Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Environmental indicators and land-use change in the Amazon-Cerrado-Pantanal transition zone of Cáceres, Mato Grosso: a Pressure-State-Response assessment

ARTICLES doi:10.4136/ambi-agua.3171

Received: 08 Apr. 2026; Accepted: 25 Jul. 2026

Luciene da Costa Rodrigues[1*]; Jesã Pereira Kreitlow[1]; Sandra Mara Alves da Silva Neves[2]; Claumir Cesar Muniz[1]; Ernandes Sobreira Oliveira Junior[1]

[1]Centro de Pesquisa em Limnologia, Biodiversidade e Etnobiologia do Pantanal. Faculdade de Ciências Agrárias e Biológicas. Universidade do Estado de Mato Grosso (UNEMAT), Avenida Santos Dumont, s/n, CEP: 78211-260, Cáceres, MT, Brazil.
E-mail: kreitlow.jesa@unemat.br, claumir@unemat.br, ernandes.sobreira@unemat.br
[2]Centro de Ensino, Pesquisa e Extensão em Geografia. Faculdade de Ciências Humanas. Universidade do Estado de Mato Grosso (UNEMAT), Avenida Santos Dumont, s/n, CEP: 78211-260, Cáceres, MT, Brazil.
E-mail: ssneves@unemat.br
[*]Corresponding author. E-mail: luciene.rodrigues@unemat.br

Editor-in-Chief: Nelson Wellausen Dias

ABSTRACT

This study analyzes the environmental indicators of the municipality of Cáceres, Mato Grosso, a territory that encompasses portions of three major Brazilian biomes: Amazon, Cerrado, and Pantanal. Due to its location at the convergence of these biomes, Cáceres represents an ecologically sensitive mosaic where land-use pressures interact with fragile transitional dynamics. The methodology combined a systematic literature review with geotechnological analysis based on data from the MapBiomas Project and Landsat images (1985–2022), integrated into the Pressure-State-Response model. The biome figures reported here refer to the fraction of each biome contained within the municipal boundary, not to the biomes in their entirety. Anthropic conversion was highest in the Amazon portion (57.8% of its area), followed by the Cerrado (33.8%) and the Pantanal (16.5%). Under a continuation of recent trends, the Amazon portion remains within the range that biome-scale studies associate with severe ecological degradation. The multivariate analysis identified cattle ranching, rather than crop expansion, as the driver whose annual dynamics most closely track native-vegetation loss. The institutional responses identified in this study encompass federal, state, and municipal legislation in environmental, economic, and social dimensions, including the Forest Code, Climate Change Policies, and specific measures for fisheries. However, gaps in implementation were revealed, particularly at the local scale. These results demand the development of integrated local environmental planning capable of articulating effective institutional responses to the ongoing environmental pressures.

Keywords: biomes, deforestation, environmental indicators, environmental planning, land use.

Indicadores ambientais e mudança de uso do solo na zona de transição Amazônia-Cerrado-Pantanal em Cáceres, Mato Grosso: uma avaliação Pressão-Estado-Resposta

RESUMO

Este estudo analisa os indicadores ambientais do município de Cáceres, Mato Grosso, território que abrange porções de três grandes biomas brasileiros: Amazônia, Cerrado e Pantanal. Por sua localização na convergência desses biomas, Cáceres representa um mosaico ecologicamente sensível onde as pressões do uso da terra interagem com dinâmicas de transição frágeis. A metodologia combinou revisão sistemática da literatura com análise geotecnológica a partir de dados do Projeto MapBiomas e imagens Landsat (1985-2022) integrados ao modelo Pressão-Estado-Resposta. Os valores por bioma referem-se à fração de cada bioma contida no limite municipal, não aos biomas em sua totalidade. A conversão antrópica foi maior na porção amazônica (57,8% de sua área), seguida do Cerrado (33,8%) e do Pantanal (16,5%). As projeções indicam que, caso as trajetórias atuais persistam, a conversão antrópica é maior na porção Amazônica (57,8% de sua área), seguida do Cerrado (33,8%) e do Pantanal (16,5%). Mantida a continuidade das tendências recentes, a porção amazônica permanece dentro da faixa que estudos em escala de bioma associam a degradação ecológica severa. A análise multivariada identificou a pecuária, e não a expansão agrícola, como o vetor cuja dinâmica anual acompanha mais de perto a perda de vegetação nativa. As respostas institucionais identificadas neste estudo abrangem legislação federal, estadual e municipal nas dimensões ambiental, econômica e social, incluindo o Código Florestal, as Políticas de Mudanças Climáticas, e específicas medidas para a pesca, revelando, contudo, vácuos na implementação, principalmente em escala local. Esses resultados exigem um desenvolvimento de planejamentos ambientais locais integrados, capazes de articular respostas institucionais efetivas diante das pressões ambientais em curso.

Palavras-chave: biomas, desmatamento, indicadores ambientais, planejamento ambiental, uso da terra.

1. INTRODUCTION

Brazilian tropical biomes rank among the most ecologically complex and biodiverse systems on Earth, and the most ecologically complex and biodiverse systems on Earth, and the scientific literature has accumulated substantial evidence over recent decades on how anthropogenic activities affect their structural and functional integrity (Myers *et al.*, 2000; Lapola *et al.*, 2023; Flores *et al.*, 2024). In these ecosystems, forest degradation consists in the progressive reduction of density, biomass, and ecosystem functions, which may occur without complete removal of the vegetation cover, and has reached concerning levels throughout tropical South America. Estimates indicate that 2.5 million km² in the Amazon are under some level of degradation, causing enormous quantities of greenhouse gas emissions and reducing evapotranspiration (Lapola *et al.*, 2023).

The vulnerability of these biomes intensifies near critical ecosystem transition thresholds. Flores *et al.* (2024), provided an estimate of the proportion of Amazon forests exposed to disturbances capable of undermining their resilience by 2050 varying from 10% to 47%, with a risk of irreversible collapse if deforestation and climate change trajectories are not altered. These thresholds are not confined to the Amazon, as the biome contributes up to 50% of the rainfall received by the Cerrado and the Pantanal through atmospheric moisture transport, commonly referred to as flying rivers, whereby water evaporated and transpired by the Amazon forest is carried by air currents toward the centre-south of the continent (Arraut *et al.*, 2012; Flores *et al.*, 2024).

The Cerrado, the largest tropical savanna in the world and a globally recognized biodiversity hotspot, has already lost between 50% and 55% of its original native vegetation cover (Strassburg *et al.*, 2017; Pereira *et al.*, 2026), with projections pointing to about 1,140 plant extinctions by 2050 if current deforestation rates continue. The transformation of the Cerrado for agriculture reduces annual evapotranspiration by up to 44%, generating negative feedback on the regional rainfall regime (Rodrigues *et al.*, 2022).

The Pantanal, the largest continuous wetland of the world, has similarly faced growing anthropogenic pressure over the past four decades. This fact becomes particularly evident observing between 1985 and 2021, when forest and savanna cover within the biome declined by approximately 40% relative to its 1985 extent, being converted mainly to pasture and soybean, reflecting the progressive replacement of natural ecosystems by livestock and agricultural land uses (Caballero *et al.*, 2025).

The study of environmental indicators makes it possible to analyze the conditions and changes in environmental quality (Gareiou *et al.*, 2023), while also favoring the understanding of sustainability interfaces and trends, constituting a support tool for decision-making and the formulation of sustainable policies and practices (Gomes and Malheiros, 2012). In this regard, the Organisation for Economic Co-operation and Development (OECD) states that indicators simplify information about complex phenomena, thereby improving communication processes. It is through this information that the stages of planning, implementation, and development of public policies are built (OECD, 1993; Kemerich *et al.*, 2014). Environmental indicators in particular assist in monitoring the operationalization of sustainable development and provide information on the state of different dimensions, including environmental, economic, socioeconomic, cultural, and institutional aspects (Van Bellen, 2008; Kemerich *et al.*, 2014).

The identification and analysis of the environmental indicators are done by asking questions about the societal anthropogenic pressures; a current state of the investigated area; and the social and institutional responses for actions (Hazbavi *et al.*, 2020), normally shown by an approval of a law or decree. To address these questions and make visible the links between society and nature, the Pressure-State-Response (PSR) model makes it possible to relate each environmental problem to its respective causes and the actions and policies designed to address them (OECD, 1993; 2003; Barreto and Almeida, 2021).

Applying the PSR model to diagnose environmental indicators in Cáceres, a municipality in an area of ecological transition and tension in Mato Grosso, is therefore necessary for understanding local environmental change. This type of analysis is conducted to reveal disturbances and damages on the landscape that impact society and nature, since it considers socioecological systems cohesive and integrated, characterized by internal connections and feedbacks between social and ecological components that determine their dynamics (Biggs *et al.*, 2022).

In this perspective, the use of geotechnologies associated with the PSR model is an important tool for identifying landscape attributes and generating cartographic representations (Silva and Costa, 2022). The quantification of data represented through thematic maps can support actions that contribute to the conservation of natural components and the recovery of degraded areas (MapBiomas, 2023).

Cáceres, in the state of Mato Grosso, is a municipality geographically and strategically positioned in the Amazon-Cerrado-Pantanal transition. Its territory encompasses portions of all three biomes within a highly sensitive ecological transition zone, making it a natural observatory for integrated environmental assessment. In this setting, the Pressure-State-Response (PSR) model proposed by the Organisation for Economic Co-operation and Development (OECD, 1993) offers a well-established analytical framework for organizing environmental indicators according to a causal logic that links human activities (Pressure), resulting environmental conditions (State), and governance actions (Response) (Barreto and

Almeida, 2021; Macêdo and Torres, 2018). This study diagnoses the environmental indicators of Cáceres using the PSR model and analyzes deforestation trends across its territory and its constituent biomes.

2. MATERIAL AND METHODS

2.1. Study area

The municipality of Cáceres (Figure 1) covers an area of 24,499.922 km² located in the state of Mato Grosso, in the Central-West region of Brazil, within the Centro-Sul Mato-Grossense mesoregion (IBGE, 2024b). It spans three biomes, whose shares of the municipal area are the Pantanal (71.5%), the Cerrado (14.5%), and the Amazon (14.0%); these percentages refer to the portion of the municipality covered by each biome, not to the biomes in their entirety. It has a population of 89,681 inhabitants, of whom 87.07% reside in urban areas and 12.93% in rural areas (IBGE, 2024a). Regarding the local economy, in 2021 was predominantly driven by services and public administration, which together accounted for approximately 76% of the municipal gross value added, followed by agropastoral activities (14.1%), particularly cattle ranching, and industry (9.8%) (IBGE, 2024c). The municipality is also home to traditional populations, including chiquitanos, extractivists (extrativistas), morroquianos, quilombolas, riverside communities (ribeirinhos), and Pantanal communities (pantaneiros), among others, as well as agrarian reform settlements, some of them are well described by the Brazilian government (see Brasil, 2017).

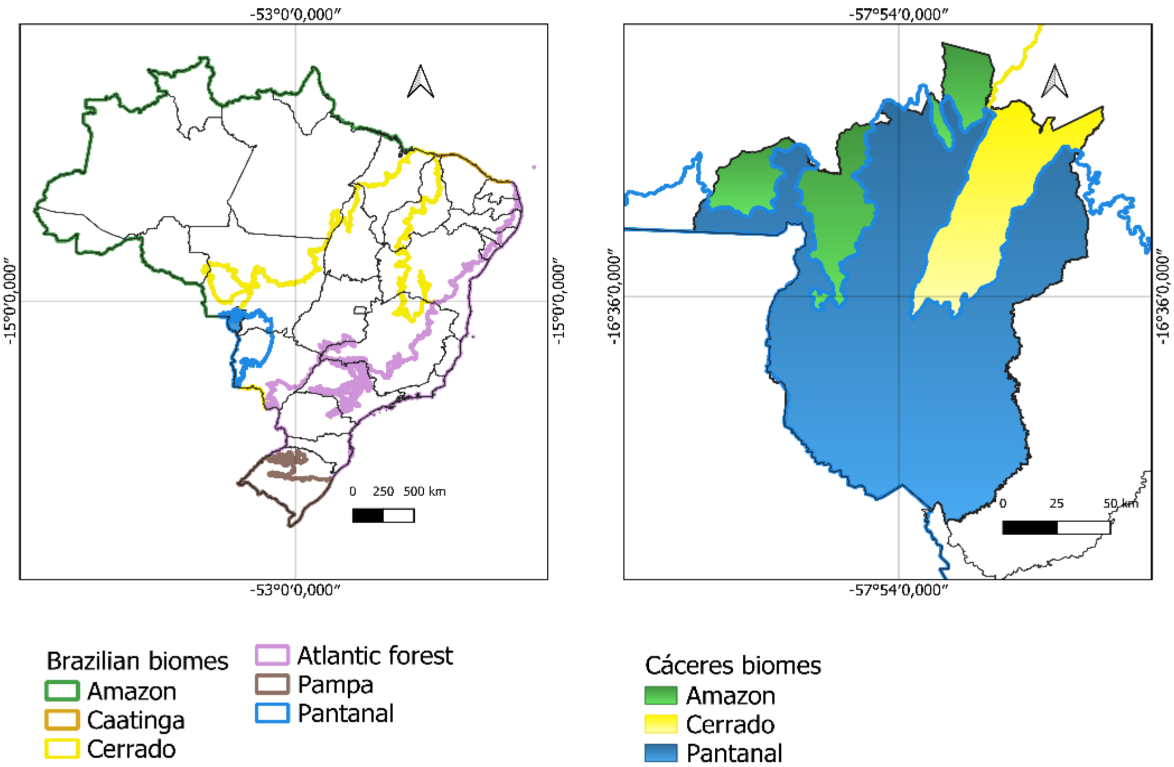

Figure 1. Location of the study area. Left: the Brazilian biomes and the position of Cáceres municipality at the Amazon-Cerrado-Pantanal junction. Right: the three biomes within the municipal boundary of Cáceres, Mato Grosso, which occupy 71.5% (Pantanal), 14.5% (Cerrado), and 14.0% (Amazon) of the municipal area. Organized: Ernandes Sobreira (2026).

2.2. Land cover and land use data

Two complementary data sources were used. The MapBiomas Collection 10 land-cover product was used to quantify the cumulative state of anthropic conversion by biome, as described above. In addition, the annual deforestation series from PRODES/INPE was used to characterize the temporal dynamics of vegetation suppression in the municipality (annual clearing rates, peaks, and declines), for which its year-by-year detection is better suited. The two sources address distinct questions: the cumulative share of each biome converted (MapBiomas) and the annual pace of suppression over time (PRODES). Vegetation cover and land-use data were obtained from the MapBiomas Project, Collection 10 (1985–2024), derived from the Landsat image catalogue on Google Earth Engine. The analysed period spans 1985 to 2022. Class areas were extracted for the municipality and, separately, for the portion of each of the three biomes (Amazon, Cerrado, and Pantanal) contained within the municipal boundary, by intersecting the MapBiomas raster with the biome and municipal limits (IBGE) in Google Earth Engine, computing the area of each class per year with the pixel-area function to account for the geographic projection. All analyses were conducted at a spatial resolution of 30 metres.2.3 Geometric Mean Growth Rate (GMGR).

Anthropic conversion was quantified, for the municipality and for each biome fraction, as the share of the biome area occupied by anthropic classes (pasture, agriculture, forest plantation, urban area, and mining) in each year, over the total area of the biome within the municipality. The historical rate of change was described using the Geometric Mean Growth Rate (GMGR), following Silva *et al.* (2011) (Equation 1):

$$GMGR = [D(t+n) / D(t)]^{(1/n)} - 1 \quad (1)$$

Where D(t+n) is the deforested area at the final year (km²), D(t) is the deforested area at the initial year (km²), and n is the interval in years (n = 37, corresponding to the period 1985-2022).

The GMGR describes the average historical rate; because extrapolating a geometric rate over long horizons yields implausible values as conversion approaches saturation, short-term projections were instead computed as a linear extrapolation of the 2010–2024 trend, to 2040 (see Section 2.3).

2.3. Conversion trajectories and critical thresholds

Conversion trajectories were projected to 2040 by linearly extrapolating the trend observed over the most recent period (2010–2024), applied to the 2022 value of each biome fraction. These projections should be interpreted as short-term trend-based scenarios rather than predictive models, as they do not incorporate feedback mechanisms, policy interventions, or climate variability. Critical thresholds were drawn from biome-scale literature: for the Amazon and Pantanal, Flores *et al.* (2024) indicate that accumulated loss around 20% of the original cover may accelerate ecosystem transitions, while for the Cerrado, Strassburg *et al.* (2017) report that more than 50% of the biome has already been converted. These thresholds were derived at the biome scale and are applied here as reference lines for the biome fractions within the municipality, rather than as thresholds calibrated at the municipal scale, to contextualize the projected trajectories.

2.4. Statistical analysis

A PCA analysis was conducted using the environmental data (Anthropogenic and Natural) between 2000-2022 to investigate the main environmental changes in the municipality. The 13 land cover classes obtained from MapBiomas Collection 10 were included as active variables: Rocky Outcrop, Agriculture, Urban Area, Flooded and Wetland Grassland, Inland Water Bodies, Floodable Forest, Grassland Formation, Forest Formation, Savanna Formation, Land Use Mosaics, Other Non-Vegetated Areas, Pasture, and Silviculture. The municipal cattle herd (IBGE, 2023, Table 3939) was added as a socioeconomic variable. The soybean class (Soy) is reported by MapBiomas as a specific crop type within the broader agricultural class; it was retained as a separate variable in the multivariate analysis because of its distinct expansion dynamic. It is therefore a component of, not additional to, total agriculture, and the proximity of the two vectors in the ordination reflects this shared origin rather than an independent association. All variables were standardized (z-scores, unit variance) prior to the analysis, and the PCA was computed on the correlation matrix. Variables were classified into natural (vegetation formations and hydrological features) and anthropogenic (land-use and disturbance-driven classes) groups. In addition, Pearson correlations were computed on the first differences of each series to control for the shared temporal trend.

2.5. Pressure-State-Response (PSR) Model

Environmental sustainability indicators were diagnosed using the Pressure-State-Response (PSR) model proposed by the OECD (1993), which is based on a causal logic connecting human activities, environmental conditions, and societal responses. According to this framework, human activities exert pressure on the environment, altering the quality and quantity of natural components and thereby modifying the state of the system. Society, in turn, responds to these changes through environmental, economic, or sectoral policies.

As outlined by Lira (2008) and Macêdo and Torres (2018), the three components of the model can be understood as follows: - 1. Pressure indicators encompass the environmental, economic, and social dimensions of human activity, describing how those activities affect natural components in both quantitative and qualitative terms. In this study, pressure for the environmental dimension was covering soil, water, climate, and biodiversity; for the economic dimension we focused on land use, livestock production and fishing; and the social dimension addressed education and income; - 2. State indicators describe the actual condition of the dimension at a given moment. Their purpose is to capture the trajectory of environmental quality over time, not the forces driving change; - 3. Response indicators address changes, whether aimed at preventing negative impacts, halting or reversing existing damages.

3. RESULTS AND DISCUSSION

3.1. Vegetation cover and trend analysis

Our analysis shows that the vegetation cover and land use for the period 1985-2022 revealed a substantial expansion of anthropogenic classes and a significant contraction of natural ones (Figures 2 and 3). The agriculture sector expanded by +5,356.5%, from 2.79 km² to 152.12 km²; this very large relative figure reflects growth from a near-zero baseline in 1985 and therefore overstates the absolute importance of the change, which remains small in area compared with pasture (Figure 2). It is important to note that soybean cultivation began in 1986, with an initial area 24 ha, and after ups and downs, in 2022 includes about 10.000 ha. The silviculture, mainly for the monoculture of *Tectona grandis* - teak - grew from a null area in 1985 to 139.27 km² in 2022. Pasture also expanded significantly (+304.0%), from 1,484.76 km² to 5,998.69 km². In contrast, the most severe reductions were observed in Inland Water Bodies (-69.5%), Forest Formation (-45.0%), Flooded and Wetland Grassland (-39.0%), Floodable Forest (-25.8%), and Savanna Formation (-21.6%). The expansion of Grassland Formation (+213.0%), in turn, may reflect the recurrent dynamics of wildfire that replace forested environments with open formations over time, which warrants further investigation as a possible lag effect between wildfire and deforestation.

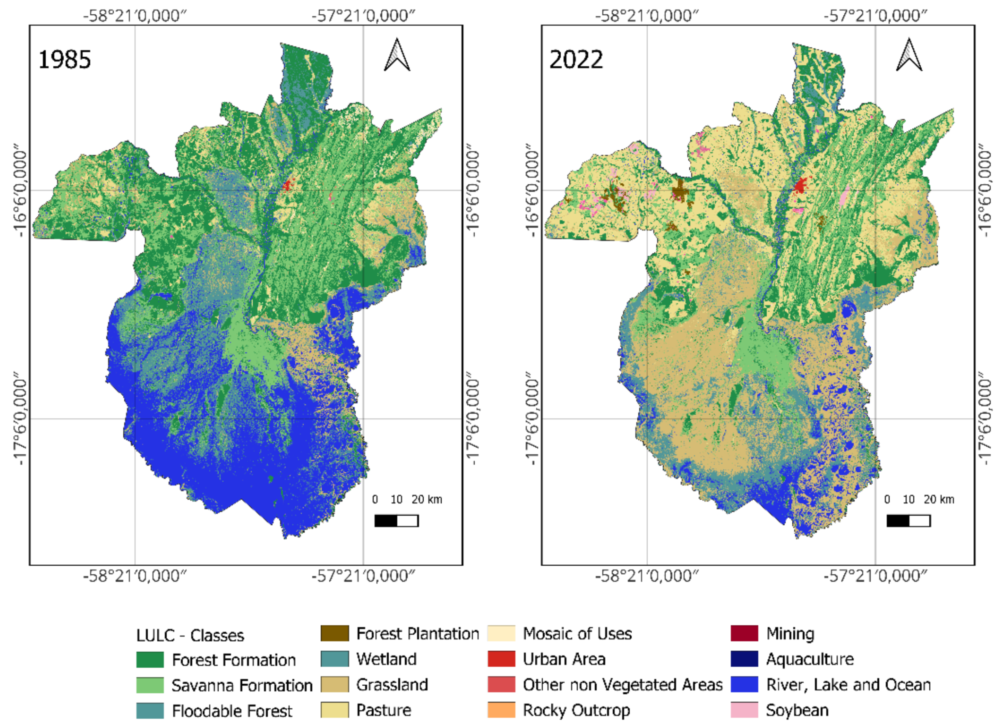

Figure 2. Land use and land cover in the municipality of Cáceres, Mato Grosso, in 1985 and 2022 (MapBiomas Collection 10). The comparison shows the replacement of forest formation and water surface, dominant in 1985, by pasture, agriculture, and mosaic-of-uses classes in 2022, most pronounced in the northern (Amazon and Cerrado) portions of the municipality. Organized: Ernandes Sobreira (2026).

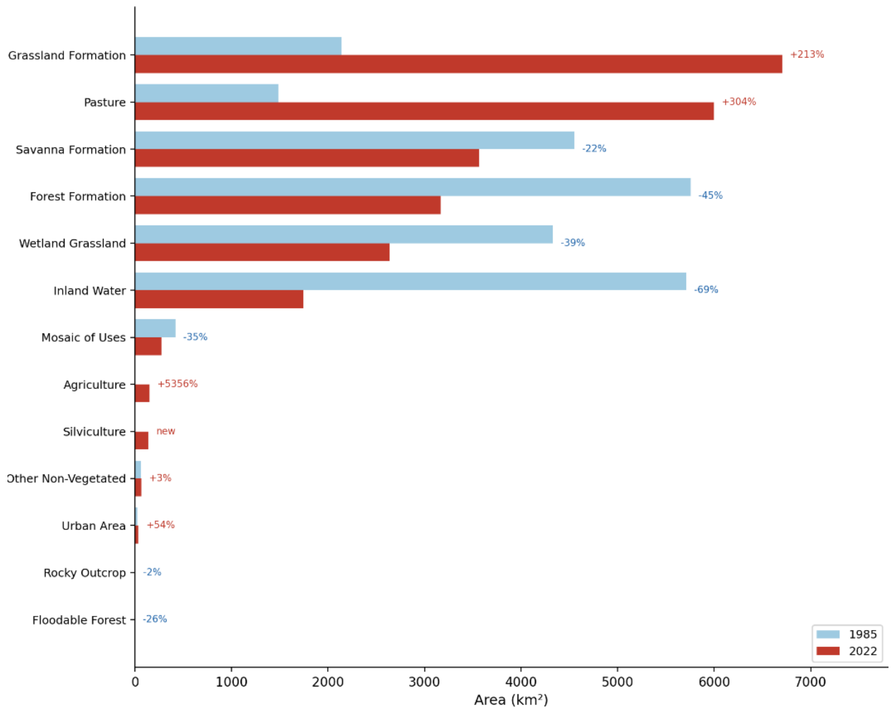

Figure 3. Area (km²) of land-cover and land-use classes in the municipality of Cáceres, Mato Grosso, in 1985 and 2022. Bars show the absolute area of each class in the two years; labels indicate the relative change over the period. Large relative increases in agriculture and silviculture reflect expansion from near-zero baselines, whereas pasture represents the largest change in absolute area. Source: MapBiomas (Collection 10).

The deforestation trend analysis showed an increased trend across all spatial units throughout the 1985-2022 period. We found annual rates of +0.27% for the municipality of Cáceres as a whole, +0.20% for the Cerrado, +0.30% for the Pantanal, and +0.31% for the Amazon. While these appear modest on an annual basis, their cumulative effect over 37 years is substantial. Primary vegetation suppression reached 5,282.9 km² across the municipality between 1987 and 2022, with an additional 631.1 km² of secondary vegetation cleared, totalling approximately 5,914 km² of suppressed cover (Figure 4). The annual deforestation peak occurred in 1999, when nearly 34,363 ha were cleared in a single year. A marked decline in deforestation was observed between 2013 and 2022, being 63% below the 1987-1996 average (8,514 ha/year vs. 23,038 ha/year), reflecting the partial, and potential, effect of improved environmental monitoring and the Forest Code (Law No. 12,651/2012). However, it is important to highlight that deforestation was never interrupted: 13,203 ha were cleared in 2022 alone, confirming that pressures on native cover remain active.

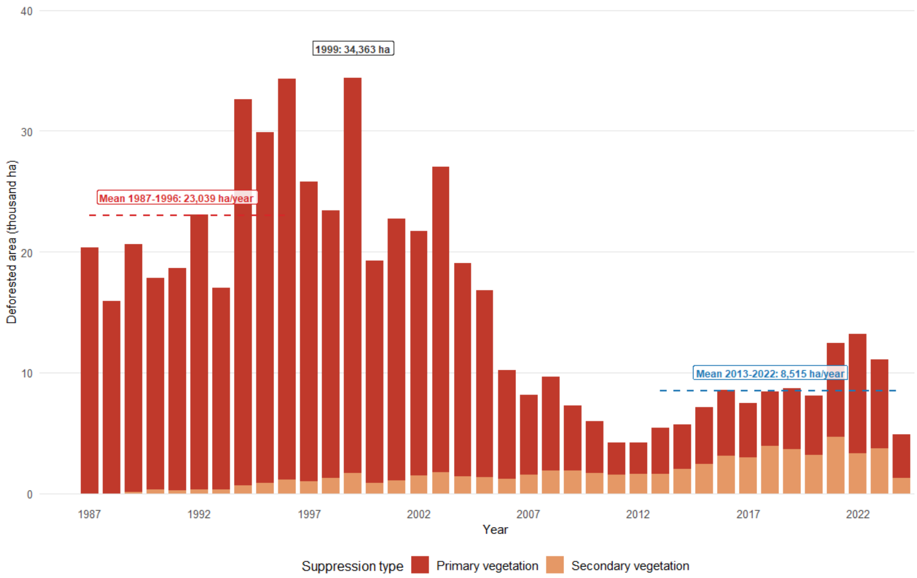

Figure 4. Annual vegetation suppression in the municipality of Cáceres, Mato Grosso, from the PRODES/INPE deforestation series. The PRODES series is available from 1987 onward, whereas the cumulative land-cover analysis (Figures 1 and 3) is based on MapBiomas for 1985–2022; the two products cover slightly different periods because they are generated by different monitoring systems. **Source:** PRODES/INPE.

Our trend projections indicate that, if the recent trajectory of anthropic conversion persists, the Amazon portion of Cáceres, already the most converted (57.8% of its area in 2022), will continue to rise, remaining well above the 20% threshold that Flores *et al.* (2024) associate with accelerated forest mortality and, indeed, above the 50% level that Strassburg *et al.* (2017) link to large-scale conversion. The Cerrado portion, at 33.8% in 2022, and the Pantanal portion, at 16.5%, are projected to increase more slowly to 2040 (Figure 5). The order of magnitude reverses the intuition that the Cerrado is locally the most threatened: within Cáceres, it is the Amazon fraction that has advanced furthest toward conversion, a finding consistent with the regional expansion of the agricultural and pastoral frontier into the southern Amazon. While projections at the municipal scale should be read as short-term trend scenarios rather than predictions, and biome-level thresholds do not translate linearly to municipal fragments, the local trajectories documented here are consistent with the broader regional pattern of declining ecological integrity across the Amazon-Cerrado-Pantanal transition zone.

Crossing these thresholds is ecologically significant: the 20% level identified by Flores *et* *al.* (2024) marks the point beyond which tree mortality may accelerate and forest-to-savanna transitions become self-reinforcing, while the 50% level discussed by Strassburg *et al.* (2017) is associated with irreversible biodiversity loss and severe habitat fragmentation. The Amazon fraction of Cáceres, already above both levels, is therefore in the range where these degradation processes are expected to intensify.

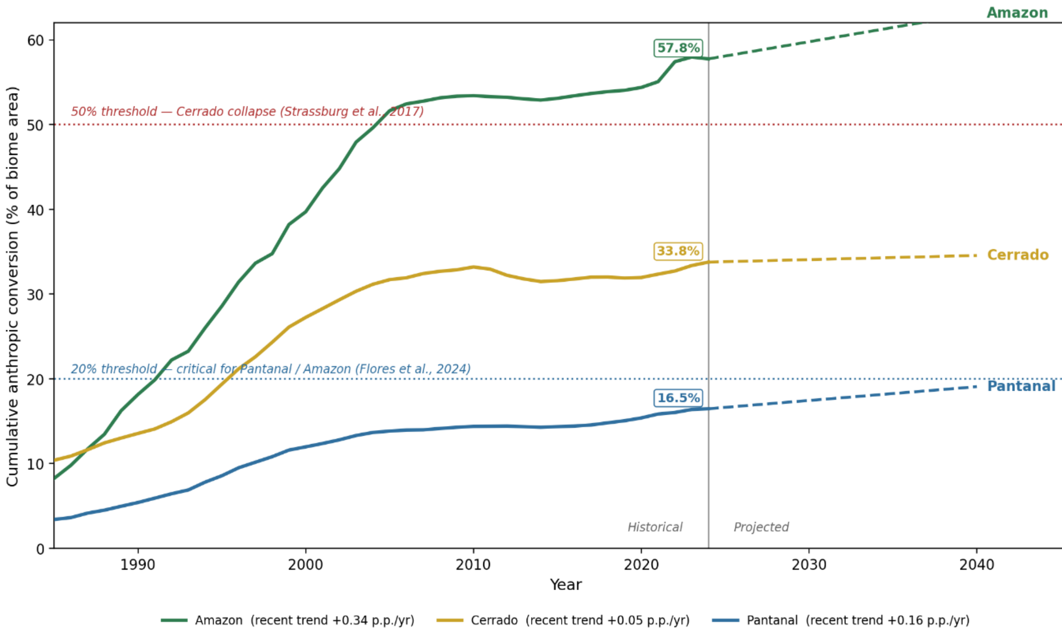

Figure 5. Cumulative anthropic conversion by biome in the municipality of Cáceres, Mato Grosso (1985–2040). Solid lines: historical data (MapBiomas, Collection 10); dashed lines: linear projection of the 2010–2024 trend; points: 2022 empirical values. The 20% and 50% reference levels derive from biome-scale studies of native-vegetation loss (Flores *et al.*, 2024; Strassburg *et al.*, 2017) and are shown for context; they are related to, but not identical with, the anthropic-conversion metric plotted here, since conversion and native-vegetation loss diverge where non-vegetated cover (e.g. water) varies, as in the Pantanal. Anthropic conversion = pasture, agriculture, forest plantation, urban area, and mining, over the total area of each biome within the municipality. From a broader continental perspective, the biomes of the Amazon-Cerrado-Pantanal transition zone are interconnected through a web of climatic and hydrological feedbacks (Flores *et al.*, 2024). Forest degradation in the Amazon, by reducing the regional hydrological cycle by up to 34%, propagates adverse effects to neighbouring biomes (Lapola *et al.*, 2023). Cerrado conversion, in turn, diminishes evapotranspiration and local precipitation, affecting the river basins that sustain the Pantanal (Rodrigues *et al.*, 2022). This functional interdependence points to the need for integrated environmental policies at the regional scale, going beyond municipality or biome-specific approaches.

3.2. Land use and landscape change of Cáceres, Mato Grosso

We used a PCA to analyse the relationship between the variables to identify the principal axes of variation and the land-use, environmental, and socioeconomic variables that account for most of the landscape change over the period. Our results suggest that the PCA of environmental variables for the period 2000-2022 revealed that 59.5% of the total environmental variance in Cáceres is explained by a single axis of territorial transformation (PC1), with an additional 18.3% captured by PC2, together accounting for 77.8% of the total variance. Along PC1, the expansion of Agriculture, Pasture, Soybean and Cattle herds are positioned in direct opposition to the contraction of Forest Formation, Water Surface, and Floodable Formations, reflecting a systematic replacement of natural ecosystems by agricultural land uses over the analyzed period. When the years are grouped into two subperiods, the earlier years (2000 to 2011 - before the Forest Code implementation) and the more recent ones (2012 to 2022 - after the Forest Code implementation) occupy distinct regions of the ordination space, the latter shifted toward the production pole, which visually confirms the direction of change described above.

Because several of these series grow jointly over time, raw correlations tend to overstate their associations. We therefore computed Pearson correlations on the annual change (first differences) of each variable, which isolates genuine year-to-year covariation from shared temporal trend. Under this detrended analysis, the cattle herd is significantly associated with Pasture ($r = 0.58$, $p = 0.005$) and inversely with Forest Formation ($r = -0.54$, $p = 0.010$), while total deforestation, whose raw correlation with the herd was weak, becomes positive and significant ($r = 0.49$, $p = 0.020$). In contrast, the strong raw correlations of Agriculture and Soybean with the herd did not persist after detrending ($r = -0.42$ and $r = -0.05$).

Although agriculture showed the largest relative expansion in the municipality (Section 3.1), this reflects growth from a near-zero baseline; the multivariate analysis indicates that it is the pasture–cattle complex, rather than crop expansion, whose annual dynamics track native-vegetation loss.

The implications of land use on the natural landscape components of Cáceres reveal intense anthropogenic transformation, as documented by the mapping of vegetation cover and land use dynamics for the period 1985 to 2022. Urban areas expanded by 54.4%, a change closely linked to the trajectory of territorial occupation and demographic growth that intensified land use over areas with limited suitability for productive activities such as agriculture and livestock, generating negative environmental and hydrological impacts under current conditions (Santos *et al.*, 2017). It is also important to note that urban expansion in Cáceres occurred over areas unsuitable for such use, disregarding stream margins and spring recharge zones due to non-compliance with the minimum limits established for environmental protection areas, and that flood-related problems have worsened over recent decades. Santos *et al.* (2017) found that flood events accompany the history of local development, as disorderly urban growth and inadequate land use have contributed to the intensification of flooding dynamics.

Population growth in Cáceres has been attributed, in part, to the expansion of agropastoral activities, silviculture, and the associated demand for labour to meet regional needs. The expansion of Agriculture in the Cerrado and Amazon biomes, livestock production in the Pantanal, and Silviculture in the Cerrado trigger a series of factors that negatively impact the environment, not only through management practices but also through the use of agrochemicals. Despite being locally and regionally relevant economic activities (Castro *et al.*, 2022; Rossetto *et al.*, 2022), the absence of adequate land management contributes to multiple ecological imbalances across the biomes.

3.3. Environmental indicators according to the PSR model

Four categories classify the environmental dimension - soil, water, climate and biodiversity. The Municipality of Caceres is dominated by Silt (46%) and Sandy Clay Loam (38%), which together account for over 80% of the total municipal area. Loam represents approximately 15% of the area, while Clay Loam, Loamy Sand, and finer clay-rich textures occupy residual fractions. Crossing soil type with deforestation, Sandy Clay Loam showed the highest absolute loss of native vegetation cover between 1985 and 2022, with 20,240 ha deforested, corresponding to 2.3% of its total extent. Silt soils followed, with 17,835 ha deforested (1.7%). These two dominant textures (Sandy Clay Loam and Silt), are characterized by low aggregate stability and high susceptibility to particle detachment and transport by water, making deforestation on these substrates particularly relevant in the context of fluvial dynamics and sediment delivery to the Paraguay River basin.

Mining is a locally relevant pressure on soil and landscape: in 2023 the municipality recorded commercial extraction of sand, limestone, and crushed rock (ANM, 2024). Beyond the direct removal of material, these activities contribute to the alteration of the "Other Non-Vegetated Areas" and mining classes identified in the land-cover analysis (Figure 2), linking mineral extraction to the mapped land-use dynamics rather than treating it as a separate economic statistic.

For Fernandes and Colleagues (2014, p. 5) the negative impacts of mining can be described mainly to the physical environment alteration by deforestation, erosion, such as contamination of water bodies by heavy metals. In fact, mining activities carry a negative environmental image due to their direct effects on natural systems, their dependence on non-renewable resources, and their disruption of ecological balance in affected areas. Mitigation measures are therefore essential to minimize socio-environmental impacts and prevent future disasters (Silva and Andrade, 2017).

Mining-related soil degradation is regulated by a chain of federal instruments, notably the requirement for a Degraded Area Recovery Plan (PRAD) for licensing (Decree 97,632/1989) and a Mine Closure Plan (ANM Resolution 68/2021). These establish clear restoration obligations on paper, but the recurrent landscape alteration observed in the study area indicates that the binding constraint lies in monitoring and post-licensing enforcement rather than in the legal framework itself.

Water resources were classified with the principal pressures derived from the discharge of domestic effluents and commercial waste into the Paraguay River, the activity of hotel boats, and the widespread use of agrochemicals across the municipality. These pressures are reflected in two critical State indicators - the municipal sanitation coverage of only 7.04% in 2022; and urban sewage network coverage of 8.02% of the served population (SNIS, 2024), among the lowest in the state of Mato Grosso.

People living in extreme poverty tend to settle in the vicinity of water bodies, a practice that gradually intensifies environmental impacts (Araújo, 2023). Funaro *et al.* (2022) show that in Cáceres the level of water degradation is partially driven by the daily discharge of sewage and domestic waste into the water bodies of the Piraputangas Stream watershed, a tributary of the Paraguay River. This situation underscores the need for systematic water quality monitoring, given the central role of the Paraguay River for the local population.

Moreover, a further concern relates to planned interventions in the Paraguay River to expand navigation capacity for heavy vessels required for the operation of the Paraguay-Paraná Waterway. This route, which uses large barges to transport commodities such as soybean, sugar, and maize, as well as cement, iron, and manganese from production areas in Brazil, Paraguay, and Bolivia to oceanic ports on the Río de la Plata, could cause irreversible damage to the Northern Pantanal by altering the flooding dynamics of the Paraguay River (Wantzen *et al.*, 2024).

As noted above, urban expansion over unsuitable areas has disregarded riparian and spring-recharge zones, aggravating flood dynamics due to non-compliance with the minimum limits established for environmental protection areas, and that flood-related problems have worsened over recent decades. Santos *et al.* (2017) found that flood events accompany the history of local development, as disorderly urban growth and inadequate land use have contributed to the intensification of flooding dynamics.

Water quality monitoring in the urban supply network includes monthly sampling of color, turbidity, residual chlorine, pH, total coliforms, and Escherichia coli, with 77 samples required and collected annually in accordance with Consolidation Ordinance No. 05/2017. Institutional responses include the National Water Resources Policy (Law No. 9,433/1997), Law No. 9,612/2011 on groundwater conservation, and Law No. 3,069/2022, which mandates monthly publication of water quality analysis results.

For the climate dimension, we qualified deforestation and wildfires as the dominant pressures. We observed that the cumulative anthropic conversion of 33.8% in the Cerrado, 57.8% in the Amazon, and 16.5% in the Pantanal (MapBiomas Collection 10), with remaining natural vegetation covering 62.86%, 16.98%, and 69.97% of each biome respectively. Fire hotspot data for 2023 indicate that the Amazon biome concentrated 58.07% of fire occurrences, followed by the Cerrado with 23% and the Pantanal with 18.02% (INPE, 2024).

Climate change is clearly contributing to the intensification of fire events, which was also showed by Lázaro *et al.* (2020), that the Northern Mato Grosso Pantanal has experienced 13% more rainless days in recent years, and that over the last decade the surface water mass has declined by 16% during the dry season. This reduction in surface water exposes organic matter to desiccation, increasing its susceptibility to ignition. During the dry season, accumulated dry biomass becomes highly flammable, and once ignited, can generate fires that are extremely difficult to control (d'El Rei Pinto *et al.*, 2024). The fire regime is also closely linked to the flood pulse, when biomass accumulated during inundation periods becomes combustible material during subsequent dry seasons, establishing feedback between hydrological dynamics and fire occurrence (Ferreira and Silva, 2023).

At the climate level, Cáceres operates within global commitments (the Paris Agreement, the 2030 Agenda, and the Sendai Framework, UN, 2015) and, at the state level, the Mato Grosso Climate Change Policy (Complementary Law 582/2017). Given the municipality's exposure to intensifying fire regimes, prolonged dry seasons, and surface-water loss, the relevant gap is not the absence of commitments but the lack of a local instrument translating these agendas into municipal action.

3.3.1. Biodiversity

As much as for climate, for biodiversity the principal pressures are suppression of native vegetation and the conversion to agricultural, silvicultural, and mining activities, alongside illegal hunting and wildlife trafficking. The State is reflected in the existence of one Integral Protection conservation unit, the Jubran Reserve (Pantanal), and two Sustainable Use units, the Taiamã Ecological Station (Pantanal) and the Serra das Araras Ecological Station (Cerrado).

In the Cerrado biome, for example, 9.09% of fauna species are listed under some category of extinction threat, including Extinct in the Wild, Critically Endangered, Endangered, and Vulnerable. In the Pantanal, this figure corresponds to 2.91%, including the Jabiru stork, the symbolic bird of the Pantanal, while in the Amazon biome, 3.55% of species fall under some threat category (Brasil, 2018). The actions driving multiple animal species, both aquatic and terrestrial, as well as plant species, toward threatened status include agricultural expansion (Ferreira and Lino, 2021), livestock farming (Maxwell *et al.*, 2016), deforestation and wildfires (Carmo and Carmo, 2019) and agrochemical use (Dutra and Souza, 2017).

To ensure the conservation of threatened species, communities, and ecosystems, different management strategies must seek to achieve minimum genetic, demographic, and ecological parameters for the maintenance of viable populations in their natural habitats (Soulé, 1987). Management can be defined as the manipulation or handling of a set of individuals from one or more species, at any stage of their development, whether living in their natural habitat or born in captivity. In situ management strategies allow the continuity of ecosystem functions and evolutionary processes. However, the effectiveness of in situ conservation strategies has been highly dependent on and largely limited to the interior of Protected Areas, and requires different forms of human intervention, such as the translocation of native individuals between subpopulations within the same region (Costa and Mello, 2020).

Institutional responses for biodiversity are anchored in the Forest Code (Law 12,651/2012) and in the recently created state fauna and fisheries bodies (CFRP and GFAU, Decree 511/2023), with the proposed Pantanal Bill (5,482/2020) still under legislative review. The reliance on general federal instruments, absent a biome-specific enacted law, is itself the principal governance gap for the Pantanal portion of the municipality.

3.4. Economic indicators according to the PSR model

3.4.1. Land use

Within the economic dimension, land use indicators document the most pronounced transformations recorded between 1985 and 2022. Silviculture expanded from a barren area to 139.27 km², driven by the introduction of teak monoculture (*Tectona grandis*) beginning in 1989. Agriculture recorded the most expressive relative growth, expanding from 2.79 km² to 152.12 km² (+5,356.5%), reflecting the intensification of mechanized crop production, particularly soybean cultivation, which increased from a negligible area in 1985 to 99.58 km² by 2022. Pasture expanded +304.0%, from 1,484.76 km² to 5,998.69 km², consolidating livestock production as the dominant land use in the municipality. Urban areas expanded +54.4%, from 23.24 km² to 35.87 km². These dynamics are driven by agricultural mechanization, widespread agrochemical use, the absence of organized productive chains for traditional agriculture, and limited incentives for agroecology. It is important to notice that the state of Mato Grosso registered the use of 142,738.855 kg of active agrochemicals ingredients, and the municipality of Cáceres had the highest consumption in the state, at 489,270 kg (Castro *et al.*, 2022). This fact intrigues, since the municipality is not the main agriculture production site in the state of Mato Grosso.

Cáceres has 3,536 agricultural establishments, of which 2,603 are identified as belonging to family farming. According to Abreu *et al.* (2021), livestock raising and other animal husbandry activities account for 85% of the economic activities carried out by family farmers, temporary crop production accounts for 10%, permanent crop production represents 3%, and horticulture and floriculture account for 1%. However, only 10% of family farmers in Cáceres receive Technical Assistance and Rural Extension (ATER) services, a figure that falls far short of the significance this service holds for the performance and development of family farming. The municipality is also registered in the State Integrated Family Farming System (SEIAF-MT), established by State Complementary Law No. 746 of August 25, 2022 (Mato Grosso, 2024), which created the Municipal Family Farming Index (IAF) and provides fiscal benefits that contribute to the strengthening of family farming in Mato Grosso. The municipality is further registered in the Municipal Family Farming Plan (PMAF) since 2023, and in the Municipal Council for Sustainable Rural Development (CMDRS) of the state (SEIAF, 2024). Additionally, it participates in the Rural Credit Operations System (SICOR) and the Agricultural Activity Guarantee Program (PROAGRO), which aims to provide rural credit through authorized financial institutions. In Cáceres, rural credit disbursements reached R$ 1,852,382.29 in 2019 (SICOR, 2024).

Regarding silviculture, Eucalyptus cultivation occurs in Cáceres over an area of 217 ha, which combined with other species covering 12,603 ha, totals 12,820 ha of planted forest. Eucalyptus planting is associated with silvopastoral systems (iLPF), as shown by Souza *et al.* (2016). This type of integration consists of adapting agricultural production systems to the ecological conditions of the region. According to Chaves *et al.* (2017) and Freire and Cavichioli (2022), the iLPF system offers numerous benefits from combining trees with pastures, including environmental services such as soil erosion reduction, and productive outputs such as timber and fruit. These benefits minimize the negative ecological implications of establishing homogeneous pastures and represent sustainability strategies. However, there are challenges in the iLPF system that hinder its adoption on rural properties, including the lack of qualified labor for system management and handling, difficulty in obtaining credit for the high initial investment costs, and inadequate logistics (Freire and Cavichioli, 2022).

Furthermore, soil conservation and land-use in the municipality of Cáceres are ruled by national and state governments rather than by specific policies, for instance, the National Environmental Policy (Law 6,938/1981), the Agrochemicals Law (Law 7,802/1989), the federal Forest Code (Law 12,651/2012), and, at the state level, the SIMCAR/CAR system established by Complementary Law 592/2017. On paper, this fact is a comprehensive framework, but in practice their effectiveness is limited by the gap between remigration and compliance. Enrolment in the CAR is high, but registration does not guarantee restoration of Legal Reserves or Permanent Preservation Areas, and there is no municipal soil-conservation policy to translate these federal obligations into local enforcement. The persistence of native-vegetation loss documented in this study (Section 3.1), concurrent with an operational CAR, indicates that the binding constraint is enforcement capacity rather than the absence of legislation.

3.4.2. Livestock production

Cáceres is the municipality with the largest number of bovines in Mato Grosso and the fourth largest in Brazil, holding 1,341,455 head of cattle (IBGE, 2023). Its livestock dominance translates into multiple simultaneous environmental pressures as pasture area expansion, severely compromising the ecological integrity of riparian zones and floodplain dynamics along the Paraguay River basin (Bergier, 2013). Going onwards, cattle trampling on the predominantly Silt and Sandy Clay Loam soils of the municipality may accelerate compaction, erosion, and sediment delivery to watercourses, while runoff from pasture areas carries nutrients and agrochemicals, including acaricides and antibiotics routinely applied in cattle management, into aquatic systems of recognized ecological sensitivity.

While Cáceres is proud of being the fourth largest producer of cattle in Brazil, livestock production also represents a significant source of greenhouse gas emissions at both global and national scales. The entire livestock chain represents circa 12% of the global anthropogenic greenhouse gas emissions (6.2 GT CO2eq), mainly because of the methane resulting from rumen fermentation, in addition to contributions from feed production, animal waste, and land-use change (FAO, 2023).

Institutional responses to livestock expansion span federal, state, and municipal scales, combining the instruments above with the Low-Carbon Agriculture Plan (ABC Plan) and the state Deforestation Prevention and Control Plan (PPCDMT). The relevant question is not whether these instruments exist, but whether they alter the trajectory of conversion. The pasture-herd association identified in Section 3.2, together with the continued expansion of pasture over the study period, suggests that the incentive-based mechanisms of the ABC Plan have not, so far, decoupled cattle production from native-vegetation loss in the municipality. This is the effectiveness gap that a Response-oriented reading of the PSR framework must foreground.

3.4.3. Fishing

In Cáceres, regarding the Economic Dimension, other anthropogenic pressures include predatory fishing driven by tourism. Fishing constitutes a relevant activity for the population of Cáceres, as in the Mato Grosso Pantanal it presents specific characteristics regarding target species, fishing gear, and strategies, which are defined according to the flood pulse and the dynamics of the flooding, high water, recession, and dry seasons. It is practiced in subsistence, professional-artisanal, and amateur/sport modalities. In this context, researchers report that sport fishing tourism in Mato Grosso is characterized as high-end tourism, particularly in the municipalities of Cáceres, Poconé, and Barão de Melgaço, which have a strong vocation for sport, amateur, artisanal, and professional fishing, as well as accommodation infrastructure with specific support facilities and equipment, including hotels, guesthouses, chalanas (boat-hotels), and fishing lodges (Catella *et al.*, 2008; Lopes *et al.*, 2022).

Fishing is regulated by the Mato Grosso Fishing Policy (Law 9,096/2009) and successive amendments, culminating in the 2024 "Cota Zero" measure, which prohibited the commercialization of fish caught in state rivers. Notably, this restriction was justified by an alleged decline in fish stocks, yet it contradicted Embrapa Pantanal's technical monitoring, which found no measurable impact on fish populations in the Upper Paraguay Basin between 2007 and 2018. This mismatch between the stated basis for regulation and the available technical evidence is a clear instance of the effectiveness and coherence gaps that a Response-oriented analysis should identify.

Although Cáceres is subordinated to the state laws, at the municipal level, Law No. 3,024/2022 establishes Fishers' Week in Cáceres, recognizing the cultural and economic importance of fishing for the local population. Complementing this recognition, the city has hosted annually since 1980 the International Sport Fishing Festival (FIPe), which in 1992 was officially recorded in the Guinness Book of Records as the largest boat fishing competition in freshwater in the world.

3.5. Social indicators according to the PSR model

Regarding education, the principal pressures include limited qualified employment, low wages that discourage schooling, and the post-pandemic disruption of 2019–2021. In 2010, the school-enrolment rate for children aged 6 to 14 was 97.8%. The 2021 Basic Education Development Index (IDEB) for the public network was 5.1 for the early years and 4.6 for the final years of primary education, below the state averages of 5.5 and 4.8, respectively. The Municipal Human Development Index (MHDI) reached 0.708 in 2021, below the state average of 0.736 (IBGE, 2021). The main response is associated with the Regional Development Plan - PDR/MT, Axis 2 (knowledge and technological innovation).

Regarding Education, in 2010, the school enrolment rate for children aged 6 to 14 years was 97.8%. The Basic Education Development Index (IDEB) in 2021 for the early years of primary education in the public network was 5.1, and for the final years, 4.6, while the state of Mato Grosso recorded 5.5 for primary and 4.8 for secondary education. Enrolments in primary education totalled 12,413 students and 4,383 in secondary education in Cáceres, compared to 486,568 and 157,928 respectively at the state level. The total number of teachers in primary education was 713 and 393 in secondary education in the municipality, while the state figures were 26,575 and 12,642. The number of primary schools was 49 and secondary schools 19 in Cáceres, compared to 1,969 and 673 across Mato Grosso (INEP, 2021).

The COVID-19 pandemic (2019–2021) temporarily disrupted schooling and contributed to the decline in the education indicators, as documented locally by Cardoso (2023) and Tomicha *et al.* (2023). Tomicha *et al.* (2023), studying education associated with interculturality involving Brazil and Bolivia in a public school in Cáceres in 2022 during the pandemic period, observed the visibility given to Bolivian students enrolled in the school, as well as the promotion of inclusion. It is important to highlight that schools are spaces where diversity prevails and where the valorisation of different cultures is fundamental.

In Cáceres there is the predominance of primary-sector activities with limited value-added processing, insufficient mechanisms for rural production outflow, and the absence of agro-industrial integration constitute the main pressures. Institutional responses include Regional Development Plan - PDR/MT Axis 4 (diversification and densification of productive chains), the Municipal Family Farming Plan (Cáceres, 2023), and the Municipal Council for Sustainable Rural Development (CMDRS).

In 2021, the average monthly salary corresponded to 3.4 minimum wages, with 15,438 formally employed persons (16.19% of the population), and 37.7% of residents had a per capita income of up to half a minimum wage in 2010; the Municipal Human Development Index was 0.708 in 2021. This income profile reflects a local economy anchored in primary, land-based activities: cattle ranching, agriculture, and extractivism. The dependence of household income on these sectors links the social dimension directly to the land-use pressures documented in this study, since the same activities that sustain local livelihoods are the principal drivers of native-vegetation conversion identified in the multivariate analysis (Section 3.2). According to Silva and O'Loiola (2019), Cáceres had its economic development linked to extractivism, cattle ranching, and commerce established in the urban center of the municipality, with rubber, timber, medicinal plants, and livestock as its main commercial products. Its socio-spatial organization emerged from several economic cycles, alternating between periods of high economic activity and stagnation throughout its history. The socioeconomic organization of women has also contributed to household income, as documented in studies on rural settlements in the municipality of Cáceres (Rocha *et al.*, 2014; Mendes *et al.,* 2014; Zart *et al.*, 2016).

The full Pressure-State-Response matrix, listing the pressures, states, and institutional responses for each environmental, economic, and social dimension, is provided as Supplementary Material (Table S1).

4. FINAL CONSIDERATIONS

Anthropogenic pressures exert severe and multi-order impacts on the municipality of Cáceres and its constituent biomes land use due to the anthropogenic transformations. The total anthropogenic area expanded 318.7% between 1985 and 2022, from 1,510.78 km² to 6,325.94 km², while natural vegetation and hydrological classes lost 4,668.76 km² over the same period. Agriculture grew from 5,356.5%, Pasture expanded from +304.0%, and Silviculture is nowadays largely present. On the contrary, Inland Water Bodies declined 69.5% and Forest Formation contracted 45.0%. These dynamics directly influence landscape structure and the conservation of natural components across the three biomes present in Cáceres.

Deforestation trend analyses at both the municipal and biome levels indicate that, should current anthropogenic pressures persist, native vegetation suppression will continue to intensify, with growing risk of species extinctions particularly in the Cerrado, whose Serra Province is especially vulnerable given the geomorphological constraints that limit agricultural and livestock expansion in that area. The Amazon fraction of the municipality has already surpassed the 20% deforestation boundary associated with risk of accelerated forest mortality. Projections indicate that, without structural changes in land governance, the Amazon fraction, already the most converted (57.8% in 2022), remains the highest, followed by the Cerrado (33.8%) and the Pantanal (16.5%), projected to 2040, with all spatial units showing uninterrupted deforestation growth throughout the projection horizon.

Cáceres needs to progress. A socioecological resilience is necessary to accomplish this, and changes in behaviour are required from both society and public managers. The development and implementation of environmental planning processes constitute the central instrument for maintaining landscape integrity and biodiversity, as the information generated through such actions has the potential to transform the municipality's future prognosis. Priority interventions identified through this diagnostic study include ecological-economic zoning, riparian forest restoration, pesticide use regulation, universalization of basic sanitation and strengthening of technical assistance for family farming, all of which require coordinated responses across the institutional frameworks identified in the PSR analysis.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

6. ACKNOWLEDGEMENTS

I would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) for the postdoctoral fellowship through the research project “Methods of data production on vulnerability and quality of life (physical-psychological, social and environmental) in the post-COVID-19 pandemic” (CAPES Notice No. 12/2021 PDPG – IMPACTS OF THE PANDEMIC).

7. REFERENCES

ABREU, C.; OLIVEIRA, A. L. A.; ROBOREDO, D. Family farming in the state of Mato Grosso: a view from the 2017 Agricultural Census. **Revista de Ciências Agroambientais**, v. 19, n. 2, p. 82–92, 2021. https://doi.org/10.30681/rcaa.v19i2.5276

AGÊNCIA NACIONAL DE MINERAÇÃO (Brasil). **Produção Mineral 2023**. Brasília, 2024.

AGÊNCIA NACIONAL DE MINERAÇÃO (Brasil). Resolução ANM nº 68, de 30 de abril de 2021. Dispõe sobre as regras referentes ao Plano de Fechamento de Mina - PFM e revoga as Normas Reguladoras da Mineração nº 20.4 e nº 20.5, aprovadas pela Portaria DNPM nº 237, de 18 de outubro de 2001. **Diário Oficial [da] União**: seção 1, Brasília, DF, n. 82, 4 de maio de 2001.

ARAÚJO, A. R. Environmental changes and water quality in urban streams: a study in Pontes e Lacerda, MT. **Caderno Prudentino de Geografia**, v. 45, n. 3, p. 20–48, 2023.

ARRAUT, J. M.; NOBRE, C.; BARBOSA, H. M. J.; OBREGON, G.; MARENGO, J. Aerial rivers and lakes: looking at large-scale moisture transport and its relation to Amazonia and to subtropical rainfall in South America. **Journal of Climate**, v. 25, n. 2, p. 543–556, 2012. https://doi.org/10.1175/JCLI-D-11-00166.1

BANCO CENTRAL DO BRASIL. **Tabelas e microdados do crédito rural e do Proagro**. Brasília, DF, 2024.

BARRETO, J. M. T. P.; ALMEIDA, J. R. Análise por geoprocessamento da pressão, estado e resposta populacional: zona costeira região de Barra de São Miguel, Alagoas, Brasil. **Engineering Sciences**, v. 9, n. 2, p. 27–45, 2021. https://doi.org/10.6008/CBPC2318-3055.2021.002.0004

BERGIER, I. Effects of highland land-use over lowlands of the Brazilian Pantanal. **Science of the Total Environment**, v. 463–464, p. 1060–1066, 2013. https://doi.org/10.1016/j.scitotenv.2013.05.036

BIGGS, R. *et al.* **The Routledge Handbook of Research Methods for Social-Ecological Systems**. London: Routledge, 2022. 526 p.

BRASIL. Ministério do Desenvolvimento Agrário. **Sistema de Informações Territoriais (SIT): Território 157 - Cáceres**. Brasília: MDA, 2017. Available: https://territoriosdobrasil.mda.gov.br/meu-territorio?territorio=157. Access 23 mar. 2026.

BRASIL. Ministério do Meio Ambiente. **Lista Nacional Oficial de Espécies da Fauna Brasileira Ameaçadas de Extinção**. Portaria MMA n. 444, de 17 de dezembro de 2014, atualizada em 2018. Brasília: Ministério do Meio Ambiente, 2018.

CABALLERO, C. B.; BIGGS, T. W.; VERGOPOLAN, N.; CAMELO, L. G. G.; DE ANDRADE, B. C.; LAIPELT, L.; RUHOFF, A. L. Decadal hydroclimatic changes in the Pantanal, the world's largest tropical wetland. **Scientific Reports**, v. 15, n. 1, 17675, 2025. https://doi.org/10.1038/s41598-025-01980-6

CARDOSO, J. A. Post-COVID-19 pandemic education. **Research, Society and Development**, v. 12, n. 3, p. 1–10, 2023.

CARMO, W.; CARMO, M. G. Deforestation, fires and extinction threats in the Brazilian Amazon. **Revista Científica do Instituto IDEIA**, v. 2, n. 8, p. 49–62, 2019.

CÁCERES (MT). Prefeitura Municipal. **Plano municipal de agricultura familiar sustentável**. Cáceres, 2023.

CASTRO, F. P.; FREITAS, L. M.; CORRÊA, M. L. M.; BITTENCOURT, N. A. **Agrotóxicos no Pantanal: contaminação das águas e impactos na saúde e ambiente em Mato Grosso**. Cuiabá: FASE, 2022. 30 p.

CATELLA, A. C.; MASCARENHAS, R. O.; ALBUQUERQUE, S. E.; ALBUQUERQUE, F. F.; THEODORO, E. F. M. Sistemas de estatísticas pesqueiras no Pantanal, Brasil: aspectos técnicos e políticos. **Pan-American Journal of Aquatic Sciences**, v. 3, n. 3, p. 174–192, 2008.

CHAVES, A. G. S.; SILVA, C. S.; FRANCO, F. M. Planning and implementation of an integrated livestock-forest system in Cáceres, MT. **Scientia Tec: Revista de Educação, Ciência e Tecnologia do IFRS**, v. 4, n. 1, p. 173–193, 2017.

COSTA, R. N.; MELLO, R. An overview of conservation biology and threats to Brazilian biodiversity. **Sapiens**, v. 2, n. 2, p. 50–69, 2020.

D'EL REI PINTO, D. O.; XAVIER, F. F.; HORIE, C. A. C.; PENTEADO, D. G.; PINHO, C. R. S.; NASCIMENTO, E. P. *et al.* A percepção de comunidades tradicionais pantaneiras a respeito dos impactos dos incêndios florestais de 2020. **Biodiversidade Brasileira**, v. 14, n. 4, p. 183–201, 2024. https://doi.org/10.37002/biodiversidadebrasileira.v14i4.2708

DUTRA, R. M. S.; SOUZA, M. M. O. Cerrado, green revolution and the evolution of pesticide consumption. **Sociedade & Natureza**, v. 29, n. 3, p. 473–488, 2017. https://doi.org/10.14393/SN-v29n3-2017-8

FAO. **Pathways towards lower emissions: a global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems**. Rome: FAO, 2023. https://doi.org/10.4060/cc9029en

FERNANDES, F. R. C.; ALAMINO, R. de C. J.; ARAUJO, E. R. (eds.). **Recursos minerais e comunidade: impactos humanos, socioambientais e econômicos**. Rio de Janeiro: CETEM/MCTI, 2014. 392 p.

FERREIRA, M. C.; SILVA, C. Análise espaço-temporal das áreas de ocorrência de fogo no Parque Nacional do Pantanal mato-grossense entre 1990 e 2020. **Estudos Geográficos**, v. 21, n. 3, p. 268–288, 2023.

FERREIRA, R. M.; LINO, E. N. S. Agricultural expansion in the Cerrado: agribusiness development in Goiás, 2000-2019. **Caminhos de Geografia**, v. 22, n. 79, p. 1–17, 2021. https://doi.org/10.14393/RCG227955420

FLORES, B. M.; MONTOYA, E.; SAKSCHEWSKI, B.; NASCIMENTO, N.; STAAL, A. *et al.* Critical transitions in the Amazon forest system. **Nature**, v. 626, n. 7999, p. 555–564, 2024. https://doi.org/10.1038/s41586-023-06970-0

FREIRE, D. N.; CAVICHIOLI, F. A. Integrated crop-livestock-forest systems (ILPF): a strategy for agribusiness. **Interface Tecnológica**, v. 19, n. 2, p. 680–690, 2022. https://doi.org/10.31510/infa.v19i2.1536

FUNARO, J. S. *et al.* Piraputangas stream watershed, Cáceres, MT: land use and environmental changes. **Revista Brasileira de Geografia Física**, v. 15, n. 6, p. 2831–2852, 2022. https://doi.org/10.26848/rbgf.v15.6.p2831-2852

GAREIOU, Z. *et al.* Review of specific environmental indicators. **E3S Web of Conferences**, v. 436, n. 07001, p. 1–8, 2023. https://doi.org/10.1051/e3sconf/202343607001

GOMES, P. R.; MALHEIROS, T. F. Proposal for analysis of environmental indicators to support sustainability. **Revista Brasileira de Gestão e Desenvolvimento Regional**, v. 8, n. 2, p. 151–169, 2012.

HAZBAVI, Z. *et al.* Watershed health assessment using the pressure-state-response (PSR) framework. **Land Degradation & Development**, v. 31, n. 1, p. 3–19, 2020. https://doi.org/10.1002/ldr.3420

IBGE. **Cáceres, Panorama**. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística, 2024b. Available: https://cidades.ibge.gov.br/brasil/mt/caceres/panorama. Access 23 mar. 2026.

IBGE. **Censo Demográfico 2022**. Rio de Janeiro: IBGE, 2024a.

IBGE. **Cidades e Estados: Cáceres – Mato Grosso**. Rio de Janeiro, 2021.

IBGE. **Produto Interno Bruto dos Municípios 2002-2021**. Tabela 5938. Rio de Janeiro: IBGE, 2024c. Available: https://sidra.ibge.gov.br/tabela/5938. Access 23 mar. 2026.

IBGE. **Produção da Pecuária Municipal: efetivo dos rebanhos, por tipo de rebanho**. Rio de Janeiro: IBGE, 2023. Available: https://sidra.ibge.gov.br/tabela/3939. Access 23 mar. 2026.

INEP. **Censo escolar da educação básica 2021: resultados**. Brasília, DF, 2021.

INPE. **Relatório de focos de incêndio e desmatamento: município de Cáceres/MT**. São José dos Campos: Instituto Nacional de Pesquisas Espaciais, Programa PRODES, 2024.

KEMERICH, P. D. C.; RITTER, L. G.; BORBA, W. F. Environmental sustainability indicators: methods and applications. **Revista Monografias Ambientais**, v. 13, n. 5, p. 3723–3736, 2014. https://doi.org/10.5902/2236130814411

LAPOLA, D. M.; PINHO, P.; BARLOW, J.; ARAGÃO, L. E. O. C.; BERENGUER, E. *et al.* The drivers and impacts of Amazon forest degradation. **Science**, v. 379, n. 6630, art. eabp8622, 2023. https://doi.org/10.1126/science.abp8622

LÁZARO, W. L. *et al.* Climate change reflected in the Northern Pantanal water regime. **Acta Limnologica Brasiliensia**, v. 32, e104, 2020. https://doi.org/10.1590/S2179-975X3919

LIRA, W. S. Análise dos modelos de indicadores no contexto do desenvolvimento sustentável. **Perspectivas Contemporâneas**, v. 3, n. 1, p. 31–45, 2008.

LOPES, K. S.; OLIVEIRA, P.; LUIZ, F.; RAMIRES, M. O turismo de pesca no Mato Grosso: uma análise socioambiental. **Revista Brasileira de Ecoturismo**, v. 15, n. 2, p. 199–227, 2022. https://doi.org/10.34024/rbecotur.2022.v15.12472

MACÊDO, H. C.; TORRES, M. F. A. Utilização do modelo pressão-estado-resposta na avaliação de indicadores ambientais do município de Brejo da Madre de Deus - PE. **Revista de Geografia (Recife)**, v. 35, n. 5, p. 224–246, 2018.

MAPBIOMAS. **Projeto de Mapeamento Anual da Cobertura e Uso do Solo do Brasil: Coleção 8**. Available: http://mapbiomas.org. Access 1 set. 2023.

MATO GROSSO. **Monitoramento do desmatamento ilegal em Mato Grosso: relatório 2022-2023**. Cuiabá: Secretaria de Estado de Meio Ambiente, 2024.

MAXWELL, S. L.; FULLER, R. A.; BROOKS, T. M.; WATSON, J. E. M. Biodiversity: the ravages of guns, nets and bulldozers. **Nature**, v. 536, n. 7615, p. 143–145, 2016. https://doi.org/10.1038/536143a

MENDES, M. F. *et al.* Organization of extractivist women in southwestern Mato Grosso, Brazil. **Revista Estudos Feministas**, v. 22, n. 1, p. 71–89, 2014. https://doi.org/10.1590/S0104-026X2014000100005

MYERS, N.; MITTERMEIER, R. A.; MITTERMEIER, C. G.; DA FONSECA, G. A. B.; KENT, J. Biodiversity hotspots for conservation priorities. **Nature**, v. 403, n. 6772, p. 853–858, 2000. https://doi.org/10.1038/35002501

OECD. **Core Set of Indicators for Environmental Review: a synthesis report**. Paris: OECD, 1993.

OECD. **Environmental Indicators: Development, Measurement and Use**. Paris: OECD, 2003.

PEREIRA, C. C. *et al.* The Cerrado crisis review: highlighting threats and providing future pathways to save Brazil's biodiversity hotspot. **Nature Conservation**, v. 61, p. 29–70, 2026. https://doi.org/10.3897/natureconservation.61.168273

ROCHA, S. C. *et al.* Visibility of women's work in the Facão Bom Jardim settlement, Cáceres-MT. **Revista Ciência em Extensão**, v. 10, n. 3, p. 219–229, 2014.

RODRIGUES, A. A. *et al.* Cerrado deforestation threatens regional climate and water availability for agriculture and ecosystems. **Global Change Biology**, v. 28, n. 22, p. 6807–6822, 2022. https://doi.org/10.1111/gcb.16386

ROSSETTO, O. C.; DALLA-NORA, G.; DURANTE, L. C.; LIMA, D. M. D. F. Pantanal brasileiro: indicadores de desenvolvimento econômico e socioambiental dos assentamentos da reforma agrária. **Revista da Casa da Geografia de Sobral**, v. 24, n. 1, p. 341–363, 2022. https://doi.org/10.35701/rcgs.v24.799

SANTOS, L.; ZAMPARONI, C. A. G. P.; SOARES, J. C. O. Susceptibility to flooding in the urban perimeter of Cáceres-MT. **Caderno de Geografia**, v. 27, n. 51, p. 623–641, 2017. https://doi.org/10.5752/p.2318-2962.2017v27n51p623

SILVA, J. L. B.; COSTA, F. R. Applicability of geotechnologies in environmental and social vulnerability analysis. **Revista da Casa da Geografia de Sobral**, v. 24, n. 1, p. 389–407, 2022. https://doi.org/10.35701/rcgs.v24.807

SILVA, J. S. V.; ABDON, M. M.; NEVES, S. M. A. S.; MORAES, J. A. Evolution of deforestation in the Brazilian Pantanal and surroundings in the timeframe 1976-2008. **Geografia**, v. 36, n. especial, p. 35–55, 2011.

SILVA, M. L. da; ANDRADE, M. C. K. Os impactos ambientais da atividade mineradora. **Meio Ambiente e Sustentabilidade,** v. 11, n. 6, 2017.

SILVA, T. P.; O'LOIOLA, V. Territorial dynamics in Cáceres-MT: conflicts in the production and use of territory. **Revista Equador**, v. 8, n. 3, p. 140–158, 2019.

SNIS. **Diagnóstico dos serviços de água e esgotos**. Brasília: Ministério das Cidades, 2024.

SOULÉ, M. E. (ed.). **Viable Populations for Conservation**. Cambridge: Cambridge University Press, 1987. 189 p.

SOUZA, H. S.; TSUKAMOTO FILHO, A. A.; VENDRUSCOLO, D. G. S.; CHAVES, A. G. S.; MOTTA, A. S. Modelos hipsométricos para eucalipto em sistema de integração lavoura-pecuária-floresta. **Nativa**, v. 4, n. 1, p. 11–14, 2016. https://doi.org/10.14583/2318-7670.v04n01a03

STRASSBURG, B. B. N. *et al.* Moment of truth for the Cerrado hotspot. **Nature Ecology & Evolution**, v. 1, n. 4, 0099, 2017. https://doi.org/10.1038/s41559-017-0099

TOMICHA, G. L. P. *et al.* Education and interculturality: Bolivian students in a public school in Cáceres-MT. **Revista de Comunicação Científica**, v. 1, n. 13, p. 19–32, 2023.

UNITED NATIONS. **Paris Agreement**. Paris: UNFCCC, 2015. Available: https://unfccc.int/process-and-meetings/the-paris-agreement. Access 23 mar. 2026.

VAN BELLEN, H. M. **Sustainability indicators: a comparative analysis**. 2. ed. Rio de Janeiro: FGV, 2008. 256 p.

WANTZEN, K. M.; ASSINE, M. L.; BORTOLOTTO, I. M.; CALHEIROS, D. F.; CAMPOS, Z.; CATELLA, A. C. *et al.* The end of an entire biome? World's largest wetland, the Pantanal, is menaced by the Hidrovia project which is uncertain to sustainably support large-scale navigation. **Science of the Total Environment**, v. 908, n. 167751, 2024. https://doi.org/10.1016/j.scitotenv.2023.167751

ZART, L. L.; MENDES, E. P.; FERREIRA, T. N. F. Socioeconomic organization of women in a peripheral neighborhood in Cáceres-MT. **Revista Cultura & Extensão Unemat**, v. 1, n. 1, p. 60–72, 2016.

SUPPLEMENTARY MATERIAL

Environmental indicators and land-use change in the Amazon-Cerrado-Pantanal transition zone of Cáceres, Mato Grosso: a Pressure-State-Response assessment.

Table S1. Dimensions, Indicators and Pressure-State-Response of Cáceres, Mato Grosso, according to the PSR/OECD Model (1993).

Dimension	Indicator	Pressure	State	Response
Environmental	Soil	Expansion of agricultural areas (monoculture) on highly erodible soils; mining activities (limestone and dolomite extraction)	Progressive soil degradation; loss of mineral components; increased flood risk in urban areas due to occupation of stream margins and spring recharge zones	Law No. 6,938/1981 (PNMA); Decree No. 97,632/1989 (PRAD); ANM Resolution No. 68/2021 (Mine Closure Plan); Law No. 9,605/1998 (Environmental Crimes); Decree-Law No. 227/1967 (Mining Code); Law No. 7,958/2003, Art. 8, VII (PRODEIC Mineração); PDR/MT, Axes 1 and 4
Environmental	Water Resources	Discharge of domestic effluents and commercial waste; hotel boat activity on the Paraguay River; pesticide use	Municipal sanitation coverage: 7.04% (2022); urban sewage network coverage: 8.02% of served population (SNIS, 2024); monthly water quality monitoring (color, turbidity, pH, coliforms, *E. coli*)	Law No. 9,433/1997 (National Water Resources Policy); Law No. 9,612/2011 (groundwater conservation); Law No. 3,069/2022 (mandatory monthly water quality reporting)
Environmental	Climate	Deforestation and wildfires; 10,231.8 fire hotspots in 2023 (INPE, 2024)	Anthropic conversion (2022): Amazon 57.8%; Cerrado 33.8%; Pantanal 16.5% (MapBiomas Collection 10)	2030 Agenda SDG; Complementary Law No. 582/2017 (Mato Grosso Climate Policy); Paris Agreement; Disaster Risk Reduction 2015-2030
Environmental	Biodiversity	Suppression of native vegetation (agriculture, silviculture, mining); illegal hunting; wildlife trafficking	Integral Protection unit: Jubran Reserve (Pantanal). Sustainable Use units: Taiamã Ecological Station (Pantanal) and Serra das Araras Ecological Station (Cerrado). CFRP and GFAU (Decree No. 511/2023). Threatened fauna: Cerrado 9.09%; Pantanal 2.91%; Amazon 3.55% (MMA, 2018)	Forest Code: Law No. 12,651/2012; Decree No. 11,687/2023 for Amazon; Bill No. 5,482/2020 (Pantanal biome, under review)

Continue...

Continued...

Dimension	**Indicator**	**Pressure**	**State**	**Response**
Economic	Land Use	Agricultural mechanization; pesticide use; absence of organized productive chains; lack of agroecology incentives; lack of local regulations	Agriculture +5,356.5%; Pasture +304.0%; Silviculture (0 → 139 km²); Urban Areas +54.4% (1985-2022)	Law No. 6,938/1981 (PNMA); Law No. 7,802/1989 (Agrochemicals); Law No. 12,651/2012 (Forest Code — CAR, APP, Legal Reserve); Law No. 7,958/2003, Ch. III (PRODER) and Ch. VI (PRODEA); Complementary Law No. 592/2017 (SIMCAR/CAR/PRA — MT); Decree No. 1,031/2017 (SIMCAR procedures — MT)
Economic	Livestock Production	Expansion of conventional extensive livestock in the Pantanal; replacement of native pastures by artificial pastures requiring agrochemical inputs; 65.58% of surveyed lots use agrochemicals for pasture management (Rossetto et al., 2022)	Anthropogenic land use in the Pantanal increased 261% between 1985 and 2020, adding 1.8 million hectares; artificial pastures in the High Paraugay Basin doubled from 15.9% to 30.9% (Rossetto et al., 2022 for regional data); Cáceres holds the largest bovine herd in Mato Grosso: 1,341,455 animals; state total of 34,473,643 cattle in 2023 (IBGE, 2024)	Forest Code: Law No. 12,651/2012; PDR/MT, Axis 1 (sustainable use of natural resources)
Economic	Fishing	Predatory fishing; alteration of the hydrological cycle; five-year ban on fish transport and commercialization	Fish stock stability; economic dependence of population	Mato Grosso Fishing Policy (Law No. 9,096/2009; Law No. 9,794/2012); Law No. 12,197/2023 – Cota Zero, revised to 12 species (Law No. 12,434/2024); Fishers' Week, Cáceres (Law No. 3,024/2022).

Continue…

Continued…

Dimension	**Indicator**	**Pressure**	**State**	**Response**
Social	Education	The limited availability of skilled employment and the low wages offered in the region may discourage people from pursuing education. There is also a lack of governmental campaigns to encourage children to attend school, particularly in the post-pandemic period.	Regarding the Basic Education Development Index (IDEB), in 2021, the score for the early years of public elementary education was 5.1, and for the final years it was 4.6. Cáceres MHDI = 0.708 (state: 0.736)	Law No. 7,958/2003, Mato Grosso Regional Development Plan (PDR/MT), Axis 2 (knowledge and technological innovation)
Social	Income	Employment is predominantly associated with the private sector. Income is insufficient to support the family. Lack of value addition to primary products (agroindustry). Mechanisms for distributing/marketing production are absent and/or insufficient, especially in rural areas.	Average monthly salary of 3.4 minimum wages; 16.19% of the population formally employed; 37.7% of residents with per capita income below half a minimum wage; MHDI = 0.708 (state average: 0.736) (Brasil, 2021ab).	The municipal wage policy is based on minimum wages established for each professional category; The PDR/MT, under Axis 4 (diversification and strengthening of productive chains); Municipal Family Farming Plan (PMAF, 2023); Municipal Council for Sustainable Rural Development (CMDRS); participation in SICOR rural credit system

Prepared by the authors.