Discover Environment

Case Study

Devastation of the cerrado of mato grosso do sul and the advance of arenization in the pardo river watershed

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Abstract
Despite the significant biodiversity in the Cerrado, the process of occupation, subsequent economic cycles, and intensification of agriculture in a predatory manner have caused profound alterations in this biome. This study analyzed changes in land use and land cover in the Cerrado of Mato Grosso do Sul between 1985 and 2022 by mapping and also investigating the formation and dynamics of sand dunes in the Bauru sedimentary basin, focusing on the Pardo River watershed. MapBiomas Network data, collection 8, were used for land use and land cover analysis. Arenization foci cartography was conducted using brightness index 2 based on Sentinel-2 satellite images in Sentinel Application Platform software. The historical analysis of land use and cover in the Cerrado of Mato Grosso do Sul revealed a rapid transformation of the landscape, with a drastic reduction of native vegetation and an intensification of large-scale monocultures. Between 1985 and 2022, the Cerrado of Mato Grosso Sul lost 4.6 million hectares of native vegetation (forest formations, savannahs, grasslands, and wetlands), representing 24.54% of this territory. Recent changes in land use include pasture-soybean and pasture-eucalyptus. In the Pardo River watershed, arenization foci cover an area of 17,834.34 hectares, with varying dimensions ranging from less than 1 hectare to 376.41 hectares. The arenization process occurs in different slope compartments, such as the base, slope, and interfluves. The physical and chemical characteristics of Quartzipsamments, such as low organic carbon content in soil, are associated with high rates of surface exposure and weakened load-dependent structures, leading to degradation. Arenization occurs where natural vegetation has been suppressed and soil has been depleted by poorly managed production processes.

Keywords Land use change · Fragmentation · Soil management · Degradation

1 Introduction

Brazil is one of the richest nations in terms of biodiversity due to its vast coastline (approximately 8,000 km) and the presence of six distinct terrestrial biomes—the Pantanal, Pampa, Caatinga, Atlantic Forest, Cerrado, and Amazon [1]. Although the country has significant biodiversity, the process of colonization and subsequent economic cycles as well as the intensification of agriculture in a predatory manner have profoundly altered these biomes.

This transformation reflects the Brazilian economic development model, which is based on the expansion of areas for commodity production and livestock [2]. This pattern of intensive exploitation of the territory has been particularly

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pronounced in regions such as the Cerrado, where a significant portion of its extent has already been converted to pastures, soybean plantations, sugarcane cultivation, and other forms of human use. Data from MapBiomas [3], with land use and land cover classification for the year 2022, show that out of the 204 million hectares (204,071,207.804 ha) of the Cerrado [4], 51 million (51,366,263 ha) were already occupied by pastures, 19 million (19,226,773 ha) by soybeans, 3 million (3,225,857 ha) by forestry (mainly eucalyptus), 3 million (3,046,503 ha) by sugarcane, 679,383 ha by perennial crops, and 820,095 ha of urbanized area. The trend of intense utilization of savanna areas is not limited to Brazil. Globally, such ecosystems have been widely exploited for agricultural activities and various other forms of human occupation [5].

The Cerrado is the second largest biome in South America; it is present in all Brazilian regions and occupies 23.3% of the Brazilian territory [4]. This biome is characterized by dry winters and rainy summers, with the main climate being tropical rainy (Köppen), which coincides with the distribution of most savannas [6]. The occurrence of two well-defined seasons characterizes the concentrated distribution of rainfall throughout the region, with a direct influence on vegetation. According to Walter, Carvalho, and Ribeiro [7], the Cerrado is mainly composed of a typical savanna characterized by a tropical formation dominated by grasses, with varying proportions of open woody vegetation and associated trees. This definition, according to Collinson [8], corresponds to savanna in the most common physiognomic sense.

However, Walter, Carvalho, and Ribeiro [7] noted that Cerradão, one of the phytophysionomies of the Cerrado (riparian forest, gallery forest, dry forest (seasonal forest), cerradão, dense cerrado, typical cerrado (*stricto* sensu), sparse cerrado, cerrado parkland, palm grove, vereda (specific type of wetland), rupestrian cerrado, rupestre field, dirty grassland (shrubby grassland) and open grassland), cannot be classified as savanna because it is a forest, just as the Open Grassland does not fit due to its pure field nature. They argue that only the Cerrado in the strictest sense and the Dirty Grassland would fall within the physiognomic definition of savanna, excluding the pure fields represented by the Campo Limpo. Thus, although the Cerrado biome contains forests (such as Gallery Forests and Dry Forests) and pure fields, it is primarily characterized by typical savanna vegetation, occupying most of its area. Due to intense human occupation and landscape changes, the phytophysionomies of the Cerrado have been transformed, resulting in a reduction in biodiversity and the loss of ecosystem services.

In recent decades, the Central-West region of Brazil (encompassing Mato Grosso, Mato Grosso do Sul, Goiás, and Distrito Federal) has become an epicenter for agricultural production, particularly for cattle and soybeans. This rapid agricultural expansion has been one of the primary drivers of environmental degradation in the Cerrado, a vast tropical savanna biome. Data from the Municipal Livestock Production and Municipal Agricultural Production, available in the Brazilian Institute of Geography and Statistics (IBGE) through the Automatic Recovery System (SIDRA), highlight the significant role of this region in Brazil's agricultural economy. In 2022, this region had the largest cattle herd, totaling 77,175,767 head, and the largest planted area of soybeans, covering 18,825,863 hectares [9, 10]. Mato Grosso do Sul ranks fifth in the national cattle herd ranking, with 18,433,728 head and a planted soybean area of 3,694,468 hectares [9, 10]. However, this economic growth associated with agricultural intensification brings with it a series of environmental and social challenges, including deforestation, loss of biodiversity, and social conflicts [11].

The Pardo River Watershed (PRW), located in the Cerrado of Mato Grosso do Sul, represents recent land use changes and the process of arenization. In this watershed, the Quartzipsamments account for 37.6% of the area [12]. As in other regions of the country, livestock farming in the Cerrado was developed by the cutting and burning of native vegetation [13]. Initially, cultivation of the soil in the Cerrado was by conventional methods, with intensive use of plows and harrows, leading to increased water erosion and microbial oxidation [14, 15], which resulted in severe environmental impacts and degradation of the local ecosystem. The predominant agricultural activity in 2022 is extensive livestock farming, with planted pastures covering 58.33% of the PRW [3].

Among the forms of soil degradation observed in the PRW are the processes of arenization, as well as erosion, compaction, and loss of organic matter, each contributing to the overall decline in soil health and productivity [16], one of the most challenging forms of soil degradation from which to recover. As described by Suertegaray [17], this process is characterized by sparse vegetative cover and the presence of patches of exposed soil, involving the "reworking of poorly or nonconsolidated sandy deposits, which promotes difficulty in vegetation establishment due to the constant mobility of sediments", resulting in sand dunes, which represent the most evident form of this process. According to Suertegaray [18], "a sand dune has an area devoid of vegetative cover, consisting of recent (Holocene) sandy deposits, therefore not consolidated, constantly being removed by current hydrological and aeolian processes".

Agricultural practices in the PRW and in the Cerrado in general, when natural limitations are disregarded, can lead to severe environmental impacts and degradation of the local ecosystem [11, 16]. This is particularly concerning in Permanent Preservation Areas (PPAs), such as paths, rivers, springs, and reservoirs, which serve as the final barrier between terrestrial and aquatic systems and also exhibit significant environmental liabilities [19]. In the PRW and throughout the

Cerrado of Mato Grosso do Sul, the situation is especially critical due to its vulnerability amidst ongoing climate change and environmental degradation, as evidenced by observations from orbital remote sensing and fieldwork.

The PRW is a critical area of the Cerrado as is responsible for 50% of the water supply to the capital of the state of Mato Grosso do Sul (MS), as well as other municipalities within the area. Despite this, numerous small hydroelectric power plants have been approved, with seven in the PRW alone, and there is already a hydroelectric power plant in operation. The eucalyptus-pulp sector and irrigated soybean cultivation are rapidly expanding in the state, compounding this issue [11, 20]. These monocultures encroach on areas with sandy soils, particularly Quartzipsamments, which are highly susceptible to erosion. This raises concerns about potential economic, social, and environmental losses and the imminent risk of conflicts over water use.

Despite the significant environmental impacts of arenization having been largely overlooked in the state of Mato Grosso do Sul, where state policies have encouraged the production of irrigated soybeans [21] and the planting of eucalyptus [22] in environmentally fragile areas, this study aims to address this gap. By analyzing changes in land cover and land use in the Cerrado of Mato Grosso do Sul between 1985 and 2022, the research provides a comprehensive assessment of the problem. Additionally, it maps and investigates the genesis and morphodynamics of arenization in soils derived from the undivided Caiuá Group sandstones, focusing on the Rio Pardo watershed as the spatial cut. This work advances the state of the art by filling critical knowledge gaps and offering new insights into the environmental impacts of arenization and land use changes, thereby contributing to a more informed approach to land management and policymaking.

2 Materials and methods

2.1 Study area

The Cerrado (Fig. 1), the second largest biome in South America, extends across all Brazilian regions and encompasses approximately 23.3% of Brazil's national territory [4]. The remarkable diversity of rocks, soils, topography, and climatic types in the Cerrado is the culmination of a complex interplay of geological, geomorphological, and climatic factors that have evolved over billions of years. Its proximity to diverse ecosystems—the Amazon Rainforest to the North, the Caatinga to the Northeast, the Pantanal to the West, the Atlantic Forest to the East, and the temperate-like grasslands to the South—influences its climatic patterns, with rainfall incidence being greater near the Amazon and lower near the semiarid regions [23].

Situated predominantly on the Brazilian Central Plateau, the Cerrado is instrumental in the distribution of water resources and is pivotal to the national hydrological balance. Among the main rivers that receive contributions from the Cerrado are the Xingu, Madeira, and Trombetas Rivers in the Amazon Basin; the Araguaia and Tocantins Rivers in

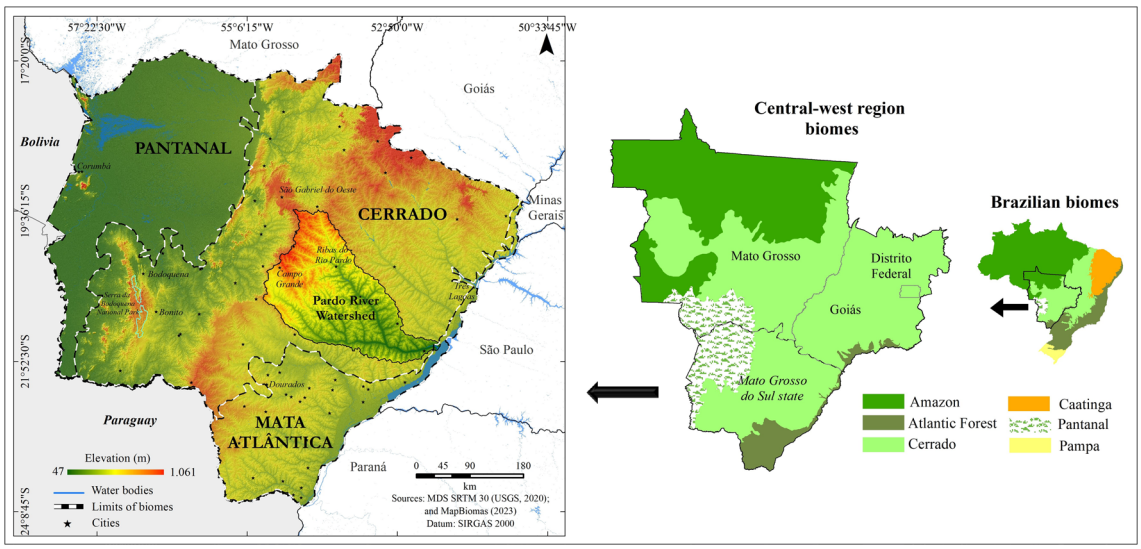


Fig. 1 Geographic context of the study area of the State of Mato Grosso do Sul and its localization within Brazil

the Tocantins Basin; the São Francisco, Pará, Paraopeba, and other rivers in the São Francisco Basin; and the Parnaíba, Itapecuru, Pardo, Jequitinhonha, and numerous other rivers across various basins [23]. The upper reaches of these hydrographic basins within the Cerrado are of particular hydrological significance, notably for the Araguaia/Tocantins, Paraná/Paraguay, and São Francisco basins. Springs and low-order channels, despite their hydrological sensitivity, especially for the regulation of flows of higher-order channels, have been adversely affected by the removal of native vegetation and unsustainable livestock grazing practices, leading to the burial of springs and territorial alteration of water sources. Large shifts in the positions of springs (downslope) and in the degree of water flow permanence are observed. The soil burial conditions of springs continue in first- and second-order rivers, not uncommonly even in third-order rivers, undermining their ecological functions. Springs and low-order channels have been neglected in the Rural Environmental Registry (CAR), an aggravating factor.

The Cerrado within the state of Mato Grosso do Sul spans an area of 220,047.4 km^2 [4]; is contiguous with the Pantanal and Atlantic Forest ecosystems; and showcases a wide array of physical environments. From a geological perspective, it encompasses rocks dating back to the Paleoproterozoic Era. Geomorphologically, the region is characterized by plateaus, erosion scarps, depressions such as Miranda, ranges such as Bodoquena, the plains of the Pantanal, and residual hills. Arruda et al. [24] delineated this area into two distinct ecoregions: the Paraná Guimarães and the Bodoquena Complex.

The Paraná Guimarães ecoregion, a component of the geomorphological unit which is known as a plateau with concordant sedimentary structure, is characterized by the Paraná sedimentary basin. This basin is morphologically organized into successive steps or plateaus shaped by erosion of layers of sandstone alternating with basalt. The landscape features mixed forms of plantation and river dissection, with wide hills and low drainage density, and table-like landforms that emerge from processes of differential erosion or local faulting [24]. The hydrographic system of this ecoregion is dominated by the Paraná and Paraguay rivers and supported by significant tributaries, including the Tietê, Grande, Paranaíba, Paranapanema, Pardo, Taquari, São Lourenço, and Miranda rivers. The altitudinal range within this ecoregion spans from 136 to 907 m (Digital Surface Model—DSM, Shuttle Radar Topography Mission—SRTM 1 arc-second), with the highest elevations located on the plateau edges and the lowest points found in the Paraná River riverbed and the Pantanal plain. The extensive plateau area of the Paraná Guimarães ecoregion allows for the exposure of a variety of geological formations across different geographical positions and altitudes. These formations predominantly consist of more recent sediments from the São Bento and Bauru groups, along with lateritic detrital coverings. The soil diversity in this ecoregion is notable, with a predominance of Oxisols and Quartzipsamments associated with smoother relief. In contrast, shallower or less developed soils are found in rugged areas or rocky outcrops.

The Bodoquena Complex ecoregion, characterized by its mountainous relief, convex hilltop, and strong dissection, with outcrops of the basement of the Paraguay-Araguaia fold belt (Amazonian craton), forms the Bodoquena Range and is encircled by the lowered reliefs of the Paraguay Depression [24]. Within this ecoregion, the sediments overlying the Pantanal Formation give rise to tabular reliefs with a gentle gradient from the hilltop to the valley bottom. The altitudinal range of the Bodoquena Complex spans from 74 to 843 m (DSM SRTM 1 arc-second), and the area's drainage system is part of the Paraguay River Basin. The region is geologically composed of the Corumbá Group and the Rio Apa Complex, as well as the Bocaina Formation, which includes limestone, dolomites, and marbles that contributed to the formation of karstic reliefs [25]. Soil diversity in the ecoregion is influenced by the relief and underlying bedrock, with Ultisols, Entisols (lithics and psamments), Inceptisols, and both eutrophic and dystrophic Oxisols present [12]. These soils primarily support seasonal forest vegetation, including Atlantic Forest enclaves and, to a lesser extent, forest/savanna transition zones. The existence of Atlantic Forest enclaves within the Cerrado biome implies a historical linkage with the Amazon Rainforest. Palynological and phylogeographic studies suggest that this connection dates to the Quaternary period, approximately between 33,000 and 25,000 years ago [26, 27].

The topography of the state of Mato Grosso do Sul varies significantly, influencing its environmental and climatic conditions. In this state, the altitudinal range spans from 47 to 1061 m. Specifically, the Cerrado of Mato Grosso do Sul exhibits altitudes between 75 and 907 m, as detailed by the DSM SRTM 1 arc-second data. The slopes in this region vary widely, from flatlands at 0% to steep inclines at 338.1%, averaging 5.99% with a standard deviation of 6.05 (DSM SRTM 1 arc-second). The most pronounced slopes are found in the erosion scarp on the western edge of the Paraná sedimentary basin, the Serra da Bodoquena, and inselbergs on the Amazonian craton.

The Pardo River watershed (PRW), situated in the eastern half of Mato Grosso do Sul (Fig. 1), covers 14 municipalities, with Ribas do Rio Pardo (37.0%), Campo Grande (22.3%), and Santa Rita do Pardo (12.9%) being the most extensive in terms of area. The lithology of the PRW comprises basalt from the Serra Geral Formation (13.9%), which traps eolian sandstones from the Botucatu Formation and is underlain by neocretaceous siliciclastic rocks from the undivided Caiuá Group (78.3%), Santo Anastácio Formation (1.5%), and Neogene detrital-lateritic coverings (1.8%). Pleistocene terraces

(1.4%), Holocene terraces (2.6%), Holocene alluvial deposits (0.3%), Holocene colluvial deposits (0.02%), and Holocene fluvial-lacustrine alluvions (0.22%) constitute the remaining area of the PRW [12, 28]. The most representative soil classes in the area are Oxisols (57.6%) and Quartzipsamments (37.6%) [12]. Soils are directly correlated with lithological substrate and relief. According to the climatic classification of Alvares et al. [29], the predominant climatic type is tropical monsoon (80%), with precipitation ranging from 1600 to 1900 mm year^{-1}. The accumulated precipitation in Campo Grande for the year 2023 was 1503.4 mm, and that in Ribas do Rio Pardo was 1328.8 mm [30]. In the hydrographic context, the PRW is a tributary of the Paraná River. In the geomorphological context, the PRW is located within the macroform of relief of the Plateaus and Chapadas of the Paraná Basin [31], with the predominant geomorphological units being the South-Mato-Grossense Plateau (42.7%), Campo Grande Plateau (35.1%), and the Sandy Ramps of the Interior Plateau (15.2%). The elevation ranges from 232 to 743 m, with a range of 511 m and slopes ranging from 0 to 56.7%, with an average of 4.2% (DSM SRTM 1 arc-second).

2.2 Cartographic base and delimitation of the pardo river watershed

The geospatial reference data used were the political boundaries of Brazil [12]; representation of biome boundaries compatible with the 1:250,000 scale [4]; and the 30-m resolution Digital Surface Model (DSM) from the Shuttle Radar Topography Mission (SRTM) of the year 2000 [32].

The boundary of the Pardo River watershed was extracted from the DSM SRTM using ArcMap 10.8.2 software with the Spatial Analyst Tools following the steps Fill → Flow Direction—D8 → Flow Accumulation—D8 → Conditional (threshold 800) → Conversion Tools—Raster to Polyline → Feature to Point → Watershed.

2.3 Land use and land cover analysis

Geographic Information Systems (GIS) and Remote Sensing play a crucial role in the analysis and monitoring of Brazil's biomes. These technologies allow for the detailed mapping and assessment of land cover changes over time, providing essential data for understanding environmental dynamics. The MapBiomas Network [3] has been instrumental in offering comprehensive land use and land cover classifications. It enables researchers and policymakers to track the impacts of human activities on ecosystems like the Cerrado, aiding in the development of strategies for conservation and sustainable management. Using GIS and Remote Sensing, MapBiomas helps visualize trends in land transformation, supporting informed decision-making and environmental stewardship.

The MapBiomas project is a collaborative network formed by non-governmental organizations, universities, and technology startups that produce annual mappings of land cover and use, monitor water surfaces, and record monthly fire scars with data since 1985. The network was established in 2015. Details about the land use and cover classification method by the MapBiomas Network can be found in the work of Souza et al. [33] and on the MapBiomas hub.

For this study, Collection 8 of the MapBiomas project was utilized, covering classifications from 1985 to 2022 [3]. The overall accuracy of Collection 8 is 90.0%, with a 9.0% allocation disagreement and a 1.0% quantity disagreement [3]. The selected years for analysis were 1985, 1994, 2004, 2014, and 2022, with 1985 marking the beginning of the Landsat image historical series and 2022 representing the most recent classification available from the MapBiomas network.

The quantification of each land use and land cover class (1985–2022) was performed using ArcMap 10.8.2 software [34]. Additionally, the land use and land cover data were cross-referenced with declarations from the Rural Environmental Registry to identify environmental liabilities [35, 36].

2.4 Mapping of arenization foci in the pardo river watershed

The mapping of arenization foci in the Pardo River watershed was conducted using multispectral images from the Sentinel-2 satellite. For mapping purposes, images from the dry season, characterized by lower humidity and higher brightness, were utilized, while the results were validated using images from the rainy season, characterized by higher humidity and lower brightness.

The radiometric index used for mapping was the brightness index 2 (BI2) [37]. This index is sensitive to the brightness of soils, which, in turn, is related to moisture, the presence of salts, and organic matter content [38]. According to Bannari et al. [39], variations in brightness can be used to distinguish soil erosion levels across different land use classes. Bachaoui et al. [40] also demonstrated that variations in brightness can provide insights into degradation status, with leached soils tending to exhibit greater brightness than soils rich in organic matter.

The Sentinel-2 satellite images were obtained from the Copernicus hub [41], and the selected dates by strip were August 3, 2023, for the Bataguassu strip (two scenes); August 11, 2023, for the Campo Grande strip (three scenes); the zone of transition of the time zone (three scenes); and August 18, 2023, for the Ribas do Rio Pardo strip (four scenes). For validation, a comparison was made with the BI2 from the rainy season in the region.

Level 2 processing is applied to Level 1C products (radiometric and geometric corrections, including orthorectification and spatial registration, providing top-of-atmosphere reflectance (TOA)). The main output consists of corrected bottom-of-atmosphere reflectance (BOA) images. The image processing protocol is available in the user manual [42].

The BI2 was calculated with the SeNtinel Application Platform (SNAP), version 9.0.0 [37], using the green, red, and near-infrared bands (BI2 = sqrt(((red_factor * red * red_factor * red) + (green_factor * green * green_factor * green) + (IR_factor * near_IR * IR_factor * near_IR))/3). The BI2 was calculated at the scene level because, according to Ponzoni, Shimabukuro, and Kuplich [43], "[…] the angle of incidence varies within a certain range according to the position of the objects in the imaged strip." Additionally, according to these authors, the backscattering coefficient, surface roughness, and water content affect the characteristics of the target analytes.

After deriving the BI2, the values were separated into classes to map the area of interest, following the methodology outlined in Capoane et al. [44]. The intervals were defined based on the histogram, satellite image analysis, and field control points. The raster image was converted into polygons, and pixels corresponding to deposition areas, such as the base of the slope and depressions in the terrain; pastures under recovery, renovation, or reform; crops with exposed soil (geometric features); sediment-filled headwater reservoirs; roads; and linear erosive processes formed by cattle trampling, were eliminated.

Fieldwork was conducted in the PRW from 2019 to 2024 to obtain control points for areas with smaller representation in the area and for photographic documentation (on the ground and with a drone). For the analysis of the genesis and morphodynamics of the arenization foci, the historical series from Google Earth was also used.

3 Results and discussion

3.1 Devastation of the cerrado and predatory agriculture

The colonization of Brazil by the Portuguese in the sixteenth century and subsequent settlement initially focused on coastal areas, giving the country an urban character even before it was rural [45]. The expansion inland occurred in a differentiated manner due to the continental dimensions of the Brazilian territory and the strategies of the Portuguese colonial system. The particularities of each region were influenced by various economic cycles, such as sugar, gold, diamonds, coffee, rubber, industrialization, and agribusiness, which shaped the agrarian and urban geography of the country.

The Brazilian demographic explosion [46] occurred after World War II, during the Great Acceleration, reflecting a global trend [47]. Until 1960, the Brazilian population was mostly rural (55%); and by 1970, the population became predominantly urban (56%); and in 2010, 84.4% of the total population was urban, with just 29,830,007 inhabitants in rural areas [46, 48]. In the North and Central-West regions, the urbanization process occurred later, initially marked by mineral exploration and later by the expansion of the agricultural frontier under the State direction [49]. These regions experienced rapid and fragmented urbanization, reconfiguring structural and sociospatial dynamics, and exacerbating the pressure and degradation of natural resources [50].

In the state of Mato Grosso do Sul, the process of land use in the eighteenth century was initially driven by gold exploration. The production of yerba mate and extensive livestock farming in the state occurred mainly in the nineteenth and twentieth centuries when mineral exploitation began to decrease [51]. Although livestock farming occupied the largest proportion of agricultural land in the twentieth century, in the twenty-first century, there was a change in land use, from livestock farming to soybean and eucalyptus cultivation [16].

Among the three biomes in Mato Grosso do Sul, the Cerrado stands out as the most extensive, encompassing 61.5% of the state's territory, which amounts to 220,249.4 km^2 [12]. In contrast, the Pantanal covers 24.8% of the state, while the Atlantic Forest accounts for 13.7%. The temporal cuts (1985, 1994, 2004, 2014, and 2022) of land use and land cover for the Cerrado of Mato Grosso do Sul show changes that have occurred in the last 38 years (Fig. 2). The natural vegetation cover has decreased drastically, which has profoundly modified the landscape, exposed the soils to erosive processes, and impacted biodiversity and ecosystem services.

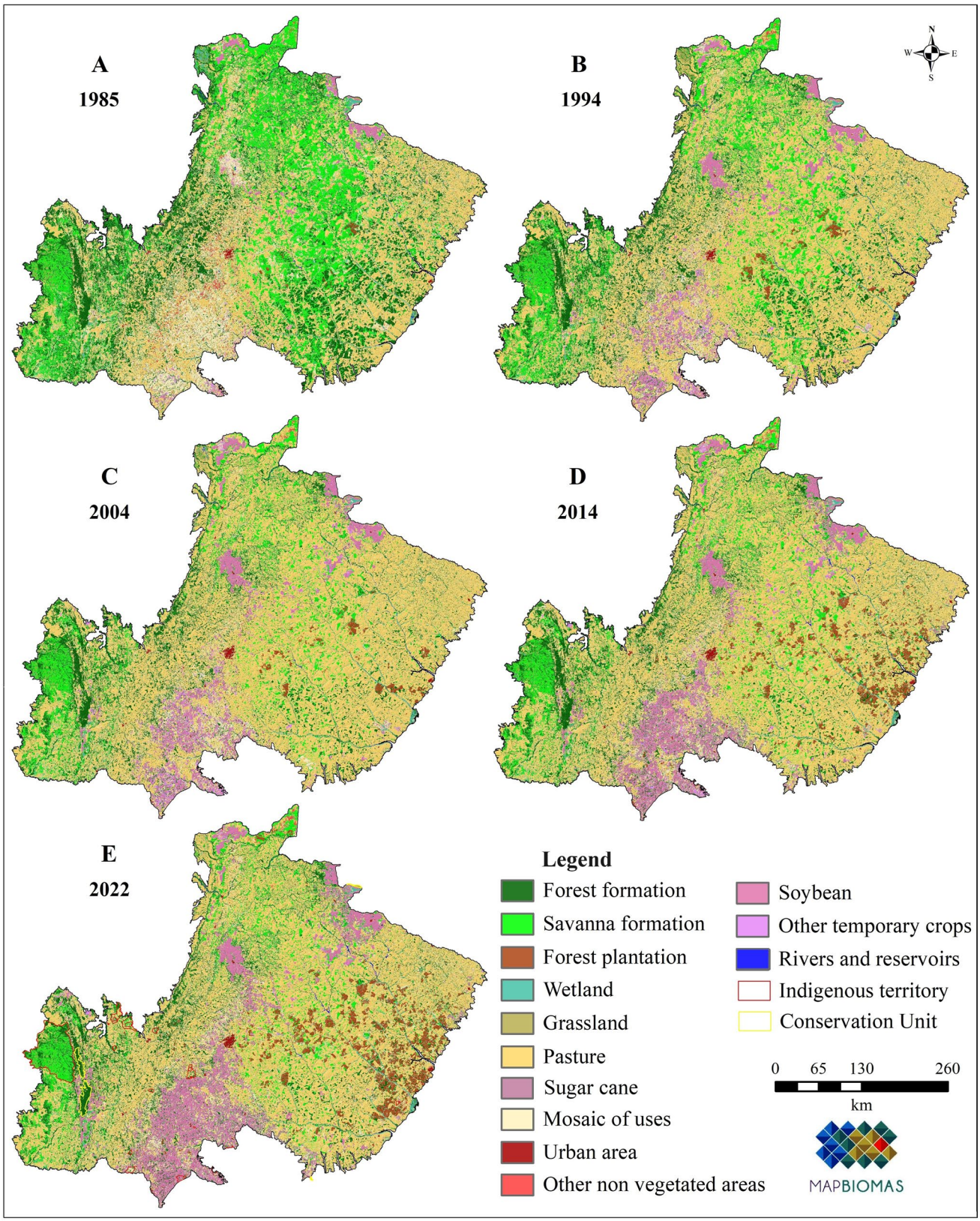


Fig. 2 Land use and land cover classes in the Cerrado of Mato Grosso do Sul. Source: MaBiomas, collection 8 (2023)

In 1985 (Fig. 2A), the native vegetation was composed of forest formations (21.21%), savannas (20.87%), grasslands (1.23%), and wetland fields (3.06%), which covered 46.37% of the Cerrado of Mato Grosso do Sul, while the predominant agricultural use was pasture, covering 33.80% of the area. By 1994, native vegetation had already decreased to 32.89%, in 2004 to 26.27%, in 2014 to 25.35%, and in 2022 to 21.82%, which corresponds to a reduction of 4,675,503.3 hectares between 1985 and 2022. In 2022 (Fig. 2E), forest formations (11.16%), savannas (7.25%), grasslands (0.95%), and wetland fields (2.46%) totaled 5,527,183.1 hectares. A decrease of 4.6 million hectares of native vegetation from 1985 to 2022 occurred at the expense of agriculture. Although the pasture class increased from 33.80% in 1985 to 51.89% in 1994 and to 58.17% in 2004, a reduction in the pasture area was observed in 2014 (53.5%). In 2022, the pasture area covered 41.73% of the Cerrado of Mato Grosso do Sul. Despite this decrease, it is still the predominant land use class.

The area of the soybean land use class, which occupied only 294,246.6 hectares (1.34%) of the total area in 1985, significantly increased over the years. By 2022, this area had grown to 2,047,924.6 hectares, representing 8.1% of the total area. Soybean cultivation initially expanded in areas of Oxisols derived from the basalt rocks of the Serra Geral Formation (Dourados microregion) and lateritic detrital coverings (for example, São Gabriel do Oeste). Recent expansion is occurring in degraded pasture areas on sandy-textured soils such as Quartzipsamments [16]. Soybeans are also advancing around the Bodoquena Range on clayey soils of the Cerradinho and Cuiabá Formations. This region, which is of great importance for tourists and attracts visitors from around the world, has its future threatened by agribusiness [3, 52].

The insertion of soybean cultivation in the Central-west occurred through the development of varieties with genes adapted to the hot climate of the savanna, tolerant to high aluminum content, and low calcium content. This adaptation allowed deep rooting of the plants, conferring them with drought tolerance and late maturation [53]. According to Klink [54] and Jasinski et al. [55], advancements in genetic improvement, combined with the use of acidity correctors and increased fertilizer use, have enabled the expansion of production. Thus, soybean plants, which were initially restricted to the southern region of Brazil in temperate climates, reached the Midwest in the 1980s and, more recently, extended to the Northern region of the country [56].

The land division of the state of Mato Grosso do Sul, characterized by the presence of large rural areas, also played a crucial role in the success of large-scale monocultures [57]. Soybean cultivation began in the mid-1970s in the southern region of the state Mato Grosso, which now corresponds to the southern part of the state Mato Grosso do Sul (Dourados microregion), driven by extensive use of technology and financing from Banco do Brasil [58]. According to Faccin [57], the soybean complex is highly important to the economy of Mato Grosso do Sul. However, she notes that soybean cultivation implies an increasingly deep productive specialization supported by the State, perpetuating Brazil's longstanding choice to be an agrarian-exporting country based on low-value-added commodities, with little job creation and numerous associated environmental impacts.

The area planted with sugarcane also significantly increased. In 1985, it was only 255.94 hectares, representing 0.001% of the total area of the Cerrado in Mato Grosso do Sul. However, by 2022, this area had considerably increased to 2,311,259.8 hectares, which accounts for 9.13% of the total area. Among the municipalities that produce sugarcane, Dourados is home to several processing plants that produce ethanol and other derivatives.

The area of planted forests (silviculture—eucalyptus) also experienced notable growth (Fig. 2DE). From 1985, when the planted area occupied 34,227.26 hectares, by 2022, it expanded considerably to 922,166.29 hectares, 3.64% of the total area of the Cerrado in Mato Grosso do Sul. Eucalyptus plantations are predominantly located in the northeastern quadrant of Mato Grosso do Sul on sandy soils (Quartzipsamments) previously used in livestock farming [16].

Overall, there is a profound modification of the landscape where the remaining native vegetation is drastically reduced and fragmented, not fulfilling its ecological functions. Areas with better preserved native vegetation are found in Conservation Units, such as the Serra da Bodoquena National Park, and in indigenous territories. These temporal snapshots illustrate the predatory agriculture practiced in Brazil.

3.2 Land use and land cover change in the pardo watershed

In the Pardo River Watershed, the Cerrado occupies an area of 33,636.2 km^2, and the Atlantic Forest occupies 37.9 km^2 [4]. Although the historical series from MapBiomas started in 1985, it allows us to observe spatiotemporal changes in land cover and land use. In 1985 (Fig. 3), the native vegetation was composed of savanna formations (24.46%), forests (17.88%), grasslands (0.97%), and wetlands (2.69%), representing 46.01% of the total area of the PRW, while the predominant agricultural use was pasture on 37.98% of the area. The mosaic class of crops and pasture, which corresponds to areas that present mixed use, where both plant food production and animal husbandry occur in an integrated manner or in mixed farming systems, is a relevant category for understanding the dynamics of agricultural landscapes and the

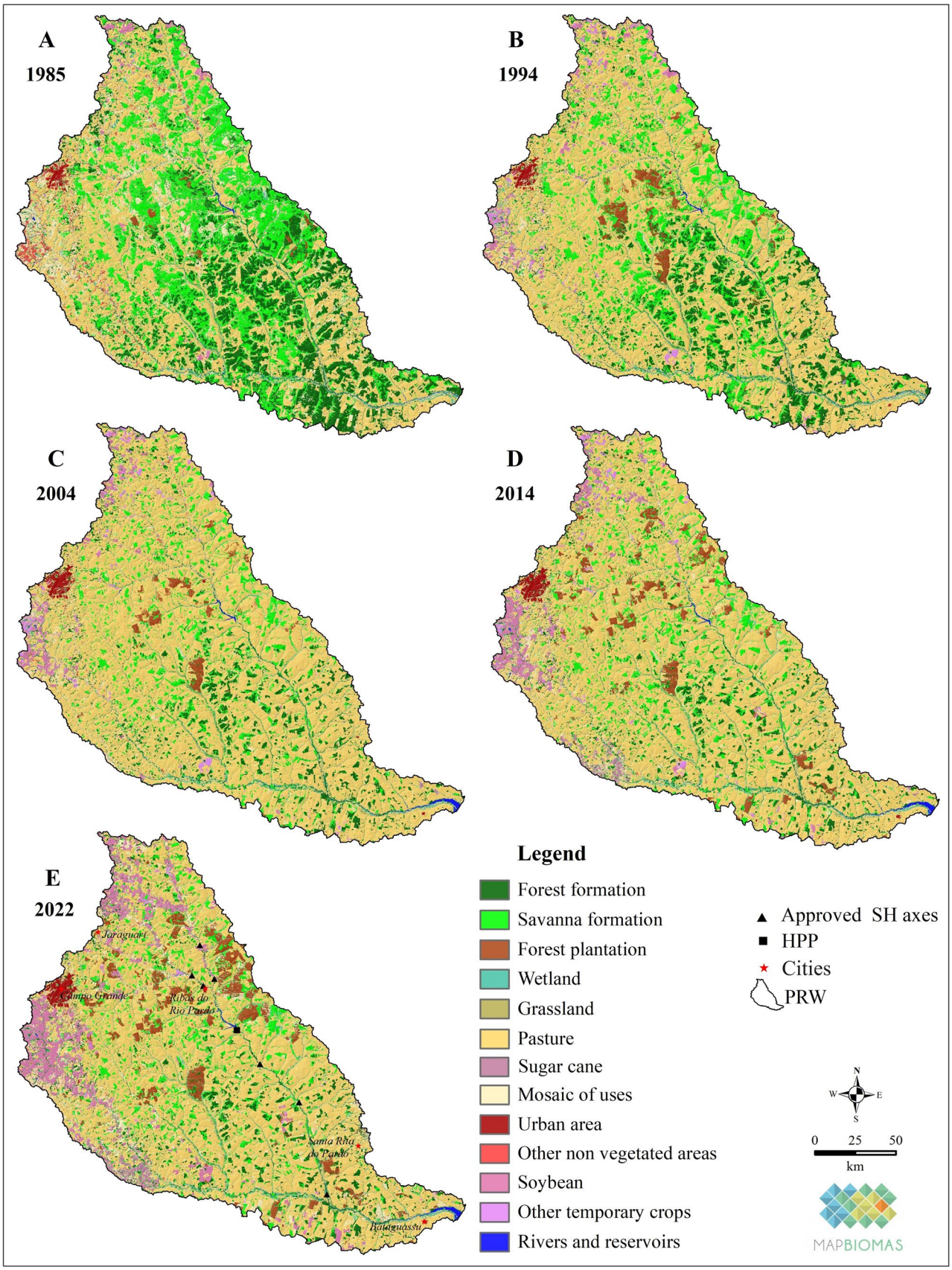


Fig. 3 Land use and land cover classes in the Pardo River watershed in the years 1985, 1994, 2004, 2014, and 2022.Source: MapBiomas, collection 8. Elaboration: this publication.

interaction between crops and livestock in certain regions, occupied 12.49% of the PRW. Other non-vegetated areas (1.54%), soybeans (0.85%), urbanized areas (0.30%), rivers and reservoirs (0.31%), other temporary crops (0.10%), and forest plantations (0.42%) composed 3.52% of the total area (Table 1).

In 1994 (Fig. 3A), compared with those in 1985, the areas covered with native vegetation—savanna formation (15.06%), forest formation (10.75%), grassland formation (0.92%), and wetland (2.42%)—had a reduction of 36.63% (Table 1). The pasture class occupied 60.57% of the PRW, which was significantly greater than that in 1985 (Table 1). An increase in pasture area occurred in deforested areas, as shown in Fig. 3B. The mosaic classes of crops and pasture (4.67%), soybeans (1.20%), other temporary crops (1.12%), other non-vegetated areas (0.32%), forest plantations (2.16%), rivers and reservoirs (0.35), and urbanized areas (0.45%) accounted for 10.28% of the Pardo River watershed area.

Source: MapBiomas, collection 8. Elaboration: this publication.

In 2004 (Fig. 3C), the native vegetation was composed of savanna formations (9.35%), forest formations (7.15%), grassland formations (0.90%), and wetlands (2.36%), representing 19.77% of the total area of the Pardo River watershed, while the predominant agricultural use was pasture (70.32%). The mosaic classes of crops and pasture (5.5%), other temporary crops (2.3%), forest plantations (0.8%), other non-vegetated areas (0.4%), urbanized areas (0.15%), and rivers and reservoirs (0.07%) corresponded to 9.90% of the PRW.

In 2014 (Fig. 3D), the native vegetation was composed of savanna formations (9.15%), forest formations (6.29%), grassland formations (0.90%), and wetlands (2.56%), representing 18.90% of the total area of the PRW. Pasture was still the class with the highest representation in the area, accounting for 65.95%. The mosaic classes of crops and pasture (6.35%), soybeans (2.48%), other temporary crops (1.13%), other non-vegetated areas (0.19%), forest plantations (3.42%), rivers and reservoirs (0.35%), sugarcane (0.56%), and urbanized areas (0.67%) made up 15.15% of the PRW. The pasture class showed a reduction in area compared to that in 2004. This reduction occurred due to the change in land use from pasture to soybean and eucalyptus.

During the period between 1985 and 2022, native vegetation decreased from 46.01% to 18.91%. In 2022 (Fig. 3E), savanna formations (8.71%), forest formations (6.38%), grasslands (0.92%), and wetlands (2.89%) represented 18.91% of the total area of the PRW. This decrease was related to deforestation and the conversion of agricultural areas, mainly pastures. Although the pasture class decreased from 65.95% in 2014 to 58.33% in 2022, it is still the predominant land use class in the watershed. The mosaic classes of crops and pasture (8.58%), soybeans (6.57%), other temporary crops (0.43%), other non-vegetated areas (0.30%), forest plantations (5.15%), rivers and reservoirs (0.33%), sugarcane (0.70%), and urbanized areas (0.71%) made up 22.77% of the PRW.

Over the past ten years, the Pardo River watershed has undergone notable transformations in land cover and usage, primarily characterized by the proliferation of soybean monocultures—an increase of 137,658.77 hectares—and the expansion of afforested areas by 58,250.30 hectares. In 2022, soybean cultivation constituted 6.57% of the watershed's total area, while afforestation, including eucalyptus and rubber tree plantations, comprised 5.15%. This agricultural intensification largely supplanted extensive livestock farming, which decreased by 256,774.12 hectares from 2014 to

Table 1 Land use and land cover classes in the Pardo River watershed in the years 1985, 1994, 2004, 2014, and 2022

Land use and land cover classes	1985	1994	2004	2014	2022
	Area %				
Forest formation	17,88	10,75	7,15	6,29	6,38
Savanna formation	24,46	15,06	9,35	9,15	8,71
Forest plantation	0,42	2,16	1,46	3,42	5,15
Wetland	2,69	2,42	2,36	2,56	2,89
Grassland	0,97	0,92	0,90	0,90	0,92
Pasture	37,98	60,57	70,32	65,95	58,33
Sugarcane	-	-	0,04	0,56	0,70
Mosaic of uses	12,49	4,67	4,52	6,35	8,58
Urban area	0,30	0,45	0,58	0,67	0,71
Other non-vegetated areas	1,54	0,32	0,33	0,19	0,30
Rivers and reservoirs	0,31	0,35	0,38	0,35	0,33
Soybean	0,85	1,20	1,54	2,48	6,57
Other temporary crops	0,10	1,12	1,07	1,13	0,43

Source: MapBiomas, colection 8 (2023). Elaboration: this publication

2022. Temporal analysis, as depicted in Fig. 3, reveals a marked escalation of soybean cultivation commencing in the early 2000s, a trend bolstered by the agrarian policies of the administrations of Luís Inácio Lula da Silva and Dilma Rousseff, which financially supported commodity exports [59]. These policy frameworks, as Perpetua and Thomaz Junior [60] assert, played a pivotal role in augmenting the agricultural sector, thereby cementing soybeans as a cornerstone of the nation's export commodities. The period between 2004 and 2007 saw a concerted effort to increase tree plantation areas under the National Forest Program, as highlighted by Dubos-Raoul [20], an initiative of the Ministry of the Environment's Secretariat of Biodiversity and Forests.

The land use class of soybeans is predominantly characterized by intensive production systems involving the use of high doses of agrochemicals, as well as heavy mechanization, aiming for maximum productivity. Soybean crops are located primarily in the upper course of the watershed in areas with clayey soils derived from the basalt of the Serra Geral Formation, and recent expansion is occurring in sandy-textured soils, mainly Quartzipsamments [16]. This could further increase pressure on natural resources such as soil and water, as excessive and inadequate use of agricultural implements has been shown to increase problems such as erosion, compaction, and destruction of soil aggregates, as noted by Silva, Lemanski, and Resck [14]. These inappropriate practices have also led to significant reductions in the organic matter content, the main component of fertility in sandy soils.

With recent changes in land use, pressure on the remaining native vegetation has increased, and forest fragments are being progressively reduced and eliminated annually. Many degraded pasture areas are being converted into soybean fields, and the few remaining native trees and forest fragments in the Cerrado biome are being cleared to facilitate machinery traffic. This process impacts all biogeochemical cycles and affects biodiversity, which has already been decimated by the conversion of natural ecosystems into agroecosystems and by wildlife roadkills, as shown in Gonçalves' work [61]. Additionally, the removal of natural vegetation results in the release of carbon dioxide into the atmosphere, contributing to climate change.

The scenario observed in the Pardo River Watershed resembles that described by Plato in the forests of Attica: "what remains now compared to what existed is like the skeleton of a sick man […] All the rich and soft soil has dissolved, leaving a country of skin and bones" [62]. The native vegetation in the PRW has been drastically reduced to fragments (Fig. 3E) that do not provide ecosystem services.

The destruction of the natural habitat of endemic species in the region causes avifauna to migrate in search of food, affecting the economy of rural settlements. In a study conducted in communities in the rural area of Três Lagoas in Mato Grosso do Sul, Dubos-Raoul [20] showed a loss of diversity, animal migration in search of food, and a loss of water resources. She highlights that typical Cerrado fruits, such as the guavira consumed in Três Lagoas, now come from the neighboring state of Goiás. In interviews with residents conducted by Dubos-Raoul [20], the authors reported that the presence of pumas (*Puma concolor*) near dwellings, mainly in rural sites and farms around the urban nucleus of rural communities, is becoming increasingly common. The loss of calves due to puma attacks is a recurring event. Reports indicate that these individuals are unable to harvest fruits from their own yards. Anta-brasileira (*Tapirus terrestris*), Tamanduá-bandeira (*Myrmecophaga tridactyla*), and monkeys roam the cities, and wildlife roadkills are frequent.

Although the five temporal snapshots (1985, 1994, 2004, 2014, and 2022) presented in Fig. 3 demonstrate changes in land use and land cover over time, Fig. 4 offers a more detailed analysis by quantifying land use and land cover classes over the past 38 years (1985–2022). As highlighted earlier, the most significant changes included a reduction in forest formations and savannas, along with an increase in pasture area until 2007. From 2008 onward, there was a decrease in pasture area in favor of soybean and eucalyptus monocultures. The following sections explore the impacts of livestock farming, silviculture, and soybean cultivation, establishing connections between these uses and the process of arenization.

3.2.1 Livestock

In the Central-west region of Brazil, as well as in other parts of the country, most livestock farming activities are characterized by low productivity levels, resulting from a model of land occupation based on patrimonialism. This model involves the appropriation of large tracts of land to secure prestige and political power without concern for rational and sustainable use of natural resources [63]. Livestock farming practiced in this region is extensive, with low investment in technology, infrastructure, and herd management. This situation contrasts with some exceptions (outliers), such as intensive and modern livestock farms observed in fieldwork in the PRW. Figure 5 depicts a degraded pasture area with environmental liability in a riparian permanent preservation area and surrounding reservoir [35, 36]. Although terraces

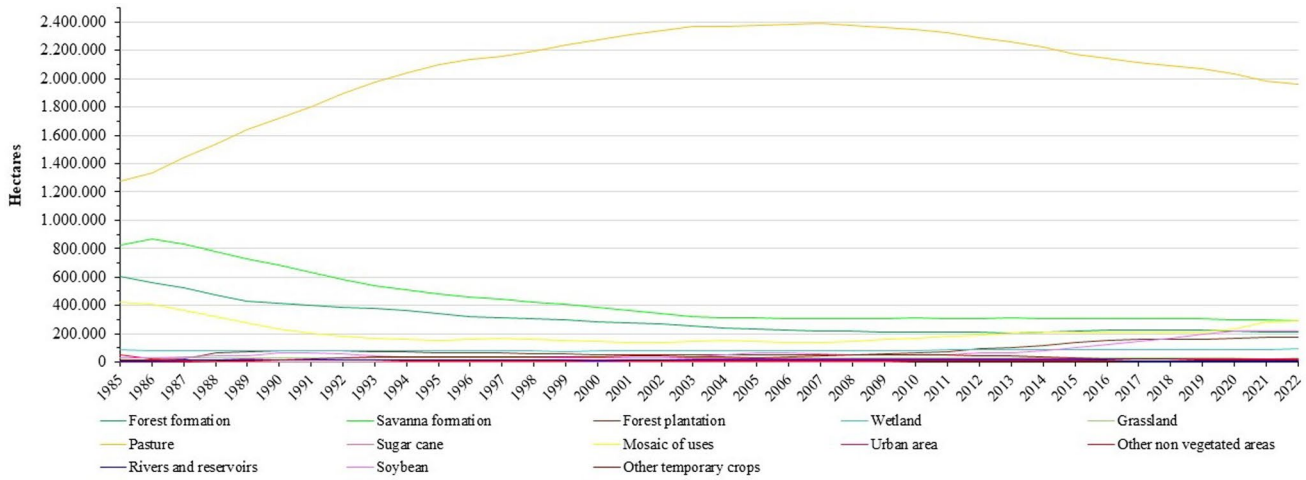


Fig. 4 Quantification of land use and land cover classes from 1985 to 2022. Source: MapBiomas, colection 8. Elaboration: This publication



Fig. 5 Environmental liabilities in permanent preservation areas in the municipality of Ribas do Rio Pardo/Mato Grosso do Sul state. Photo DJI Mavic 3E: Capoane, V., date 20/07/2023

can be observed in the image, this mechanical practice for soil and water conservation is complementary and, by itself, does not solve the erosion problem.

Cattle are gregarious animals with a habit of staying in defined social groups [64], which, according to Mota and Marçal [64, 65], may be instinctually inherited from pre-domestication periods. When one member of the herd follows a specific path, others may instinctively follow it. This behavior of following the leader helps to keep the group cohesive and reduces the risk of herd members separating. Like many other animals, cattle tend to choose the path of least resistance when moving in search of food, water, and resting places. Individuals generally opt for existing trails or smoother, firmer paths to save energy during movement. This preference is particularly relevant in areas of extensive livestock farming, where prior knowledge of these routes saves time and effort. Cattle often avoid rugged terrain, muddy areas, or dense vegetation due to the challenges these conditions pose for movement. As a result, well-defined trails are commonly formed around these obstacles, such as along the edges of forest fragments. Additionally, trails are also frequently observed along fences. As cattle repeatedly move along a particular trail, they may learn to prefer that specific path, further consolidating the trail over time. Cattle trampling compacts the soil and triggers linear erosion processes because when surface flows encounter trails, they tend to follow the path of least resistance. Over time, the grooves, or rill, which are initially small, have the potential to grow as cattle continue to transit through these areas, and runoff continues to transport sediments, deepening them and thus forming gullies. This phenomenon was observed in the work of Capoane [66], developed in a sub-basin of the Pardo River Watershed.

Humans can also influence herd movement by creating paths or trails to direct cattle movement for herd management and administration, such as installing water troughs and feeders for feeding and administering medications. The movement of animals to these points results in trails, and the concentration of animals around water troughs and feeders,

coupled with improper management practices, can create conditions conducive to soil erosion. This occurs because compaction reduces the soil porosity. As a result, rainwater cannot gradually infiltrate into the soil; instead, it flows superficially. As rainwater flows over the surface of compacted terrain, it gains energy (a process that can be accentuated in the face of steep slopes), which can result in the removal of surface soil layers, creating grooves that can evolve into gullies [66]. The concentration of nutrients, such as feces and urine, around water troughs and feeders can also create areas of nutrient overload in the soil. This accumulation of nutrients not only compromises soil quality but also increases the risk of contamination in aquatic ecosystems.

Over time, poorly managed livestock grazing, characterized by low vegetation cover and animal trampling, exposes the soil to erosive agents, increasing susceptibility to erosion. This situation is even more critical in Quartzipsamments, which occupy 37.6% of the area in the PRW. In this context, erosion causes a worrying dynamic, resulting in the progressive loss of the soil's fertile layer and the exposure of mineral particles to the environment. Consequently, arenization foci form, characterized by the absence of vegetation and the presence of sandy material, making conditions less conducive to the sustainability of the local ecosystem.

3.2.2 Forest plantation (*Eucalyptus*)

Deforestation and decades of overgrazing in Mato Grosso do Sul weakened the state's economic base, which, according to Dubos-Raoul [20], became the central argument for changing land use and planting eucalyptus in the state (Fig. 6). According to Kudlavicz [67], the discourse on sandy lands and the option of "reforestation" with eucalyptus as a solution for land correction and management merged with a narrative of sustainability as a development strategy appropriated

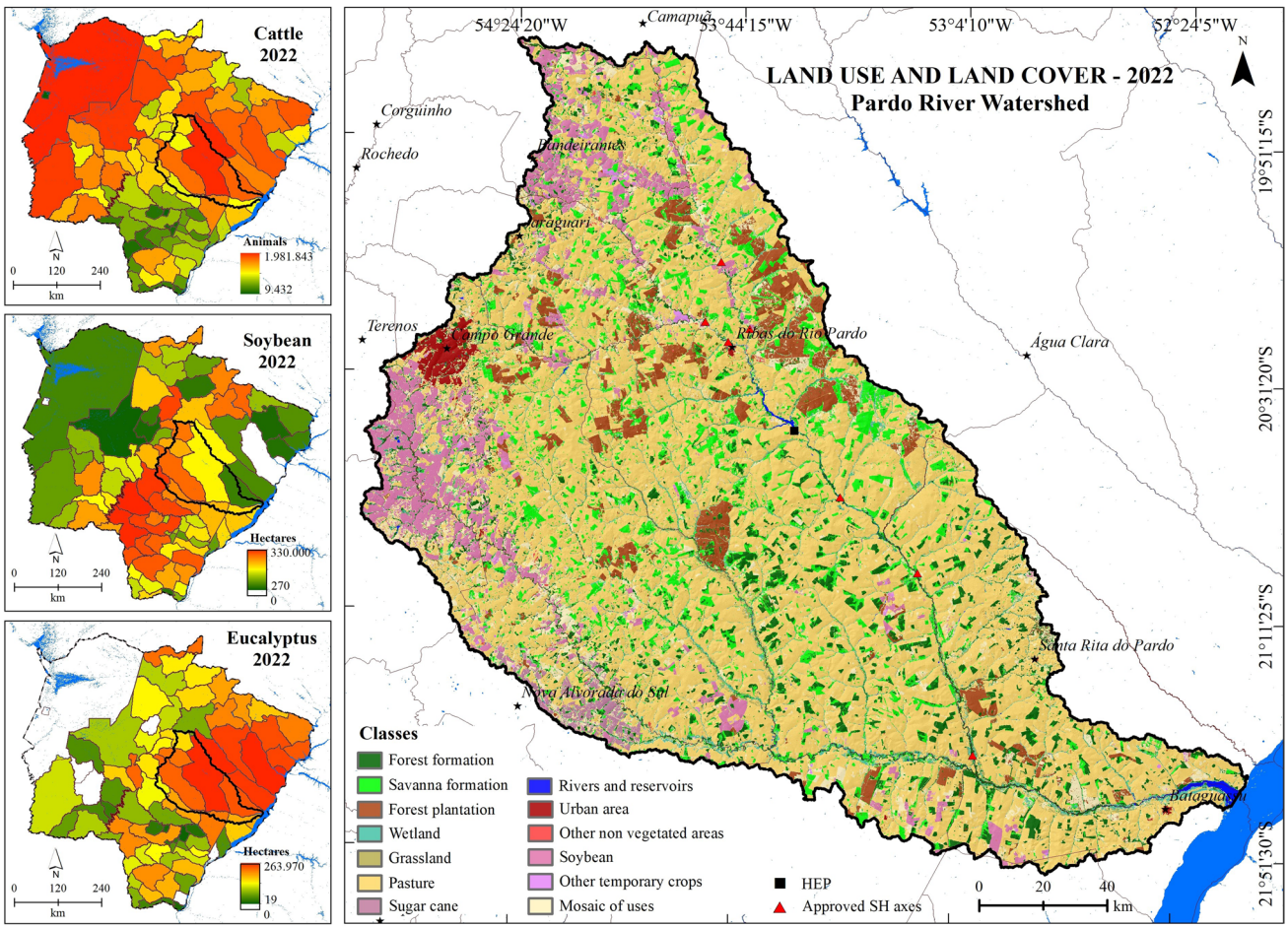


Fig. 6 Cattle herd, soybean and eucalyptus planted areas in municipalities of Mato Grosso do Sul and land use and land cover in the Pardo River watershed for the year 2022. Source: PPM/PAM/PEVS-SIDRA-IBGE (2023); MapBiomas (2023). Elaboration: this publication

by the eucalyptus-pulp complex to build a sustainable image. However, eucalyptus monocultures significantly impact the hydrology of slopes/watersheds [68, 69].

The demand for water by eucalyptus plants to sustain their growth and maintain vital functions, along with their high rate of evapotranspiration, places considerable pressure on the local water system [68, 69]. This can accelerate the water cycle, leading to decreased soil moisture and reduced water volume in aquatic systems, which may result in water bodies shrinking or drying due to increased consumption and evapotranspiration. Furthermore, the groundwater level is lowered, particularly affecting headwater and low-order streams, which regulate flows in higher-order channels and are most impacted. This can adversely affect aquatic communities [70] and negatively impact water resources available for human activities, such as agriculture, public water supply, and hydropower production. After tree harvesting, soil remobilization for new planting or returning to extensive grazing can increase sediment loss, potentially burying springs.

Like other crops, eucalyptus monocultures also use agrochemicals. According to Dubos-Raoul [20], rural populations in these areas already experience the impacts of pesticide use, particularly through increased populations of food crops. Walter, Carvalho, and Ribeiro [7]note that human intervention in nature can reduce the diversity of plant, animal, and microbial communities. The greater the technological level applied during soil use, the more simplified ecosystems become, particularly concerning the diversity of fauna and flora [71].

The eucalyptus-cellulose complex in Mato Grosso do Sul was initiated in the Bolsão region, including municipalities like Água Clara, Aparecida do Taboado, and Três Lagoas, starting in 2009 with the inauguration of the first pulp mill in Três Lagoas [20]. Eucalyptus planting is expanding in the northeastern quadrant of Mato Grosso do Sul, particularly in the Quartzipsamments area, which is highly susceptible to erosion [16].

As mentioned earlier, the territorialization of the eucalyptus–cellulose complex in Mato Grosso do Sul is the result of public policies in favor of agribusiness expansion and, more specifically, in the Cerrado, in a vast project of national incorporation into the capitalist system of production. According to Dubos-Raoul [20], on the one hand, the expansion of the eucalyptus-cellulose complex has contributed to the increase and concentration of income in the region. Companies in the sector generate direct and indirect jobs, promoting local economic development. Additionally, pulp production can represent a significant source of revenue for the state through taxes and royalties. However, this territorialization does not occur without significant socioenvironmental impacts. Extensive eucalyptus monoculture can result in drastic changes in local ecosystems, with consequences for biodiversity [70], and ecosystem services. The conversion of degraded pastures and the removal of native vegetation, which is already fragmented, to make way for eucalyptus plantations leads to the loss of natural habitats, affecting native species and compromising ecosystem resilience. Furthermore, the intensive use of pesticides and fertilizers in eucalyptus production impacts soil quality, affecting local communities and aquatic ecosystems.

Considering that the expansion of eucalyptus plantations occurs predominantly on sandy soils such as Quartzipsamments [16], in areas of degraded pastures, silviculture masks the severity of environmental degradation. This is demonstrated in Fig. 7, where a degraded pasture area near the Pardo River in the city of Ribas do Rio Pardo was converted into a eucalyptus plantation. The few remaining native trees were cut down and piled up within the plantation.

As mentioned earlier, the amount of water is also altered, as eucalyptus plantations are known to consume large volumes of water [68, 69], which can result in competition for available water resources in the region. Excessive water withdrawal from the soil (absorption and transpiration) can lead to groundwater depletion, affect local watercourses, harm aquatic ecosystems and increase the vulnerability of communities that depend on these water sources for their basic needs. In the context of the Cerrado of Mato Grosso do Sul, a region that already experiences a pronounced dry season [72], climate change and global aridification can intensify aridity, increasing the duration and severity of drought periods and exacerbating socioeconomic and environmental impacts [73].

3.2.3 Irrigated soybean

Soybean cultivation in the PRW occupied an area of 28,612.1 hectares in 1985 and 221,161.6 hectares in 2022. Until recently, rainfall was the main source of moisture for plants, without the need for artificial irrigation. However, the government of the state of Mato Grosso do Sul has been providing tax incentives for irrigation [21]. The exploitation of large volumes of water from rivers and aquifers can lead to reduced water levels and compromised aquatic ecosystems. Additionally, the use of agrochemicals in plantations can result in contamination of water bodies, affecting water quality and aquatic life. This situation is exacerbated as soybean expands in sandy-textured soils [11]. Figure 8 shows the central pivot irrigation system used for cultivating soybeans in the summer and millet in the winter. A

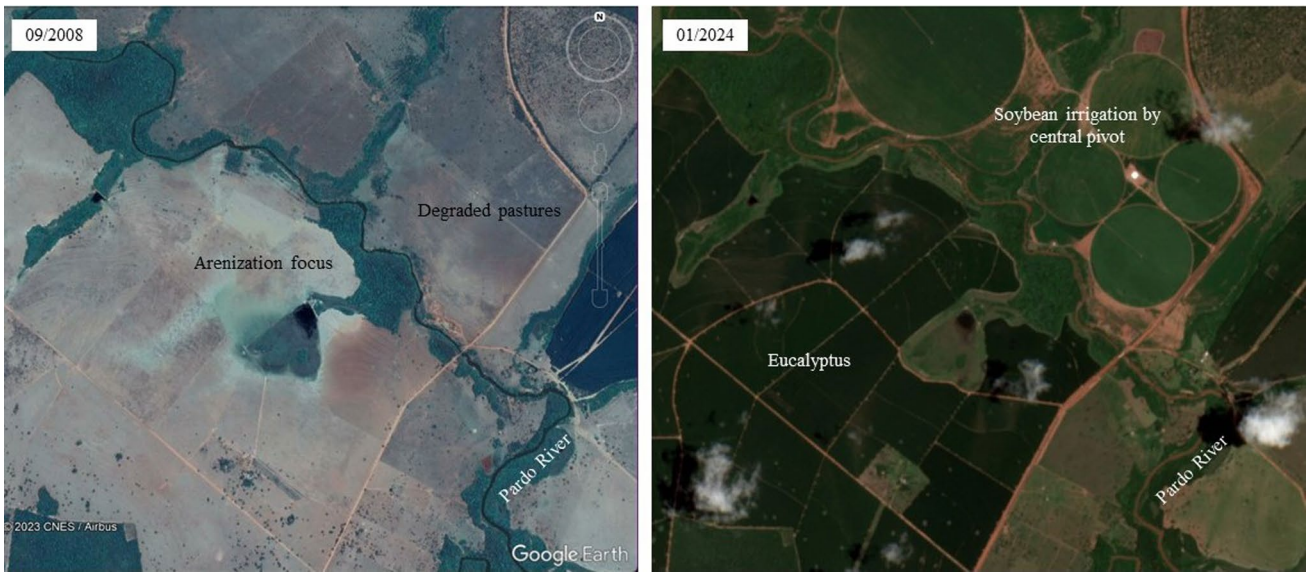


Fig. 7 Area of degraded pasture with arenization focus converted into eucalyptus monoculture and soybean irrigated by central pivoting. Sources: Google Earth and Copernicus, Sentinel-2, 25/01/2024



Fig. 8 Soybean production area irrigated by central pivot. Photo DJI Mavic 3E: Capoane, V., data 19/07/2023

man-made reservoir with a waterproof lining is visible, from which water is pumped for irrigation. The water is extracted from a reservoir built in a riparian wetland area. Additionally, foci of arenization can be observed.

Figure 9 shows that a degraded pasture area occurred in 2021, with focus of arenization. In the following year, 2022, the same area was converted into a soybean plantation with a central pivot irrigation system. Water for irrigation is extracted from rivers and directed to a reservoir built in an interfluve zone. A waterproof lining was also placed in the reservoir, as the soil texture is sandy and therefore highly permeable. It was observed that, in the arenization focus, although isolated, there were no signs of area recovery. Consequently, the focus tends to expand.

Most soybeans cultivated in Brazil for export come from intensive agricultural systems using inputs such as pesticides, fertilizers, and genetic technology to achieve high yields per hectare. The use of these agrochemicals can have adverse effects on soil biota, human health, and local fauna, as indicated by studies from Bombardi [74], Pignati et al. [75], and Tygel et al. [76]. Exposure to these toxic substances can cause health problems, while pest control can

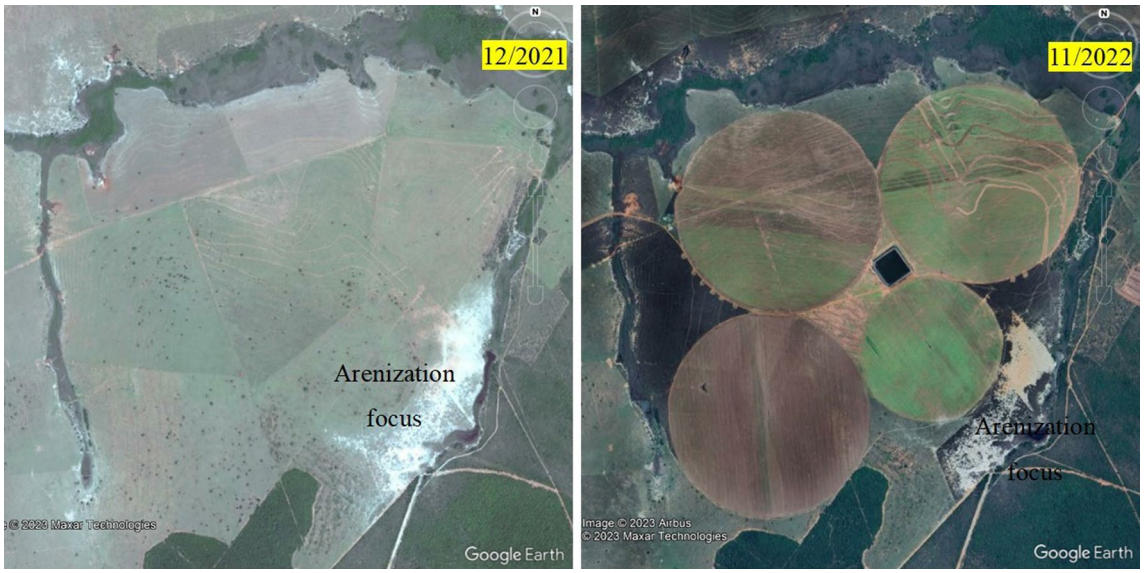


Fig. 9 Degraded pasture with signs of arenization converted to irrigated soybean cultivation using a central pivot system in the watershed of the Pardo River. Source: Google Earth

affect natural food chains. Additionally, due to the permeability of sandy soils and their low organic matter content, there is a risk of groundwater contamination.

In the PRW, until recently, soybeans were cultivated in clayey soils, which have greater agricultural suitability. However, with the reduction in interest rates during the second term of President Dilma, there was a devaluation of the Real [59]. This, in addition to the political impacts of the 2016 coup [77, 78] and the environmental setbacks of the Temer (2016–2018) and Bolsonaro (2019–2022) governments, made Brazilian exports more attractive, incentivizing changes in land use from livestock to soybeans.

Deforestation and predatory agriculture practiced in Brazil can result in global environmental, economic, and humanitarian catastrophes [73, 79]. The Intergovernmental Panel on Climate Change indicates that future droughts will be more frequent and severe in the La Plata River basin, where the study area is located, although they will be potentially shorter. Given this scenario, an increase in the adoption of irrigated production systems is expected, which, in addition to soil disturbance during land use change and subsequent management, may increase erosion and sedimentation rates. Arenization clusters, in turn, tend to expand in area, while new clusters may emerge in response to agricultural practices used.

In this context, the adoption of conservation agricultural practices, efficient water management, and more sustainable technologies is urgently needed to mitigate the negative impacts of aridification and ensure a balanced coexistence of economic production and environmental preservation in the face of anthropogenic climate change. These measures are crucial for promoting the sustainable development and resilience of local communities amid a scenario of global climate transformation. According to Lal [80], the strategy should be to produce more food with fewer resources, which requires restoring soil health and increasing the concentration of organic carbon to more than 1.5–2.0% in the root zone [81].

3.3 Arenization in the pardo river watershed

Arenization foci have been identified in the lower, middle, and upper reaches of the watershed (Fig. 10). The arenization foci cover an area of 17,834.34 hectares. The foci have different dimensions ranging from < 1 ha to 376.41 ha. The process occurs in different compartments of the slope, such as interfluves, the mid-slope, and the foot of the slope. The occurrence of processes in different slope compartments highlights the human triggers through anthropic activities. This was previously demonstrated in the work by Capoane et al. [44] in the Guariroba river watershed, located within the PRW.

The morphodynamics of the arenization synthesized into three phases by Suertegaray (2023) for the southwest of Rio Grande do Sul/Brazil do not apply to the context of the Bauru sedimentary basin. According to the author, in that region, the first phase corresponds to the formation of abatement steps, the second to the formation of rills and gullies, and the third to the formation of the sandbank itself. The author emphasizes that not all mapped foci in Rio Grande do Sul state express these phases sequentially. The morphodynamics of the PRW are related to the extensive elimination of primary

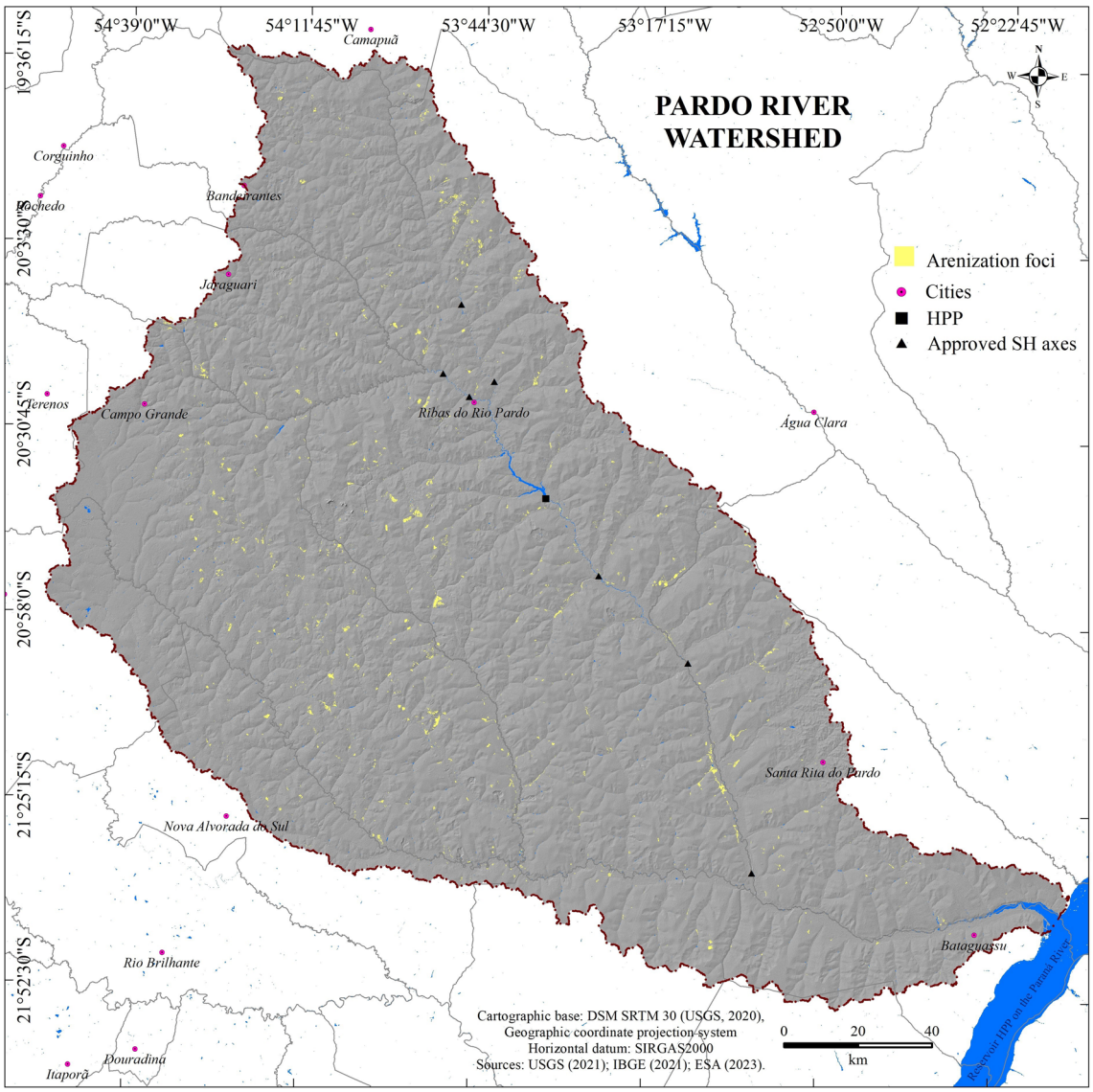


Fig. 10 Arenization foci in the Pardo River Watershed, Mato Grosso do Sul/Brazil. Elaboration: this publication

vegetation cover and conversion to agriculture, disregarding the natural fragility of sandy soils. This increased susceptibility to erosion resulted in nutrient loss and soil organic matter oxidation. Over time, degraded areas with exposed soil have evolved into arenization focus that have expanded over degraded pasture areas (on-site effects). Additionally, the arenization process contributes to the siltation of rivers and reservoirs in the region because soil erosion is a selective process, and fine particles can be transported over long distances during the rainy season (off-site effects).

The anthropogenic origin of the arenization and sand dune formation is illustrated in Fig. 11. Temporal snapshots of an arenization focus show that by 1985, the primary vegetation cover had already been extensively eliminated, and small areas of exposed soil were visible. In 2006, there was a significant increase in the degraded area. It is also possible to observe an artificial channel formed by diverting the watercourse into headwater reservoirs, bypassing the slope, and connecting two tributaries. By 2022, the artificial channel that bypassed the slope was covered, and the arenization focus expanded over pasture areas.

The arenization focus depicted in the Fig. 12 covers an area of 51.5 hectares and is located on two rural properties. Currently, sediments are being mobilized by both water and wind. This focus is situated on the mid-slope in the interfluve zone between two tributaries of the Galho Quebrado stream. Although both water and wind transport agents act in the area, it is evident that, in this specific focus, wind has a more significant influence than water. As mentioned, the focus is in an interfluvial zone. Considering factors such as relief and gravity, it is expected that sediments will



Fig. 11 Temporal snapshots of arenization focus formation in the Guariroba River watershed. Source: Google Earth



Fig. 12 Arenization focus with a larger representation in the Guariroba River watershed, Campo Grande/MS. Photo DJI Mavic 3E: Capoane, V., data: 18/01/2024



Fig. 13 Fence on the property boundary being buried. Photos Canon PowerShot SX70 HS: Capoane, V., date: 18/01/2024

move toward the tributaries and the main channel. However, the analysis of Fig. 12 reveals a predominance of transport in the northwest direction, specifically on the right side of the image, where sediments have already reached the riparian wetland. In contrast, on the left side, it can be observed that the predominant particle transport occurs in the opposite direction to the slope. This highlights the importance of wind in the morphodynamics of sand dunes.

Winds are important agents of erosion and deposition that selects and transport large amounts of sand, silt and clay across extensive areas if sediment particles are loose and dry. In this context, wind is most effective at transporting materials during the dry season; when precipitation levels are low, soil moisture is reduced, and soil exposure is greater [82]. Figure 13A, B shows that the fence acted as a barrier and became partially buried. In B, the landowner extended the fence post to prevent cattle from entering the neighboring property.



Fig. 14 Small-scale compound parabolic dunes located on the mid-slope. Photo Canon PowerShot SX70 HS: Conceição, M. R. M., date: 21/03/2023



Fig. 15 Temporal snapshots of arenization focus in the Guariroba River watershed. Source: Google Earth

During the dry season, in winter, low soil cover facilitates sediment mobility due to wind action, especially in areas devoid of vegetation. As sand and silt particles become loose and dry, the wind can lift and carry them, gradually eroding the land surface in a process called deflation [83] and forming dunes. In spring, although precipitation volumes increase, soil moisture remains low, favoring material transport by the wind. In summer, which corresponds to the wettest season in the region, wind continues to play an important role in dune expansion.

The formation and morphology of eolian dunes are primarily controlled by sediment availability and climatic parameters such as wind speed and vegetation presence [84, 85], not only by aridity conditions [86]. The process of arenization in the studied area ensures a sufficient sand supply, while wind is an important agent for sediment mobility. Thus, with sufficient sand and wind, any obstacle, such as fences or tufts of vegetation, can serve as a barrier for sediment and initiate dune formation. The morphology of the dunes is predominantly compound parabolic (sensu Pye [87]) and secondarily barchanoid. A compound parabolic dune has a U or V shape and is characterized by the presence of a depositional lobe in the windward direction, trailing arms, and deflated basin between the arms [88]. Figure 14 shows the deflation basin between the arms of the dune and the depositional lobe, where the convexity of the slip face indicates the direction of the wind, in this case, northwest winds. Although the effectiveness of northwest winds is more intense in winter and early spring, in response to meteorological and soil cover conditions, in sandy areas, due to the continuous supply of sand, the wind acts as a shaping agent throughout the year.

Figure 15 also illustrates the anthropogenic origin of the arenization focus. In 1985, native vegetation predominated. By 2003, native vegetation had been mostly suppressed in the area, and it was converted to pasture. In the year 2022, the focus of arenization is observed. These historical snapshots highlight the influence of human actions on the origin and morphodynamics of the arenization process.

Figure 16 depicts an arenization focus covering an area of 17.1 hectares. The significant contribution of laterites is evident from the soil color and lower brightness index values due to the presence of iron oxides. In the area, the landowner attempted recovery by constructing terraces. However, due to the physical characteristics of these soils, such as their sandy texture and low clay and organic matter content, which are components that contribute to soil particle cohesion, even with low slopes, the terraces have ruptured (Fig. 16C).

The transformation of natural ecosystems into agricultural landscapes, especially concerning Quartzipsamments, presents significant environmental challenges due to their inherent low water retention and high susceptibility to erosion. These characteristics may lead to exacerbated consequences under the current trajectory of climate change and

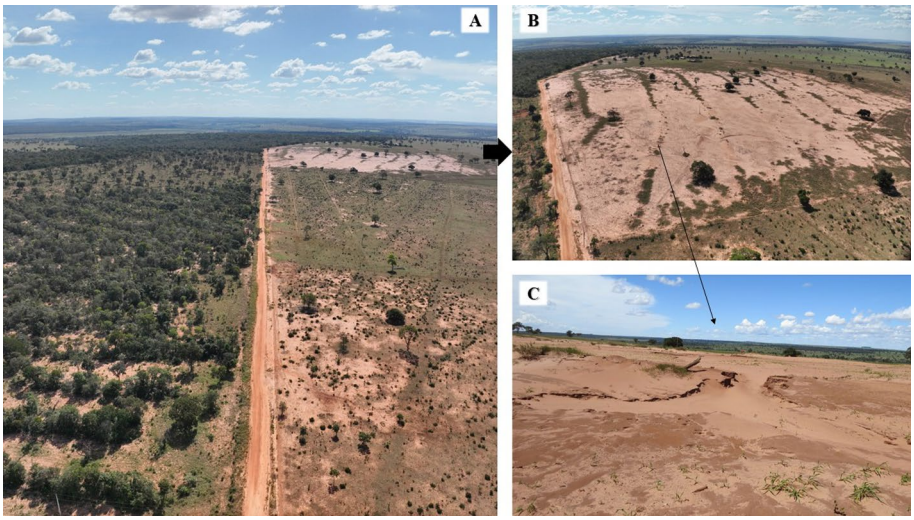


Fig. 16 **A** Arenization foci of different sizes and areas undergoing the arenization process; **B** Construction of terraces in arenization focus; **C** Terrace rupture. Photos DJI Mavic 3E, Canon Power-Shot SX70 HS: Capoane, V., date: 26/05/2023 (**A** e **B**) and 21/03/2023 (**C**)

increasing global aridity. In Mato Grosso do Sul, the propensity of sandy soils to erode and subsequently degrade into arenization necessitates a strategic approach to land management that harmonizes agricultural and silvicultural activities with electricity production and natural resource conservation. State water management is further complicated by competing demands from these diverse sectors.

Appropriate land use planning, integrated with the implementation of soil and water conservation techniques and the restoration of areas affected by arenization, is imperative for the preservation of biodiversity and the revitalization of ecosystem services. Regarding the application of brightness index 2 for delineating areas of arenization, the limited literature provides valuable insights. Saadat et al. [89] assumed that soils with advanced degradation reflect higher brightness levels than their preserved counterparts, utilizing this index to map erosion intensity with noted precision, efficiency in resource utilization, and data accessibility. Similarly, Vieira et al. [90] leveraged the brightness index to quantify soil losses within an Environmental Protection Area in the Uberaba River watershed in the Brazilian State of Minas Gerais, underscoring the efficacy of detecting soil degradation across vast regions through remote sensing data, with the advantage of the use of a single parameter that is easily accessible through remote sensing data.

Although there are no studies yet that have used BI2 for arenization mapping, the performance of the index was satisfactory. For degraded areas with a greater contribution of ferruginous material, the brightness values were lower, demonstrating that classification intervals cannot be arbitrary. In addition to histogram analysis, this requires the classifier to have knowledge of remote sensing, geoprocessing, interpretation of orbital images, and understanding of the abiotic aspects and land use and land cover of the study area. Exploratory fieldwork and validation of mapping are also fundamental.

4 Conclusion

The Cerrado of Mato Grosso do Sul has undergone rapid landscape transformations due to human activities, as shown by our historical analysis of land use and cover changes. From 1985 to 2022, the Pardo River Watershed experienced a drastic reduction in native vegetation, from 46.01% to 18.91%, primarily due to the proliferation of soybean monocultures and eucalyptus plantations in recent decades. This shift has not only reduced biodiversity but also compromised vital ecosystem services. The expansion of soybean cultivation and eucalyptus cultivation has occurred in degraded pasture areas on sandy soils that are highly susceptible to erosion and vulnerable to arenization.

Arenization, a critical concern in the region, arenization foci covering an area of 17,834.34 hectares within the watershed. The arenization process occurs in different parts of the slope, including the base of the slope, the slope itself, and the interfluves. The physical and chemical characteristics of the Quartzipsamments, along with the low organic carbon content in the soil and high rates of surface exposure, weaken load-dependent structures, leading to their degradation. This process occurs where natural vegetation has been cleared and the soil has been depleted by poorly managed production processes.

The climatic conditions of the region facilitate the advancement of arenization foci, with different agents acting in distinct periods. During the rainy season, the impacts of raindrops on deforested areas, low biomass production (forage), and overgrazing stand out as agents and factors contributing to soil degradation. In the dry season, wind acts as a transporter of particles detached by rain and animal trampling. This interaction between biotic factors (low production of plant biomass and livestock) and abiotic factors (rocks, soils, wind, and rain) plays a crucial role in the arenization process in the Pardo River watershed. In these foci, due to the continuous supply of sand, wind acts as a dune-shaping agent throughout the year.

Author contributions 1 Conceptualization, project administration, methodology, software, validation, data curation, formal analysis, wrote the draft (Viviane Capoane), 2 revised the draft (Melina Fushimi), 1–2 funding acquisition, review and editing of the final version of the manuscript (Viviane Capoane and Melina Fushimi).

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Data availability The analysis of land use and land cover in the Cerrado of Mato Grosso do Sul and in the Pardo River basin was carried out based on the classification of the MapBiomas Network. The data collection is open access https://plataforma.brasil.mapbiomas.org/cobertura?activeBaseMap=9&layersOpacity=100&activeModule=coverage&activeModuleContent=coverage%3Acoverage_main&activeYear=2022&mapPosition=-15.072124%2C-51.459961%2C4&timelineLimitsRange=1985%2C2022&baseParams[territoryType]=1&baseParams[territories]=1%3BBrasil%3B1%3BPa%C3%ADs%3B0%3B0%3B0%3B0&baseParams[activeClassTreeOptionValue]=default&baseParams[activeClassTreeNodeIds]=1%2C7%2C8%2C9%2C10%2C11%2C2%2C12%2C13%2C14%2C15%2C16%2C17%2C3%2C18%2C19%2C28%2C30%2C31%2C32%2C33%2C34%2C29%2C35%2C36%2C37%2C38%2C20%2C21%2C4%2C22%2C23%2C24%2C25%2C5%2C26%2C27%2C6&baseParams[activeSubmodule]=coverage_main&baseParams[yearRange]=1985–2022 To obtain the annual classification for a specific year (1985–2022), simply replace the year https://storage.googleapis.com/mapbiomas-public/initiatives/brasil/collection_8/lclu/coverage/brasil_coverage_2022.tif. Datasets about arenization mapping generated and analyzed during this study are available on request from the authors.

Declarations

Ethics approval and consent to participate Not applicable, as the study does not involve human or animal participants, but all procedures were conducted ethically and responsibly.

Competing interests The authors declare no competing interests.

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