A Reproducible Landsat Workflow for Mapping Burn Severity and Recovery in the Pantanal Wetlands

Douglas Bazo de Castro[a][0009-0000-2198-4369], Vinícius dos Santos Pereira[a][0009-0002-5016-396X]

[a]*Universidade Estadual de Campinas, Campinas, State of São Paulo, Campinas, Brazil;*

Corresponding author: Douglas Bazo
Universidade Estadual de Campinas, Campinas, State of São Paulo, Campinas, Brazil.
Email: d196159@dac.unicamp.br

A Reproducible Landsat Workflow for Mapping Burn Severity and Recovery in the Pantanal Wetlands

In 2020, the Pantanal, the world's largest tropical wetland, experienced unprecedented wildfires, yet spatially explicit assessments of severity and recovery remain scarce. This study examines how fire severity and vegetation recovery varied across the region from 2020 to 2025. Using open-access Landsat imagery, we applied the delta Normalized Burn Ratio (dNBR) to map burn severity and monitor post-fire regrowth. Burned areas were classified with standardized USGS thresholds, and recovery was measured as positive dNBR change within fire-affected zones. Results show pronounced spatial heterogeneity in both fire impacts and recovery, reflecting environmental gradients across the wetland landscape. Implemented entirely with free satellite data and open-source tools, the workflow provides a scalable, reproducible method for tracking fire dynamics in data-scarce regions. Although field validation was not feasible, the approach establishes a transferable baseline for wildfire monitoring and recovery assessment in tropical wetlands and other floodplain ecosystems.

Keywords: Pantanal wetlands; floodplain ecosystem resilience; dNBR; wildfire impact assessment; burn severity mapping.

Introduction

The Pantanal is the largest tropical wetland on Earth and one of the most biologically rich floodplain ecosystems (Opperman, 2012; Sanches et al., 2011). Spanning portions of Brazil, Bolivia, and Paraguay, it supports a complex mosaic of aquatic and terrestrial habitats and hosts thousands of species, many of which are endemic or threatened (Frota et al., 2020). Despite its ecological importance and UNESCO World Heritage status, the Pantanal has become increasingly vulnerable to anthropogenic pressures, including land use changes, prolonged droughts, and, most notably, wildfires (Alho et al., 2019; Lázaro et al., 2020; Oliveira et al., 2021).

In 2020, the Pantanal experienced one of the most devastating fire seasons in its recorded history (Barbosa et al., 2022). Satellite imagery and official assessments showed that more than 4 million hectares (around 30% of the biome) were impacted by fire (Barbosa et al., 2022; Rosário et al., 2022). These events caused ecological disturbances, threatened wildlife, altered hydrological processes, and reduced essential ecosystem services for biodiversity and local communities (Neto & Evangelista, 2022). Such events' increasing frequency and intensity underscore the urgent need for spatially explicit monitoring tools to support fire management, ecological restoration, and conservation planning. Remote sensing techniques have become indispensable for wildfire assessment because they deliver consistent, large-scale observations (Guindon et al., 2021). The Normalized Burn Ratio (NBR) and its derivative, delta NBR (dNBR), are commonly used spectral indices to assess burn severity and vegetation change (Hao et al., 2022). These studies utilize near-infrared and shortwave-infrared reflectance to identify fire-affected areas by detecting changes in vegetation cover and moisture content (Tariq et al., 2021; Hao et al., 2022). When applied across time, dNBR also facilitates the evaluation of post-fire vegetation recovery, a process that remains insufficiently explored in contrast to the more commonly analyzed fire impact, highlighting a critical gap in the literature that this study addresses.

We assessed burn severity and post-fire vegetation recovery in the Pantanal wetlands using multispectral Landsat imagery from 2020 and 2025. Using the NBR and dNBR, we quantified fire impacts and vegetation regrowth, generating severity and recovery maps limited to burned areas. Our workflow uses only open-access satellite data and open-source GIS tools, emphasizing reproducibility and cost-efficiency. By applying established spectral indices in a tropical wetland context, we offer a reproducible approach for monitoring fire dynamics in ecosystems with limited field validation or long-term ground data.

Study Area

The study area (23,225 km^2) is located in the north portion of the Brazilian Pantanal, a vast alluvial plain encompassing approximately 150,000 square kilometers across the states of Mato Grosso and Mato Grosso do Sul. The Brazilian Highlands bounds it to the east and north, the Chaco to the south, and the Amazon basin to the west. The region is seasonally flooded and characterized by a dynamic hydrological regime supporting a heterogeneous mosaic of wetlands, grasslands, and forested patches (Pinho & Marini, 2011). Ecologically, the Pantanal is one of the richest wetland systems on the planet, with high biodiversity levels, including over 650 bird species, 120 mammals, 80 reptiles, and a wide variety of fish and plant life (Thielen et al., 2021; Tomás et al., 2021). The area is culturally and economically significant for cattle ranching, fishing, and ecotourism. Climate irregularities, deforestation, and increased human activities have heightened the region's vulnerability to severe wildfires.

The 2020 fire season was particularly catastrophic, with fires affecting protected areas and private lands (Tomás et al., 2021). These fires were exacerbated by extreme drought and prolonged dry seasons, causing long-lasting ecological damage (Figueiredo & Filho, 2023). In this study, the research focuses on a selected subregion of the Pantanal where fire damage in 2020 was especially severe. Satellite imagery with minimal cloud cover was available across multiple time steps (pre-fire, post-fire, and long-term recovery). The selected area includes a portion of the Pantanal Matogrossense National Park and surrounding floodplain ecosystems. Geographically, it spans latitudes approximately between 17.8°S and 18.7°S and longitudes between 57.0°W and 57.9°W. Elevations range from 80 to 160 meters above sea level, and the predominant land cover types include seasonally flooded grasslands, savannas (cerrado), gallery forests, and riparian vegetation along the Cuiabá and São Lourenço Rivers.

This spatial context provides an ideal setting to evaluate wildfire impact and post-fire vegetation recovery using remote sensing. The combination of high ecological diversity, recurring fire disturbances, and the availability of cloud-free satellite scenes makes this region particularly suitable for long-term monitoring and cartographic analysis. Figure 1 shows the geographic extent of the study area within the Pantanal biome, including key hydrographic and political features.

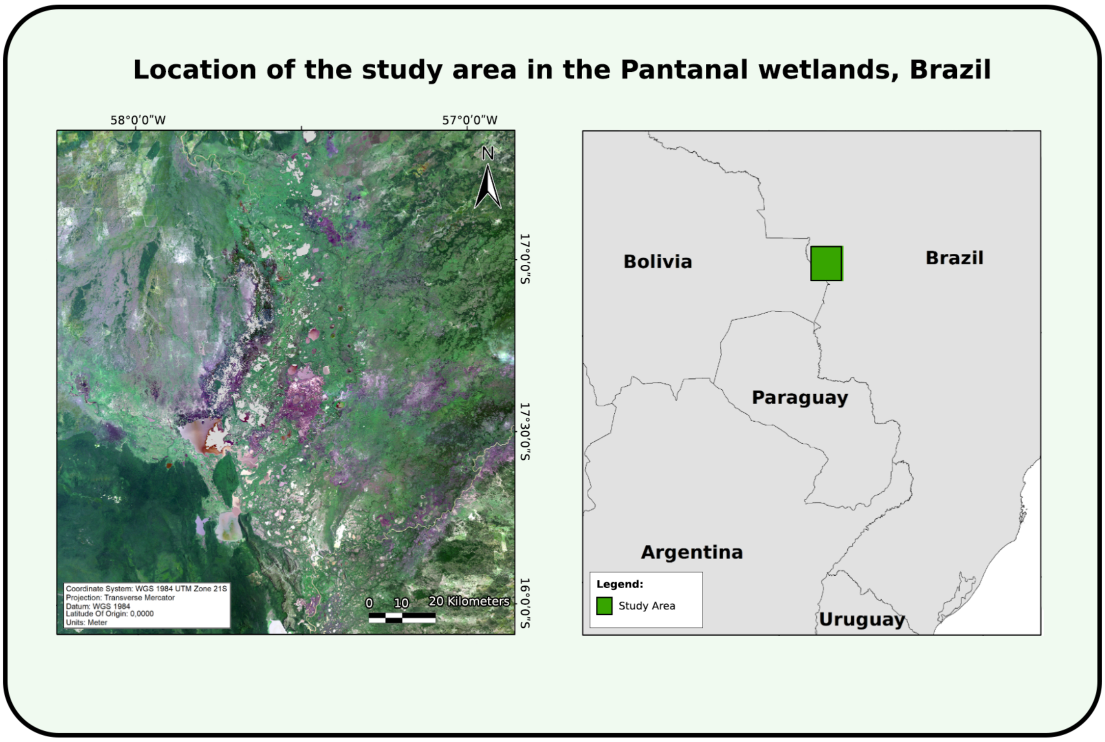

Figure 1. Location of the study area within the Pantanal wetlands, Brazil.

Data and Methods

The proposed workflow prioritizes reproducibility and affordability by exclusively utilizing open-access Landsat imagery and open-source GIS tools. This strategy is particularly well-suited to wetlands, where logistical constraints often hinder field-based monitoring, reinforcing remote sensing as the most reliable method for consistent, spatially explicit assessment. The methodological design of this study integrates spectral analysis and spatial classification to assess wildfire impact and post-fire vegetation recovery in the Pantanal wetlands. The workflow prioritizes reproducibility, and cost-efficiency, leveraging open-access satellite imagery to generate ecologically interpretable, spatially explicit outputs. This approach is suited to wetland regions like the Pantanal, where logistical challenges often preclude frequent field monitoring, and fire impact varies significantly across heterogeneous land cover types.

3.1 Satellite Data

We used surface reflectance imagery from the Landsat 8 Operational Land Imager (OLI) to assess wildfire effects and vegetation recovery in the Pantanal wetlands. We selected three acquisition dates with minimal cloud cover and consistent seasonal conditions:

Pre-fire: July 3, 2020

Post-fire: October 7, 2020

Recovery: July 5, 2025

All imagery consisted of Level-2 Collection 2 products from the USGS EarthExplorer platform (Path/Row: 227/72; centroid ≈16°37′S, 57°24′W). We masked cloud, shadow, and saturated pixels using the QA_PIXEL band and Fmask classifications. To minimize phenological variation, we selected only dry-season scenes. For qualitative interpretation, we generated true-color composites (bands 4–3–2) for each date to visualize changes across the study area (Figure 2).

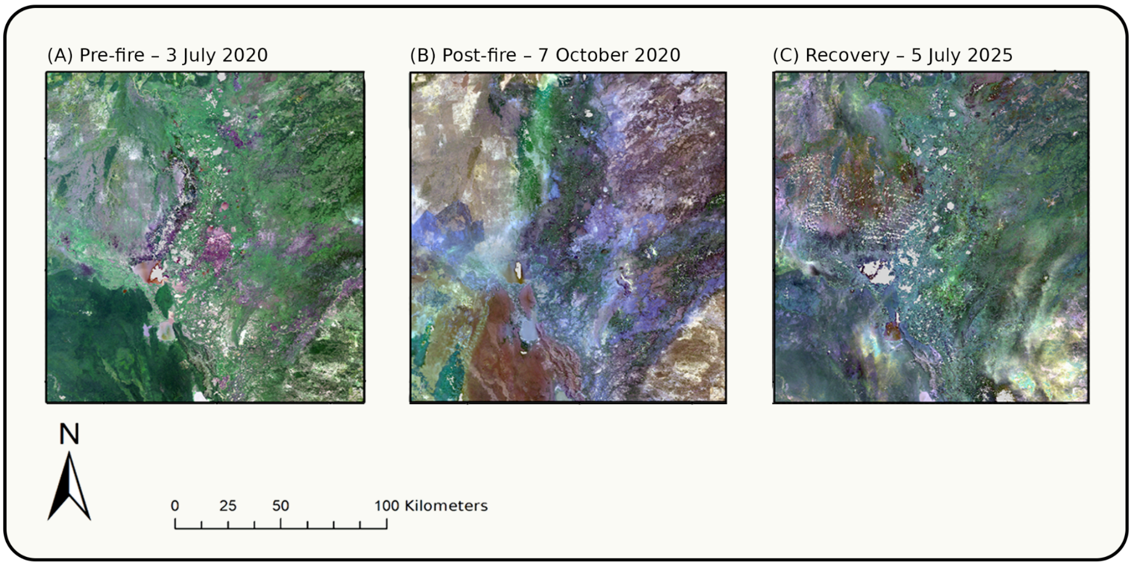

Figure 2. Natural color RGB composites derived from Landsat 8 surface reflectance imagery (bands 4–3–2), showing the Pantanal study area at three key time points.

3.2 Spectral Index Calculation

To map burned areas and quantify vegetation change, the NBR was calculated for each image:

$NBR = (B5 - B7) / (B5 + B7)$

B5 is the Near-Infrared (NIR) band (0.85–0.88 µm)

B7 is the Shortwave Infrared 2 (SWIR-2) band (2.11–2.29 µm)

From these, two dNBR maps were derived:

Burn severity (2020):

$dNBR\_burn = NBR\_pre - fire - NBR\_post - fire$

Vegetation recovery (2025):

$dNBR\_recovery = NBR\_2025 - NBR\_post - fire$

Positive values of dNBR_burn indicate vegetation loss due to fire; positive values of dNBR_recovery indicate post-fire regrowth. Vegetation recovery was calculated as dNBR_recovery = NBR_2025 − NBR_post-fire, capturing spectral change between the immediate post-fire state and the 2025 image.

3.3 Burn Mask and Classification

We identified burned areas using a dNBR threshold of 0.10, the minimum detectable disturbance under USGS standards (Key & Benson, 2006). We validated this cutoff by visually inspecting RGB composites and dNBR histograms, which consistently identified 0.10 as the breakpoint between burned and unburned pixels (Table 1). We classified post-fire vegetation recovery using dNBR thresholds adapted from Jiang et al. (2015) and Chou et al. (2008): 0.05–0.20 (low), 0.20–0.40 (moderate), and >0.40 (high) recovery. We adjusted these classes to match the spectral distribution in the 2025 recovery scene, and previous studies have shown them to perform reliably in tropical wetlands (e.g., Lu et al., 2012; Dikshit & Evans, 2024) (Table 2). We retained only pixels that met these thresholds, ensuring consistent recovery analysis across regions with limited ground data.

Table 1. Binary classification of burn severity in the study area based on dNBR values from 2020.

dNBR Value	Severity Level
< 0.10	Unburned
≥ 0.10	Burned

Recovery was similarly categorized using dNBR_recovery values:

Table 2. Classification of post-fire vegetation recovery based on dNBR differences between 2020 (post-fire) and 2025.

dNBR_recovery	Vegetation Recovery
0.05 – 0.20	Low recovery
0.20 – 0.40	Moderate recovery
> 0.40	High recovery

3.4 Image Preprocessing

The study performed all image processing and index calculations. The workflow also exported and visualized burn masks and classified rasters, preparing map layouts, symbolizations, and legends. The final product comprises final maps, adhering to the cartographic quality standards.

3.5 Cartographic Processing

All images were atmospherically corrected Level-2 products. Raster analysis and classification were conducted in QGIS 3.32 using the Raster Calculator and manual reclassification; final maps were created using Print Layout, with all data projected in WGS 84 / UTM Zone 21S. No additional radiometric normalization or co-registration was required due to standardized Landsat processing. However, minor misalignments or seasonal reflectance shifts may introduce classification noise, particularly in heterogeneous or water-affected areas. Future work could benefit from Top-of-Canopy NDVI compositing or BRDF correction to improve inter-scene comparability.

3.6 Limitations

This workflow has three main limitations. First, field validation was not feasible due to limited access in the Pantanal, precluding an independent accuracy assessment of burn severity and recovery classifications. Second, classification thresholds were adapted from widely used studies outside wetland contexts, introducing potential uncertainty when applied to tropical wetlands. Third, the analysis assumes no major fires occurred between 2020 and 2025 that would confound recovery patterns, an assumption that cannot be fully verified with the available imagery. These limitations should inform interpretation of the results but do not affect the workflow's reproducibility.

Results

The burn severity analysis using the dNBR revealed that, out of a total study area of 23,225 km², approximately 2,736 km² (11.8%) were affected by fire in 2020 (Figure 3A). The remaining 20,489 km² (88.2%) showed no spectral evidence of burning and were classified as unburned. The spatial distribution of burn severity varied considerably across the landscape, with fire scars predominantly concentrated in the western portion of the study area near transition zones. Figure 3A shows the burn severity classification based on dNBR thresholds.

Post-fire vegetation recovery, assessed using the difference between NBR in 2025 and post-fire NBR in 2020, showed heterogeneous regrowth patterns across the burned zones. Recovery was evaluated only within the masked area identified as burned in 2020. The resulting classification revealed that a portion of the fire-affected area demonstrated high or partial regeneration, while other areas remained unchanged or degraded. Table 3 summarizes the spatial distribution of burned and recovered areas, both as a percentage of the total study area and of the burned region:

Table 3. Area and percentage of burned and recovered zones within the Pantanal study region (2020–2025).

Class	Area (km^2)	% of Total Area	% of Burned Area
Unburned	20,489	88.2%	–
Not recovered	777	3.3%	28.4%
Partially recovered	1,053	4.5%	38.5%
High spectral recovery	906	3.9%	33.1%
Classified burned area	2,736	11.8%	100%

The vegetation recovery assessment in 2025 was conducted over the 2,736 km² of the study area that were identified as burned in 2020 and had valid data for both periods. This corresponds to the entire burned extent considered in the analysis, after excluding areas affected by data gaps or inconsistencies. Figure 3B illustrates the spatial distribution of vegetation recovery levels, highlighting clusters of high spectral recovery.

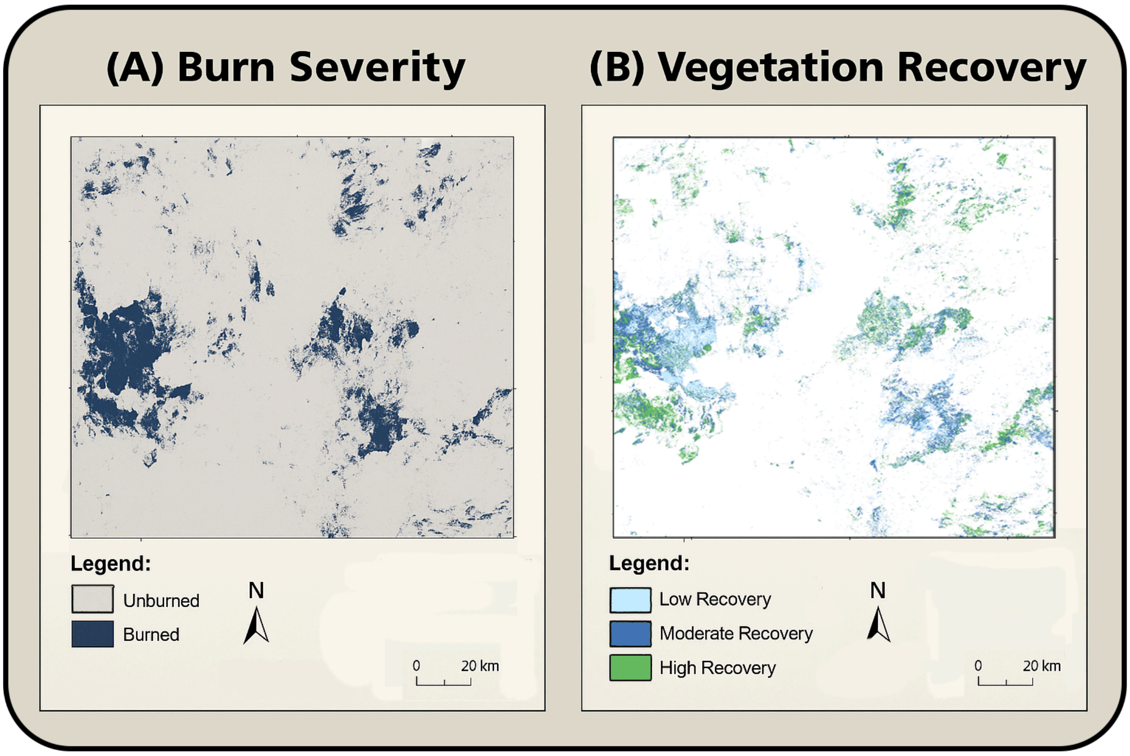

Figure 3. (A) Burn severity classified using delta dNBR between July and October 2020. (B) Vegetation recovery evaluated using dNBR differences between October 2020 and July 2025.

Discussion

The burn severity and recovery maps reveal strong spatial heterogeneity, consistent with the Pantanal's mosaic of wetland and upland environments. High-severity scars were concentrated in low-lying floodplains, while recovery was more variable in drier or sparsely vegetated zones. The 2020 fire season produced large contiguous burn scars in lowland floodplains, where drought and fuel accumulation likely intensified fire spread. These areas exhibited high dNBR values, consistent with severe loss of vegetative biomass.

Recovery dynamics over the five years following the fire were uneven. Certain zones showed strong regeneration, especially where hydrological conditions stabilized and riparian vegetation persisted. Recovery was slower in parts of the study area, suggesting that local environmental constraints can limit vegetation regrowth after fire. This delayed regrowth can be due to poor soil, lack of water, or few seeds available in the ground. It shows how the shape of the land, the small features on the ground, and the strength of fires affect how plants recover after disturbances.

Although the masking approach used in this study restricts recovery assessment to previously burned areas, discrepancies between mapped burn scars and recovery classifications (e.g., unclassified burned pixels) suggest possible limitations related to sensor sensitivity, image misalignment, or threshold calibration. Seasonal timing of image acquisition (dry vs. wet season) can influence spectral reflectance and vegetation vigor. Although we followed established USGS dNBR standards, the lack of local calibration adds uncertainty to how severity and recovery classes reflect ecological conditions. In heterogeneous wetlands like the Pantanal, fixed spectral thresholds may overestimate damage in sparse vegetation and underestimate it in dense, waterlogged forests. Nonetheless, the method yields consistent and interpretable spatial outputs using free satellite imagery and reproducible workflows.

This study shows the feasibility of combining fire monitoring and ecological recovery assessment into a single map for decision-makers. By tracking damage and resilience over time, the map aids restoration prioritization, biodiversity conservation, and land-use planning. The maps can also inform local agencies and NGOs involved in post-fire ecological recovery efforts in the Pantanal, where fire severity and vegetation regeneration remain poorly documented at scale.

Finally, while the approach is tailored to the Pantanal, it can be adapted to other floodplain ecosystems or savanna-wetland transition zones facing similar fire pressures. Future studies may incorporate additional variables such as rainfall data, vegetation indices like NDVI or EVI, or field-based validation to improve classification accuracy and ecological interpretation.

5.1 Policy Implications and Interdisciplinary Considerations

The burn severity and recovery maps generated in this study offer baseline spatial data to support environmental monitoring and fire management in the Pantanal. Because the workflow uses only open-access satellite imagery and open-source tools, it is well suited to regions lacking resources for high-resolution proprietary data. Although developed for the Pantanal, the approach is readily transferable to other wetland and savanna systems affected by similar fire regimes, providing reproducible spatial outputs to guide management and restoration planning.

5.2 Future Work

Future research should extend this workflow in several directions. First, integrating ground-truth campaigns with remote sensing would allow empirical calibration of severity and recovery thresholds. Second, multi-temporal and multi-sensor approaches (e.g., combining Landsat and Sentinel-2) could capture recovery dynamics at finer spatial and temporal scales, including potential re-burns. Third, testing vegetation- and water-sensitive indices such as NDVI, EVI, and MNDWI would better account for wetland-specific spectral variability. Fourth, coupling fire and recovery mapping with rainfall and hydrological datasets could clarify how climate and flood regimes influence regrowth. Finally, applying this open-source workflow across larger areas of the Pantanal and other tropical wetlands would test its generalizability and strengthen its utility as a reproducible tool for fire monitoring in data-scarce ecosystems.

5.3 Comparative Applications of dNBR

The dNBR remains a widely used metric for assessing burn severity and post-fire vegetation recovery across diverse ecosystems, including wetlands, savannas, and tropical forests. Studies using Landsat imagery in tropical and subtropical regions (e.g., Lacouture et al., 2020; Lu et al., 2012) have confirmed its effectiveness in detecting vegetation loss and regrowth, consistent with patterns observed in the Pantanal. Threshold-based applications in Southeast Asian peatlands and African savannas (Chou et al., 2008; Dikshit & Evans, 2024) further support the use of conservative cutoffs where field data are unavailable. However, these studies also highlight the need for local calibration, as hydrological variability and vegetation structure can influence the interpretation of recovery signals (Yang et al., 2018). Recovery trajectories additionally vary with vegetation type, rainfall, and initial fire severity, for example, delayed regrowth has been observed in subtropical forests (Jiang et al., 2015) and montane savannas (Zhang et al., 2015). While this study applied standardized USGS thresholds for reproducibility, future work could incorporate precipitation data, explore alternative indices (e.g., NDVI, EVI), and employ multi-sensor time series to enhance classification accuracy in wetland settings.

Conclusion

This study presents a reproducible workflow for mapping wildfire impacts and post-fire vegetation recovery in the Pantanal wetlands using open-access Landsat imagery and spectral indices. The resulting maps captured spatial heterogeneity in burn severity and regrowth, highlighting the uneven distribution of fire effects across the landscape. By leveraging free satellite data and open-source tools, the workflow offers a scalable approach for monitoring fire dynamics in data-scarce regions. Although developed for the Pantanal, it is transferable to other wetland and savanna ecosystems, providing a practical baseline for fire monitoring and recovery assessment.

Author Contributions

Douglas Bazo de Castro: Performed the data collection, conducted the formal analysis, and produced the visualizations, and led the writing of the original draft. Vinícius dos Santos Pereira: Provided supervision, resources, and critical revisions of the manuscript, contributed to the drafts, and gave final approval for publication.

Declarations Section

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors

Funding

This work was supported by the Universidade Estadual de Campinas (Unicamp).

Data availability statement

The datasets used in the research can be obtained from the corresponding authors upon reasonable request, while other datasets can be obtained directly from the data sources mentioned in the paper.

Clinical Trial Number

Not applicable.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Consent to Publish declaration

Not applicable.

Competing interests

The authors declare no competing interests.

Ethics and Consent to Participate declarations

Not applicable.

References

Alho, C. J. R., Mamede, S., Benites, M., Andrade, B. S., & Sepúlveda, J. J. O. (2019). Threats to the biodiversity of the Brazilian Pantanal due to land use and occupation. Ambiente & Sociedade, 22. https://doi.org/10.1590/1809-4422asoc201701891vu2019l3ao

Barbosa, M. L. F., Haddad, I., Nascimento, A. L. S., Silva, G. M., Veiga, R. M., Hoffmann, T. B., & Anderson, L. O. (2022). Compound impact of land use and extreme climate on the 2020 fire record of the Brazilian Pantanal. Global Ecology and Biogeography, 31(10), 1960–1975. https://doi.org/10.1111/geb.1356

Chou, W., Lin, W., & Lin, C. (2008). Vegetation recovery patterns assessment at landslides caused by catastrophic earthquake: A case study in central Taiwan. Environmental Monitoring and Assessment, 152(1–4), 245–257. https://doi.org/10.1007/s10661-008-0312-8

Dikshit, A., & Evans, J. (2024). Quantifying vegetation recovery after fire considering post-fire rainfall. Environmental Research Communications, 6(12), 121501. https://doi.org/10.1088/2515-7620/ad9dbd

Figueiredo, M. Z., & Filho, O. R. B. (2023). Medición de las emisiones brutas de dióxido de carbono de los incendios forestales en la zona del proyecto Abrace o Pantanal. Naturaleza, Sociedad y Desafíos Medioambientales, 5, 28–40. https://doi.org/10.53010/nys5.02

Frota, A. V. B., Vitorino, B. D., Nunes, J. R. S., & Silva, C. J. (2020). Main trends and gaps in studies for bird conservation in the Pantanal wetland. Neotropical Biology and Conservation, 15(4), 427–445. https://doi.org/10.3897/neotropical.15.e52905

Guindon, L., Gauthier, S., Manka, F., Parisien, M., Whitman, E., Bernier, P. Y., & Skakun, R. (2021). Trends in wildfire burn severity across Canada, 1985 to 2015. Canadian Journal of Forest Research, 51(9), 1230–1244. https://doi.org/10.1139/cjfr-2020-0353

Hao, B., Xu, X., Wu, F., & Tan, L. (2022). Long-term effects of fire severity and climatic factors on post-forest-fire vegetation recovery. Forests, 13(6), 883. https://doi.org/10.3390/f13060883

Jiang, W., Jia, K., Wu, J., Tang, Z., Wang, W., & Li, X. (2015). Evaluating the vegetation recovery in the damage area of Wenchuan earthquake using MODIS data. Remote Sensing, 7(7), 8757–8778. https://doi.org/10.3390/rs70708757

Key, C. H., & Benson, N. C. (2006). Landscape assessment: Ground measure of severity, the Composite Burn Index, and remote sensing of severity, the Normalized Burn Ratio. In D. C. Lutes (Ed.), FIREMON: Fire Effects Monitoring and Inventory System (Gen. Tech. Rep. RMRS-GTR-164-CD). Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Lacouture, D., Broadbent, E., & Crandall, R. (2020). Detecting vegetation recovery after fire in a fire-frequented habitat using normalized difference vegetation index (NDVI). Forests, 11(7), 749. https://doi.org/10.3390/f11070749

Lázaro, W. L., Oliveira, E. S., Silva, C. J., Castrillon, S. K. I., & Muniz, C. C. (2020). Climate change reflected in one of the largest wetlands in the world: An overview of the northern Pantanal water regime. Acta Limnologica Brasiliensia, 32. https://doi.org/10.1590/s2179-975x7619

Leeuwen, W. J. D. (2008). Monitoring the effects of forest restoration treatments on post-fire vegetation recovery with MODIS multitemporal data. Sensors, 8(3), 2017–2042. https://doi.org/10.3390/s8032017

Libonati, R., Geirinhas, J. L., Silva, P. S., Russo, A., Rodrigues, J. A., Belém, L. B. C., & Trigo, R. M. (2022). Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. Environmental Research Letters, 17(1), 015005. https://doi.org/10.1088/1748-9326/ac462e

Lu, T., Zeng, H., Luo, Y., Wang, Q., Shi, F., Sun, G., … Wu, N. (2012). Monitoring vegetation recovery after China's May 2008 Wenchuan earthquake using Landsat TM time‐series data: A case study in Mao County. Ecological Research, 27(5), 955–966. https://doi.org/10.1007/s11284-012-0976-y

Neto, N. M., & Evangelista, H. (2022). Human activity behind the unprecedented 2020 wildfire in Brazilian wetlands (Pantanal). Frontiers in Environmental Science, 10. https://doi.org/10.3389/fenvs.2022.888578

Oliveira, M. R., Szabo, J. K., Júnior, A. S., Guedes, N. M. R., Tomás, W. M., Camilo, A. R., & Garcia, L. C. (2021). Lack of protected areas and future habitat loss threaten the hyacinth macaw (Anodorhynchus hyacinthinus) and its main food and nesting resources. Ibis, 163(4), 1217–1234. https://doi.org/10.1111/ibi.12982

Opperman, J. J. (2012). A conceptual model for floodplains in the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science, 10(3). https://doi.org/10.15447/sfews.2012v10iss3art4

Pinho, J. B., & Marini, M. Â. (2011). Using birds to set conservation priorities for Pantanal wetland forests, Brazil. Bird Conservation International, 22(2), 155–169. https://doi.org/10.1017/s0959270911000207

Rosário, N. E., Sena, E. T., & Yamasoe, M. A. (2022). South American 2020 regional smoke plume: Intercomparison with previous years, impact on solar radiation, and the role of Pantanal biomass burning season. Atmospheric Chemistry and Physics, 22(22), 15021–15033. https://doi.org/10.5194/acp-22-15021-2022

Sanches, L., Vourlitis, G. L., Alves, M. C., Pinto, O. B., & Nogueira, J. S. (2011). Seasonal patterns of evapotranspiration for a Vochysia divergens forest in the Brazilian Pantanal. Wetlands, 31(6), 1215–1225. https://doi.org/10.1007/s13157-011-0233-0

Tariq, A., Shu, H., Gagnon, A. S., Li, Q., Mumtaz, F., Hysa, A., & Munir, I. (2021). Assessing burned areas in wildfires and prescribed fires with spectral indices and SAR images in the Margalla Hills of Pakistan. Forests, 12(10), 1371. https://doi.org/10.3390/f12101371

Thielen, D., Ramoni‐Perazzi, P., Puche, M. L., Márquez, M., Quintero, J. I., Rojas, W., & Libonati, R. (2021). The Pantanal under siege—On the origin, dynamics and forecast of the megadrought severely affecting the largest wetland in the world. Water, 13(21), 3034. https://doi.org/10.3390/w13213034

Tomás, W. M., Berlinck, C. N., Chiaravalloti, R. M., Faggioni, G. P., Strüssmann, C., Libonati, R., & Morato, R. G. (2021). Distance sampling surveys reveal 17 million vertebrates directly killed by the 2020's wildfires in the Pantanal, Brazil. Scientific Reports, 11(1). https://doi.org/10.1038/s41598-021-02844-5

Yang, W., Qi, W., & Zhou, J. (2018). Effects of precipitation and topography on vegetation recovery at landslide sites after the 2008 Wenchuan earthquake. Land Degradation & Development, 29(10), 3355–3365. https://doi.org/10.1002/ldr.3098

Zhang, H., Wang, X., Fan, J., Chi, T., Yang, S., & Peng, L. (2015). Monitoring earthquake-damaged vegetation after the 2008 Wenchuan earthquake in the mountainous river basins, Dujiangyan County. Remote Sensing, 7(6), 6808–6827. https://doi.org/10.3390/rs70606808