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Deforestation on an Amazonian frontier magnifies impact by changing the configuration of forest cover

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Amazon deforestation magnifies its impact by changing the configuration of forest cover

Summary

The Amazon comprises the most biodiverse region in the world but, despite being highly threatened by human-induced environmental changes, little is known about how those changes influence the remaining forest's extent and configuration in Brazil's arc of deforestation. We analysed the spatial and temporal dynamics and the configuration of forest cover in Brazil's state of Rondônia over 34 years. We calculated seven landscape metrics based on freely available satellite imagery to understand the habitat transformations. Overall, native vegetation cover declined from 90.9% to 62.7% between 1986 and 2020, and fragmentation greatly increased, generating 78,000 forest fragments and 100,000 fragments of "native vegetation", which also includes forest. We found that *c*. 50% of the vegetation is within *c*. 1 km of the nearest forest edge and the mean isolation between fragments is *c*. 2.5 km. More than 50% of the fragments are >10 km away from the nearest PA or IT. This reduction of natural vegetation in Rondônia is posing major threats to the survival of species and is undermining the dynamics of ecosystems. Measures to control deforestation and avoid the reduction of large remnants are urgently needed.

Keywords: MapBiomas, connectivity, forest fragmentation, Rondônia, Brazil

Introduction

The Amazon holds the largest and most biodiverse tropical forest in the world (Raven et al. 2020), providing essential ecosystem services that include contributing to global climate balance (Pires et al. 2023). Despite its importance, this forest has been increasingly threatened over the last 40 years by deforestation and consequent forest fragmentation, as well as by other human pressures such as forest degradation (Lapola et al. 2023). As of 2023, more than 21% of Brazil's Amazon forest had been cleared (INPE 2022). The expansion of anthropogenic activities has destroyed a vast area of forest, especially along the region's southern and eastern edges, known as the "arc of deforestation", covering all or part of the Brazilian states of Pará, Mato Grosso, Acre, Maranhão and Rondônia (IPAM 2023). The arc of deforestation is characterized by a vast array of variable-sized forest fragments, mostly isolated within cattle pastures and agricultural croplands (Fearnside 2005). Due to unprecedented deforestation rates in the Amazon — widely recognized as the principal driver of biological depletion — measures based on scientific evidence are necessary for effective conservation actions (e.g., Bogoni et al. 2020).

Despite empirical evidence of the consequences of deforestation and fragmentation of Amazonian habitats, deforestation in Rondônia is rampant (Chaves et al. 2024). This state has a unique history of colonization and settlement projects (Gomes et al. 2012), rubber cycles, and infrastructure projects (e.g., the Madeira-Mamoré railway and the BR-364 and BR-319 highways). The impacts of this history include depletion of biodiversity in the state's unique tropical ecoregions, including hyper-diverse areas such as the Rondônia endemism zone (Borges and da Silva 2012, Marsh et al. 2022). Rapid land-use change in the state necessitates the application of robust ecological metrics to assess the intensity, extent, and magnitude of natural-habitat conversion and allow analysis of the effects of these changes. Especially in a scenario where multifaceted vertebrate declines are observed (Goebel et al. 2025), these metrics are essential to analyse the effects of these changes and define conservation strategies.

Understanding the vegetation cover dynamics and configuration over time is necessary to infer the degree of threat, and these are measurable using landscape ecology metrics (e.g., Vancine et al. 2024). These metrics allow comparison of landscapes with different territorial extents and in different periods. Deforestation and fragmentation induce significant changes in the composition and configuration of the landscape, that is, changes in the physical structure and spatial organization of ecosystems, which constrain populations and ecosystem services (Melo et al. 2013). Native Amazonian ecosystems have been giving way to anthropogenic habitats, causing simplification in species diversity as fragmentation intensifies, with the remaining fragments becoming smaller, affecting species richness and abundance (Palmeirim et al. 2020, Goebel et al. 2025), while increased isolation limits movement patterns and affects species distributions (Fahrig 2003, 2017). The forest fragments are subject to edge effects that alter vegetation structure, reducing food resources and increasing vulnerability to forest fires (Malcolm 1994). Fragmentation also promotes interference with ecosystem functions such as pollination and seed dispersal, degrading the integrity of forest environments (Galetti et al. 2003, Laurance et al. 2018, Pires et al. 2023). There are also cumulative impacts that include invasions of alien species (Young et al. 2016), disease outbreaks, and increased competition between species (Palmeirim et al. 2020).

We analysed spatial and temporal changes in vegetation cover and configuration in Rondônia between 1986 and 2020, employing annual satellite images on a five-year basis. We calculated landscape metrics, including vegetation cover, fragment size, number of fragments, edge area, mean isolation, functional connectivity, and vegetation overlap and distances from protected areas (PAs, which are known as "conservation units" in Brazil) and Indigenous territories (ITs) (similar to Vancine et al 2024). We expected that, over time, the metrics would respond to the fragmentation context of Rondônia, showing a reduction in vegetation cover and connectivity, and an increase in the number of fragments, edge area, and mean isolation, but a habitat conservation in PAs and ITs (Vancine et al. 2024). We provide insights into habitat fragmentation with a view to improving conservation policies and an analytical framework that could be replicated in other tropical regions, as well as foster international collaborations.

Methods

Study Area

Our study area was Rondônia (in the southwestern Brazilian Amazon), to which many people from non-Amazonian parts of Brazil migrated in the 1970s and 1980s, after the construction and paving of the BR-364 highway and implementation of colonization and settlement projects supported by the Brazilian Federal Government (Fearnside 1987). Rondônia (7-13°S, 59-66°W) covers an area of 237,765 km^2 (IBGE 2023), or 4.6% of Brazil's Legal Amazon region. It currently has 52 municipalities (counties) and, with *c.* 1,580,000 inhabitants, is the fourth most populous of the nine states in the Legal Amazon (IBGE 2023). However, its human development index (0.690) is ranked seventh in the Legal Amazon and eighteenth among Brazil's 27 states (IBGE 2023). Rondônia has the fifth largest gross domestic product in the Legal Amazon and is 22nd in the country, with an economy based on agriculture, livestock, food industry, and extractive activities (IBGE 2023).

The predominant vegetation is Amazonian open and dense tropical forests, but in roughly 10% of the state the original vegetation is savannas such as cerrado or other non-forest Formations (Fearnside 1997). Rondônia's main water courses are the Madeira, the Machado (or Ji-Paraná) and the Guaporé Rivers (Gomes 2012). Biodiversity in Rondônia is composed of 1,724 known plant species, 118 snakes (Bernarde et al. 2012), 802 birds, 147 amphibians, and 211 mammals (Marsh et al. 2022).

Land use and land cover dataset and classification

Our assessments of vegetation cover dynamics and landscape structure were based on the classification of land use and land cover (LULC) provided by the open-source MapBiomas project (Souza Jr. et al. 2020). We used a 34-year series of changes in LULCbetween 1986 and 2020 using images every five years, following Vancine et al. (2024): 1986, 1990, 1995, 2000, 2005, 2010, 2015, and 2020. The classification is from MapBiomas Collection 7.1 in Raster format (GeoTIFF) with a spatial resolution of 30 m and Datum WGS-84 in the Universal Transverse Mercator (UTM) coordinate system. We defined two vegetation classes for the analyses: 'forest vegetation' (FV) and 'native vegetation' (NV), which also includes forest (Table S1). In FV we only considered habitats classified by MapBiomas as 'forest', while NV includes both 'forest' and non-forest formations: 'savannas', 'wetlands', 'grasslands' and 'other types of natural vegetation'.

Vectorial data for protected areas and Indigenous territories, as well as geospatial data on roads and the geographical limits of Rondônia, were obtained from the Brazilian Institute of Geography and Statistics platform (IBGE 2021). We selected only roads that were built, paved, and in operation. Data on roads were used to exclude areas of FV and NV overlapping these constructions and thus prevent overestimation of the areas of vegetation (Antongiovanni et al. 2018, Vancine et al. 2024). Using the roads dataset, we tested the effect of these constructions on deforestation, considering that these roads allow access to previously inaccessible areas (Barber et al. 2014). All datasets were rasterized with a resolution of 30 m and reprojected to UTM Zone 20S, and Datum SIRGAS2000. The roads were rasterized using a parameter that creates "densified lines", meaning that all cells touched by the line will be defined as part of the path (Vancine et al. 2024).

Metrics used in spatial and temporal analyses

All maps were built in QGIS 3.22 LTR software (QGIS Development Team 2023) using Natural Earth delimitations (1:10,000,000). All landscape metrics were processed using GRASS GIS 8.2.1 (Neteler et al. 2012) and R 4.3.0 (R Core Team 2023) via the rgrass (Bivand 2022) and LSMetrics packages in R (Niebuhr et al. pers. comm. 2025). We calculated seven landscape metrics: vegetation cover, number of fragments, mean fragment size, edge area, mean isolation, functional connectivity, and vegetation overlap and distance from PAs and ITs (Table S1. The vegetation cover was calculated as the amount of vegetation (FV, NV and each vegetation forest and natural classes (see in Table S2) divided by the total area of Rondônia. The number and size of fragments allowed us to account for the area of the remaining fragments, in addition to examining the increase, reduction, or stability of these areas throughout the landscape. We also summarized the fragment size data by calculating their means per year (i.e., arithmetic mean). The fragments were defined using the "rule of eight neighbours", which can define areas connected by pixels in eight directions (Turner and Gardner 2015). The edge area was calculated for different depths (Table S2), allowing us to estimate the amount and percentage of forest area subject to edge effects.

We used two functional connectivity metrics for different gap-crossing distances, which calculate the capabilities of species to cross non-natural habitats (Table S2). First, we calculated the sum of the areas of all fragments closer than the range-crossing distance, which we considered to be the available functional area (Awade and Metzger 2008) or the amount of functional habitat (i.e., suitable and well-connected habitat) (van Moorter et al. 2023). Second, we calculated the mean cluster size (i.e., arithmetic mean assumed to represent the expected size), and compared it with the largest cluster size in the study region (Vancine et al. 2024). In the isolation metric, we used an index adapted from the 'empty space function' developed by Ribeiro et al. (2009) and Vancine et al. (2024), and we created a Euclidean-distance map of all fragments, from which all distance values were extracted, and the mean isolation distance (i.e., the arithmetic mean) was calculated. This process was repeated in several steps for the different size classes (Table S2 and Table S3). Mean isolation provides insights into the importance of fragments as "steppingstones". We also calculated the amount of FV and NV that overlap with protected areas (Pas in 2022) and indigenous territories (ITs in 2021), and the shortest Euclidean distance from each FV and NV pixel to these areas.(Tables S1 and S2). We analysed vegetation scenarios considering only trimmed scenarios, where the area occupied by roads was removed ("trimmed") from the forest area. The scenarios were 'forest vegetation with roads trimmed' and 'native vegetation with roads trimmed'. . Scenarios in which the roads were not trimmed did not yield a difference from that in our analyses, although an effect of including areas occupied by roads has been found in other Brazilian ecosystems such as the Atlantic Forest (Vancine et al. 2024) and Caatinga (Antongiovanni et al. 2018).

Results

Vegetation cover

Vegetation cover in Rondônia decreased over the 34 years from 1986 to 2020 (Figure 1) from 85.34% (20.3 Mha) to 57.1% (13.6 Mha) for FV, while NV decreased from 91% (21.6 Mha) to 62.7% (14.9 Mha) (Figure 2, Tables S3 and S4). Savannas, grasslands, and wetlands contributed significantly to the composition of NV (Figure 2). Over the 34-year period there was a 0.19% reduction in savanna formations. Compared to 1986, the area of wetlands in 2015 had increased by 0.15% and in 2020 it had decreased by 0.12% , while grasslands had increased by 0.10% (Figure 2).

Distribution, size, and number of forest and native habitat fragments

The number of fragments increased over the years (Figure 3). Considering all native vegetation classes over the 1986-2020 period there were 100,874 fragments, of which 77,730 had forest-only vegetation cover (Figure 3a). In 1990, the number of NV and FV fragments was nearly equal, with 32,440 and 29,316 respectively, but by 1995 the number of NV fragments had grown to 52,889. The mean size of fragments fell sharply between 1990 and 1995, with a drop of 42.2% (671.5 to 388.3 Mha) for FV, and 42.6% (646.2 to 370.9 Mha) for NV. In 2020, the mean size of FV and NV fragments was around 150 ha (mean ± SD = 154 ± 226 ha) (Figure 3b, Tables S3 and S4).

We observed a reduction in the size of the fragments of FV and NV over the 1986-2020 period for all years and scenarios (Figure S1 and Table S4), mainly in vegetation fragments larger than 1,000,000 ha, the total area of which decreased by 24% for FV and 22% for NV. For fragments of 2,500-1,000,000 ha range there was little variation in the total number. There was an increase in the number of fragments in the 1-2,500 ha range but there was a decrease in the number of fragments smaller than 1 ha (Figure S1).

Core and edge areas

The percentage of all FV and NV that was less than 1,020 m from an edge increased over the 34 years, from 50% to 52% for FV, and 35% to 50% for NV (Figure 4[a-b]). The percentage of areas less than 500 m from an edge also increased, from 33.4% to 40.6% for FV, and 24.7% to 34.6% for NV. The percentage of area less than 2,520 m from an edge remained at 75% for FV and increased from 65% to 75% for NV. The maximum edge distances were 23,353 m for FV and 26,281 m for NV, showing that NV had larger central areas (Figure 4[a-b]). For distances over 240 m from an edge there was an inversion of the trend in the percentages of vegetation: the percentages of vegetation in FV and NV decreased over the years as a result of the conversion of the core areas of the fragments into edge areas (Figure 4[c-d]).

Functional connectivity

We found that the mean functionally connected area also declined over the years. Considering functional connectivity for species that cannot cross non-habitat (i.e., gap crossing equals 0 m), the mean functionally connected area of FV decreased by 78.6% (816.2 to 174.3 ha), and for NV by 82.7% (860.0 to 147.6 ha) (Figure 5[a-b]). The same pattern occurs for all gap-crossing classes. For values above 1,200 m, connectivity showed an increase in 2015; however, it had declined by 2020. In the 1,200 and 1,500-m gap-crossing classes, NV was greater in 2010 but by 2020 it had dropped dramatically in the 1,500-m class (Figure 5). Above 600 m the largest cluster size did not change, showing a limit value for functional connectivity in Rondônia for all years analysed (Figure 5 [c-d]).

Mean isolation

Mean isolation occurred across all size classes of the remaining fragments (Figure 6[a-b]). There were peaks in 2005 and 2020 for both FV and NV, reaching the highest values in the historical series in 2020, with mean isolation between fragments of *c.* 2.5 km (Figure 6). The 500-ha class had the highest mean isolation, followed by the 350 and 250-ha classes. In 2020, the 500-ha fragments had a mean isolation of 2,647 m for FV and 2,341 m for NV. For FV and NV, we observed increases in mean isolation for areas from 200 to 500 ha in 2000, a reduction in 2005 and 2010 (except for the 500-ha class), and a large increase in 2020.

Distance from Protected Areas and Indigenous Territories

PAs covered 328,026,915 ha (13.8%) and ITs 486,647 ha (20.5%) of Rondônia in 2020 these areas represented, respectively, 20.4% and 21.8% of the total FV and NV in PAs, and 33.6% and 32.2% of the total FV and NV in ITs. Our results indicate that 2.7 Mha (20.4%) of FV and 3.2 Mha (21.8%) of remaining NV was in PAs (Figure 7[a-b]), while for FV 4.5 Mha (33.6%) was in PAs and 4.7 Mha (32.2%) was in ITs. Only 1.9% of the FV and NV outside of PAs and ITs was within 1 km of a PA, and 1.6% of the FV and NV outside of PAs and ITs was within 1 km of an IT (Figure 6). In contrast, 63.2% of FV and 61.4% of NV were more than 10 km from PAs, and 53.1% of FV and 54.3% NV were more than 10 km from ITs (Figure 6).

Discussion

Our results show dramatic changes in the spatial and temporal dynamics of landscape structure in Rondônia. Over a period of 34 years there was a huge reduction in native vegetation cover (from 21.6 Mha to 14.9 Mha), mainly due to agriculture and ranching expansion and urban growth (Souza Jr. et al. 2020). Fragmentation also greatly increased, totalling more than 70,000 fragments of FV and 90,000 fragments of NV. Fragments are progressively decreasing in size (with a mean size reduced to 150 ha by 2020), contributing edge effects and isolation from other fragments or protected areas and Indigenous territories.

We observed a clear increase in smaller fragments and reduction in large remnants in the state, which can have a direct impact on maintaining the diversity and population size of multiple taxonomic groups, as has been found in other studies of Amazonian fragments (Laurance et al. 2018, Palmeirim et al. 2022, Goebel et al. 2025). Fragments with larger areas tend to shelter more species and provide more ecosystem functions, which ensure human well-being and agricultural productivity (Pires et al. 2023). As predicted by Piontekowski et al. (2019), there was a major decrease in Rondônia's vegetation cover and increase the number of fragments. A similar pattern has been found in the Tapajós basin in the states of Pará and Mato Grosso (Borges et al. 2022). Although the number of fragments has increased continuously in Rondônia, there was a reduction in the rate of increase between 2005 and 2010 (Figure 3), coinciding with the creation of the Action Plan for the Prevention and Control of Deforestation in the Amazon (PPCDAM) in 2004 (MMA 2011), as well as other factors that reduced the rate of deforestation during that period (Fearnside 2017, West and Fearnside 2021).

In addition to effects related to the amount of habitat, from 2010 onwards there was an increase in isolation and loss of connectivity between the remaining fragment of vegetation. The degree of isolation limits the species colonization process (Palmeirim et al. 2020) and interferes with small fragments acting as steppingstones that connect smaller areas with large remnants and thereby maintain genetic flow (Pires et al. 2023). Edge effects have also increased, which causes deleterious changes in vegetation structure, food webs, microclimate, and the carbon cycle (Benchimol and Peres 2015). Fragmentation, as measured by metrics such as ours, generates persistent deleterious effects (Haddad et al. 2015); species composition changes, with a boom in generalist species (Palmeirim et al. 2020).

Between 2012 and 2015, large infrastructure projects were implemented in Rondônia (e.g., road networks and hydroelectric dams), causing a negative effect on landscapes due to greater deforestation and fragmentation rates (Cabral et al. 2018, Escada et al. 2013). Roads play a crucial role in this process, exacerbating the extent and rate of deforestation (Laurance et al. 2009); in the Amazon they facilitate access to previously inaccessible forest areas, allowing agricultural expansion, illegal logging, mining, and urban development (Laurance et al. 2009, 2015, Barber et al. 2014, Fearnside 2022). Roads contribute to soil erosion, changes in drainage patterns, and increased risk of forest fires, further amplifying the harmful effects on ecosystems (Laurance et al. 2015). Understanding the role of roads in the deforestation process is crucial to developing strategies for conservation in the Amazon.

As a result of the deforestation and fragmentation in Rondônia, the largest vegetation remnants are now located in PAs and ITs (Figure 1), and 63% of the remaining vegetation outside of PAs and ITs is more than 10 km from the nearest PA or IT. Because deforestation outside PAs and ITs is overwhelming, these areas are essential for biodiversity conservation in the Amazon (Qin et al. 2023). PA and IT creation is one of the most important mechanisms for slowing biodiversity loss and maintaining ecological functions and ecosystem services (Godet and Devictor 2018, Gatagon-Suruí et al. 2024). The isolation of PAs reduces the likelihood of species colonizing or recolonizing other fragments and leads to population declines, reducing the species' reproductive potentials and genetic flows (Estrada et al. 2022). As a cascade effect, population decline can affect forest dynamics, by reducing seed dispersal (Magioli et al. 2021). Food resources that are essential for Indigenous people and other traditional groups for population growth and cultural development may suffer declines in abundance and biomass, which can have critical consequences for subsistence (Flores et al. 2024).

PAs are responsible for reducing deforestation, degradation, and carbon emissions, compared to non-protected areas (Sze et al. 2022). They are effective for connecting smaller unprotected fragments, generally in private properties (Noss et al. 2012). Based on our results, we suggest that new PAs need to be created, in addition to preventing damaging human actions with efficient inspections and resources applied to environmental protection. Although these areas play a vital role in Rondônia, over the 2020-2023 period, the state government's policies were focused on reducing or extinguishing state-protected areas (e.g., Fearnside and Cruz 2018). Forestry policies were also weakened (Moreira et al. 2022). Environmental damage from these policies contributes to ongoing climate change, including a lengthening dry season in the southern and southwestern Amazon (Butt et al. 2011, Costa and Pires 2010, Fu et al. 2013, Leite-Filho et al. 2020), which threatens agricultural activities (Costa et al. 2019, Fearnside 2020, Leite-Filho et al. 2021). Increasing frequency of extreme events in this region, also linked to deforestation and global warming, adds to this threat (da Silva et al. 2023).

Our chrono-sequence of deforestation and fragmentation in Rondônia indicates effects on fauna and flora that are still poorly investigated through on-site research, reflecting deficiencies in biodiversity knowledge (Bogoni et al. 2022). Effects related to health and well-being may be enhanced, as Rondônia has a high risk of emerging zoonotic diseases due to anthropogenic pressures and social vulnerability (Ellwanger et al. 2020, 2022). This highlights the complexity and interconnectedness of environmental phenomena that influence ecosystems and the need for understanding this complexity.

Our findings, based on landscape metrics of spatial and temporal changes in the landscape over three decades, should inform Brazilian government policies to reduce and control deforestation in the Amazon. The changes in Rondônia's landscape are like those found in the Atlantic Forest, which has an even greater degree of isolation between the fragments (Amaral et al. 2025, Vancine et al. 2024). However, the Atlantic Forest has a history of degradation over more than 500 years, while the changes in Rondônia are a mere 50 years old (Fearnside 1989). Our information and interpretations should be used as a guide for developing public policies before Rondônia's landscapes reach a point of no return. Our results help understanding of the causes and consequences of landscape change, which can generate crucial information for compensating environmental services (Qin et al. 2023). The implementation of appropriate laws would help counter the pressure to reduce the number and size of protected areas and Indigenous territories, and favour the implementation of conservation projects, including ecological corridors. Such actions might be financed, for example by the Amazon Fund (https://www.amazonfund.gov.br/en/home/). Natural vegetation has greater value than deforested areas but redirecting the course of development towards more sustainable actions requires strong measures to prevent unsustainable development (Fearnside 2018); otherwise, the outlook in the Amazon will be increasingly bleak.

Conclusions

Our understanding of the dynamics of deforestation and consequent fragmentation in Rondônia reveals drastic reductions in forest cover, size of forest fragment, and connectivity between natural areas. There has been increase in the number of fragments, in the area exposed to edge effects and in the isolation of fragments, which affects protected areas and indigenous territories. We warn that these environmental impacts on a landscape scale have severe ecological and socioeconomic consequences, especially for traditional and Indigenous peoples. We emphasize the urgency of conservation and restoration actions.

Greater investment is needed in inspection technology and in on-the-ground control actions, especially close to highways, which are key drivers of deforestation. It is paramount to promote connectivity between small fragments and large areas, planning the management of a landscape matrix to minimize edge effects and improve the connectivity of natural areas. We contribute to the evidence base for conservation policies in Rondônia and other Amazonian states. It is urgent to stop the political attacks that aim to reduce and weaken the existing protected-area network. We reinforce the appeal to create new protected areas and for more efficient supervision in natural areas and to defend fragments in private properties against the expansion of agribusiness frontiers throughout the Amazon. The landscape metrics and interpretation methods we used can be applied to any biogeographic region, giving this study the potential to positively influence practices and policies on a global scale.

Supplementary material. To view supplementary material for this article, please visit the link available at.

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Data availability Data will be made available on request.

Competing interests. The authors declare none.

Ethical standard. Compliant.

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Figure 1. Vegetation dynamics over 1986-2020 at five-year intervals for the whole of Rondônia (Brazilian Amazon). In 2020, we highlighted the remaining native vegetation (NV) and the limits of protected areas and Indigenous territories.

Figure 2. Percentages of vegetation cover of the different types in the state of Rondônia (Native Vegetation with roads trimmed) from 1986 to 2020. NV = native vegetation, FF = forest formations, SF = savanna formations, WT = wetlands and GL = grasslands.

Figure 3. Distribution of the (a) thousandth of fragments and (b) mean size of fragments of forest vegetation and native vegetation (including forests) in Rondônia from 1986 to 2020 (with roads trimmed).

Figure 4. Cumulative percentages of (a-b) area and (c-d) per edge-proximity class for the forest vegetation and native vegetation (including forests) remaining (with roads trimmed) in Rondônia. Note log10 scale of edge distance s continuum in a-b, but not log10 distances in categorical c-d.

Figure 5. (a-b) Expected cluster size (mean functional size; ha on $\log_{10}$ scale) of functionally connected forest vegetation and native vegetation fragments, for different functional distance values with roads trimmed (meters), and (c-d) largest functionally connected vegetation cluster (% of total remaining FV and NV) estimated at various functional distances (meters) for Rondônia.

Figure 6. Influence of smallest fragment size (ha) on isolation (m) in Rondônia: (a) forest vegetation fragments and (b) native vegetation fragments. Fragment sizes: 0 ha (all), 50 ha, 100 ha, 150 ha, 200 ha, 250 ha, 350 ha, 500 ha, 1000 ha. Percentages of remaining vegetation in Rondônia (area and percentage) by distance class (meters, with roads trimmed and railways) from protected areas: (c) forest vegetation and (d) native vegetation (including forests); and from Indigenous territories: (d) forest vegetation and (e) native vegetation (including forests).

Supplementary Material

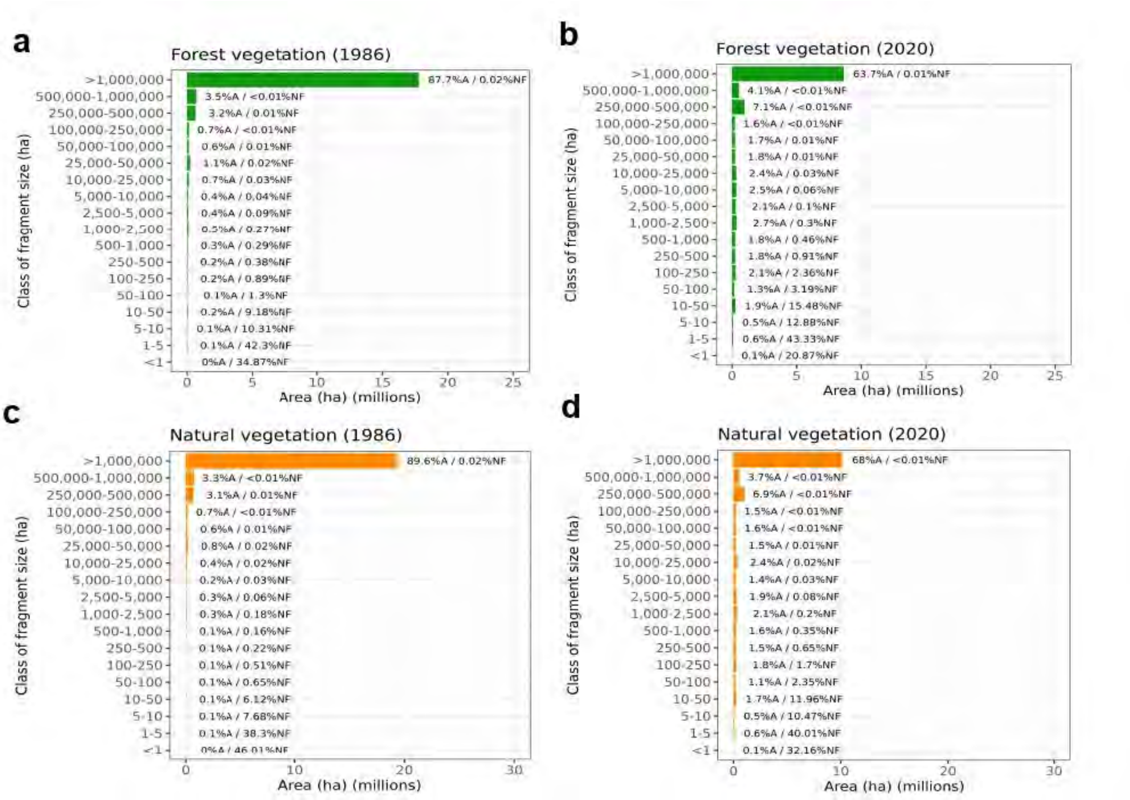

Figure S1. Distribution of the total areas of Forest Vegetation (FV) in 1986 (a) and 2020 (b) and Native Vegetation (NV) fragments in 1986 (c) and 2020 (d) in Rondônia, where: %A = percentage of the total area; %NF = percentage of the number of fragments. Note the different scales in the x-axis between the FV and NV plots.

Table S1. Land-use and land-cover codes and MapBiomas classes used to compose "Forest Vegetation" (FV) and "Native Vegetation" (NV).

Vegetation class	Land use and land cover	Land-use and land-cover abbreviation	MapBiomas class code
Forest Vegetation (FV)	Forest Formation	FF	3
	Savanna Formation	SF	4
Native Vegetation (NV)	Forest Formation	FF	3
	Savanna Formation	SF	4
	Wetland	WT	11
	Native Vegetation	NV	10
	Grassland	GL	12

Table S2. Landscape metrics used to analyse the structure of landscapes in Rondônia.

Metric	Description	Class
Number of fragments and fragment size	Number of fragments, fragment size and percentage of habitat cover in different size classes.	fragment size classes (ha): <1, 1–5, 5–10, 10–50, 50–100, 100–250, 250–500, 500–1000, 1000–2500, 2500–5000, 5000–10000, 10000–25000, 25000–50000, 50000–100000, 100000–250000, 250000–500000, 500000–1000000, and >1000000.
Vegetation cover, fragment size and number of fragments	Areas of fragments that showed increase, reduction, or that that remained stable through time, and the area and number of fragments that appeared or disappeared .	Values in Figure S4
Edge area	Percentage of habitat area submitted to edge effects for different edge widths.	Edge widths (m) (pixel size): <30, 30–90, 90–240, 240–510, 510–1020, 1020–2520, 2520–5010, 5010–11010, and 11010–32010.
Functional connectivity	Area of functionally connected fragments, considering different distance rules for fragment linkage.	Gap-crossing (m) (pixel size): 0, 60, 120, 180, 240, 300, 600, 900, 1200, and 1500.
Mean isolation	Meandistance to the nearest habitat fragment. To analyse the effect of small fragments in estimating isolation, the smallest fragments were successively removed.	Size of the small fragments removed (ha): 0 (i.e., no fragments removed), <50, <100, <150, <200, <250, <350, <500, and <1000.
Distance from Protected Areas and Indigenous Territories	Distance of any given habitat pixel to the nearest Protected Area or Indigenous Territory.	Distance classes (m): 0 (i.e., inside a Protected Area or Indigenous Territories), <100, 100–250, 250–500, 500–1000, 1000–2500, 2500–5000, 5000–10000, 10000–25000, 25000–50000, and >50000.

Table S3. Remaining FV and NV classes in Rondônia between 1986 and 2020 with roads trimmed and not trimmed . Area values (hectares) are presented for each year and vegetation scenario, the following.

Year	**Scenario**	**Classes**	**Class Abbreviation**	**Class Description**	**Area (ha)**	**P**
1986	Forest vegetation (not trimmed)	3	FF	Forest formation	20267325	85.35
1986	Forest vegetation (not trimmed)	1	FV	Forest vegetation	20267325	85.35
1986	Forest vegetation (trimmed)	3	FF	Forest formation	20265944	85.34
1986	Forest vegetation (trimmed)	1	FV	Forest vegetation	20265944	85.34
1986	Natural vegetation (not trimmed)	3	FF	Forest formation	20267325	85.35
1986	Natural vegetation (not trimmed)	4	SF	Savanna formation	552664.3	2.33
1986	Natural vegetation (not trimmed)	11	WT	Wetland	65593.44	0.28
1986	Natural vegetation (not trimmed)	12	GL	Grassland	716891.8	3.02
1986	Natural vegetation (not trimmed)	10	NV	Natural vegetation	21602475	90.98
1986	Natural vegetation (trimmed)	3	FF	Forest formation	20265944	85.34
1986	Natural vegetation (trimmed)	4	SF	Savanna formation	550895.8	2.32
1986	Natural vegetation (trimmed)	11	WT	Wetland	65560.23	0.28
1986	Natural vegetation (trimmed)	12	GL	Grassland	715709.4	3.01
1986	Natural vegetation (trimmed)	10	NV	Natural vegetation	21598109	90.95
1990	Forest vegetation (not trimmed)	3	FF	Forest formation	19685467	82.9
1990	Forest vegetation (not trimmed)	1	FV	Forest vegetation	19685467	82.9
1990	Forest vegetation (trimmed)	3	FF	Forest formation	19684282	82.9
1990	Forest vegetation (trimmed)	1	FV	Forest vegetation	19684282	82.9
1990	Natural vegetation (not trimmed)	3	FF	Forest formation	19685467	82.9
1990	Natural vegetation (not trimmed)	4	SF	Savanna formation	548185.4	2.31

1990	Natural vegetation (not trimmed)	11	WT	Wetland	60517.71	0.25
1990	Natural vegetation (not trimmed)	12	GL	Grassland	693356.6	2.92
1990	Natural vegetation (not trimmed)	10	NV	Natural vegetation	20987526	88.38
1990	Natural vegetation (trimmed)	3	FF	Forest formation	19684282	82.9
1990	Natural vegetation (trimmed)	4	SF	Savanna formation	546457.3	2.3
1990	Natural vegetation (trimmed)	11	WT	Wetland	60471.27	0.25
1990	Natural vegetation (trimmed)	12	GL	Grassland	692264.8	2.92
1990	Natural vegetation (trimmed)	10	NV	Natural vegetation	20983475	88.37
1995	Forest vegetation (not trimmed)	3	FF	Forest formation	18306038	77.09
1995	Forest vegetation (not trimmed)	1	FV	Forest vegetation	18306038	77.09
1995	Forest vegetation (trimmed)	3	FF	Forest formation	18305162	77.09
1995	Forest vegetation (trimmed)	1	FV	Forest vegetation	18305162	77.09
1995	Natural vegetation (not trimmed)	3	FF	Forest formation	18306038	77.09
1995	Natural vegetation (not trimmed)	4	SF	Savanna formation	547394.1	2.31
1995	Natural vegetation (not trimmed)	11	WT	Wetland	49597.02	0.21
1995	Natural vegetation (not trimmed)	12	GL	Grassland	715179.8	3.01
1995	Natural vegetation (not trimmed)	10	NV	Natural vegetation	19618209	82.62
1995	Natural vegetation (trimmed)	3	FF	Forest formation	18305162	77.09
1995	Natural vegetation (trimmed)	4	SF	Savanna formation	545689.3	2.3
1995	Natural vegetation (trimmed)	11	WT	Wetland	49556.16	0.21
1995	Natural vegetation (trimmed)	12	GL	Grassland	714204.7	3.01
1995	Natural vegetation (trimmed)	10	NV	Natural vegetation	19614612	82.61
2000	Forest vegetation (not trimmed)	3	FF	Forest formation	16927429	71.29
2000	Forest vegetation (not trimmed)	1	FV	Forest vegetation	16927429	71.29
2000	Forest vegetation (trimmed)	3	FF	Forest formation	16926819	71.28
2000	Forest vegetation (trimmed)	1	FV	Forest vegetation	16926819	71.28
2000	Natural vegetation (not trimmed)	3	FF	Forest formation	16927429	71.29
2000	Natural vegetation (not trimmed)	4	SF	Savanna formation	534601.2	2.25

2000	Natural vegetation (not trimmed)	11	WT	Wetland	89160.3	0.38
2000	Natural vegetation (not trimmed)	12	GL	Grassland	721445.7	3.04
2000	Natural vegetation (not trimmed)	10	NV	Natural vegetation	18272636	76.96
2000	Natural vegetation (trimmed)	3	FF	Forest formation	16926819	71.28
2000	Natural vegetation (trimmed)	4	SF	Savanna formation	532966.3	2.24
2000	Natural vegetation (trimmed)	11	WT	Wetland	89119.17	0.38
2000	Natural vegetation (trimmed)	12	GL	Grassland	720526.2	3.03
2000	Natural vegetation (trimmed)	10	NV	Natural vegetation	18269430	76.93
2005	Forest vegetation (not trimmed)	3	FF	Forest formation	15155238	63.82
2005	Forest vegetation (not trimmed)	1	FV	Forest vegetation	15155238	63.82
2005	Forest vegetation (trimmed)	3	FF	Forest formation	15154726	63.82
2005	Forest vegetation (trimmed)	1	FV	Forest vegetation	15154726	63.82
2005	Natural vegetation (not trimmed)	3	FF	Forest formation	15155238	63.82
2005	Natural vegetation (not trimmed)	4	SF	Savanna formation	520435.1	2.19
2005	Natural vegetation (not trimmed)	11	WT	Wetland	80114.76	0.34
2005	Natural vegetation (not trimmed)	12	GL	Grassland	706306.5	2.97
2005	Natural vegetation (not trimmed)	10	NV	Natural vegetation	16462095	69.32
2005	Natural vegetation (trimmed)	3	FF	Forest formation	15154726	63.82
2005	Natural vegetation (trimmed)	4	SF	Savanna formation	518869.2	2.19
2005	Natural vegetation (trimmed)	11	WT	Wetland	80073.99	0.34
2005	Natural vegetation (trimmed)	12	GL	Grassland	705395.3	2.97
2005	Natural vegetation (trimmed)	10	NV	Natural vegetation	16459065	69.32
2010	Forest vegetation (not trimmed)	3	FF	Forest formation	14646252	61.68
2010	Forest vegetation (not trimmed)	1	FV	Forest vegetation	14646252	61.68
2010	Forest vegetation (trimmed)	3	FF	Forest formation	14645774	61.68
2010	Forest vegetation (trimmed)	1	FV	Forest vegetation	14645774	61.68
2010	Natural vegetation (not trimmed)	3	FF	Forest formation	14646252	61.68
2010	Natural vegetation (not trimmed)	4	SF	Savanna formation	519467	2.19

2010	Natural vegetation (not trimmed)	11	WT	Wetland	83963.79	0.35
2010	Natural vegetation (not trimmed)	12	GL	Grassland	712563.7	3
2010	Natural vegetation (not trimmed)	10	NV	Natural vegetation	15962247	67.22
2010	Natural vegetation (trimmed)	3	FF	Forest formation	14645774	61.68
2010	Natural vegetation (trimmed)	4	SF	Savanna formation	517894.6	2.18
2010	Natural vegetation (trimmed)	11	WT	Wetland	83921.58	0.35
2010	Natural vegetation (trimmed)	12	GL	Grassland	711626.4	3
2010	Natural vegetation (trimmed)	10	NV	Natural vegetation	15959217	67.21
2015	Forest vegetation (not trimmed)	3	FF	Forest formation	14226794	59.91
2015	Forest vegetation (not trimmed)	1	FV	Forest vegetation	14226794	59.91
2015	Forest vegetation (trimmed)	3	FF	Forest formation	14226264	59.91
2015	Forest vegetation (trimmed)	1	FV	Forest vegetation	14226264	59.91
2015	Natural vegetation (not trimmed)	3	FF	Forest formation	14226794	59.91
2015	Natural vegetation (not trimmed)	4	SF	Savanna formation	521328.3	2.2
2015	Natural vegetation (not trimmed)	11	WT	Wetland	119357	0.5
2015	Natural vegetation (not trimmed)	12	GL	Grassland	709641.9	2.99
2015	Natural vegetation (not trimmed)	10	NV	Natural vegetation	15577121	65.6
2015	Natural vegetation (trimmed)	3	FF	Forest formation	14226264	59.91
2015	Natural vegetation (trimmed)	4	SF	Savanna formation	519726.2	2.19
2015	Natural vegetation (trimmed)	11	WT	Wetland	119291.2	0.5
2015	Natural vegetation (trimmed)	12	GL	Grassland	708660.4	2.98
2015	Natural vegetation (trimmed)	10	NV	Natural vegetation	15573941	65.58
2020	Forest vegetation (not trimmed)	3	FF	Forest formation	13551764	57.07
2020	Forest vegetation (not trimmed)	1	FV	Forest vegetation	13551764	57.07
2020	Forest vegetation (trimmed)	3	FF	Forest formation	13551254	57.07
2020	Forest vegetation (trimmed)	1	FV	Forest vegetation	13551254	57.07
2020	Natural vegetation (not trimmed)	3	FF	Forest formation	13551764	57.07
2020	Natural vegetation (not trimmed)	4	SF	Savanna formation	507027	2.14

2020	Natural vegetation (not trimmed)	11	WT	Wetland	90891.81	0.38
2020	Natural vegetation (not trimmed)	12	GL	Grassland	740395.1	3.12
2020	Natural vegetation (not trimmed)	10	NV	Natural vegetation	14890077	62.71
2020	Natural vegetation (trimmed)	3	FF	Forest formation	13551254	57.07
2020	Natural vegetation (trimmed)	4	SF	Savanna formation	505455.4	2.13
2020	Natural vegetation (trimmed)	11	WT	Wetland	90829.89	0.38
2020	Natural vegetation (trimmed)	12	GL	Grassland	739354.1	3.11
2020	Natural vegetation (trimmed)	10	NV	Natural vegetation	14886894	62.69

Table S4. The remaining PV and NV for Rondônia between 1986 and 2020 with roads trimmed and not trimmed. For each year and vegetation scenario the following values are presented: total percentage, number of fragments, and descriptive statistics (mean, standard deviation, median and maximum) in hectares.

Year	Scenario	Percentage	Numbers of patches	Total area (ha)	Mean area (ha)	Standard deviation area (ha)	Median area (ha)	Maximum area (ha)
1986	FV not trimmed	12.45	24406	20267325	830	101723	1.71	15597491
1986	FV trimmed	12.45	24831	20265944	816	81851	1.62	12263543
1986	NV not trimmed	13.27	22636	21602475	954	133718	1.26	20078603
1986	NV trimmed	13.27	25113	21598109	860	89636	1.17	13577564
1990	FV not trimmed	12.1	28842	19685467	683	82449	1.8	13665360
1990	FV trimmed	12.1	29316	19684282	671	69693	1.8	11422423
1990	NV not trimmed	12.9	29862	20987526	703	106677	1.44	18371290
1990	NV trimmed	12.89	32470	20983475	646	74033	1.26	12846565
1995	FV not trimmed	11.25	46761	18306038	391	57495	1.8	12125435
1995	FV trimmed	11.25	47141	18305162	388	49331	1.8	10247761
1995	NV not trimmed	12.05	50035	19618209	392	74095	1.53	16509993
1995	NV trimmed	12.05	52889	19614612	371	52640	1.44	11668219

2000	FV not trimmed	10.4	50375	16927429	336	49014	2.43	10735249
2000	FV trimmed	10.4	50692	16926819	334	42492	2.43	9184748
2000	NV not trimmed	11.23	62244	18272636	294	59204	1.8	14723175
2000	NV trimmed	11.23	65029	18269430	281	43298	1.71	10660532
2005	FV not trimmed	9.31	62759	15155238	241	37025	2.61	9097977
2005	FV trimmed	9.31	63064	15154726	240	31975	2.61	7762568
2005	NV not trimmed	10.12	78709	16462095	209	38663	1.89	10668787
2005	NV trimmed	10.11	81470	16459065	202	32746	1.8	9068834
2010	FV not trimmed	9	65804	14646252	223	33217	2.7	8364277
2010	FV trimmed	9	66114	14645774	222	23112	2.7	5305775
2010	NV not trimmed	9.81	82892	15962247	193	35681	1.98	10137164
2010	NV trimmed	9.81	85838	15959217	186	29941	1.89	8520154
2015	FV not trimmed	8.74	71405	14226794	199	30347	2.7	7960782
2015	FV trimmed	8.74	71788	14226264	198	26254	2.7	6778197
2015	NV not trimmed	9.57	89178	15577121	175	33004	1.98	9729611
2015	NV not trimmed	9.57	92306	15573941	169	27468	1.89	8093592
2020	FV not trimmed	8.33	77354	13551764	175	27739	2.79	7584067
2020	FV trimmed	8.33	77730	13551254	174	23844	2.79	6405106
2020	NV not trimmed	9.15	97764	14890077	152	29933	1.98	9247364
2020	NV trimmed	9.15	100874	14886894	148	24976	1.89	7697136