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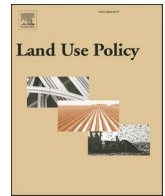
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Linking vegetation indices and land tenure to assess passive restoration dynamics in the Brazilian Cerrado

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ABSTRACT

The Cerrado biome, a biodiversity hotspot, faces challenges such as soil degradation and water resource depletion. Passive restoration is a strategy used to recover its ecosystem, with remote sensing technology enabling monitoring of forest recovery and environmental changes. This study applied multi-temporal analysis using environmental data and vegetation indices to assess a passive restoration area in a reserve at Brotas, Brazil. Data were gathered from a meteorological station and Landsat-8 satellite images. Vegetation indices such as the Simple Ratio Index (SRI), Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), and Enhanced Vegetation Index (EVI) were calculated and analyzed over time (2014–2020) by year and season (winter and summer). The environmental analysis revealed seasonal differences, highlighting the contrast between the dry winter months and wet summer months. All vegetation indices varied across years, SRI and EVI also showing seasonal differences. A noticeable deviation was observed in 2014–2015, attributed to the severe drought of 2014, with a lagged response in vegetation. Our results demonstrate that vegetation indices are effective tools for assessing ecological resilience under climate extremes and can provide evidence for designing public policies. Specially, linking passive restoration outcomes to land tenure security and watershed conservation highlights the role of tenure – restoration nexus in ensuring long-term success. These findings have implications for conservation policy in Brazil and elsewhere, reinforcing that ecological recovery strategies must be integrated with land use and land tenure frameworks to achieve sustainable climate adaptation and ecosystem services.

1. Introduction

The Cerrado biome is recognized as one of the world's biodiversity hotspots, it hosts a rich variety of fauna and flora, with approximately 160,000 species of plants, fungi, and animals, many of which are endemic (Sano et al., 2019; Ratter et al., 1997). Beyond its ecological significance, the Cerrado plays a crucial role in hydrological regulation,

serving as the source of numerous major rivers in Brazil due to its highland and plateau landscapes (Silva and Lacher, 2020). However, the biome faces increasing pressure from intensive agricultural activities, which have significantly degraded its soil and water resources (Carvalho et al., 2023).

Land-use changes in the Cerrado have been linked to soil erosion, reduced water quality, and altered hydrological dynamics, especially in

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areas lacking permanent vegetation cover (Hunke et al., 2015; Fonseca et al., 2021). These disturbances compromise the biome's ability to provide essential ecosystem services, emphasizing the urgent need for effective restoration strategies. Among these, passive restoration, which relies on natural regeneration processes without human intervention, has emerged as a cost-effective and ecologically viable option. This approach is particularly effective in landscapes with moderate disturbance and low abiotic stress, allowing for biodiversity recovery and ecosystem functionality (Morrison and Lindell, 2011).

Monitoring the success of passive restoration requires robust methodologies to track vegetation recovery over time. Advances in remote sensing technologies, particularly the use of satellite imagery, have revolutionized the ability to assess ecological changes across large spatial and temporal scales (Del Río-Mena et al., 2020). Landsat time-series data, for example, allow researchers to monitor forest dynamics, including disturbance events and recovery patterns, using spectral indices sensitive to vegetation conditions and growth stages (Griffiths et al., 2014; Nguyen et al., 2018). Commonly used vegetation indices (VI), such as the Normalized Difference Vegetation Index (NDVI) and the Soil-Adjusted Vegetation Index (SAVI), provide valuable insights into vegetation health and biomass (Pickell et al., 2016; Boonprong et al., 2018). Furthermore, hydrological indicators such as the Normalized Difference Water Index (NDWI) are sensitive to changes in the liquid water content of vegetation canopies, making them valuable tools for assessing plant health, water stress and soil moisture availability (Gao, 1996; Ashok et al., 2021). Integrating these indices with temperature and precipitation data provides a comprehensive view of ecosystem recovery processes under changing climatic conditions.

Beyond ecological and climatic factors, the success of restoration is also strongly influenced by land governance. Recent studies emphasize that land tenure - the way land is held, owned, and managed - plays a critical role in determining whether restoration initiatives are sustained over time (Chigbu et al., 2022; Chigbu, 2023, 2025). The so-called tenure-restoration nexus highlights that insecure tenure arrangements can undermine long-term ecological gains, while secure frameworks foster continuity in conservation efforts and resilience under climate change. This perspective is particularly relevant in Brazil, where instruments such as Private Natural Heritage Reserves (PRNPs) legally safeguard conservation purposes even when ownership changes (Brazil SNUC, 2000). This study aims to evaluate the passive restoration dynamics of the Cerrado biome within the Water Perennial Forest (Floresta das Águas Perenes), a Private Reserve of Natural Patrimony (PRNP) in São Paulo, Brazil. Using satellite-derived vegetation and environmental indices, we analyze multi-temporal patterns of temperature, and humidity over a seven-year period to relate to vegetation indices of an area with different stages of restoration. Our research contributes to understanding the interplay between passive restoration and hydrological processes, and governance perspectives, offering insights to guide conservation and management strategies in degraded tropical savannas.

2. Materials and methods

2.1. Study area

The study was carried out in Water Perennial Forest (Floresta das Águas Perenes), which is a Private Reserve of Natural Patrimony (PRNP) located in Brotas County, São Paulo, Brazil (22°11.754'S and 48°6.523'W, 647 m above sea level). In 2011, it was designated as High Conservation Value Forest by the Forest Stewardship Council because it provides basic environmental services such as watershed protection. PRNP covers more than 809 ha of the Cerrado area, and its phytosociology is classified as secondary Cerrado vegetation *stricto sensu* (where trees cover more than 30 % of the ground, but a fair amount of grass grows on open savanna) and Cerradão (closed woodland savanna without grass coverage) (Ratter et al., 1997; Oliveira and Marquis, 2002; Durigan et al., 2012). The climate in Brotas County is Cwa

(Köppen/Geiger's classification), which means that annual precipitation reaches 1337 mm, and the mean annual temperature is 20°C (INMET, 2022). Quartzarenic Neosol prevails as the most common soil type in this area (Santos et al., 2018).

Seeking to observe a climatic pattern that could indicate a seasonality in the temperature and humidity/water of the PRNP, we analyzed the differences in these two environmental factors over the course of a year, so this seasonality could be a factor in the vegetation index analysis.

2.2. Environmental index analysis

The precipitation data used in this study was obtained by the weather station datalogger (ID=83726) in the nearest city of the PRNP, belonging to the Brazilian Meteorological National Institute (INMET – Instituto Nacional de Meteorologia) located in São Carlos – SP county (INMET, 2022). This data was analyzed by monthly descriptive metrics.

All images analyzed came from Landsat-8 satellite (USGS - USGS - United States Geological Survey, 2022). For the temperature and water index analysis was used images from 2013 to 2019, the image gray levels (NC) were converted to radiance and calculated the surface temperature in Kelvin with subsequent transformation to degrees Celsius (°C) with equations 1 and 2 presented in Table 1. The Normalized Difference Water Index (NDWI), which is related to vegetation moisture, was obtained by equation 3 in Table 1 to represent the moisture in the study area.

Subsequently, the descriptive metrics of these two environmental variables were calculated for each month, therefore an algebraic map operation was used to show how the average monthly temperature is distributed spatially and seasonally across the study area.

2.3. Vegetation indices analysis

For the multi-temporal analysis of the vegetation indices, images from 2014 to 2020 were used, for each year was collected images on the dry (Jun-Jul) and wet (Dec-Jan) seasons. Regarding the layers used, the blue, green, red and infrared bands (NIR) were selected, which are the images used by the algorithms for determining land use and occupation.

After obtaining the images, it was processed in a GIS environment using QGIS 3.22 with GRASS 7.8.2 software, so that the images were cropped to the perimeter of the PRNP. The Semi-Automatic Classification Plugin (SCP) was used for classification, which allows supervised classification of the type of land cover. The blue, green, red and infrared (NIR) band images were merged, and then an image with the merged

Table 1.
Equations of environmental and vegetation indices.

Index type	Variable	Equation	Ref.
Environmental indices	Atmosphere spectral radiance ($L\lambda$)	$L\lambda = ML \times Q_{cal} + A_l$	(U.S. Geological Survey, 2019)
	Brightness temperature (T_b)	$T_b = (K2 / \ln(k1 / L\lambda + 1))$	(Chander et al., 2009)
	Normalized difference water index	$NDWI = (NIR - SWIR) / (NIR + SWIR)$	(Wahelo et al., 2024)
Vegetation indices	Simple Ratio	$SRI = P_{nir} / P_{red}$	(Jensen, 2000)
	Normalized Difference Vegetation Index	$NDVI = (P_{nir} - P_{red}) / (P_{nir} + P_{red})$	(Rouse et al., 1973)
	Soil-Adjusted Vegetation Index	$SAVI = (1 + L) * ((P_{nir} - P_{red}) / (P_{nir} + P_{red} + L))$	(Huete, 1988)
	Enhanced Vegetation Index	$EVI = G * ((P_{nir} - P_{red}) / (P_{nir} + (C1 * P_{red}) - (C2 * P_{blue}) + L))$	(Justice et al., 1988)

bands was generated.

Using SCP, 10–15 samples were separated and classified as: advanced restoration, medium restoration, initial restoration, and exposed soil (Fig. 1), so that the program can classify the remaining areas. These samples were classified according to their color and texture of the merged image, compared with Google Earth satellite image and with on-site visits to the PRNP. Finally, the maximum similarity algorithm was selected, that is, the most similar possible, and the land use map was generated. The vegetation indices used are described in equations 4–7 in Table 1.

To assess the influence of years and seasons, an analysis was conducted using Generalized Linear Models (GLM) (Fox, 2016), where Gaussian identity and Gaussian inverse frequency distributions were tested, with the help of R v4.3.1. software (R CORE, 2022). Model selection was done using Akaike's Information Criterion (AIC) (Akaike, 1992) and by graphical analysis through Semi-Normal Plots with Simulation Envelopes (hnp: Half-Normal, 2022). Tukey's test was subsequently applied with the aid of the 'multcomp' package (Multcomp, 2024).

3. Results

3.1. Environmental indices over the years

The lowest monthly precipitation records occurred in June (41 mm), July (29 mm), and August (32 mm), classified as the dry season. Even though there is not abundant precipitation in June, July, and August, the interaction of vegetation with the water drainage network within the PRNP area significantly contributes to moisture and temperature balance, playing a crucial role in ecological equilibrium.

The monthly average maximum temperatures varied from 22.1°C (± 1.9) in June to 34.6°C (± 0.0) in November, while the average minimum temperatures ranged from 17.1°C (± 1.6) in June to 26.8°C (± 2.8) in October. June had the smallest temperature range (5°C), in contrast to November, which showed a range of 8.1°C. The maximum temperatures occurred in October, November, and December, while minimum temperatures occurred in May and June. When analyzing the average temperature in the PRNP, we observe that, particularly in the warmer months (August to February), the temperature decreases as it gets closer

to bodies of water. (Fig. 2), showing the higher temperatures in the areas at the ends of the river basin, therefore, the highest areas and closest to the springs and far from the densest bodies of water where the temperature is lower.

The highest NDWI values, which is related to vegetation moisture, occurred in October, November, and December, followed by January, February, March, April, and May. It is also observed that the period from June to September showed the lowest NDWI values (Fig. 3).

3.2. Vegetation indices over the years

For all vegetation indices, the best model was the Gaussian inverse frequency. The SRI (Fig. 4) showed a statistically significant difference across the years ($p = 2.979e-07$) and seasons ($p = 0.001014$). The years 2014 and 2015 did not differ significantly from each other but showed a significant difference ($p < 0.001$) when compared with all other years (2016–2020).

The NDVI (Fig. 5) showed a statistically significant difference only across years ($p = 2.513e-06$). Similarly with SRI, 2014 and 2015 did not differ significantly from each other, but both differed significantly ($p < 1e-04$) from all other years (2016–2020).

The SAVI (Fig. 6) showed statistically significant differences across the years ($p = 0.02654$). The year 2014 differed significantly from all the years, excepted 2015. The other years showed not statistically significant difference between themselves.

The EVI (Fig. 7) showed statistically significant differences across years ($p = 6.389e-06$) and seasons ($p = 1.175e-06$). Different from the other indices, this index revealed significant differences between the years 2014 and 2015.

Therefore, all vegetation indices had significant difference in years, but only the SRI and EVI had difference in season (Dry/Wet), also the indices showed a distinguish result for the years 2014 and 2015, but only in EVI index they differentiated from each other.

Regarding the current land use of the PRNP, using the last images – from 2020 – most of the area is characterized as being in an initial (35.4 %) and a medium (45.2 %) stages of restoration, with a smaller area in an advance stage (19.4 %) of restoration, and there was no area (0 %) of exposed soil in the PRNP. It is important to highlight the relationship between watercourses and restoration, as restoration tends to

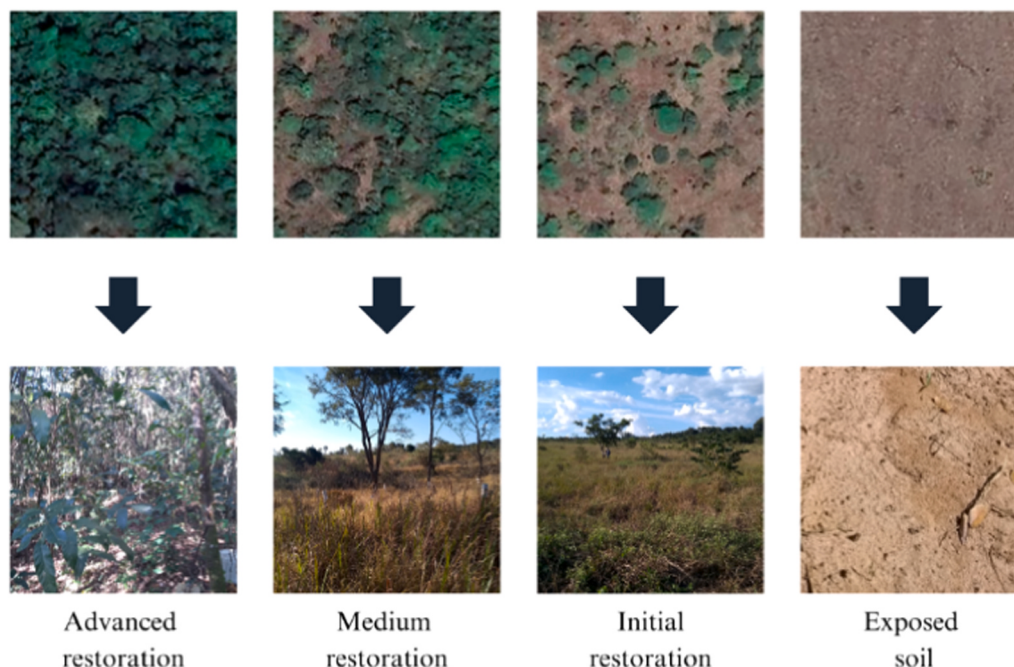


Fig. 1. Classification of restoration stages.

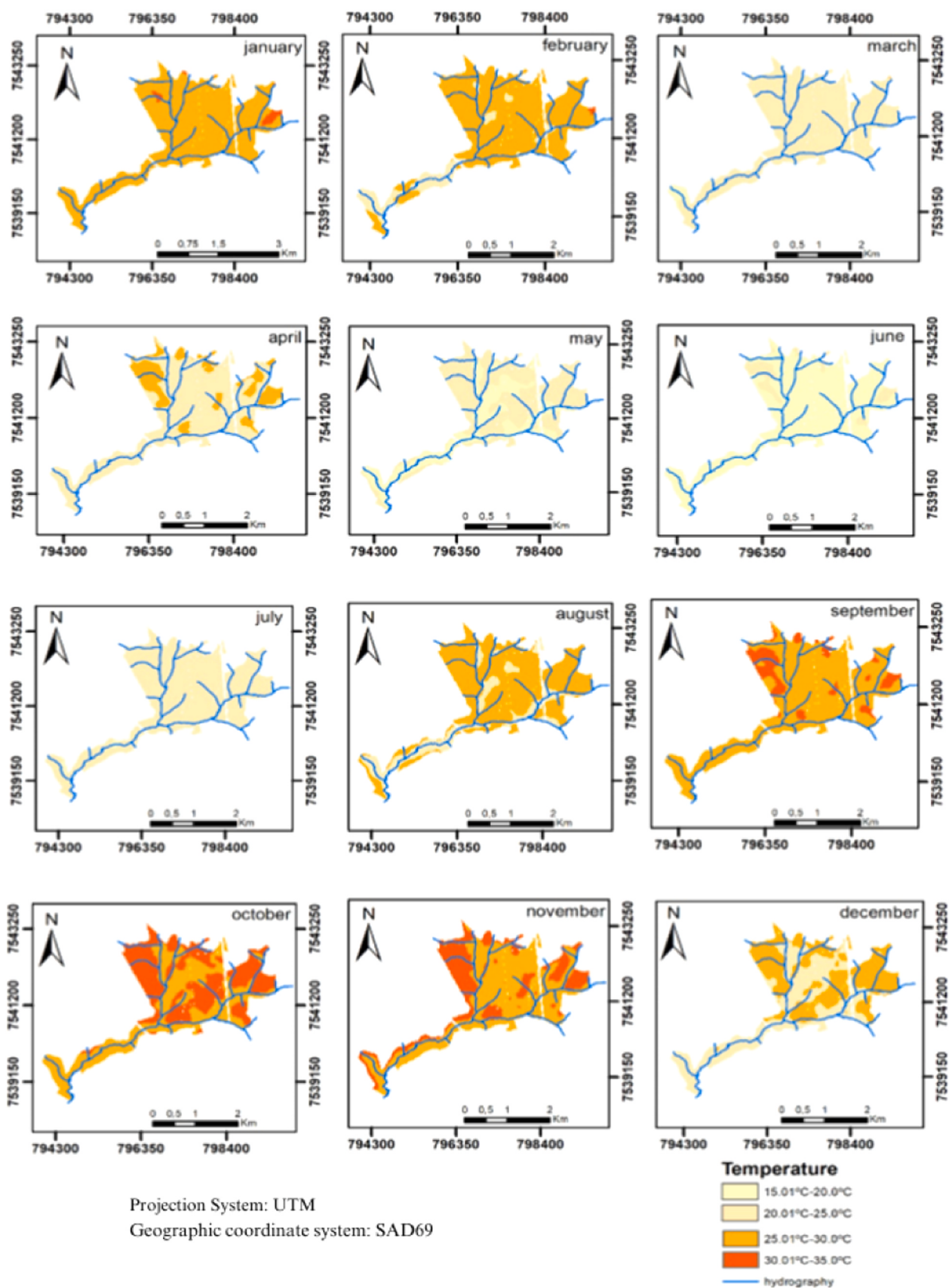


Fig. 2. Monthly spatial representation of temperature in PRNP.

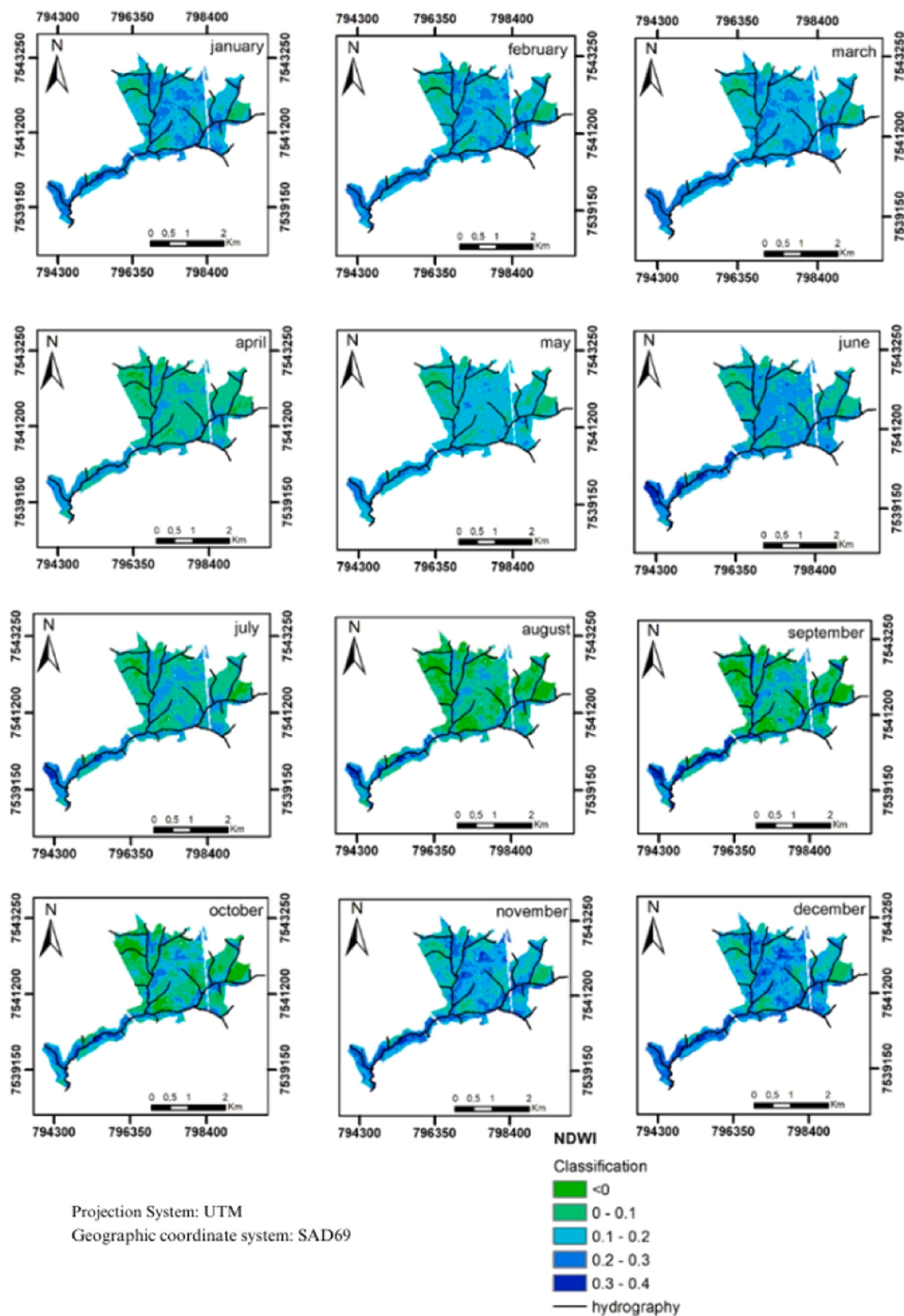


Fig. 3. Monthly spatial representation of NDWI in PRNP.

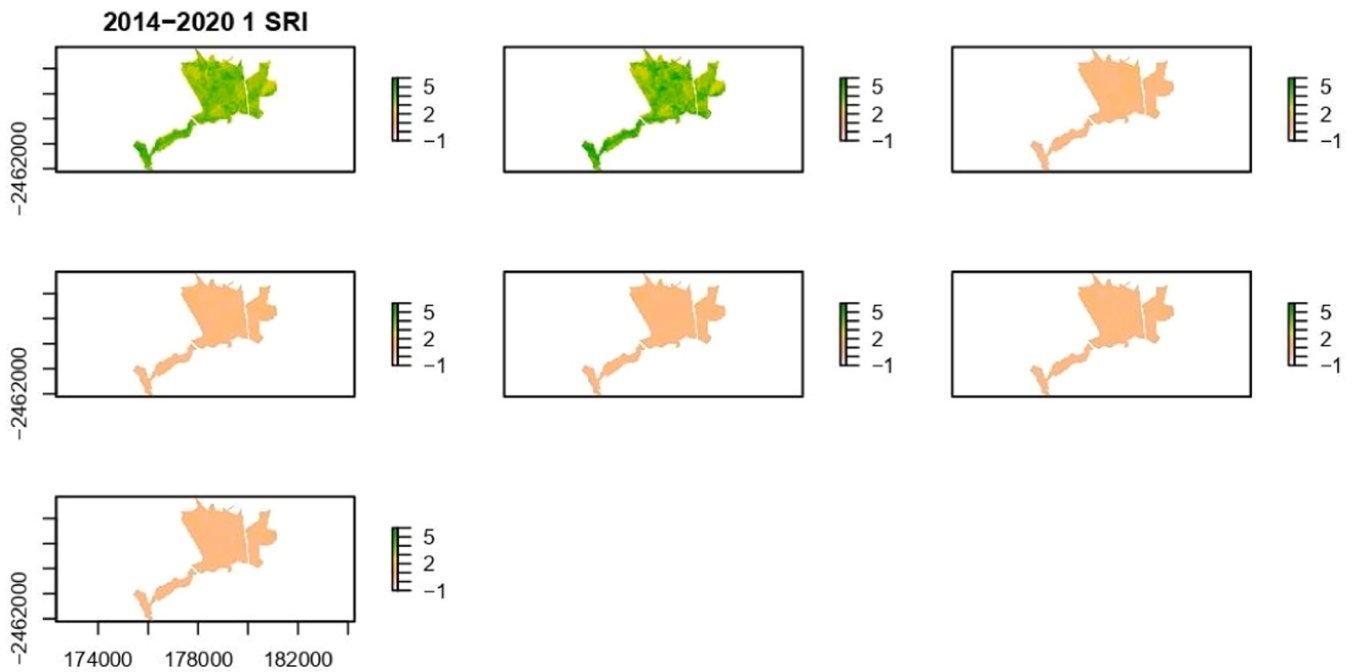


Fig. 4. Annually (2014–2020) SRI in PRNP.

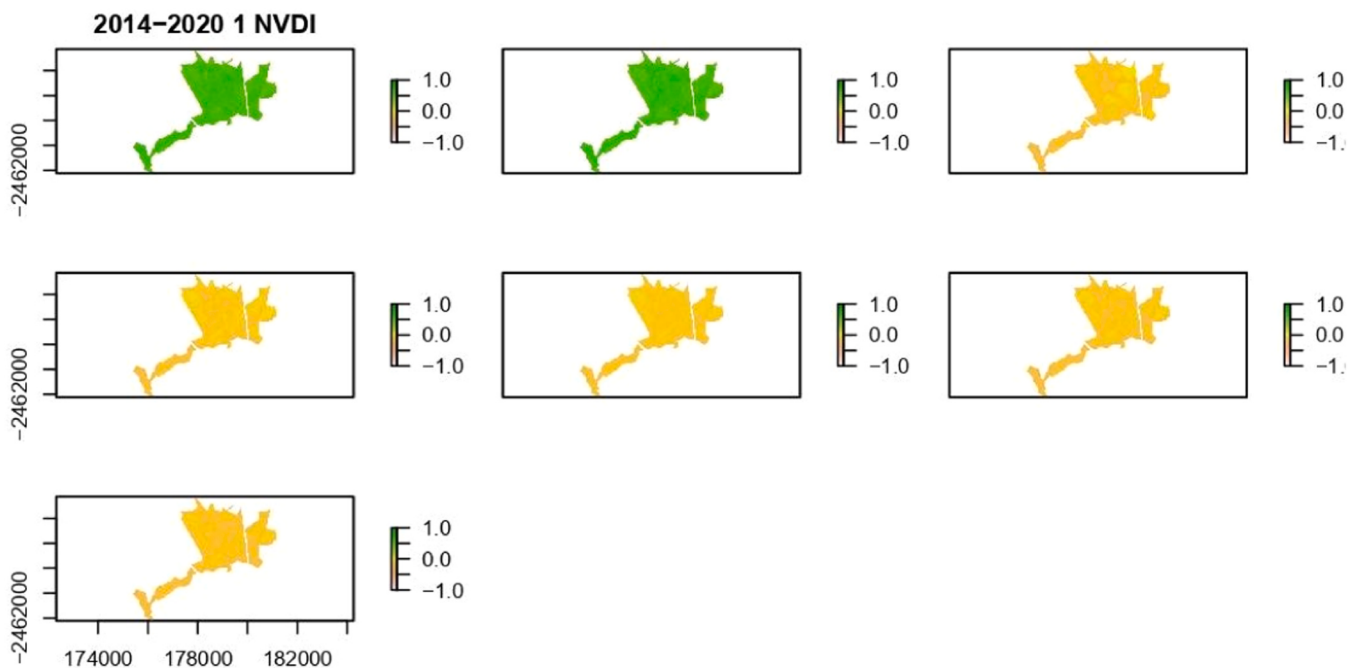


Fig. 5. Annually (2014–2020) NDVI in PRNP.

follow the course of these water bodies as we can see in Fig. 8.

4. Discussion

Water bodies can cool the surrounding environment, reducing temperatures by 2–6°C (Manteghi et al., 2015; Yang et al., 2020). They also provide essential moisture, which supports diverse vegetation and enhances local biodiversity (Lixin et al., 2012), both of which are critical for plant growth, particularly in arid regions (Elnashar et al., 2021). Which are characterized by low rainfall and high evaporation rates, face significant water scarcity, in such areas, water bodies play a vital role mitigating these challenges, thus water and soil conservation systems

are crucial for sustaining vegetation and preventing land degradation (Elnashar et al., 2021). The proximity to water provides additional benefits that enhance the success of ecological recovery, such as changes in soil enzyme activities, which may be key drivers of increases in soil available nutrients like NO_3^- -N and NH_4^+ -N (Liu et al., 2021). Water bodies also influence the distribution and density of seed banks, which are crucial for vegetation recovery (Cui et al., 2013). Moreover, riparian vegetation plays a vital role in maintaining water bodies. Vegetation along riverbanks significantly reduces erosion, supports plant growth, and decreases water turbidity (McMahon et al., 2019).

The environmental results of temperature and NDVI show that the study area is influenced by climate factors throughout the year.

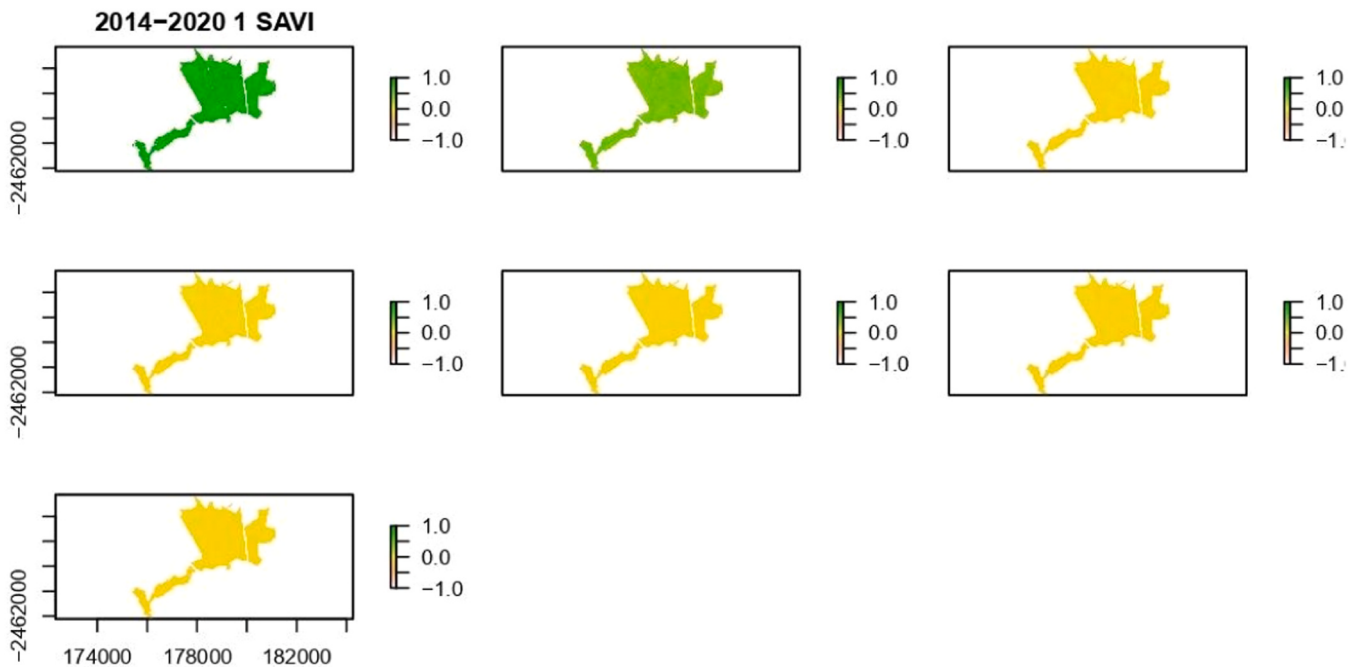


Fig. 6. Annually (2014–2020) SAVI in PRNP.

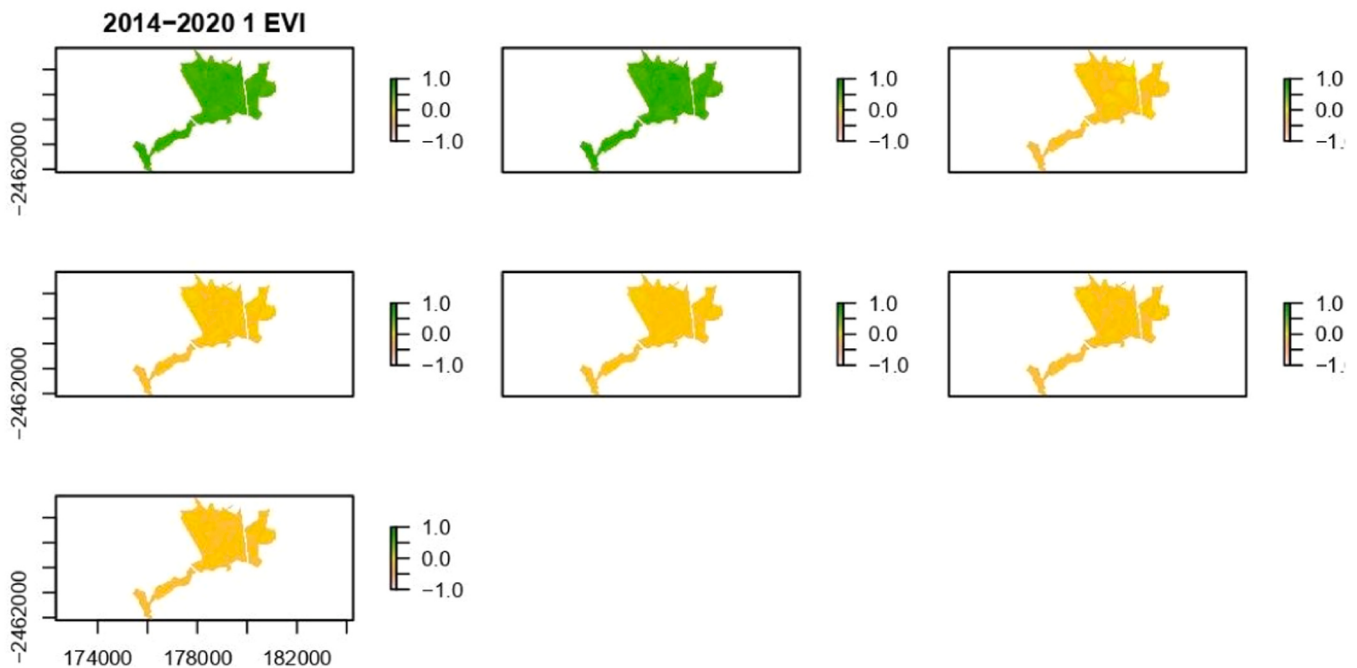


Fig. 7. Annually (2014–2020) EVI in PRNP.

Although climate change has altered ecological patterns and seasonal water availability (Hajek and Knapp, 2021), a clear seasonality is still present and can be used to interpret vegetation responses. In this regard, only two vegetation indices (SRI and EVI) captured seasonal differences, while NDVI and SAVI showed significant variation only across years. This is consistent with findings of a positive correlation between NDVI and SAVI reported by Shibani et al. (2023), indicating that, therefore only one of them could be used to give the same information. The divergent vegetation responses observed in 2014 and 2015, largely shaped by the severe drought of 2014, also illustrate how ecological resilience interacts with governance structures. While biophysical factors explained much of the variability in vegetation indices, the

long-term capacity of landscapes to withstand and recover from extreme climatic events depends on tenure security and land-use arrangements. In contexts where land tenure is insecure, restoration investments tend to be limited or short-term, reducing the effectiveness of passive restoration strategies during drought episodes. Conversely, secure tenure frameworks can promote continuity in land stewardship, ensuring that regeneration processes initiated before climatic disturbances are maintained and expanded thereafter. Thus, the drought detected in our indices not only reflects ecological vulnerability but also underscores the need to integrate land tenure considerations into restoration planning and climate adaptation policies. The SRI, also known as RVI (Ratio Vegetation Index), showed both interannual and seasonal differences.

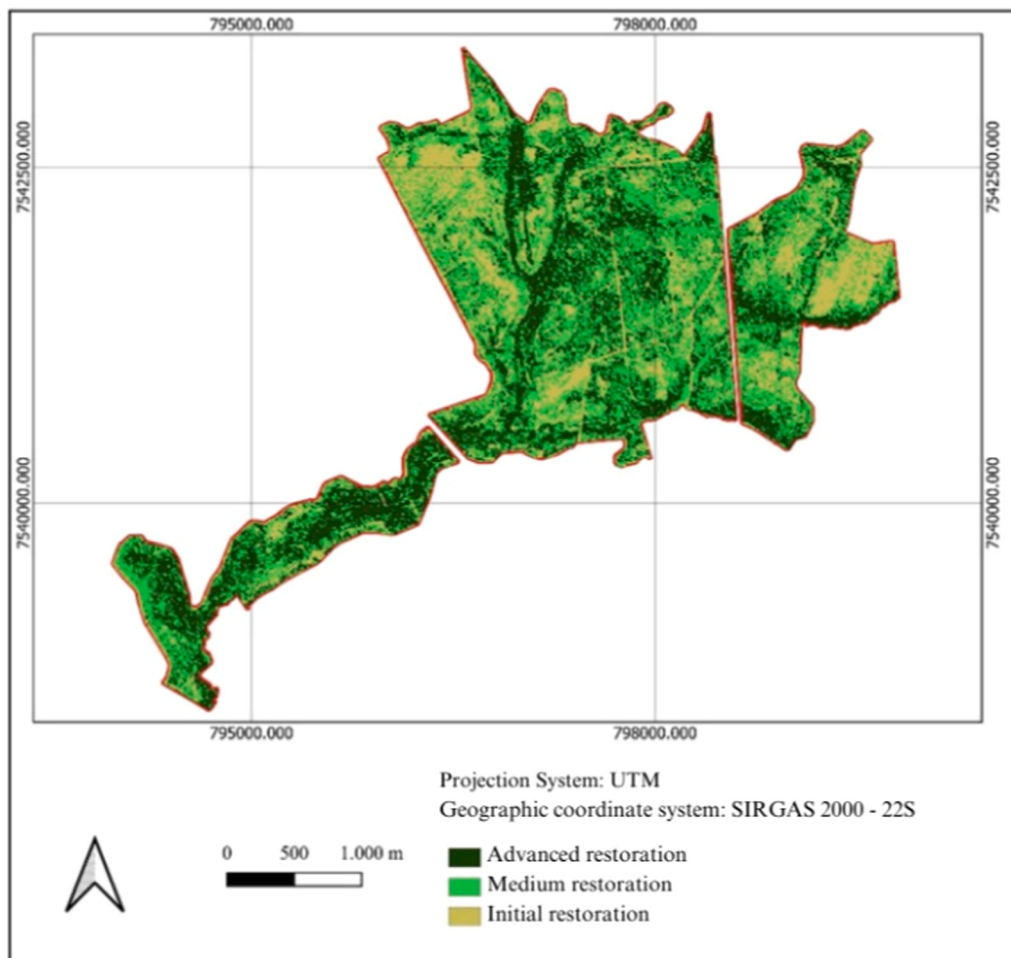


Fig. 8. Restoration stages in PRNP in 2020.

This can be explained by its lack of normalization, making it more sensitive to variations in the NIR and red band reflectance (Wei et al., 2017). The EVI, on the other hand, improves upon NDVI by reducing atmospheric and canopy background noise, making it more reliable in dense vegetation areas (Avtar et al., 2014; Hu et al., 2021). Indeed, EVI was the only index to detect differences between 2014 and 2015, suggesting that it may be more effective in advanced restoration areas, even though such areas accounted for only 19.4 % of the PRNP in 2020. This supports the view that EVI is particularly responsive in environments with greater vegetation cover, which are more sensitive to climate variability (You et al., 2017).

All vegetation indices revealed statistical difference across the years, confirming that they capture spatiotemporal variations influenced by precipitation, temperature, and soil moisture (Lou et al., 2021). Similar patterns have been reported in semi-arid regions, where vegetation indices often show lagged responses to rainfall and temperature anomalies (Olmos-Trujillo et al., 1939). The atypical behavior of 2014–2015 is consistent with the severe hydrological drought that occurred in the study region during 2014 (Marengo et al., 2015; Marengo and Alves, 2015; Fearnside and Laurance, 2015). Reduced precipitation and delayed soil moisture recovery vegetation stressed, a process captured by the indices analyzed here. César and de, (2017) quantified this anomaly, reporting that precipitation in 2014 was nearly half of the usual levels, with only 679.2 mm compared to the historical average of 1128.9 mm. Numerous studies have demonstrated the influence of precipitation and soil moisture on vegetation indices, confirming their sensitivity to environmental changes (Liu et al., 2021; Ji and Peters, 2003; Li et al., 2015; Rousta et al., 2020; Wang et al., 2020). The

divergent vegetation responses observed in 2014 and 2015, largely shaped by this severe drought, also illustrate how ecological resilience interacts with governance structures. While biophysical factors explained much of the variability in vegetation indices, the long-term capacity of landscapes to withstand and recover from extreme climatic events depends on tenure security and land-use arrangements. In contexts where land tenure is insecure, restoration investments tend to be limited or short-term, reducing the effectiveness of passive restoration strategies during drought episodes. Conversely, secure tenure frameworks can promote continuity in land stewardship, ensuring that regeneration processes initiated before climatic disturbances are maintained and expanded thereafter. Thus, the drought signal detected in our indices not only reflects ecological vulnerability but also underscores the need to integrate land tenure considerations into restoration planning and climate adaptation policies.

Fig. 2 illustrates seasonal temperature differences in the study region. Winter months, such as June and July, exhibited lower temperatures compared to summer months, like December and January. However, only the SRI and EVI indices showed significant differences between seasons, contrasting with other studies (Guha and Govil, 2020; Pandey et al., 2024), which observed seasonal differences using NDVI. One possible explanation is the influence of moisture availability. In the study region, winter coincides with the dry season, and NDVI values confirmed lower vegetation moisture from June to September. This likely reduced the sensitivity of some indices, as reported in previous studies (Sun et al., 2013; Wang and Qu, 2007). Integrating vegetation indices with climatic indicators such as temperature and soil moisture is therefore crucial for accurately interpreting restoration trajectories and

guiding land management decisions (Khikmah et al., 2024).

These findings confirm that vegetation indices are valuable tools for assessing environmental restoration processes over time. However, such ecological improvements can only be sustained if the land in question has tenure security that allows ecosystems to play their role indefinitely, without an “expiration date.” Unfortunately, in many contexts this is not the case. Reports such as those from the Intergovernmental Panel on Climate Change (IPCC) emphasize that climate change adaptation must address not only land use but also land tenure, yet policy debates have disproportionately focused on land use, with comparatively less attention to tenure (Chigbu, 2025). In the process of natural regeneration aimed at achieving land degradation neutrality (LDN), tenure plays a crucial role through the so-called tenure–restoration nexus (Chigbu et al., 2022). Tenure insecurity may manifest in diverse forms, including the absence of land titles, short-term tenancy contracts, restrictions on transferability, and risks of expropriation or eviction (Lovo, 2016; Chilombo, 2021). These conditions undermine long-term investments in restoration and conservation, highlighting the need to strengthen governance frameworks that safeguard land stewardship. A clearer understanding of the tenure–restoration connection is vital for academics, practitioners, and policymakers. By clarifying this relationship, restoration can gain greater prominence in development debates, especially from land administration and management perspectives (Chigbu, 2023). In Brazil, initiatives such as the creation of Private Natural Heritage Reserves (PRNPs) demonstrate how public policies can institutionalize long-term conservation: even if land ownership changes, the restoration purpose remains safeguarded, ensuring that conservation goals are maintained across generations (Brazil SNUC, 2000).

5. Conclusions

All the vegetation indices analyzed in our study demonstrated sensitivity to temporal variations, capturing the ecological effects of the extreme drought of 2014 and its delayed impacts in subsequent years. Among them, only the SRI and EVI were able to effectively detect seasonal differences between the summer and winter periods, underscoring their suitability for monitoring restoration dynamics in seasonally dry environments. Methodologically, our approach highlights the value of integrating multi-temporal remote sensing data, environmental indicators, and statistical modeling to provide robust assessments of passive restoration processes. Beyond methodological contributions, the study emphasizes that restoration outcomes are not merely ecological, but also strongly shaped by land governance. By linking the vegetation responses observed here to the broader literature on the tenure–restoration nexus, we demonstrate that restoration success depends not only on ecological conditions but also on land tenure security and policy frameworks that ensure continuity over time. In the Brazilian context, initiatives such as Private Natural Heritage Reserves exemplify how tenure instruments can safeguard restoration purposes despite changes in ownership, contributing to long-term climate adaptation and ecosystem service provision. Nevertheless, some limitations must be acknowledged. The use of Landsat imagery (30 m resolution) constrains the detection of fine-scale ecological processes, and the absence of local socioeconomic data on land tenure and management limited our ability to directly test governance–ecology linkages. Future research should combine satellite-based indicators with detailed field data on tenure arrangements, land management practices, and socioeconomic drivers to strengthen the integration of ecological monitoring and policy analysis. Our findings reinforce that passive restoration in the Cerrado is both feasible and detectable through vegetation indices, but its sustainability is inseparable from secure land tenure and supportive policy frameworks. Integrating ecological and governance perspectives is thus essential for achieving land degradation neutrality and climate resilience in Brazil and comparable savanna ecosystems worldwide.

Author contributions

KCT, DCCS and LB contributed to the conception and design of the experiment. KCT, DCCS, GNM, and LB conducted the experiment and organized the database. KCT, LCP, and GNM performed the statistical analyses and wrote the first draft of the manuscript. EON and KCT reviewed the original manuscript and the English version. All authors contributed to manuscript revision, and read and approved the submitted version.

CRediT authorship contribution statement

Nnadi Ernest: Writing – review & editing, Validation. **Kelly Cristina Tonello:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization. **Castilho Luara:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Leonardo Balbinot:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Darllan Collins da Cunha e Silva:** Writing – original draft, Supervision, Methodology, Conceptualization. **Gregório Nolasco Matus:** Writing – original draft, Methodology, Investigation, Conceptualization.

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Declaration of Competing Interest

The authors hereby declare that there is no conflict of interest in relation with this study and manuscript.

Data availability

Data will be made available on request.

References

- Akaike, H., 1992. Information theory and an extension of the maximum likelihood principle. *Inst. Stat. Math.* 1, 267–281.
- Ashok, A., Rani, H.P., Jayakumar, K.V., 2021. Monitoring of dynamic wetland changes using ndvi and ndwi based landsat imagery. *Remote Sens.* 23, 100547. <https://doi.org/10.1016/j.rse.2021.100547>.
- Avtar, R., Herath, S., Saito, O., Gera, W., Singh, G., Mishra, B., Takeuchi, K., 2014. Application of remote sensing techniques toward the role of traditional water bodies with respect to vegetation conditions. *Environ. Dev. Sustain.* 16, 995–1011. <https://doi.org/10.1007/s10668-013-9507-4>.
- Boonprong, S., Cao, C., Chen, W., Bao, S., 2018. Random forest variable importance spectral indices scheme for burnt forest recovery monitoring—multilevel rf-vimp. *Remote Sens.* 10, 807. <https://doi.org/10.3390/rs10060807>.
- Carvalho, A.M., de Jesus, D.R., de Sousa, T.R., Ramos, M.L.G., de Figueiredo, C.C., de Oliveira, A.D., Marchão, R.L., Ribeiro, F.P., Dantas, R.A., Borges, L.A.B., 2023. Soil carbon stocks and greenhouse gas mitigation of agriculture in the Brazilian Cerrado—A review. *Plants* 12, 2449. <https://doi.org/10.3390/plants12132449>.
- César, B., Henrique de, 2017. P. A caracterização da precipitação do ano hidrológico de 2013-2014 na região de São Carlos/SP e sua repercussão no espaço geográfico. *Rev. Bras. De Climatol.* 135–152.
- Chander, G., Markham, B.L., Helder, D.L., 2009. Summary of current radiometric calibration coefficients for landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sens. Environ.* 113, 893–903.
- Chigbu, U.E., 2023. Connecting land tenure to land restoration. *Dev. Pract.* 33 (7), 762–770. <https://doi.org/10.1080/09614524.2023.2198681>.
- Chigbu, U.E., 2025. Connecting land tenure to climate change. *Land Use Policy* 155, 107587. <https://doi.org/10.1016/j.landusepol.2025.107587>.
- Chigbu, U.W., Chilombo, A., Lee, C., Mabakeng, M.R., Alexander, L., Simataa, N.V., Siukuta, M., Rivardo, P., 2022. Tenure-restoration nexus: a pertinent area of concern for land degradation neutrality. *Curr. Opin. Environ. Sustain.* 57, 101200. <https://doi.org/10.1016/j.cosust.2022.101200>.
- Chilombo, A., 2021. Multilevel governance of large-scale land acquisitions: a case study of the institutional politics of scale of the farm block program in Zambia. *Land Use Policy* 107, 105518. <https://doi.org/10.1016/j.landusepol.2021.105518>.

- Cui, N., Wu, J., Dongfang, X., Cheng, S., Zhou, Q., 2013. A field study on seed bank and its potential applications in vegetation restoration of a polluted urban river in China. *R. Ecol. Eng.* 60, 37. <https://doi.org/10.1016/J.ECOLENG.2013.07.048>.
- Del Río-Mena, T., Willemen, L., Tesfamariam, G.T., Beukes, O., Nelson, A., 2020. Remote sensing for mapping ecosystem services to support evaluation of ecological restoration interventions in an arid landscape. *Ecol. Indic.* 113. <https://doi.org/10.1016/j.ecolind.2020.106182>.
- Durigan, G., Melo, A.C.G., Brewer, J.S., 2012. The root to shoot ratio of trees from open- and closed-canopy cerrado in south-eastern Brazil. *Plant Ecol. Divers.* 5, 333–343. <https://doi.org/10.1080/17550874.2012.691564>.
- Elnashar, A., Abbas, M., Sobhy, H., Shahba, M., 2021. Crop water requirements and suitability assessment in arid environments: a new approach. *Agronomy* 11, 260. <https://doi.org/10.3390/agronomy11020260>.
- Fearnside, P.M., Laurance, W.F., 2015. Infrastructure in amazonia: lessons from Brazil's pluri-annual plans. *Cad. CRH* 25 (64), 87–98.
- Fonseca, M., Uagoda, R., Chaves, H., 2021. Rates, factors, and tolerances of water erosion in the cerrado biome (Brazil): a meta-analysis of runoff plot data. *Earth Surf. Process. Landf.* 47, 582–595. <https://doi.org/10.1002/esp.5273>.
- Fox, J., 2016. Generalized linear models. In: Knight, V. (Ed.), *Applied Regression Analysis and Generalized Linear Models*, 3. SAGE, SAGE California, pp. 418–472.
- Gao, B.C., 1996. NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sens. Environ.* 58, 257–266. [https://doi.org/10.1016/S0034-4257\(96\)00067-3](https://doi.org/10.1016/S0034-4257(96)00067-3).
- Griffiths, P., Kuemmerle, T., Baumann, M., Radeloff, V., Abrudan, I., Lieskovský, J., Munteanu, C., Ostapowicz, K., Hostert, P., 2014. Forest disturbances, forest recovery, and changes in forest types across the carpathian ecoregion from 1985 to 2010 based on landsat image composites. *Remote Sens. Environ.* 151, 72–88. <https://doi.org/10.1016/J.RSE.2013.04.022>.
- Guha, S., Govil, H., 2020. Land surface temperature and normalized difference vegetation index relationship: a seasonal study on a tropical city. *SN Appl. Sci.* 2, 1661. <https://doi.org/10.1007/s42452-020-03458-8>.
- Hajek, O., Knapp, A., 2021. Shifting seasonal patterns of water availability: ecosystem responses to an unappreciated dimension of climate change. *N. Phytol.* 233, 119–125. <https://doi.org/10.1111/nph.17728>.
- hnp: Half-Normal Plots with Simulation Envelopes. Available online: (<https://cran.r-project.org/web/packages/hnp/hnp.pdf>) (Accessed on 20 August 2022).
- JSTOR. In: Oliveira, Paulo S., Marquis, Robert J., Oliveira, Paulo S., Marquis, Robert J. (Eds.), 2002. *The Cerrados of Brazil: Ecology and Natural History of a Neotropical Savanna*. Columbia University Press. <https://doi.org/10.7312/oliv12042>.
- Hu, P., Sharifi, A., Tahir, M.N., Tariq, A., Zhang, L., Mumtaz, F., Shah, S.H.I.A., 2021. Evaluation of vegetation indices and phenological metrics using Time-Series MODIS data for monitoring vegetation change in punjab, Pakistan. *Water* 13, 2550. <https://doi.org/10.3390/w13182550>.
- Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). *Remote Sens. Environ.* 1988 25 (3), 295–309. [https://doi.org/10.1016/0034-4257\(88\)90106-X](https://doi.org/10.1016/0034-4257(88)90106-X).
- Hunke, P., Mueller, E., Schröder, B., Zeilhofer, P., 2015. The Brazilian cerrado: assessment of water and soil degradation in catchments under intensive agricultural use. *Ecohydrology* 8, 1154–1180. <https://doi.org/10.1002/eco.1573>.
- INMET - Instituto Nacional de Meteorologia. Available in: (<https://tempo.inmet.gov.br/TabelaEstacoes/A711>) (Accessed in 20 August 2022).
- Jensen, J., 2000. *R. Remote Sensing of Environment an Earth Resource Perspective*, 07458. Prentice Hall Upper Saddle River, New Jersey (Series in geographic information science).
- Ji, L., Peters, A., 2003. Assessing vegetation response to drought in the Northern great plains using vegetation and drought indices. *Remote Sens. Environ.* 87, 85–98. [https://doi.org/10.1016/S0034-4257\(03\)00174-3](https://doi.org/10.1016/S0034-4257(03)00174-3).
- Justice, D.H., Salomonson, V., Privette, J., Riggs, G., Strahler, A., Lucht, R., Myneni, R., Knazjzhin, Y., Running, S., Nemani, R., Vermote, E., Townshend, J., Defries, R., Roy, D., Wan, Z., Huete, A., van Leeuwen, R., Wolfe, R., Giglio, L., Muller, J.-P., Lewis, P., Barnsley, M., 1988. The moderate resolution imaging spectroradiometer (MODIS): land remote sensing for global change research. *IEEE Trans. Geosci. Remote Sens.* 36, 1228–1249.
- Khikmah, F., Sebald, C., Metzner, M., Schwieger, V., 2024. Modelling vegetation health and its relation to climate conditions using copernicus data in the city of constance. *Remote Sens.* 16, 691. <https://doi.org/10.3390/rs16040691>.
- Li, Z., Zhou, T., Zhao, X., Huang, K., Gao, S., Wu, H., Luo, H., 2015. Assessments of drought impacts on vegetation in China with the optimal time scales of the climatic drought index. *Int. J. Environ. Res. Public Health* 12, 7615–7634. <https://doi.org/10.3390/ijerph120707615>.
- Liu, Q., Zhang, J., Zhang, H., Yao, F., Bai, Y., Zhang, S., Meng, X., Liu, Q., 2021. Evaluating the performance of eight drought indices for capturing soil moisture dynamics in various vegetation regions over China. *Sci. Total Environ.* 789, 147803. <https://doi.org/10.1016/j.scitotenv.2021.147803>.
- Lou, J., Xu, G., Wang, Z., Yang, Z., Ni, S., 2021. Multi-Year NDVI values as indicator of the relationship between spatiotemporal vegetation dynamics and environmental factors in the qaidam basin, China. *Remote Sens.* 13, 1240. <https://doi.org/10.3390/rs13071240>.
- Lovo, S., 2016. Tenure insecurity and investment in soil conservation. Evidence from Malawi. *World Dev.* 78, 219–229. <https://doi.org/10.1016/j.worlddev.2015.10.023>.
- Manteghi, G., Limit, H., Remaz, D., 2015. Water bodies an urban microclimate: a review. *Math. Models Methods Appl. Sci.* 9, 1–12. <https://doi.org/10.5539/MAS.V9N6P1>.
- Marengo, J.A., Alves, L.M., 2015. Crise Hídrica em São paulo em 2014: seca e desmatamento. *GEOUSP Espaço e Tempo (Online)* 19 (3), 485..
- Marengo, J.A., Nobre, C.A., Seluchi, M.E., Cuatras, A., Alves, L.M., Mendiondo, E.M., Obregón, G., Sampaio, G., 2015. A seca e a crise hídrica de 2014- 2015 em São paulo. *Rev. USP* (106), 31–44.
- McMahon, J., Olley, J., Brooks, A., Smart, J., Stewart-Koster, B., Venables, W., Curwen, G., Kemp, J., Stewart, M., Saxton, N., Haddadchi, A., Stout, J., 2019. Vegetation and longitudinal coarse sediment connectivity affect the ability of ecosystem restoration to reduce riverbank erosion and turbidity in drinking water. *Sci. Total Environ.* 707, 135904. <https://doi.org/10.1016/j.scitotenv.2019.135904>.
- Morrison, E., Lindell, C., 2011. Active or passive forest restoration? Assessing restoration alternatives with avian foraging behavior. *Restor. Ecol.* 19, 170–177. <https://doi.org/10.1111/j.1526-100X.2010.00725.x>.
- Multcomp: Simultaneous Inference in General Parametric Models. Available online: (<http://cran.r-project.org/web/packages/multcomp/index.html>) (accessed on 26 august 2024).
- Nguyen, T., Jones, S., Soto-Berelov, M., Haywood, A., Hislop, S., 2018. A spatial and temporal analysis of forest dynamics using landsat time-series. *Remote Sens. Environ.* 2018 217, 461–475. <https://doi.org/10.1016/J.RSE.2018.08.028>.
- Olmos-Trujillo, E., González-Trinidad, J., Jérez-Ferreira, H., Pacheco-Guerrero, A., Bautista-Capetillo, C., Avila-Sandoval, C., Galván-Tejada, E., 1939. Spatio-Temporal response of vegetation indices to rainfall and temperature in a semiarid region. *Sustainability* 2020 12. <https://doi.org/10.3390/su1205193>.
- Pandey, A., Mondal, A., Guha, S., Upadhyay, P.K., Rashmi, Kundu, S., 2024. Comparing the seasonal relationship of land surface temperature with vegetation indices and other land surface indices. *Geol. Ecol. Landsc.* 1–17. <https://doi.org/10.1080/24749508.2024.2392391>.
- Pickell, P., Hermosilla, T., Frazier, R., Coops, N., Wulder, M., 2016. Forest recovery trends derived from landsat time series for north American boreal forests. *Int. J. Remote Sens.* 37, 138–149. <https://doi.org/10.1080/2150704X.2015.1126375>.
- R CORE T.E.A.M. R: A language and environment for statistical computing Vienna: R Foundation for Statistical Computing, 2022. Available in: (<http://www.r-project.org/>).
- Ratter, J.A., Ribeiro, J.F., Bridgewater, S., 1997. The Brazilian cerrado vegetation and threats to its biodiversity. *Ann. Bot.* 80, 223–230. <https://doi.org/10.1006/ambio.1997.0469>.
- Rouse, J.W.; Haas, R.H.; Schell, J.A.; Deering, D.W. Monitoring Vegetation Systems in the Great Plains with ERTS (Earth Resources Technology Satellite). 1973 Proceedings of 3rd Earth Resources Technology Satellite Symposium, Greenbelt, 10-14 December, SP-351, 309-317.
- Rousta, I., Olafsson, H., Moniruzzaman, M., Zhang, H., Liou, Y.-A., Mushore, T.D., Gupta, A., 2020. Impacts of drought on vegetation assessed by vegetation indices and meteorological factors in Afghanistan. *Remote Sens.* 12, 2433. <https://doi.org/10.3390/rs12152433>.
- Sano, E., Rodrigues, A., Martins, É., Bettiol, G., Bustamante, M., Bezerra, A., Couto, A., Vasconcelos, V., Schüler, J., Bolfe, É., 2019. Cerrado ecoregions: a spatial framework to assess and prioritize Brazilian savanna environmental diversity for conservation. *J. Environ. Manag.* 232, 818–828. <https://doi.org/10.1016/j.jenvman.2018.11.108>.
- Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumberas, J.F., Coelho, M. R., Almeida, J.A., de Araujo Filho, J.C. de, Oliveira, J.B. de, Cunha, T.J.F., 2018. Sistema brasileiro de Classificação de solos. *Embrapa Solos*, 5th ed. Brasília, Brazil, p. 286.
- Shibani, N., Pandey, A., Satyam, V., Bhari, J., Karimi, B., Gupta, S., 2023. Study on the variation of NDVI, SAVI and EVI indices in punjab state, India. *IOP Conference Series Earth Environmental Science* 1110. <https://doi.org/10.1088/1755-1315/1110/1/012070>.
- Silva, J., Lacher, T., 2020. Cerrado — South America. *Encycl. World'S Biomes* 546–553. <https://doi.org/10.1016/b978-0-12-409548-9.11983-9>.
- Sun, H., Zhao, X., Chen, Y., Gong, A., Yang, J., 2013. A new agricultural drought monitoring index combining MODIS NDWI and day–night land surface temperatures: a case study in China. *Int. J. Remote Sens.* 34 (24), 8986–9001. <https://doi.org/10.1080/01431161.2013.860659>.
- U.S. Geological Survey. Department of the Interior U.S. Geological Survey, Landsat 8 (L8) Data Users Handbook, Version 4.0., USGS, South Dakota, 2019.
- USGS - United States Geological Survey. Available in: (<https://www.usgs.gov/landsat-missions/landsat-8>) (Accessed on 15 August 2022).
- Wahelo, T.T., Mengistu, D.A., Merawi, T.M., 2024. Spatiotemporal trends and drivers of forest cover change in metekel zone forest areas, northwest Ethiopia. *Environ. Monit. Assess.* 196, 1170. <https://doi.org/10.1007/s10661-024-13294-7>.
- Wang, Lixin, Liu, J., Sun, G., Wei, Xiaohua, Liu, S., Dong, Preface, Q., 2012. Water, climate, and vegetation: ecohydrology in a changing world. *Hydrol. Earth Syst. Sci.* 16 (12), 4633–4636. <https://doi.org/10.5194/HESS-16-4633-2012>.
- Wang, L., Qu, J.J., 2007. NMDI: a normalized multi-band drought index for monitoring soil and vegetation moisture with satellite remote sensing. *Geophys. Res. Lett.* 34, L20405. <https://doi.org/10.1029/2007GL031021>.
- Wang, Y., Zhang, C., Meng, F., Bourque, C., Zhang, C., 2020. Evaluation of the suitability of six drought indices in naturally growing, transitional vegetation zones in inner Mongolia (China). *PLoS ONE* 15. <https://doi.org/10.1371/journal.pone.0233525>.
- Wei, X., Gu, X., Meng, Q., Yu, T., Jia, K., Zhang, Y., Wang, C., 2017. Cross-Comparative analysis of GF-1 wide field view and Landsat-7 enhanced thematic mapper plus data. *J. Appl. Spectrosc.* 2017 84, 829–836. <https://doi.org/10.1007/S10812-017-0552-X>.
- Yang, L., Liu, X., Qian, F., 2020. Research on water thermal effect on surrounding environment in summer. *Energy Build.* 207, 109613. <https://doi.org/10.1016/j.enbuild.2019.109613>.
- You, N., Meng, J., Zhu, L., 2017. Sensitivity and resilience of ecosystems to climate variability in the semi-arid to hyper-arid areas of Northern China: a case study in the heihe river basin. *Ecol. Res.* 33, 161–174. <https://doi.org/10.1007/s11284-017-1543-3>.