Functional Integrity as a Baseline for Multi-Scale Impact Assessment

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Introduction

The planetary boundaries approach has shown that humanity is increasingly entering a risk zone from which abrupt changes in ecological and social systems may occur (Steffen *et al.*, 2015; Richardson *et al.*, 2023). It is critical to integrate planetary systems alteration and uneven distribution of environmental changes into impact assessment tools to improve local and regional decision making (Raworth, 2012; Rockström *et al.*, 2023; Gupta *et al.*, 2024). However, there is a methodological challenge about how to cross these scales and provide reference measures to prompt timely societal responses to global changes (Biermann, 2012; Biermann and Kim, 2020).

In Brazil and other countries of the Global South, advancements in remote sensing have enabled land-use and land-cover change data to serve as key proxies for understanding territorial transformations (Souza *et al.*, 2020). Adapting these data for broader analyses in a bottom-up sense can help to bridge the above mentioned gap, providing massive and accessible information that can be used as a baseline data for impact assessment.

In this context, this study advances the operationalization of the planetary boundaries through the lens of functional integrity (FI), understood as the ability of ecosystems to contribute to biosphere processes and sustain benefits to society through the ecologically functional presence of species (Mohamed *et al.*, 2024). Currently, FI is one of the most affected dimensions of Earth system stability: globally, 70% of human-modified lands are below a minimum threshold of 25% of natural or semi-natural habitats (Mohamed *et al.*, 2024).

Focusing on the Cerrado biome, in Brazil, previous assessments have revealed a widespread decline in ecological functionality, with only a fraction of the biome maintaining high integrity levels (Reis *et al.*, 2017; Santos Junior, Mello and Montaño, 2025). Building upon these findings, we aimed to assess the temporal and spatial distribution of FI as defined at the planetary scale for the entire biome and compare it to a proposed approach to define FI for two watersheds locally. This analysis establishes a spatial reference to identify local thresholds and inform a baseline that matches with planetary boundaries approach, potentially guiding impact assessment practitioners.

The present work proposes a FI framework as the basis for a multi-scale baseline capable of supporting impact assessment (Figure 1). FI emerges from the potential of nature contributions to people (NCP) from different socioecological systems depending on landscape requirements (Díaz *et al.*, 2018; Mohamed *et al.*, 2024). While socioecological systems are composed by the integration of biotic, abiotic, and human features, landscape requirements are determined based on habitat quality, quantity, and its spatial configuration. In combination, socioecological features and landscape requirements can deliver NCP. Furthermore, natural and anthropic drivers of change can influence NCP and the underlying components of FI. As a result, FI is dynamic across time and space, varying from detailed to broader scale.

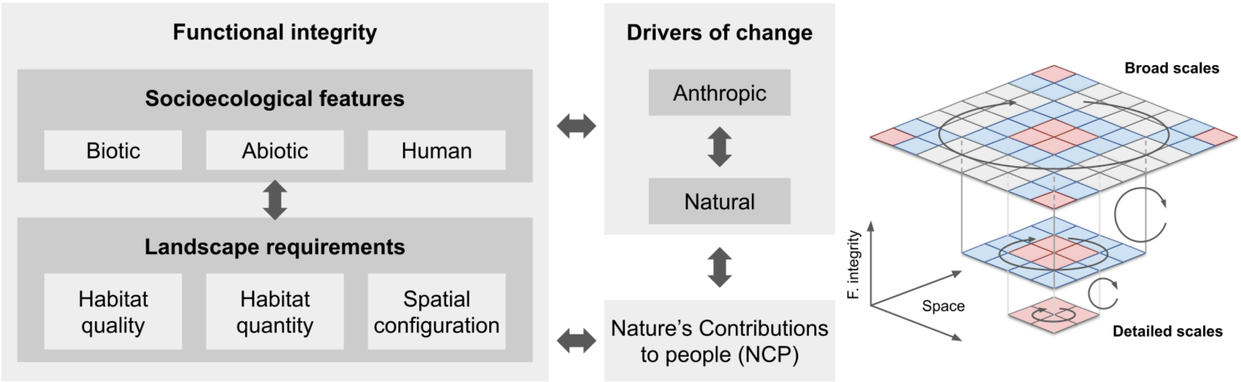

Figure 1. Conceptual framework.

Methods

Study area

Located predominantly in Brazil and covering 24% of the national territory (2.06 million km^2), the Cerrado also extends into Paraguay (1,767 km^2) and Bolivia (22,478 km^2) (Sawyer *et al.*, 2017) (Figure 2a). The Cerrado is home to around 35 million people (IBGE, 2022), including traditional populations with a direct dependence on natural resources (David *et al.*, 2020).

Our study was developed considering the Brazilian Cerrado to apply the FI threshold as defined to planetary scale, but was also detailed into two selected watersheds as study cases. They were (a) the Pardo watershed, located in Mato Grosso do Sul state (MS), fully within the Cerrado biome, covering 82.15 thousand km², of which approximately 80% is used for farming (Figure 2b); and (b) the also-named Pardo watershed, located between Minas Gerais and São Paulo states, in the transition zone between the Atlantic Forest and Cerrado biomes, covering 53 thousand km², of which 81% is used for farming (Figure 2a). These two watersheds were selected due to their similarities in land use, latitudinal positions, alongside their varying degrees of insertion within Cerrado.

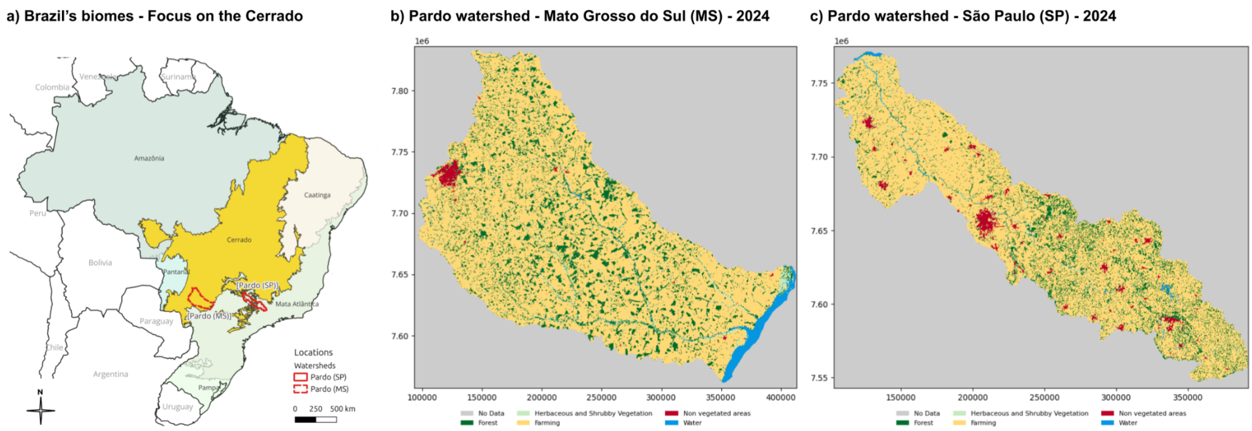

Figure 2. Study areas. a) Cerrado biome. b) Pardo River watershed (MS), totally located in the Cerrado. c) Pardo River watershed (SP), located in the transition from Atlantic Forest biome to Cerrado. Land use and land cover data refer to the year of 2024, gathered and simplified from MapBiomas project, Collection 10 (MapBiomas, 2025), described by Souza *et al.* (2020).

Procedures

According to the Safe and Just Earth System Boundaries (ESB) framework, maintaining FI in human-modified landscapes requires at least 20–25% (semi-)natural habitat per kilometer square (Rockström *et al.*, 2023; Mohamed *et al.*, 2024). We applied this threshold in the Cerrado biome

(Brazil) from 1985 to 2024 and developed a classification of FI using Random Forest for the studied cases to compare the approaches (Figure 3).

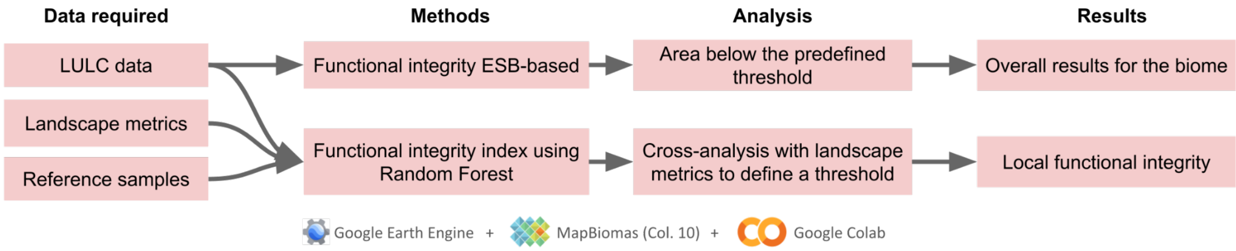

Figure 3. Methodological steps.

For both approaches, we used the same land use and land cover data and a uniform 1 km² grid. For the Cerrado biome, we calculated LULC proportions per year using Google Earth Engine (GEE) and applied the ESB threshold to estimate the area that does not meet minimum levels of integrity. For the watershed cases, we used Google Colab to calculate the following landscape metrics per grid cell: dominant class, percentage of the dominant class, number of patches, patch density, edge density, Shannon diversity index, Simpson diversity index, and proportions for each LULC class.

We sampled high FI areas using protected areas and natural cover, and low integrity areas using degraded, urban, or intensive agricultural lands. These sampled reference sites and the associated landscape metrics were used to train a Random Forest classifier (total of 255 samples, 70% training, 30% validation) for each watershed. The results, estimated as the probability of each grid cell being classified as high or low FI, were assessed in terms of overall accuracy (number of validation samples corrected classified divided by the number of validation samples), and interpreted as an index. This index was then cross-analyzed with the calculated metrics to capture variation and to estimate a local threshold of FI, discussed along with the value defined by the ESB framework.

Results

FI ESB-based

The Cerrado has more than 675,000 km² of areas that do not meet minimum thresholds of FI based on the original FI approach (an increase of approximately 330,000 km² since 1985) (Figure 4). Across the biome, the proportion of natural cover necessary to ensure NCP decreased from 0.70 to 0.50 between 1985 and 2024.

FI watershed-based

The FI classification accuracy was 97%. For the Pardo (MS), the average FI was 0.24 and median was 0.09 (Figure 5a). For Pardo (SP), average was 0.30, while median value was 0.23 (Figure 5b). For Pardo (MS), a sharp decline occurred between 34 and 37% of forest coverage with a concurrent increase of farming activities above 61% (Figure 6a). For the Pardo (SP), such sharp alteration was evident between 27 and 30% of forest, with farming reaching 70% of LULC proportion (Figure 6b).

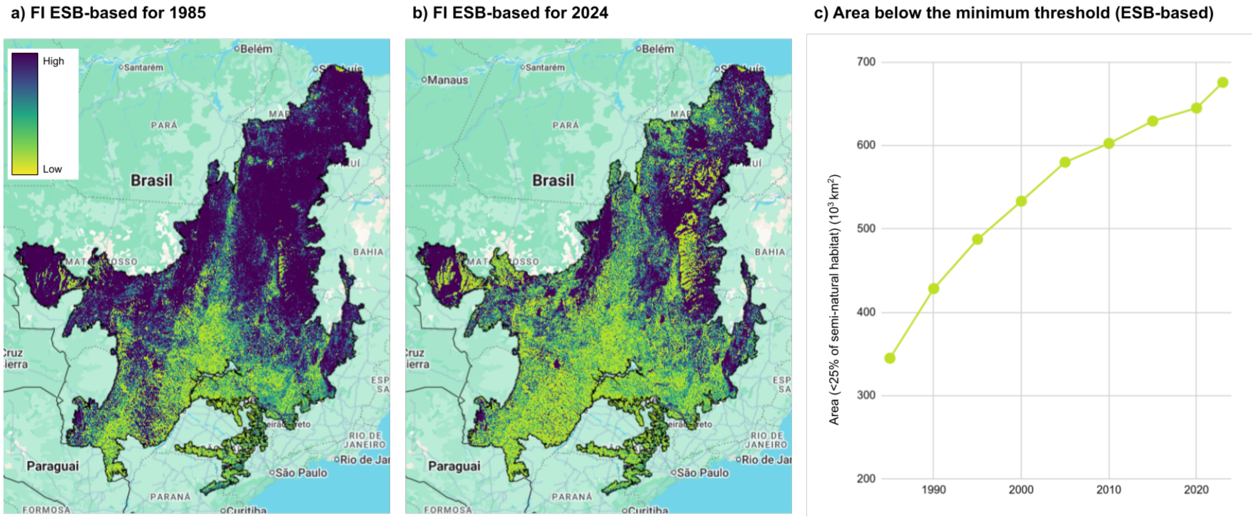

Figure 4. Decline in the functional integrity (FI) of the Cerrado. a) FI ESB-based for 1985. b) FI ESB-based for 2024. c) Estimated area below FI ESB-based for the entire Cerrado.

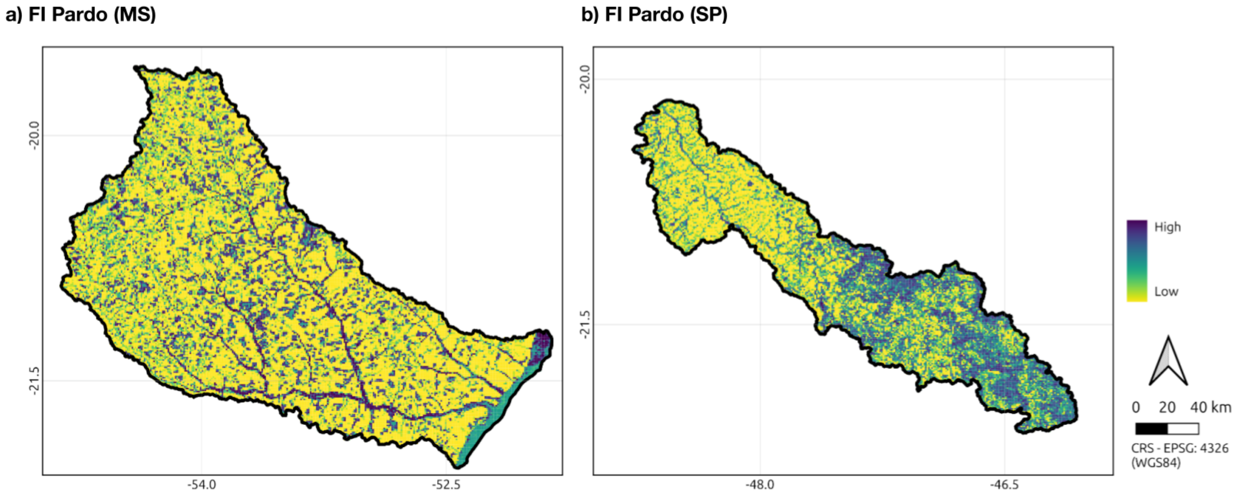

Figure 5. Results of the FI based on Random Forest classification.

Discussion and final considerations

The direct application of the FI ESB-based threshold (25% semi-natural habitat) revealed an accelerated decline in FI across the biome, corroborating previous localized assessments of ecological integrity. This finding confirms that the planetary-scale boundary captures the broader trend of integrity loss, but our local-scale analysis indicates that more stringent thresholds may be needed for effective regional assessment.

When applying the Random Forest approach to estimate FI locally, we identified higher thresholds (between 27% and 37% semi-natural habitat assumed from forest coverages) for the two watersheds. While the ESB reference (25%) may be appropriate for global assessments, our results suggest that a stricter boundary should be considered for the Cerrado biome, particularly for areas fully embedded within it. This reinforces the notion that regional contexts demand context-specific thresholds to reflect local ecological and social conditions.

The results also revealed clear relationships between landscape configuration and FI decline for both watersheds. The proposed index captured the increasing level of anthropogenic land use, showing a sharp decline in FI beyond certain landscape thresholds, particularly in relation to forest proportion and farming intensity (Figure 6). This suggests a possible limit beyond which human activities exceed the carrying capacity of each location, a finding that should be further explored in conjunction with spatial configuration metrics in future studies.

Following the same rationale of the Safe Operating Space for humanity (Rockström *et al.*, 2009), the FI boundary should be positioned before the increasing risk of resilience loss. Although our calculated values were based on average land cover proportions, impact assessment and policy-making processes should consider higher semi-natural cover references as buffers to prevent further losses of NCP. Additionally, future studies could refine these estimates by incorporating more detailed forest features beyond the simplified LULC classes used here.

Overall, this work indicates that the FI approach proposed by the ESB framework can be adapted locally, bridging the gap between planetary-scale boundaries to regional contexts, making it available as a baseline for impact assessment. The thresholds identified for the Cerrado watersheds provide spatially explicit reference conditions for impact assessment and regional planning. From this perspective, the probability-based integrity index enables quantitative evaluation of how individual projects or policies participate in the transgression or recovery of safe boundaries, thereby supporting more robust and adaptive decision-making.

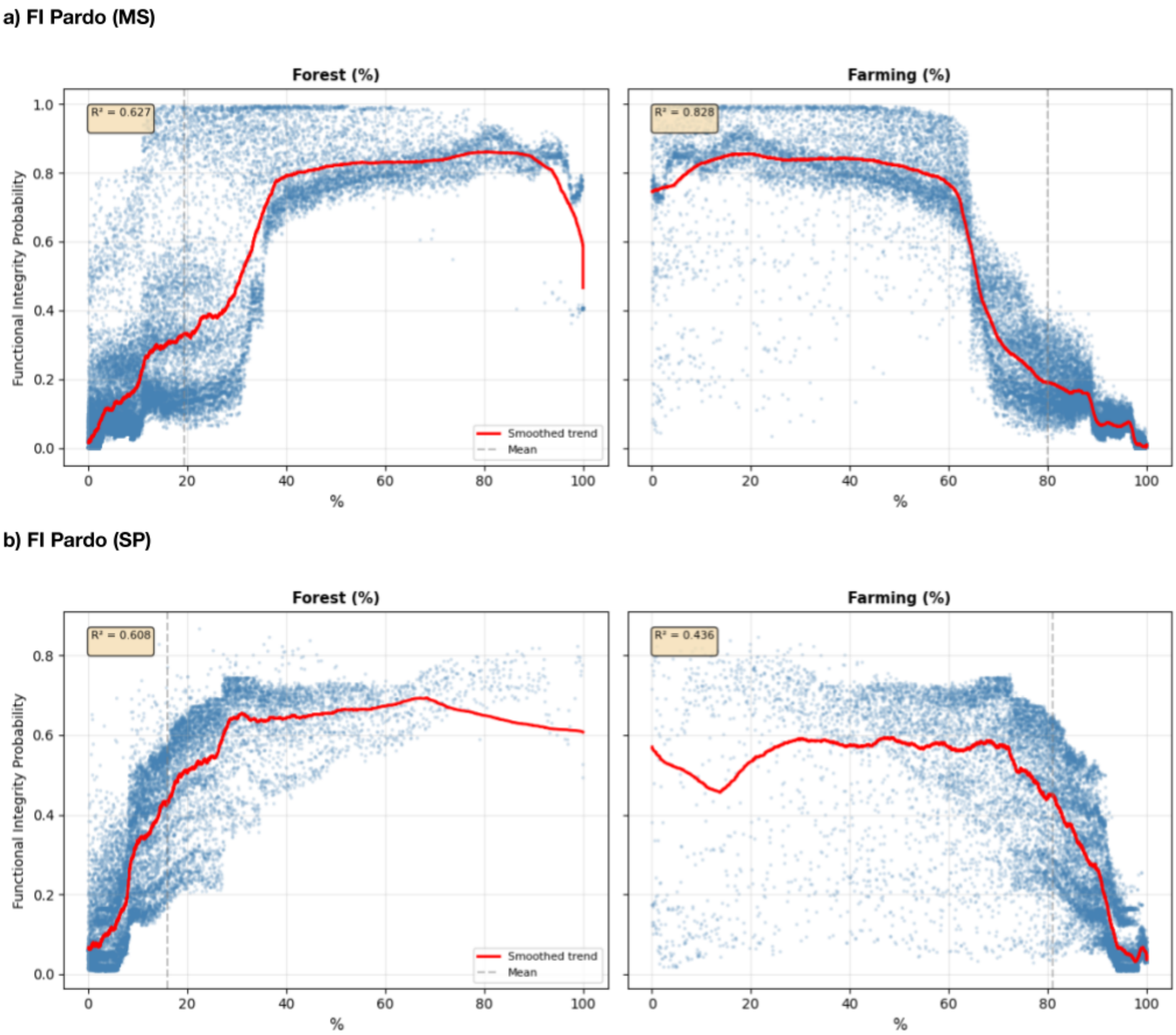

Figure 6. Cross-analysis of the calculated FI and landscape metrics.

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