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Connectivity of natural vegetation in a Cerrado–Pantanal ecological corridor declined nearly twice as fast as habitat area

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Article

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Connectivity of natural vegetation in a Cerrado–Pantanal ecological corridor declined nearly twice as fast as habitat area

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Abstract

Ecological corridors are designated to keep natural vegetation connected, yet their performance is rarely tracked with the annual satellite records that document vegetation loss. We combined annual 30 m land-cover maps (2014–2024), landscape metrics, graph-based connectivity and a decision tree of spatial processes to examine how natural vegetation changed in a 766,000 ha ecological corridor linking the Cerrado plateaus to the Pantanal floodplain in central Brazil. Natural vegetation declined by 5.2%, whereas the equivalent connected area fell by 8.7–9.6% across dispersal distances of 200–5,000 m, a loss 1.7–1.8 times larger than that of habitat. Dissection and attrition were the dominant processes in 70% of 5 km cells. Conversion was concentrated at patch edges: 21.2% of the vegetation lying within 30 m of an edge in 2014 had been converted by 2024, against 0.3% beyond 1 km, and savannas were converted at twice the rate of forests. A 221 ha remnant ranked among the ten most important patches for network connectivity because of its stepping-stone position. Area-based monitoring therefore underestimates the ecological cost of vegetation loss in corridors, and edges, savannas and small stepping stones deserve explicit protection targets.

Keywords: habitat fragmentation; landscape connectivity; equivalent connected area; edge effects; Brazilian savanna; MapBiomas

Introduction

Natural vegetation cover is one of the most direct indicators of ecosystem condition, and its loss is the main driver of terrestrial biodiversity decline [1,2]. Loss, however, rarely proceeds as a uniform shrinkage of habitat. As vegetation is cleared, remnants are subdivided, edges multiply and the distances that organisms must cross between patches increase, so that the same amount of habitat can support very different ecological flows depending on its spatial configuration [3–5]. Whether configuration matters independently of habitat amount is still debated for species richness [5–7], but for processes that depend on movement, such as dispersal, recolonization and gene flow, connectivity declines non-linearly as habitat is removed and can collapse well before habitat disappears [8,9].

The Cerrado, the most species-rich tropical savanna on Earth, has lost about half of its native vegetation to pastures and croplands [10–12]. Its plateaus also feed the headwaters of the Pantanal, and vegetation loss in these uplands threatens the hydrology and biodiversity of the floodplain downstream [13–15]. Fragmentation in the Cerrado has been described through landscape metrics at regional scales [16–20], and connectivity has been shown to matter more than the amount of remaining habitat for the persistence of Cerrado species under warming [21]. Conservation opportunities for endemic vertebrates are shrinking as large contiguous areas disappear [22]. In tropical forests, multi-decadal analyses have recently shown that functional connectivity falls faster than forest cover [23,24], that apparent stability of forest area can conceal a structural reorganization of the landscape [25], that the area under edge influence is growing [26–28] and that small fragments are lost at higher rates than large ones [29].

Three gaps limit the use of this knowledge for the management of Cerrado corridors. First, most connectivity trends have been estimated for forest cover, whereas savannas and grasslands

dominate the natural vegetation of the Cerrado and are converted extensively [30]. In the studies retained by our systematic search of the literature (Methods), graph-based connectivity trends were reported mostly for forest cover [23,25], whereas assessments of savanna landscapes relied mainly on patch-based metrics [16,17,20] or on connectivity computed at decadal intervals [18]. Second, ecological corridors are a legal instrument in Brazil [31], but they are seldom evaluated as functional networks with annual data; corridors mapped in the Upper Paraguay Basin were lost to conversion within three years of being identified [32]. Third, connectivity outcomes are rarely linked to the spatial processes that produce them, such as edge erosion, perforation or the attrition of small patches [33], although these processes determine where protection and restoration would be most effective.

Here we examine the dynamics of natural vegetation in the São Lourenço River Basin Ecological Corridor, which links the Cerrado plateaus to the Pantanal floodplain in Mato Grosso, Brazil, using annual MapBiomas maps from 2014 to 2024. We asked whether connectivity declined faster than habitat amount, which spatial processes and which positions in the landscape concentrated the conversion of natural vegetation, and which remnants hold the connectivity of the corridor. We expected (i) a loss of equivalent connected area proportionally larger than the loss of habitat, (ii) conversion concentrated at edges, in small patches and in non-forest formations, and (iii) a network dependent on a few large remnants and on small stepping stones.

Results

Habitat declined steadily while patches multiplied

Natural vegetation (forest, savanna, grassland and wetland grassland) covered 261,549 ha (34.1% of the corridor) in 2014 and 247,903 ha (32.4%) in 2024, a net loss of 13,646 ha (5.2%) and a monotonic decline of 0.56% per year (Table 1). The loss was uneven among formations: savanna

decreased from 79,572 to 69,224 ha (13.0%), wetland grassland by 19.8% and forest by only 1.8%, whereas grassland increased from 2,671 to 3,455 ha, a net gain that hides a high turnover (see below). Over the same period the number of patches increased from 7,919 to 8,273 (4.5%) and mean patch size fell from 33.0 to 30.0 ha. Core area, more than 90 m from any edge with land use, decreased by 6.5%, faster than habitat, and the share of vegetation within 90 m of an edge rose from 41.4% to 42.2%. In 2014, 73.3% of the natural vegetation was already within 300 m of an edge and 94.2% within 1 km (Fig. 1).

Table 1. Landscape metrics of natural vegetation and of forest formation in the São Lourenço River Basin Ecological Corridor in 2014 and 2024.

Metric	2014	2024	Change (%)
Natural vegetation			
Habitat area (ha)	261,549	247,903	−5.2
Share of corridor (%)	34.1	32.4	−5.2
Number of patches	7,919	8,273	+4.5
Mean patch size (ha)	33.0	30.0	−9.3
Largest patch (ha)	70,173	69,755	−0.6
Edge density (m ha^{-1})	31.9	31.3	−1.9
Core area, >90 m (ha)	153,372	143,333	−6.5
Habitat within 90 m of an edge (%)	41.4	42.2	+2.0
Effective mesh size (ha)	7,830	7,180	−8.3
Forest formation			
Habitat area (ha)	174,560	171,417	−1.8
Share of corridor (%)	22.8	22.4	−1.8
Number of patches	10,520	10,747	+2.2
Mean patch size (ha)	16.6	16.0	−3.9
Largest patch (ha)	19,265	18,090	−6.1
Edge density (m ha^{-1})	35.4	35.6	+0.6
Core area, >90 m (ha)	66,117	63,261	−4.3
Habitat within 90 m of an edge (%)	62.1	63.1	+1.6
Effective mesh size (ha)	905	869	−4.0

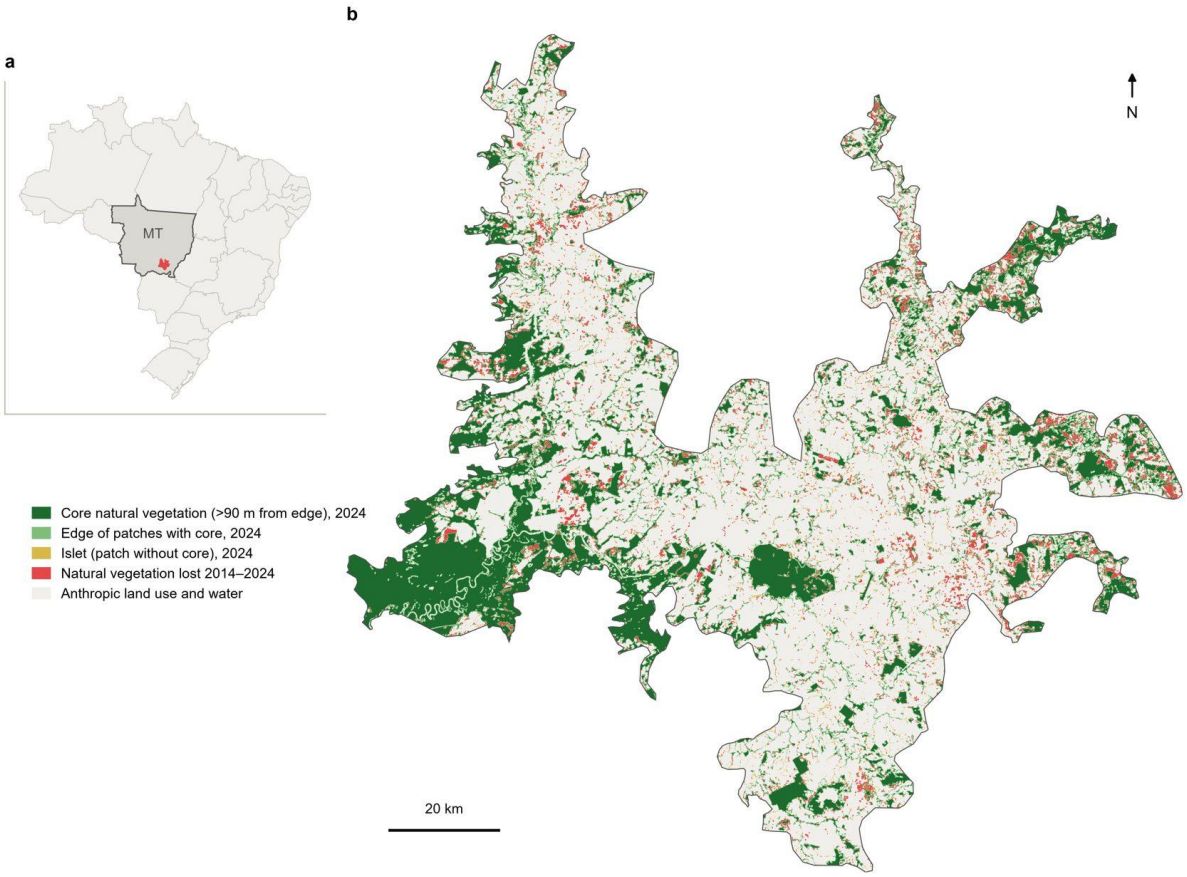


Figure 1. Study area and natural vegetation of the São Lourenço River Basin Ecological Corridor. (a) Location in Mato Grosso, Brazil. (b) Morphological classes of natural vegetation in 2024 (core, more than 90 m from an edge; edge of patches with core; islets, patches without core) and natural vegetation converted to anthropic uses between 2014 and 2024. Source of land cover: MapBiomas Collection 11.

Connectivity declined faster than habitat

The equivalent connected area (ECA) of natural vegetation decreased by 8.7–9.6% between 2014 and 2024 for the four dispersal distances, that is, 1.7–1.8 times the relative loss of habitat (Fig. 2a, Table 2). The decline was consistent through time (Kendall $\tau \leq -0.78$, $P \leq 0.0003$), with Sen slopes indicating losses of 0.77% to 1.04% per year, against 0.56% per year for habitat area. The amplification did not depend on analytical choices: ECA losses ranged from 7.8% to 12.7% when the minimum node size varied from 2 to 50 ha, and core-area losses ranged from 6.2% to 6.9% for edge depths of 60–150 m (Supplementary Table S1). The effective mesh size fell by 8.3% between the two end years but fluctuated without a monotonic trend ($\tau = 0.05$, $P = 0.88$), because

it is dominated by the largest remnant, which kept most of its area (70,173 ha in 2014 and 69,755 ha in 2024).

When only forest formation was treated as habitat, the picture changed. Forest area declined by 1.8% and its ECA by 1.4–2.7% (Fig. 2b), with significant trends only at the two longest dispersal distances ($P = 0.026$ at 1,500 m and $P = 0.0003$ at 5,000 m; $P \geq 0.16$ at 200 and 500 m). The loss of connectivity in the corridor was therefore carried mainly by savanna and grassland formations, which a forest-only assessment would have missed.

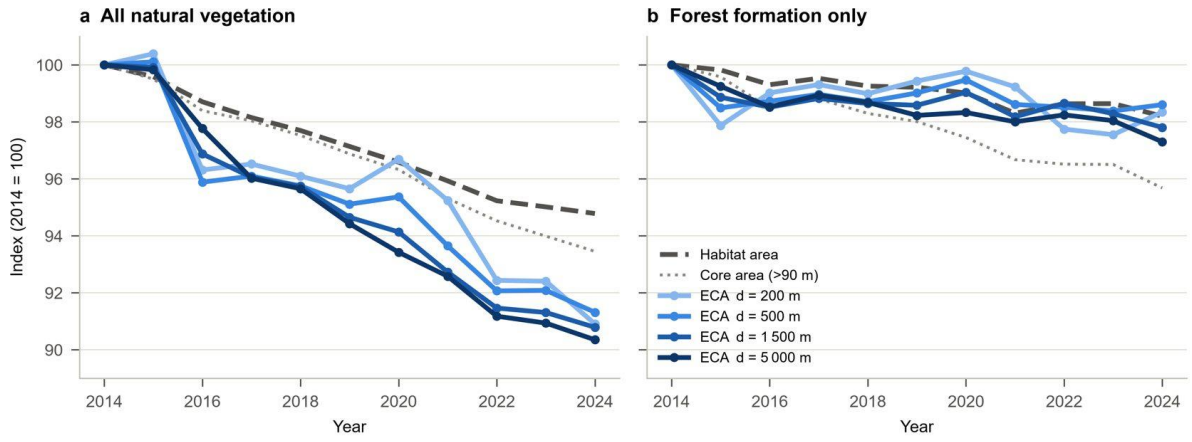


Figure 2. Annual change in habitat area, core area and equivalent connected area (ECA) for four median dispersal distances, indexed to 2014. (a) All natural vegetation. (b) Forest formation only.

Table 2. Equivalent connected area (ECA) for four median dispersal distances (*d*), change between 2014 and 2024, ratio between the relative loss of ECA and the relative loss of habitat area, and annual trend (2014–2024).

Habitat	d (m)	ECA 2014 (ha)	ECA 2024 (ha)	Change (%)	ECA loss / habitat loss	Sen slope (% yr^{-1})	Kendall τ	P
Natural vegetation	200	107,086	97,347	−9.1	1.74	−0.82	−0.78	0.0003
Natural vegetation	500	121,195	110,668	−8.7	1.66	−0.77	−0.85	<0.0001
Natural vegetation	1,500	146,677	133,166	−9.2	1.77	−0.92	−1.00	<0.0001
Natural vegetation	5,000	194,253	175,509	−9.6	1.85	−1.04	−1.00	<0.0001
Forest formation	200	42,570	41,866	−1.7	0.92	−0.11	−0.31	0.2183
Forest formation	500	51,792	51,068	−1.4	0.78	−0.05	−0.35	0.1646

Forest formation	1,500	70,399	68,852	−2.2	1.22	−0.12	−0.53	0.0264
Forest formation	5,000	106,510	103,635	−2.7	1.50	−0.20	−0.78	0.0003

Dissection and attrition dominated the spatial processes

Of the 305 cells of 5 × 5 km analysed, 241 (79%) were classified into one of the five processes of habitat loss and 61 into processes of habitat gain (Fig. 3a). Dissection, in which habitat decreases while the number of patches increases without a severe loss of area, was the most frequent process (120 cells), followed by attrition, the disappearance of patches (95 cells). In cells under dissection the median loss of habitat was 5.9%, but the effective mesh size decreased by 17.6%; in cells under attrition the corresponding values were 6.6% and 10.8%. Among the 243 cells that lost habitat, 194 (80%) lost proportionally more effective mesh size than habitat, with a median ratio of 2.0 (Fig. 3b).

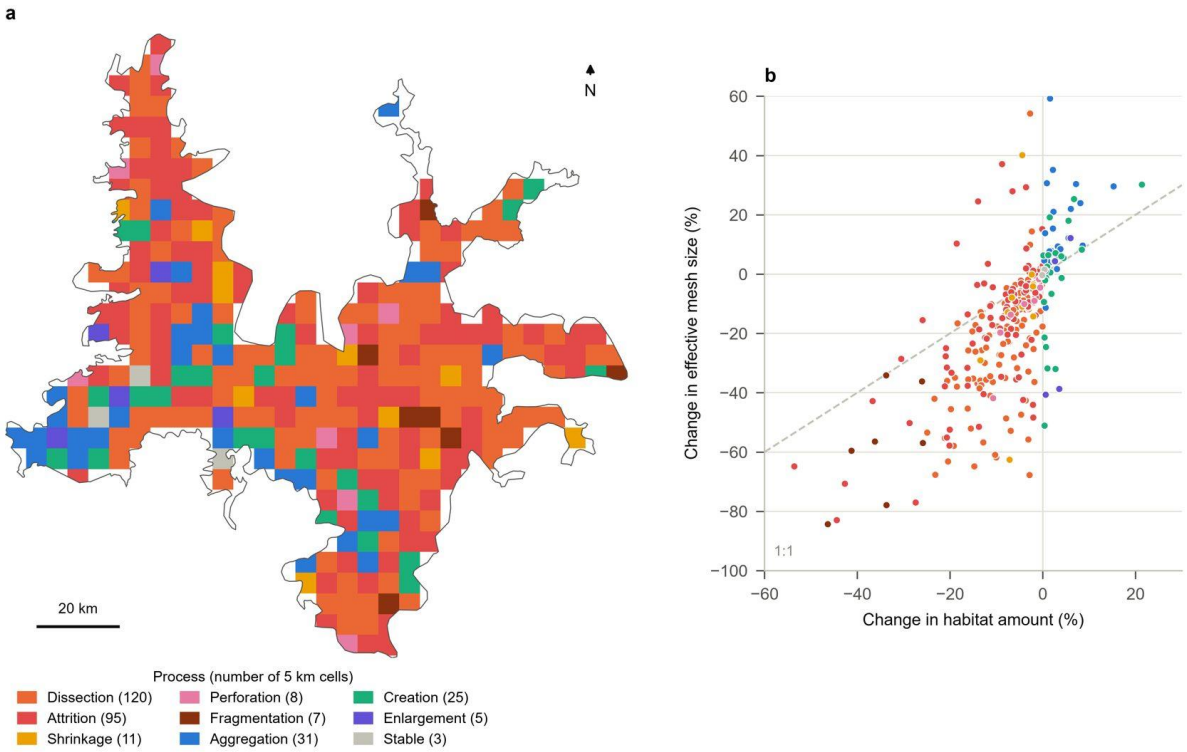


Figure 3. Spatial processes of landscape transformation between 2014 and 2024. (a) Dominant process in 5 × 5 km cells, according to the decision tree of Bogaert et al.; numbers in parentheses are cell counts. (b) Change in effective mesh size against change in habitat amount in each cell; the dashed line is the 1:1 line, and points below it indicate a loss of effective mesh size larger than the loss of habitat.

Conversion concentrated at edges, in small patches and in savannas

Of the natural vegetation present in 2014, 23,865 ha had been converted to anthropic uses by 2024. The probability of conversion decreased steeply with distance to the nearest edge: 21.2% of the vegetation within 30 m of an edge was converted, compared with 11.4% at 31–90 m, 6.6% at 91–300 m, 2.4% at 301–1,000 m and 0.3% beyond 1 km, a 76-fold difference between the outermost and innermost classes (Fig. 4a). The vegetation within 90 m of an edge represented 41% of the habitat in 2014 but 71% of the conversion. Patch size modulated this gradient: within the outermost 30 m the conversion rate varied little with patch size (19.6–24.0%), whereas at 91–300 m from the edge it ranged from 5.0% in patches larger than 10,000 ha to 14.1% in patches smaller than 10 ha. Overall, patches smaller than 10 ha lost 21.8% of their area and those larger than 10,000 ha lost 5.3%.

Savannas were converted at a rate of 14.0% and grasslands at 20.4%, against 6.8% for forests and 6.2% for wetland grasslands (Fig. 4b). Savannas held 30% of the natural vegetation in 2014 but accounted for 47% of the conversion. In a logistic model fitted to a systematic sample of 29,158 pixels (2,596 converted), the odds of conversion decreased with distance to the edge (odds ratio per standard deviation of log distance, 0.40 (95% CI 0.38–0.43)) and with patch size (0.75 (95% CI 0.71–0.78)), and were higher for savanna (3.69 (95% CI 3.36–4.04)) and for grassland and wetland grassland (1.84 (95% CI 1.46–2.31)) than for forest (Fig. 4c; area under the curve 0.77).

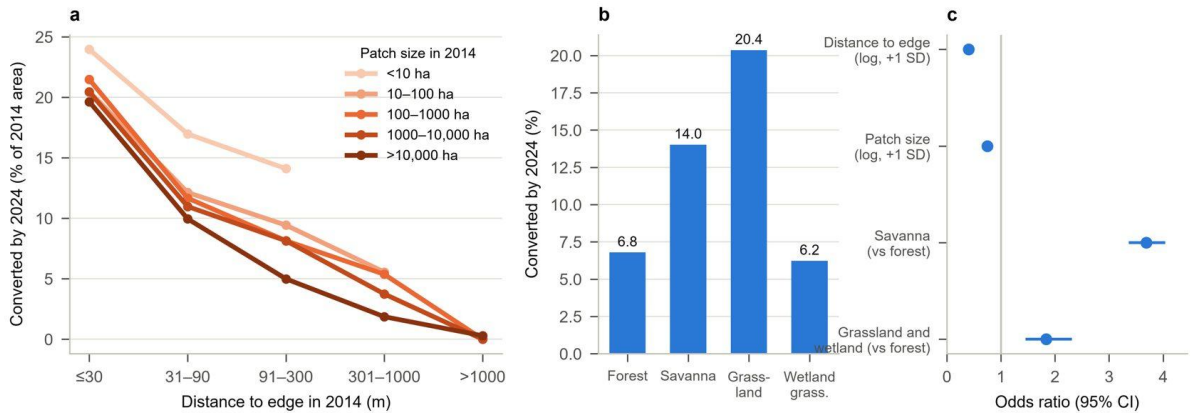


Figure 4. Conversion of 2014 natural vegetation to anthropic uses by 2024. (a) Conversion rate by distance to the nearest edge and patch size. (b) Conversion rate by formation. (c) Odds ratios and 95% confidence intervals from a logistic regression fitted to a systematic 300 m sample; continuous predictors per standard deviation of their logarithm, formations relative to forest.

A few remnants, including small stepping stones, hold most of the network

The 2024 network at a dispersal distance of 1,500 m comprised 1,144 patches of at least 10 ha, which held 94% of the natural vegetation. Connectivity was highly concentrated (Fig. 5). The largest remnant, 69,755 ha in the southwestern sector towards the Pantanal floodplain, had a patch importance (dPC) of 78.4%, of which 27.4% came from the habitat within it, 43.7% from the dispersal flux it exchanges with other patches and 7.2% from its role as a connector. A total of 15 patches contributed more than 1% each through the connector fraction alone. The clearest case of a stepping stone was a 221 ha remnant, 0.09% of the natural vegetation, that ranked 7th among all patches with a dPC of 4.4%, almost entirely as connector (4.2%), and a patch of only 13 ha had a connector fraction of 1.6%. In the 2014 network, the 480 patches that lost more than 10% of their area by 2024 had together accounted for 35% of the habitat-and-flux component of connectivity.

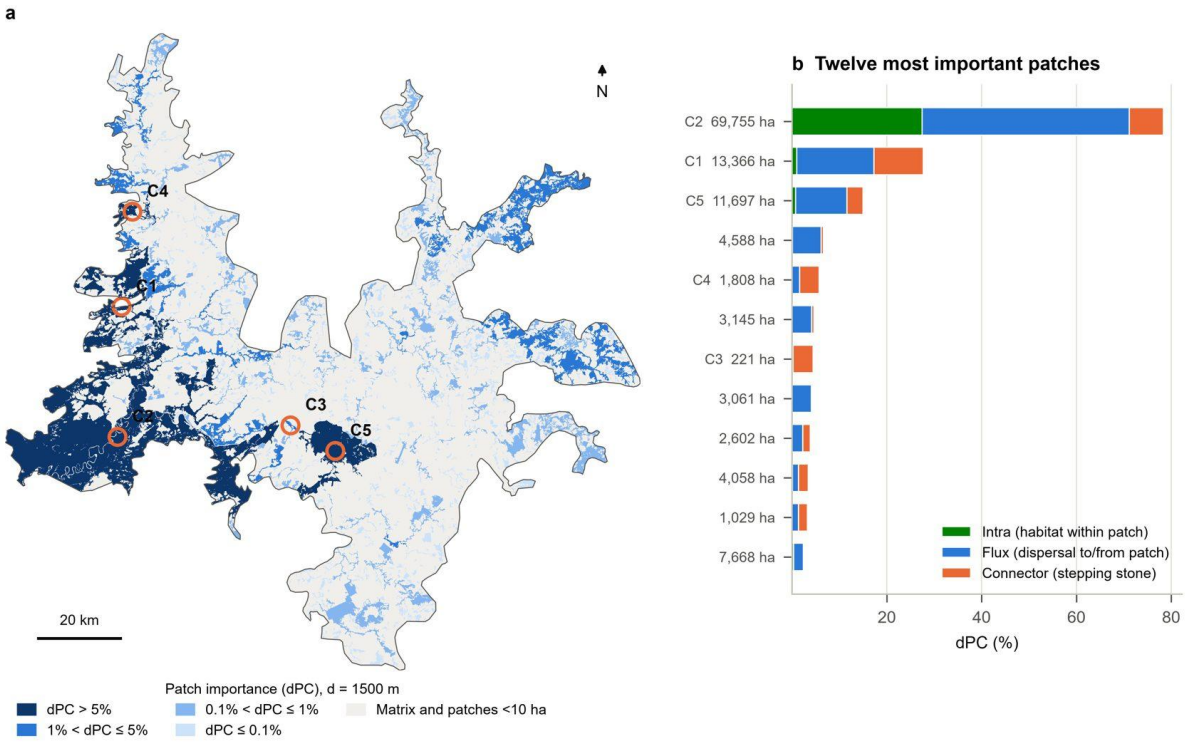


Figure 5. Importance of natural vegetation patches for connectivity in 2024 at a median dispersal distance of 1,500 m. (a) Patch importance (dPC); circles mark the five patches with the largest connector fraction (C1 to C5). (b) Decomposition of dPC into intra, flux and connector fractions for the twelve most important patches.

Discussion

Over a single decade, the ecological corridor lost about one-twentieth of its natural vegetation but close to one-tenth of its equivalent connected area. This amplification, consistent across dispersal distances and robust to the choice of minimum patch size and edge depth, supports the expectation that connectivity responds non-linearly to habitat loss [8,9]. It mirrors the declines reported for the Amazon arc of deforestation over four decades [23,24] and for a forest–Cerrado ecotone in which stable forest area concealed landscape reorganization [25], but it was detected here in a savanna-dominated landscape and over a much shorter period. For a legally designated corridor, whose purpose is to maintain the flow of organisms between protected areas [31,34], the relevant indicator of performance is therefore the connected area, not the vegetation area reported by most monitoring systems.

The spatial signature of change points to a mechanism. Conversion did not perforate the interior of remnants; it advanced from their edges, so that dissection and attrition, rather than perforation or shrinkage, dominated the landscape processes. The probability of conversion fell by almost two orders of magnitude from the outermost 30 m to the interior beyond 1 km, and edge exposure explained conversion better than patch size: within the outer band, small and large patches were converted at similar rates, whereas the advantage of large patches appeared only in their interiors. Small fragments are therefore lost faster mainly because a larger share of their area lies near an edge, a pattern consistent with the higher clearance of small tropical forest fragments [29]. Edges are also where vegetation structure and dynamics are altered by microclimate and disturbance [35,36], and agriculture-driven edge effects can penetrate hundreds of metres into dry forests [37]. Because the share of habitat within 90 m of an edge increased, the corridor is accumulating vegetation that is both more degraded and more likely to be converted, a feedback that is invisible in net area balances.

The contrast between physiognomies is central to the ecological interpretation. Forests, which include riparian and gallery forests protected as permanent preservation areas under the Forest Code [38], kept almost all of their area and connectivity. Savannas and grasslands, in contrast, were converted at two to three times the rate of forests and carried most of the connectivity loss. The Cerrado biota includes many species restricted to open savanna and grassland formations [11], and species adapted to open, fire-prone vegetation cannot use gallery forests as substitute habitat. A monitoring approach centred on forest cover, as in most connectivity trend studies [23,24,28], would have reported a connectivity loss of 1.4–2.7% for this corridor, several times smaller than the loss experienced by the full set of natural formations. The high turnover of grasslands, which lost a fifth of their 2014 area to conversion while gaining area elsewhere, may partly reflect the lower accuracy of grassland mapping and deserves field verification.

Our results do not test species responses, and they do not settle the debate on the effects of fragmentation per se [5–7]. In Cerrado mammals, habitat amount has been shown to predict species richness [39], and in the Pantanal habitat quality outweighs habitat amount for mammal habitat use [40]. They show, however, that in the landscape processes that affected most cells, the effective size of habitable units decreased faster than habitat, so that any process depending on movement between patches, such as dispersal of seeds and animals or recolonization after fire, is exposed to a larger loss than habitat area suggests. This is consistent with evidence that connectivity is a stronger determinant of the persistence of Cerrado species than the amount of remaining habitat [21], and with the shrinking set of conservation opportunities for endemic vertebrates in the southern Cerrado [22].

The concentration of connectivity in few remnants has direct implications for corridor management. The largest remnant, in the sector towards the Pantanal floodplain, sustains most of the network and should be the first priority for protection. Equally important, small remnants in stepping-stone positions contribute to the network out of proportion to their size, as also found for small Cerrado fragments in reducing isolation [18] and for small wildcats in the Brazilian savanna [41]. Because these stepping stones are the patches most exposed to edge-driven conversion, protecting them, restoring the gaps between key nodes and maintaining buffers along edges are likely to yield greater gains in connectivity per hectare than the protection of interior areas alone. Corridor effectiveness has empirical support across taxa [42,43], but only if the corridor remains continuous on the ground; our annual indicators provide a way to verify this.

Some limitations must be considered. MapBiomas maps carry classification errors that are larger for savannas and grasslands than for forests and that produce spurious year-to-year transitions [30,44]. We reduced their influence by analysing trends over eleven annual maps rather than single transitions, and edge pixels are more prone to mixed-pixel errors; nevertheless, the

conversion rate at 31–90 m from the edge, beyond the first pixel, was still 41 times higher than beyond 1 km. Connectivity was modelled with Euclidean distances and generic dispersal distances rather than species-specific resistance surfaces [45], and the planar graph approximates links between non-adjacent patches through intermediate ones [46]. The decade analysed is short relative to the history of occupation of the region, and extending the series back to 1985 would show whether the amplification is a recent feature or a long-term trajectory. Finally, the systematic review that supported the framing of the study was screened by a single reviewer.

In conclusion, the natural vegetation of the São Lourenço corridor is not only shrinking but losing its capacity to function as a connected system, at almost twice the rate suggested by its area. The loss advances from edges, falls disproportionately on savannas and grasslands, and threatens a network that depends on a few large remnants and on small stepping stones. Annual connectivity indicators computed from open satellite maps can be adopted to monitor the performance of ecological corridors across the Cerrado and beyond.

Methods

Study area

The São Lourenço River Basin Ecological Corridor lies in southeastern Mato Grosso, Brazil, and links the upper and middle courses of the São Lourenço and Vermelho rivers on the Guimarães Plateau to their floodplains in the transition to the Pantanal (Fig. 1). Its boundary was delimited by combining the river network on the plateau, the floodplain below the 400 m contour and the interpretation of high-resolution imagery [47]. The corridor covers 766,269 ha in the 30 m raster used here and includes parts of eleven municipalities. The climate is Aw in the Köppen classification, with a rainy season from October to March [48], and the vegetation spans the Cerrado gradient from grasslands to savannas and forests, with riparian and gallery forests along

the drainage network. Under Brazilian law, ecological corridors are portions of ecosystems that connect protected areas and allow gene flow and the movement of biota [31].

Land-cover data and habitat definition

We used the annual land use and land cover maps of MapBiomas Collection 11 for 2014 to 2024 [49], produced from Landsat imagery with Random Forest classification and spatial–temporal filters [30,44]. All years came from the same collection to avoid discontinuities between collections. Maps were clipped to the corridor and projected to SIRGAS 2000/UTM zone 21S at 30 m. Natural vegetation (habitat) comprised the classes forest formation, savanna formation, grassland and wetland grassland; rock outcrop, water and all anthropic classes formed the matrix. A second, forest-only habitat definition was analysed to assess how the inclusion of open formations affected the results. Patches were defined with an eight-cell neighbourhood. Edges were defined as interfaces between habitat and non-habitat cells inside the corridor; the corridor boundary itself was not treated as an edge, because land cover outside it was not analysed.

Landscape metrics

For each year and habitat definition we computed habitat area, number of patches, mean and area-weighted mean patch size, the area of the largest patch, edge density, core area (habitat more than 90 m from an edge, three cells), the share of habitat within 30, 90, 300 and 1,000 m of an edge, and the effective mesh size, the expected area accessible from a random point of the corridor without crossing an edge [50]. Each habitat cell was also assigned to a simplified morphological class: core, edge of patches with core, or islet (patch without core) [51,52].

Graph-based connectivity

Patches of at least 10 ha were treated as nodes; they held about 94% of the habitat in every year. Links were derived from a planar graph, as in Graphab [46]: every cell of the corridor was allocated to the nearest node by a Euclidean distance transform, nodes whose allocation zones touched were linked, and the link length was the minimum edge-to-edge distance between them. Shortest paths over this graph gave the effective distance between every pair of nodes. The probability of direct dispersal between nodes i and j followed a negative exponential kernel, $p_{ij} = \exp(-k\, d_{ij})$, with k set so that $p = 0.5$ at the median dispersal distance d, and the maximum-product probability p_{ij}^{*} was obtained along the shortest path. The probability of connectivity and the equivalent connected area were computed as $\mathrm{PC} = \Sigma\Sigma\, a_i a_j p_{ij}^{*} / A_L^{2}$ and $\mathrm{ECA} = (\Sigma\Sigma\, a_i a_j p_{ij}^{*})^{1/2}$, where a is patch area and A_L the corridor area [8,53,54]. We used four median dispersal distances, 200, 500, 1,500 and 5,000 m, spanning the range of natal dispersal of small to large terrestrial birds and mammals [55,56]. For 2024 and d = 1,500 m, we computed the importance of each node as the relative decrease in PC after its removal (dPC) and partitioned it into intra, flux and connector fractions; the connector fraction was obtained by recomputing all shortest paths without the node [9]. To quantify how much of the 2014 network was held by patches that later lost area, we computed the intra and flux fractions for the 2014 nodes and the share of each node converted by 2024.

Spatial processes of landscape transformation

The corridor was divided into cells of 5 × 5 km, and the 305 cells with at least half of their area inside the corridor were analysed. For each cell we compared habitat area, perimeter and number of patches in 2014 and 2024 and assigned one of nine processes (aggregation, attrition, creation, dissection, enlargement, fragmentation, perforation, shrinkage or stability) with the decision tree of Bogaert et al. [33], using a threshold of 0.75 for the ratio of final to initial area to separate

dissection from fragmentation and a tolerance of 0.5% to define stability. Changes in effective mesh size were computed for the same cells.

Where conversion occurred

Each habitat cell of 2014 was characterized by its distance to the nearest edge, the area of the 2014 patch to which it belonged and its formation, and was classified as converted when it belonged to an anthropic class in 2024. Conversion rates were computed by class of distance and patch size and by formation. To estimate the independent association of these variables with conversion, we fitted a logistic regression to a systematic sample of one cell every 300 m, which reduces spatial autocorrelation; log-transformed distance and patch size were standardized, and formations entered as indicator variables with forest as reference. Discrimination was measured by the area under the receiver operating characteristic curve.

Trends and sensitivity analyses

Monotonic trends in the annual series were tested with Kendall's τ, and their magnitude was estimated with Sen's slope [57]. The sensitivity of ECA to the minimum node size was assessed with thresholds of 2, 10 and 50 ha, and that of core area with edge depths of 60, 90 and 150 m.

Literature review

The framing of the study and the choice of metrics were supported by a systematic search following PRISMA 2020 [58] and the Parsifal protocol, with five validation gates (protocol, search coverage, relevance, eligibility and evidence). On 11 November 2026 we searched OpenAlex, the index used by the open search of the CAPES Journal Portal, and Semantic Scholar with three conceptual blocks (fragmentation or connectivity; Cerrado, Pantanal or tropical savanna; remote sensing or land cover) and complementary queries. The 1,909 records retrieved

were reduced to 1,719 after removing duplicates; titles and abstracts were screened against predefined criteria, and 143 records were retained. The search recovered 11 of 18 predefined seed articles; the remaining ones were added from known literature (Supplementary Note S2, Supplementary Fig. S1).

Software and use of artificial intelligence

All analyses were run in Python 3.12 with NumPy, SciPy, pandas, rasterio, GeoPandas and Matplotlib. Claude (Anthropic), a large language model, assisted in writing and debugging the analysis code, in the screening of search records and in language editing. The author designed the study, checked the code and its outputs, verified every reference against its source and takes full responsibility for the content.

Code availability

The Python code used for all analyses (landscape metrics, graph-based connectivity, patch importance, spatial processes, conversion models, trend and sensitivity analyses, and figures) is available under the MIT licence in the Zenodo repository, https://doi.org/10.5281/zenodo.24137643.

Data Availability

MapBiomas Collection 11 maps are openly available at https://brasil.mapbiomas.org. The datasets generated during the current study (annual landscape metrics, connectivity values, patch importance, spatial-process and conversion maps, and the records of the literature review) and the MapBiomas subset analysed are available in the Zenodo repository, https://doi.org/10.5281/zenodo.24137643, under a CC BY 4.0 licence.

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Author contributions

D.A.A. is the sole and lead author. D.A.A. conceived and designed the study (conceptualization and analytical framework), curated the land-cover data, wrote the analysis code, performed the landscape, connectivity and statistical analyses, conducted the literature review, prepared the figures and tables, interpreted the results and wrote and revised the manuscript. D.A.A. provided the conceptual leadership of the work and is accountable for all of its aspects.

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Additional Information

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