS)



Source: The authors (2024).

With regard to land use and land cover (Figure 1), in 2023, soybean cultivation predominated in the territory of Jari (RS), extending from north to south, mainly in the central portions, and covering approximately 373.9 km² (43.6%). Grassland Formation, in turn, covered 248 km² (28.9%), mainly in areas located in the northwest, southwest, and southeast of the municipality. In addition, Forest Formation occupied an area of 140 km² (16.3%), prevailing especially in the south and associated with the Plateau Escarpment. Time-series data indicate a 330% increase in the area occupied by soybean between 2000 and 2022 (Beilfuss *et al.*, 2024).

With regard to relief, elevations range from 130 to 460 m, and the predominant slope classes are 2-5% (375.8 km²) and 5-15% (349 km²), corresponding to 44% and 40.9% of the municipal area, respectively. Jari (RS) is located within the unit known as the Southern Plateau, characterized by a predominance of gentle slopes and relatively small local topographic differences, formed mainly by volcanic rocks of Mesozoic age (Guareschi; Nummer, 2014). Accordingly, Beilfuss *et al.* (2022) reported that the municipality is predominantly composed of gently undulating hills (65.1%), which facilitated the expansion of soybean cultivation.

The municipality of Jari (RS) lies within the Subtropical Climate II zone, with annual precipitation ranging from 1,500 to 1,700 mm, according to Rossato (2011). According to the same author, the northwestern portion is in transition to the Subtropical Climate III zone, with annual precipitation ranging from 1,700 to

1,800 mm. Beilfuss *et al.* (2022) reported that mean annual precipitation in Jari is 1,922 mm, ranging from 1,000 mm to 2,800 mm over the period from 1990 to 2020, therefore exceeding the values reported by Rossato (2011). These data are important for understanding precipitation behavior and its impact on local agriculture.

Database and Processing of Remote-Sensing Products

The first step of the research consisted of downloading NDVI files generated on the Google Earth Engine (GEE) (Gorelick *et al.*, 2017) platform from high-resolution, multispectral, orthorectified Sentinel-2 images (COPERNICUS/S2_SR_HARMONIZED). A search was conducted for images from each month analyzed between October 2022 and March 2024. It should be noted that Sentinel-2 proved suitable for the spatial scale of the research because it has a spatial resolution of 10 m, enabling analysis of vegetation cover at the municipal scale. GEE was also used because it facilitated the processing and analysis of remote-sensing images throughout the study period.

The selection of dates was based on the approach adopted by Da Silva *et al.* (2017), who used remote sensing to monitor soybean from soil preparation through harvest. This study also investigated the off-season period to observe how farmers prepare the soil for the next soybean planting cycle. In addition, the soybean sowing calendar established by SDA Ordinance No. 261, of July 4, 2022, and SDA Ordinance No. 840, of July 11, 2023, was considered.

NDVI was developed to explore unique plant characteristics, such as the absorption of sunlight in the visible portion of the spectrum by chlorophyll present in the leaves and reflectance in the near-infrared (NIR) portion, which is determined by plant cell structure. Thus, higher NDVI values indicate denser and greener vegetation (Yagci *et al.*, 2015). According to Rouse *et al.* (1973), NDVI is expressed as shown in Equation 1.

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1)$$

where: Red and NIR represent, respectively, the reflectance values in the red and near-infrared regions of the electromagnetic spectrum of objects on the Earth's surface.

The NDVI images downloaded from GEE were imported into a database in QGIS 3.30.0 (Qgis Development Team, 2023). The raster images were then clipped using the soybean-field shapefile provided by the MapBiomas project (Souza *et al.*, 2020). Data from the MapBiomas platform have previously been validated in studies by Beilfuss *et al.* (2022), Beilfuss *et al.* (2024), Beilfuss *et al.* (2025a), Beilfuss *et al.* (2025b), and Beilfuss *et al.* (2025c). The NDVI class thresholds were defined based on Crusiol *et al.* (2024), using the following intervals: -1 to 0: non-vegetated target or plant without physiological activity, including water bodies, shaded areas, and other targets without vegetation cover; 0 to 0.33: unhealthy plant; 0.33 to 0.66: moderately healthy plant; and 0.66 to 1: very healthy plant. Finally, the area of each class was calculated using the *r.report* tool.

Fieldwork

Fieldwork was carried out on January 25, 2023, July 12, 2023, and January 27, 2024, to analyze soybean fields in summer and land use and land cover during the off-season period in autumn, winter, and spring. During these visits, NDVI images from GEE corresponding to the fieldwork dates or dates close to them were downloaded. In total, 30 points were visited, at which photographs with geographic coordinates were taken using the SW Maps application and Mavic Air Pro and Mini Mavic drones. The NDVI values obtained from the satellite images were then compared with the photographs obtained in the field. For this purpose, each photograph was associated with its respective geographic location, making it possible to identify the NDVI value in the satellite image corresponding to the same location recorded in the field.

Precipitation Data Acquisition

Rainfall data for the municipality of Jari (RS) were obtained from the HidroWeb platform (ANA, 2024), maintained by the National Hydrometeorological Network, based on information from station 02954005 for the period from 2022 to 2024. The historical monthly average was calculated considering a 30-year period (1994 to 2024). The Oceanic Niño Index (ONI) was used to analyze the influence of ENSO.

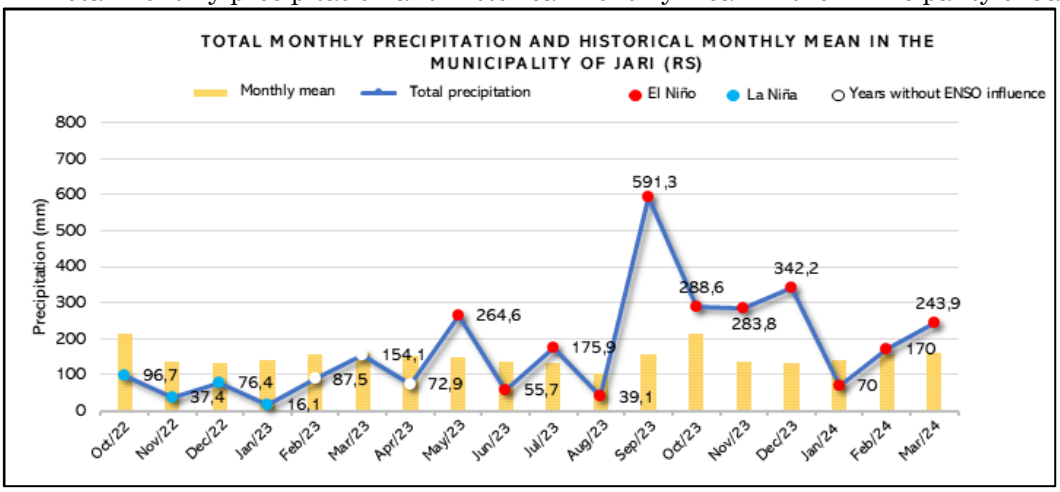
RESULTS

This section presents precipitation data, the analysis and field validation of NDVI, and the annual behavior of NDVI in areas where soybean is planted in Jari (RS) between October 2022 and March 2024.

Precipitation Recorded during the Soybean NDVI Analysis Period

The historical monthly mean values for Jari (RS) range from 102 mm to 212 mm, corresponding to August and October, respectively. Between October 2022 and March 2024, the municipality of Jari (RS) showed significant variations in total monthly precipitation relative to the historical monthly mean (Figure 2). Over the 18 months evaluated, precipitation was below the historical monthly mean in 9 months.

Figure 2 – Total monthly precipitation and historical monthly mean in the municipality of Jari (RS)



Source: The authors (2024).

Some data are particularly noteworthy. In September 2023, cumulative precipitation reached 591.3 mm, a value significantly above the historical average of 156 mm. In contrast, January 2023 recorded only 16.1 mm, far below the historical monthly average of 141 mm. These fluctuations in precipitation relative to the historical monthly averages can be partially explained by ENSO activity. Months associated with El Niño, such as September, October, November, and December 2023, coincided with significant increases in precipitation, demonstrating the impact of this phenomenon on the increase in precipitation. Conversely, periods influenced by La Niña, between October 2022 and January 2023, showed reductions in precipitation levels. However, the relationship between these phenomena and rainfall variations is not always linear and may be influenced by other climate phenomena.

Fieldwork and NDVI Validation in Soybean-Cultivated Areas

During the field visits conducted in January 2023 and January 2024, a significant difference was observed in the vegetation cover of the fields (Figure 3). In January 2023, the drought period delayed planting and impaired plant growth, and farmers had replanted soybean in several of the fields visited. Most NDVI values represented areas dominated by crop residue or mixed pixels of crop residue and soybean at the vegetative stage under water-deficit conditions. On the first field-validation date (Figure 4A), only 13% of the area under soybean cultivation contained plants classified as very healthy, while 39% contained plants classified as unhealthy.

In contrast, in January 2024, the values approached 1, corresponding to reproductive stages and canopy closure between rows in the field, with 91% of the areas classified as very healthy (Figure 4B). In this regard, it was possible to analyze the correspondence between NDVI and the points observed in the field, as well as to observe the impacts of the ENSO phenomenon on the crops.

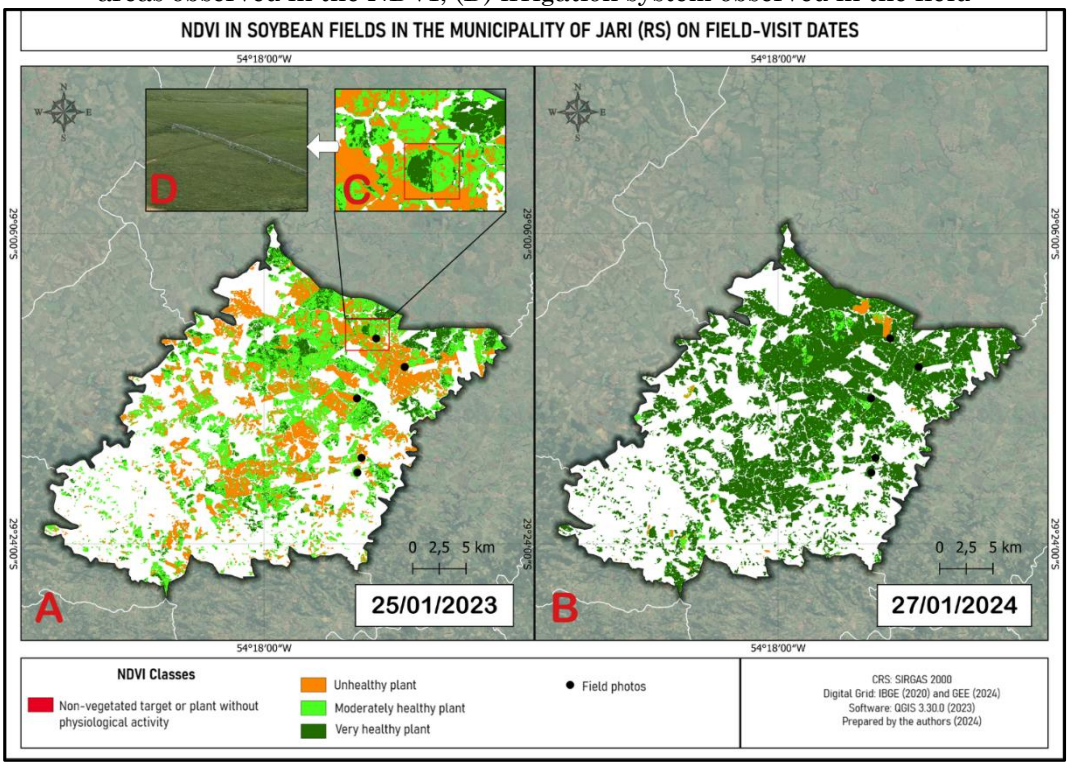
Figure 3 – Photographs of some of the locations visited in the field, showing the 2022/2023 and 2023/2024 crop seasons with their respective NDVI values

Location	Photograph 25/01/2023	Photograph 27/01/2024
54°12′58,430″W 29°21′33,760″S	 NDVI value = 0.288	 NDVI value = 0.922
54°12′21,110″W 29°19′1,160″S	 NDVI value = 0.162	 NDVI value = 0.861
54°12′36,320″W 29°15′31,620″S	 NDVI value = 0.214	 NDVI value = 0.915
54°9′50,920″W 29°13′41,930″S	 NDVI value = 0.154	 NDVI value = 0.901
54°11′30,060″W 29°12′4,210″S	 NDVI value = 0.174	 NDVI value = 0.906

Source: The authors (2024).

Given the drought observed in January 2023, farmers adopted some agricultural practices, such as irrigation, especially in areas in the northern portion of the municipality where the largest properties are concentrated (Figure 4D). NDVI analysis showed that this technique was effective because the plants fell within the healthier categories, while others were classified as moderately healthy (Figure 4C).

Figure 4 – NDVI in soybean fields in the municipality of Jari (RS) on January 25, 2023 (A) and January 27, 2024 (B); (C) close-up of the northern portion of the municipality to highlight irrigated areas observed in the NDVI; (D) irrigation system observed in the field

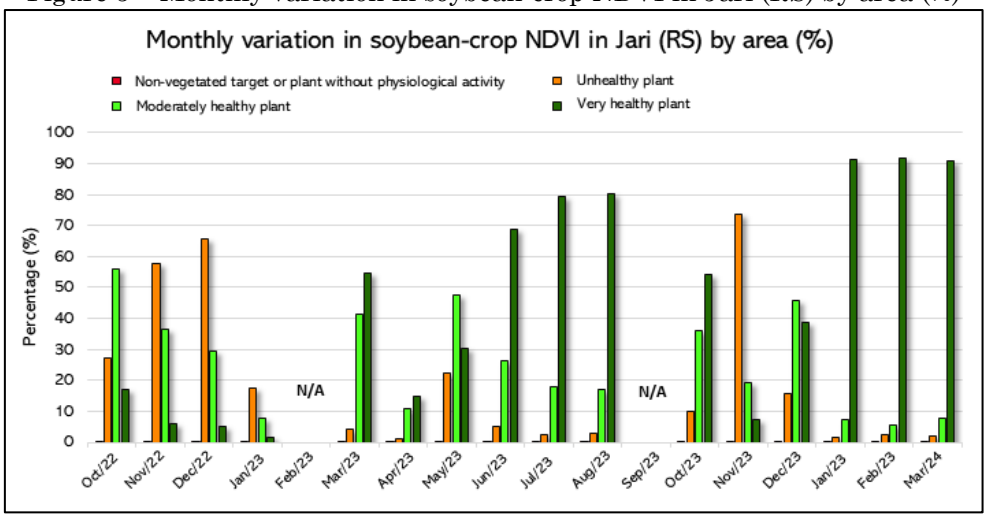


Source: The authors (2024).

Monthly NDVI Analysis and Impacts of the ENSO Phenomenon

The monthly NDVI analysis for the two crop seasons (Figure 5) revealed the impact of drought in 2022, which resulted in delayed planting, as also observed in the field. In October 2022, moderately healthy plants predominated (55%) because soil preparation for soybean planting had begun. Between November and December 2022, crops classified as unhealthy predominated because crop residue was present and soybean had not germinated. The replanting carried out in January, combined with increased precipitation in February and March 2023, favored crop development. In March 2023, NDVI values indicated a predominance of very healthy plants (54.7%), mainly in the northern and northwestern portions of the municipality (Figure 6). Maturation and harvest occurred between April and May 2023.

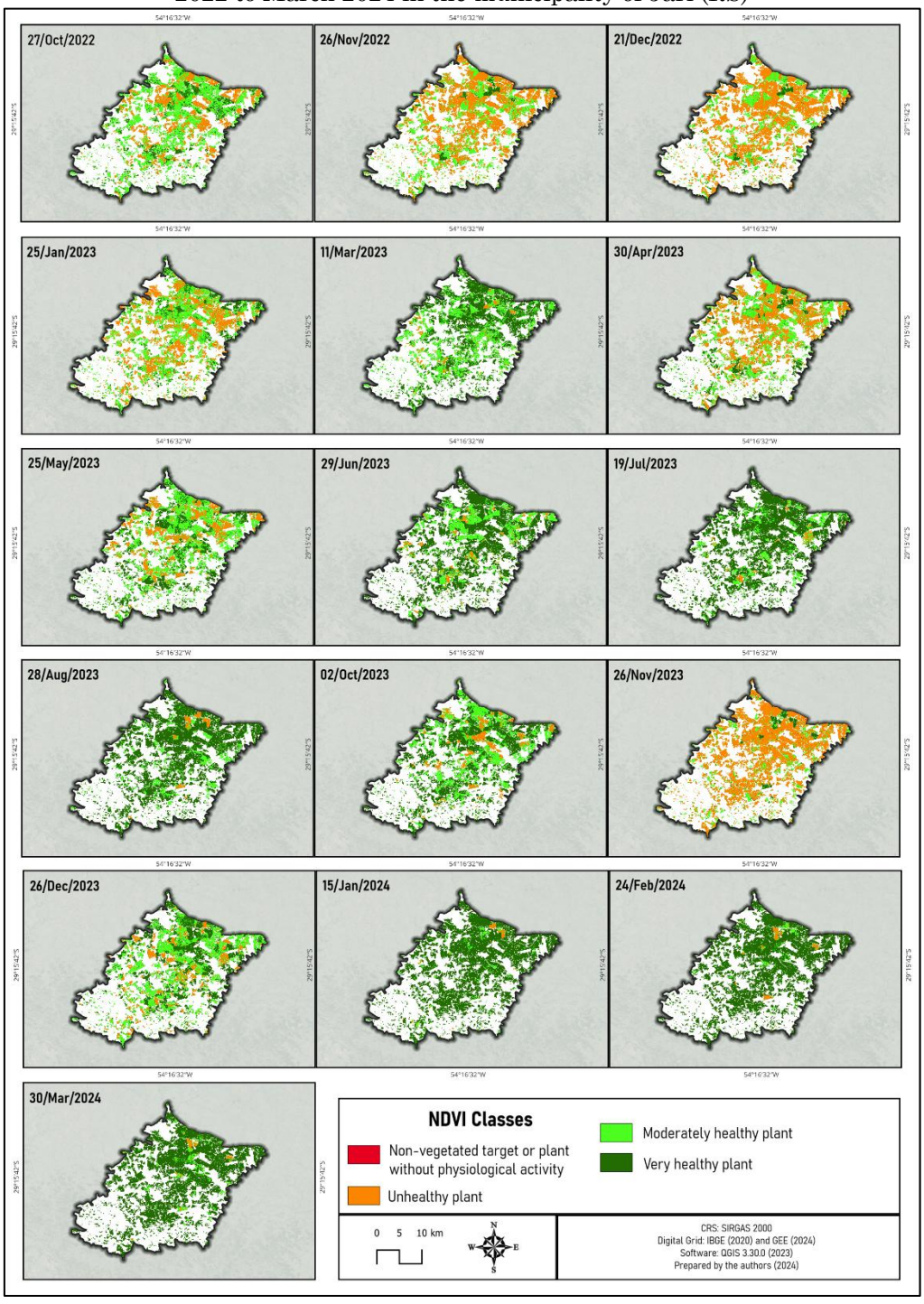
Figure 5 – Monthly variation in soybean-crop NDVI in Jari (RS) by area (%)



The term N/A refers to months with no satellite imagery because of cloud cover.

Source: The authors (2024).

Figure 6 – Mosaic showing the application of NDVI to soybean land use and land cover from October 2022 to March 2024 in the municipality of Jari (RS)



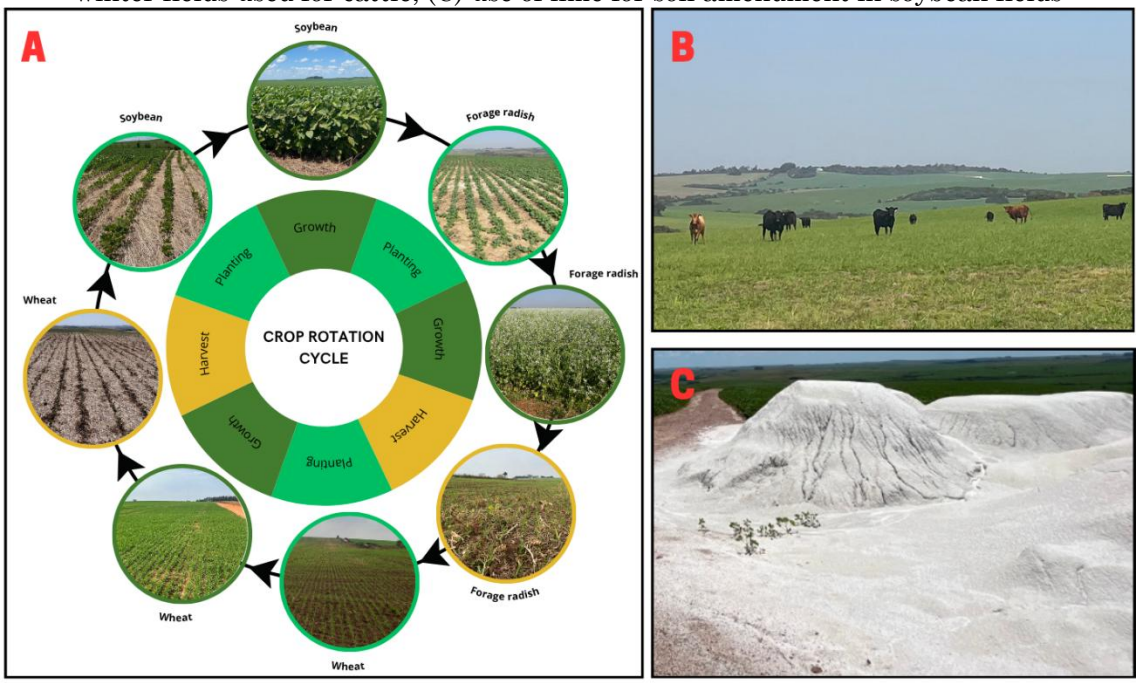
Source: The authors (2024).

During the off-season period (June to October 2023), farmers maintained vegetation cover, resulting in NDVI values corresponding to very healthy plants because of the presence of forage radish, oats, and ryegrass. In November, the areas showed a predominance of unhealthy plants (74%) because of soil preparation for the 2023/2024 crop season. In December 2023, plant growth began, and the greater plant density resulted in an increase in areas classified as moderately healthy (46%), as shown in Figure 5. Between January and March 2024, the very healthy plant class predominated, accounting for more than 90% of the area (Figure 5), because precipitation was close to historical average values; therefore, the agricultural calendar was followed without disruptions.

Field observations indicated that during the off-season period, wheat, forage radish, or oats may be planted, or the fields may also be used

for livestock. Based on these observations, distinct patterns were identified in Jari (RS): (i) small fields, especially in the southern portion of the municipality, are cultivated with soybean during summer and used for cattle in winter (Figure 7B); (ii) producers managing large fields in the northern portion of the municipality adopt a three-crop annual cycle (Figure 7A), planting forage radish, wheat, and then soybean, and invest in soil amendment techniques such as lime application (Figure 7C), in addition to irrigation practices to optimize production (Figure 4D). As a result, some fields in the northern areas remained classified as healthy throughout the entire period analyzed, even during months of lower precipitation.

Figure 7 – (A) Crop rotation cycle identified during field visits in the municipality of Jari (RS); (B) winter fields used for cattle; (C) use of lime for soil amendment in soybean fields



Source: The authors (2024).

DISCUSSION

The selected study period was important for observing the behavior of NDVI in soybean and off-season crops during a period of precipitation variability in Jari (RS). Given the increase in events of extreme precipitation or drought in RS, Zanon *et al.* (2016) point out that conducting studies to assess the influence of climatic factors on soybean production in the state is crucial. Although cumulative precipitation increased with El Niño activity, precipitation values were below the historical monthly average in 9 of the 18 months, which is concerning for soybean planting and crop development.

Several studies have used NDVI to monitor the effects of drought on soybean (Crusiol *et al.*, 2018; Pei *et al.*, 2021; Tavares *et al.*, 2022; Zhang *et al.*, 2023). In Jari (RS), the application of this index proved effective because the values adequately reflected the conditions observed in the field, resulting from both drought and precipitation levels near or above the historical averages. In this context, field validation is essential for understanding the complexity of the spectral response of objects in Sentinel-2 images, especially during the drought period. During this period, fields with different cover conditions were identified, including a predominance of bare soil, the presence of crop residue, and soybean covering the inter-row spaces, highlighting the spectral complexity of these pixels.

The analysis of NDVI and precipitation data between October 2022 and March 2024 in Jari (RS) made it possible to observe the temporal variation of these indicators throughout the period analyzed. Drought periods, such as that between October 2022 and January 2023, had a direct impact on the crops, with NDVI values indicative of water stress and low vegetative development. Therefore, the results obtained in this study reinforce the influence of climate as the main factor affecting agricultural production, because soybean requires adequate water availability during its cycle and is highly sensitive to water stress (Basal *et al.*, 2020; Zhang *et al.*, 2023). Sensitivity to water stress in Jari (RS) is aggravated by soybean expansion

into areas with shallow soils and steep slopes, according to data from Beilfuss *et al.* (2022). Shallow soils have a low moisture-retention capacity (Pilau *et al.*, 2018), and, as observed in the monthly NDVI patterns, a larger area of soybean remains classified as healthy on the deeper soils in the northern portion of Jari (RS).

It should be emphasized that factors other than climate can also alter the NDVI values of a field. Conditions such as fires, floods, changes in land use and land cover, and pest infestations can also reduce index values (Yagci *et al.*, 2015). In addition, some cultivars may respond differently to drought, as reported by Tavares *et al.* (2022). In this context, the investments made by farmers play a crucial role, as observed in the field. Large producers, in particular, have greater adaptive capacity during drought periods and adopt practices such as soil amendment and crop rotation. In addition, these large fields are already located in areas with physical-environment conditions more favorable to soybean cultivation. These issues can be explored in greater depth in other studies.

In studies monitoring soybean cultivation with NDVI, Sampaio *et al.* (2021) and Silva *et al.* (2023) identified a limitation in the use of NDVI because of its tendency to saturate under conditions of high biomass and closed canopy. Sampaio *et al.* (2021) indicated that at more advanced soybean phenological stages, NDVI loses sensitivity to variations in vegetative vigor. Similarly, Silva *et al.* (2023) reported that NDVI reaches its saturation level precisely when soybean reaches its maximum vegetative development. In the present study, this problem was not observed during the data-validation period (January), which corresponded to an intermediate stage of soybean development. In the subsequent months of the analysis, possible data saturation became clearer only in the rainy year.

FINAL CONSIDERATION

Given the expansion of soybean cultivation in RS, the increase in the incidence of extreme events, and ENSO activity, it is crucial to conduct studies and validate remote-sensing techniques that enable monitoring of climate impacts on crops in the state. The use of Sentinel-2 images enabled monthly monitoring and provided a spatial resolution suitable for a municipality of approximately 850 km². Moreover, the use of GEE enabled rapid image processing without requiring high-performance computers for geoprocessing.

The occurrence of La Niña during this period contributed to reduced precipitation, causing planting delays and the need for emergency management practices, such as replanting in affected areas. However, the intensity of drought effects was not homogeneous among the fields, because investments in technical management and irrigation systems helped minimize the impacts of water deficit on certain properties. Some farmers in the northern portion used irrigation techniques, particularly on larger properties with greater investment in soybean cultivation.

Conversely, the transition to conditions influenced by El Niño, beginning in May 2023, resulted in a significant increase in precipitation, which in turn favored plant development during the off-season period. At the peak of the soybean crop season, in January 2024, 91% of soybean fields were classified as very healthy, in contrast to only 13% in January 2023.

Fluctuations in NDVI throughout the period analyzed, mainly associated with ENSO activity, indicate the potential for economic problems in the municipality of Jari (RS) resulting from drought and the consequent reduction in soybean production. Considering that the municipality's GDP is largely dependent on this crop, there is an urgent need to develop mitigation and adaptation strategies in the face of climate change, as well as to introduce other sources of income in the municipality.

Strategies that may be considered include the preparation of Agricultural Climate Risk Zoning (ZARC) to support the planning of agricultural activities, the adoption of management practices that help conserve soil moisture, the use of irrigation systems in areas where they are technically feasible, and the diversification of agricultural crops. These measures can help producers reduce their vulnerability to drought periods and, at the municipal management level, contribute to the planning of actions aimed at reducing the economic impacts associated with climate variability. In addition, future studies should expand the spatial and temporal scope to include other soybean-producing municipalities and conduct comparative analyses among different areas in order to monitor the evolution of the phenomenon and broaden understanding of the effects of climate variability on agricultural production.

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Eric Moises Beilfuss: Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing. Carina Petsch: Formal analysis, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing. Romario Trentin: Formal analysis, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing.

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DATA AVAILABILITY: The data that underpin the results of this study may be made available by the corresponding author, upon duly justified request. [Eric Moises Beilfuss].

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