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Research Letters

Forest fragmentation in the Brazilian Amazon: Trends and conservation strategies

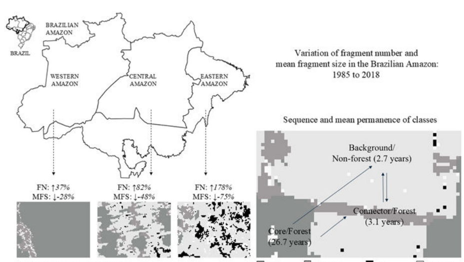
Pedro Trejo [a], Claudia Azevedo-Ramos [a,*], Felipe Lenti [b]

[a] Center for Advanced Amazonian Studies – NAEA, Universidade Federal do Para, 66075-750 Belém, Pará, Brazil
[b] Instituto de Pesquisa Ambiental da Amazônia, 70863-520 Brasilia, Brazil

HIGHLIGHTS

- Amazon forest fragmentation shows an increase in fragments and reduction in size in three decades.
- The Amazon's fragmentation trajectory shifts from Core to Connector to Background.
- Central Amazon demands target conservation to avoid fragmentation like Eastern Amazon.
- Secondary forest may be used to reverse fragmentation.
- Fragmentation metrics and trajectory nourish conservation actions.

GRAPHICAL ABSTRACT



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ABSTRACT

Tropical forests have experienced increasing fragmentation. The trajectory of forest fragmentation (sequence, permanence, and location) offers valuable insights for shaping environmental strategies. We examined fragmentation trends and metrics in the Brazilian Amazon over a 34-year period, encompassing its macroregions: Western (WA), Central (CA), and Eastern Amazon (EA). The findings reveal an ongoing fragmentation, characterized by an increase in fragment numbers (WA: +37%, from 49,871 to 68,067 fragments; CA: +82%, 72,463–132,051 fragments; EA: +178%, 164,249–456,399 fragments) and a reduction in mean fragment size (WA: −28%, from 2825.7–2036.8 ha; CA: −48%, 1747.4–905.4 ha; EA: −75%, 651.8–162.3 ha), particularly in the east. Transitions occurred across few forest classes, typically, from forest Core to connecting forest, and eventually to anthropogenic areas. The Core class's permanence was longest in WA (32 years), while anthropogenic areas had the highest permanence in EA (7.6 years) and the lowest in WA (<1 year). Intermediate fragmentation classes were more prevalent in EA, which also demonstrated higher entropy. CA requires immediate attention actions from decision-makers to prevent the intense fragmentation shown in EA. We suggested strategies to mitigate Amazon fragmentation, emphasizing integrated metrics and region-specific approaches for enhanced connectivity and reduced forest loss.

* Corresponding author.
E-mail addresses: trejopedro21@gmail.com (P. Trejo), claudia.azevedoramos@gmail.com, claudia.ramos@ufpa.br (C. Azevedo-Ramos), felipe.lenti@ipam.org.br, felipelenti.bio@gmail.com (F. Lenti).

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Introduction

Forests worldwide face an escalating crisis of fragmentation, especially due to agricultural expansion (FAO and UNEP, 2020). Forest fragmentation has been defined as "the division of habitat into smaller and more isolated fragments separated by a matrix of human-transformed land cover" (Haddad et al., 2015) or other natural land cover (Ewers and Didham, 2006). While the Amazon is one of the least fragmented and most contiguous tropical forests, escalating demands for land conversion are triggering swift and profound alterations, requiring immediate conservation measures (FAO and UNEP, 2020).

Brazil shoulders a substantial responsibility, harboring 61.9% of the Amazon rainforest, with forest fragmentation emerging as a pressing (and oft-neglected) challenge alongside deforestation (Montibeller et al., 2020). While deforestation in the Amazon persists, efforts targeting forest fragmentation remain lacking (Trejo et al., 2021), creating a gap in conservation strategies.

The Brazilian Amazon's fragmentation is intensifying (Montibeller et al., 2020; Skole and Tucker, 1993). From 2001–2017, the number of fragments increased by 68.5%, along with a 46.1% reduction in mean fragment size (Montibeller et al., 2020). Expansion of the agricultural frontier drives this process, starting from "the Arc of Deforestation" in the biome's southern reaches and progressively spreading across the Amazon (Montibeller et al., 2020; Trindade, 2013; Vedovato et al., 2016).

Research on fragmentation within the Brazilian Amazon spans various disciplines and scales, from ecological and political-administrative analyses to hydrographic studies (Barbosa et al., 2018; Batistella et al., 2003; Cabral et al., 2018; Coutinho, 2019; Jesus et al., 2019; Lisboa et al., 2019; Michalski et al., 2008; Montibeller et al., 2020; Pinheiro, 2019; Skole and Tucker, 1993; Vedovato et al., 2016). Particularly underexplored is the trajectory of fragmentation in the Brazilian Amazon — its sequence, duration, and spatial distribution of changes within the fragmented landscape. Such trajectory analysis has been increasingly addressed in landscape analysis, including deforestation (Carrero et al., 2020), secondary vegetation dynamics (Nunes et al., 2020), forest regeneration (Müller-Hansen et al., 2017) and land use changes (Hernández et al., 2016). Understanding fragmentation trajectory within the Amazon rainforest assumes crucial importance for planning effective conservation strategies, especially for natural forest patches.

This study aims to delineate forest fragmentation characteristics across Brazilian Amazon macroregions over a 34-year span. We used the trajectory analysis to evaluate the level of forest fragmentation in the Brazilian Amazon. We further present targeted conservation strategies aimed at mitigating fragmentation within the Brazilian Amazon, based on our findings and limited to distinct fragmentation dynamics among macroregions with divergent development paths.

Material and methods

The Brazilian Amazon Forest Biome (hereafter the Brazilian Amazon) was divided into three macroregions (Becker, 2005; Trindade, 2013), which reflect historical differences in socioeconomic and environmental dynamics: Western Amazon (WA, comprising the states Acre, Amazonas, and Roraima), Central Amazon (CA, Amapá, part of Amazonas and Pará), and Eastern Amazon (EA, part of Acre, Amapá, part of Maranhão, part of Mato Grosso, Rondônia, part of Tocantins) (Supplementary Material: study area; Figure S1). WA, with greater forest conservation and low human occupation, contrasts with EA, with the largest human concentration and rampant deforestation. CA, while under high pressure on natural resources, has several protected areas.

The trajectory of the fragmentation on the Brazilian Amazon and its macroregions from 1985 to 2018 was analyzed by adapting from Mas et al. (2019), using the TraMineR package in R (Gabadinho et al., 2011), along with classes samples from Morphological Spatial Pattern Analysis (MSPA) (Vogt et al., 2007). Fragmentation quantity, mean area, and an aggregation index were also obtained via FRAGSTATS (McGarigal et al., 2015). The aggregation index measures a class's pixel clustering in a raster image, reaching a maximum (1) when pixels share the most edges and a minimum (0) when pixels are fully separated. It was calculated as a percentage (0–100%) (He et al., 2000).

MSPA evaluates spatial patterns in a binary landscape (forest x non-forest). It outputs seven spatial pattern classes of forest related to ecological functions in a fragmented landscape (Core, Edge, Perforation, Bridge, Loop, Branch, and Islet) and a non-forest class denominated Background (Fig. 1). In our study, forested pixels also include secondary forest. All anthropogenic land covers were aggregated into the 'Background' class. Forest Core is the only forest cover class not in contact with the anthropized areas (Background), thus, it does not experience edge effects like the other classes. It may be primary or secondary forest in process of recovery. Edge and Perforation classes serve as transitions between Core and Background. Bridge and Loop are forest strips connecting to Core, potentially acting as ecological corridors. Branch is connected to Core but mostly surrounded by Background, offering potential for species rescue in anthropogenic matrix. Islets are small forest remnants, too small to sustain a Core area, but valuable for restoration and connectivity, functioning as "stepping stones" between fragments.

Input data, for the MSPA classes, comprised MapBiomas-collection 4.0 raster images (89% accuracy for level 2 – a more specific subdivision of land use and cover classes than level 1) from 1985 to 2018 (Souza et al., 2020). The pixel size was resized from 30 m to 120 m using the nearest-neighbor resampling method and the classes were reclassified to distinguish between anthropogenic cover (assigned value 1, such as agriculture and infrastructure), forest cover (2) and other natural cover (0), such as water. As MapBiomas makes no distinction between primary and secondary forest, in this study we treated them as the same class.

MSPA analysis utilized GuidosToolbox software (Vogt and Riitters, 2017), with Edge Width set at four pixels (480 m), according to the estimated 400 m edge effect within fragments in the biome (Laurance et al., 2018). More details about the analysis parameters can be found in Vogt et al. (2007).

MSPA generated classification results for each year, while the TraMineR package analyzed trajectories based on specific locations, assigning one class per year to each sequence. This approach limited the

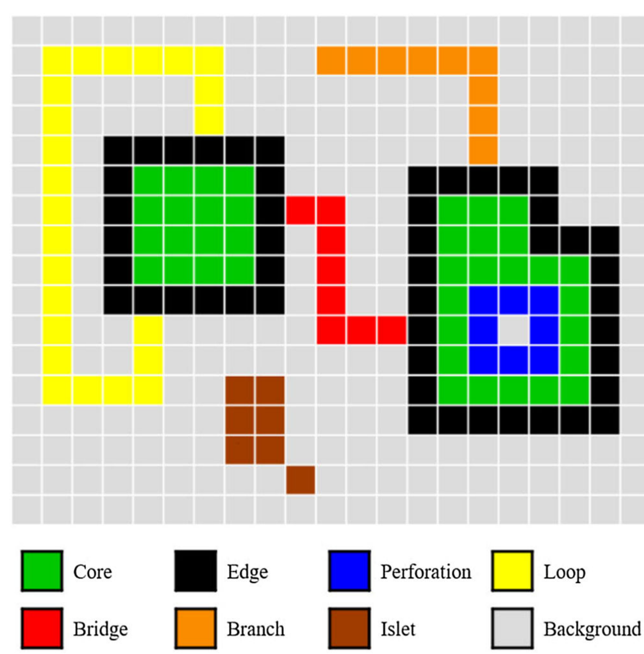

Fig. 1. Diagram of output classes in Morphological Spatial Pattern Analysis (MSPA). See text for details.

analysis of sample patterns with multiple pixels, as it could not account for areas containing more than one class per year. The samples were generated from MSPA classes via systematic sampling with fixed centroids using a regular grid (60 × 60 km), generating 1020 samples per year, where one sample corresponded to one pixel and only one class. Population proportions and standard errors were conservatively estimated for the random sample design (Cochran, 1977) (Supplementary Material; Tables S1 and S2). Classes with similar ecological functions were grouped: *Bridge* and *Loop* were grouped into *Connector*; and *Edge* and *Perforation* were grouped into *Edge*, resulting in five classes of spatial pattern.

Samples from MSPA classes were used as input for trajectory analysis with the TraMineR package, producing outputs like class sequences, transitions, entropy (location), and permanence — the average time (in years) a sample stays within a class. Entropy assessed spatial and temporal trajectory variability. Entropy is the diversity of the observed states of a pixel over its 34 annual time steps, where zero entropy means no diversity, and its value increases according to the amount of variation in the states. Derived from this indicator is the transversal entropy, which measures the variability in the distribution of classes across sequences at a specific time point (Gabadinho et al., 2011).

Results

Brazilian Amazon biome

In 1985, forests covered 92% (3.87 million km^2) of the Amazon biome in Brazil (4.2 million km^2), while anthropogenic activities (Background) occupied only 3% (0.14 million km^2) of the land. The remaining 5% comprised other non-forest categories. In 2018, 34 years later, the area occupied by Background had increased to 14% (0.59 million km^2), while forest cover had dwindled to 80% (3.4 million km^2). The annual increase in anthropized areas was 4.5% of its 1984 extent annually but has stabilized at approximately 1% per year since 2009.

The Core class, dominant throughout the study period, experienced a 15% reduction. Forest classes in contact with anthropogenic activities were progressively encroached upon by the latter (more details in the next section). Among these classes, the Connector class consistently held dominance throughout the period. The fragmentation pattern suggests patchy deforestation, even in areas with high intensity, where fragments remain interconnected. Among the regions, the Eastern Amazon (EA) was most affected by fragmentation, reflecting a development model that generally promotes forest conversion to other land uses.

Over the entire 34-year time series, the Core had a mean permanence of 26.7 years, whereas Background had a mean permanence of 2.7 years (Table 1). Among intermediate classes between Core and Background, Connector had the longest permanence (3.1 years). This implies that, on average, Core fragments remained connected for 3 years after the emergence of the Connector class, a potentially relevant aspect for conservation and restoration efforts. A similar interpretation can be applied to other classes. However, the high variance in these estimates underscores diverse dynamics and necessitates caution in their interpretation. For instance, although permanence of the Core is limited by the period of this study (34 years), it was lower than the studied period, indicating that its permanence is reducing and that might be influenced by transitions in secondary forests within the Core.

Table 1
Permanence of classes in years.

Class	Mean	Variance	Standard deviation
Core	26.7	140.5	11.9
Edge	1.0	9.4	3.1
Branch	0.2	2.3	1.5
Connector	3.1	45.9	6.8
Islet	0.2	2.3	1.5
Background	2.7	54.3	7.4

Aside from Core, the most prevalent classes were Connector and Background. Transitions rate among classes were presented in Supplementary Material (Table S3). The main sequence of the fragmentation trajectory in the Amazon included few classes identified as Core-Connector-Background. A small part of the Background may revert to forested classes, especially becoming a Connector. Intermediate classes like Edge and Connector can also transition to Core.

Brazilian Amazon macroregions

From 1985 to 2018, all three macroregions showed a consistent increase in fragment numbers and a decrease in mean fragment size. This trend was least pronounced in the WA, with a 36.5% rise in fragment numbers (from 49,871 to 68,067) and a 28% drop in mean area (from 2825.7 to 2036.8 ha). In contrast, the EA showed the largest changes, with a 178% increase in fragments (from 164,249 to 456,399) and a 75% reduction in mean size (from 651.8 to 162.3 ha). The CA fell in between, with an 82% increase in fragment numbers (from 72,463 to 132,051) and a 48% decrease in mean area (from 1747.4 to 905.4 ha).

The EA had the lowest aggregation index values (96% in 1985, and 92% in 2018). In contrast, the WA (99% in 1985 and 99% in 2018) and the CA (98% in 1985 and 98% in 2018) showed similar values with little variation over time. Thus, while the EA is comparatively the most fragmented macroregion, forest aggregation remains relatively high across all three macroregions. This could come in handy for ongoing conservation efforts and future restoration measures.

The WA experienced fewer trajectory changes and less anthropogenic activity, with low Background and Edge class presence, resulting in lower fragmentation. In contrast, the CA experienced increased anthropogenic activity, leading to more Connector and Edge classes. The EA saw a rise in Background, with increases in Edge, Branch, and Islet classes, which were rare in the other macroregions. By 2018, the EA exhibited notably higher values for Edge (8%), Branch (3%), and Islet (5%) compared to the CA (3%, 1%, and 0.4% respectively) and the WA (1%, 0.1%, and 0.1% respectively).

Distinct class characteristics across macroregions are also evident in terms of permanence. In the EA, the shortest permanence for Core (18 years) and the longest permanence for all other classes, underscore the more advanced stage of fragmentation in this macroregion. Additionally, the sequences of classes also varied across macroregions (Fig. 2a,b). In the WA, Core predominated with minimal transitions to Connector or Edge. In the CA, there was a greater transition from Core to Connector, followed by Connector transitioning to Background. Conversely, in the EA, there were more substantial changes among the classes, with reductions in Core and increased flows to Connector, Background, Branch, and Islet, classes with little or no presence in the other macroregions.

In each macroregion, these transitions occur at different frequencies (Fig. 2b). In the WA, the permanence of Core was positive and significantly more frequent ($X^2 = 0.05$, Pearson Residuals) compared to the EA (rare). In addition, the transitions to the other classes in EA, specially to Connector and Background were positive with lower significant, in contrats with the same transitions in WA were they were rare. The CA macroregion remained neutral in both of these scenarios. All values remain within −2 and +2, meaning not significant under- or over-representation.

These macroregion variations directly impacted entropy (Fig. 3), with the EA showing the highest mean value, though overall entropy remained low across all regions (WA: 0.06, CA: 0.12, EA: 0.28) and varied widely. Entropy's spatial distribution best explained macroregion variation, with high values in the EA and CA. Transversal entropy, reflecting class variety per year, increased over the study period, stabilizing in the early 2000s, with the EA having the highest values and the WA having the lowest.

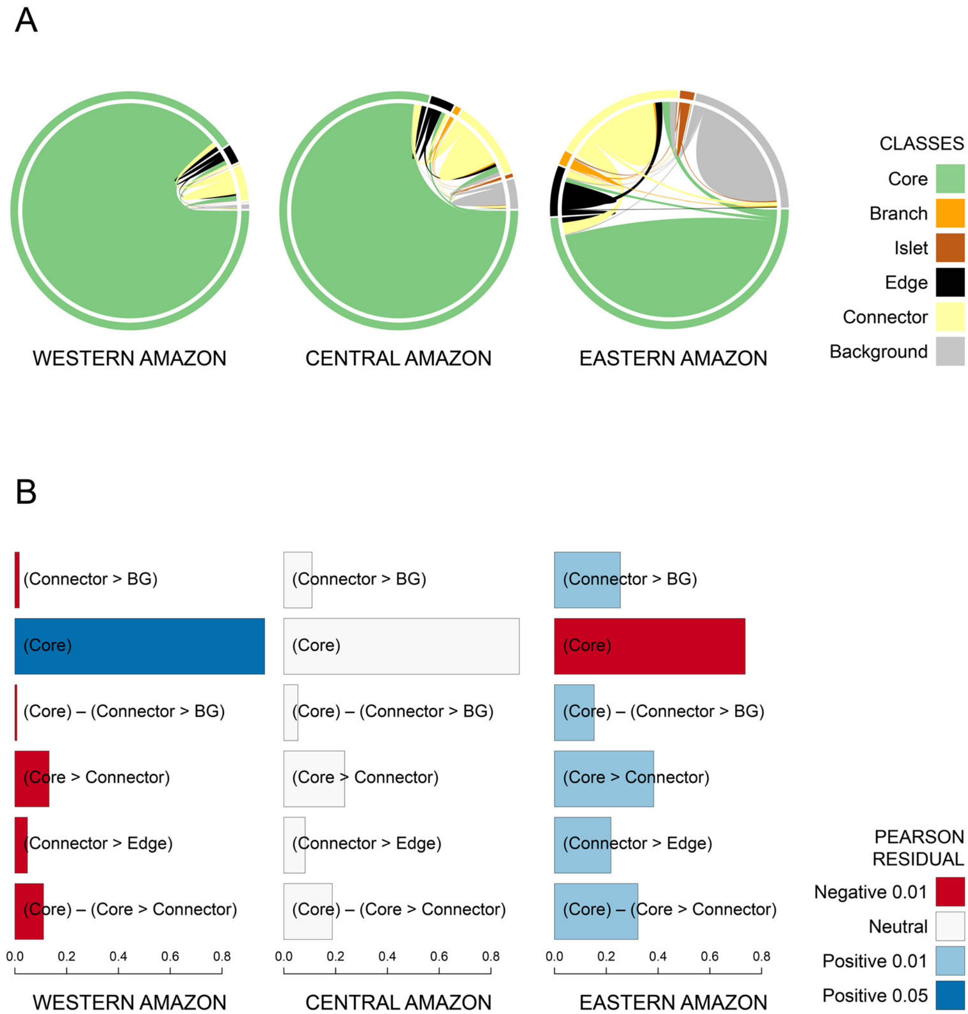

Fig. 2. Fragmentation classes and sequences in the Brazilian Amazon macroregions: In (A), the origin class is indicated by the outer ring colour, while the band extending to a different colour represents the destination class, showing the transition between them. Areas without class transitions, particularly in Core, Background, and Connector, indicate stable zones. In (B), Pearson Residuals for each macroregion are shown, with positive values (blue) indicating frequent transitions and negative values (red) signifying rare or unexpected transitions. The legend values represent significance levels, and bar length shows the magnitude of deviation; a value of 1 indicates some over-representation but is not significant (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

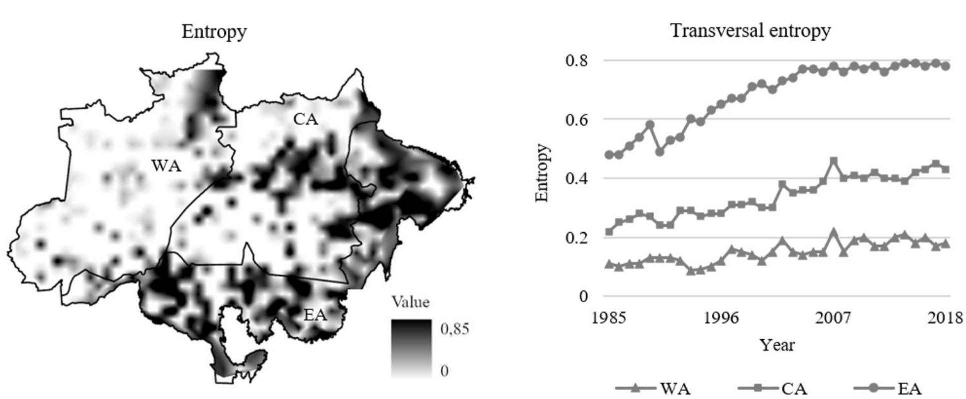

Fig. 3. Entropy (left) and transversal entropy (right) within the macroregions (CA: Central Amazon; EA: Eastern Amazon; WA: Western Amazon).

Discussion

The Brazilian Amazon has experienced relevant forest fragmentation between 1985 and 2018, with fragment numbers rising and sizes decreasing across all macroregions. The EA was most affected, while the WA showed the least change. Despite this, forest aggregation remains relatively high in all regions, indicating opportunities for conservation and restoration.

Forest connections between large fragments are fragile, as shown by the short permanence of classes, and are increasingly disrupted by deforestation, especially since 2008 (Assis et al., 2019), and may quickly convert forests into clear-cut areas. In addition to reducing deforestation, mitigating fragmentation contributes to ecosystem services and conservation (Mitchell et al., 2015; Ng et al., 2013). Yet, as the Amazon fragmentation trajectory was short in stages – from Core to Connector to Background – and permanence, conservation actions have an opportunity to increase effectiveness. For instance, from the perspective of land sharing/land sparing (Grass et al., 2019), Branch classes may be vital habitats for species across the landscape. However, efforts for Branch connectivity or maintenance may fail due to longer planning and implementation timelines than its permanence at a location (e.g., 0.54 years in the EA), unlike Connector, a more viable option (e.g., 5.4 years in the EA).

Maintaining high permanence levels reduces entropy, while transversal entropy remains stable. Together with other indicators (e.g., class frequency), entropy serves as a key metric for monitoring efforts to reduce fragmentation and enhance connectivity. The transversal entropy increased at the beginning of the time series and stabilized since early 2000s, especially in the EA. Cause effects may include local deforestation reduction, deforestation spillover, and secondary forest recovery (Montibeller et al., 2020; Nunes et al., 2020; Wang et al., 2020).

The expansion of secondary forest fragments in the Amazon may exceed those with primary forest (Montibeller et al., 2020; Nunes et al., 2020). Secondary forests may elucidate the transition dynamics among classes such as the reversion from the Background class to forested classes, as well as from intermediate classes (Edge and Connector) to Core. Moreover, the deforestation–recovery–deforestation cycle can recur in the Amazon for multiple reasons, including land speculation (Brito and Barreto, 2020) and abandoned pastures (Wang et al., 2020). Without protective laws, younger secondary forest classes (<5 years) are particularly prone to multiple deforestations over time (Nunes et al., 2020; Wang et al., 2020), collectively contributing to increased entropy.

Integrating fragmentation metrics into conservation strategies can enhance effectiveness and guide targeted actions. Based on forest fragmentation dynamics in the Brazilian Amazon, we propose several policy recommendations:

a **Utilize and conserve secondary forests:** Developing a national legal framework for the management of secondary forests can mitigate the effects of fragmentation and promote the long-term persistence of fragment classes, buying time for reforestation, aligning with species mobility (Laurance et al., 2018) and international forest protection agreements (Montibeller et al., 2020; Nunes et al., 2020; Wang et al., 2020). This approach is particularly suitable for the Amazon biome's southern reaches (Arc of deforestation).
b **Include private forests to enhance connectivity across the landscape:** Amazon private properties also have their share in mitigation efforts, leveraged by the mandatory maintenance of up to 80% native forests (Trejo and Azevedo-Ramos, 2020). Prioritizing strategies in large properties may enhance connection of large blocks of Amazon forests and permanence of forest classes. Environmental agencies may contribute advising on the spatial allocation of private forests (Legal reserves) within the properties. This measure is reinforced when current connector areas are considered in the strategic planning, due to their permance, medium-term strategies can be considered. This approach is particularly suitable for EA.
c **Expand and strengthen protected areas based on socio-environmental and economic context:** Protected areas strengthening is crucial due to their deterrent effect on fragmentation compared to their surroundings (Cabral et al., 2018; Montibeller et al., 2020). Moreover, utilizing over 50 million hectares of undesignated public forest in the Amazon can establish new protected areas, foster connectivity, and curb deforestation and illegal encroachment (Moutinho and Azevedo-Ramos, 2023). This approach is particularly suitable for the WA and CA.

Giving the rising demand for natural resources, pressure on Amazon forests is expected to increase. Sustainable development plans should be tailored to the specificities of macroregions, reinforcing good practices, social inclusion, and local life quality. Actions should be geared towards greater protection in the WA and CA and reforestation efforts in the EA.

Conclusion

The Brazilian Amazon Forest Biome has experienced significant forest fragmentation, with fragments increasing in number and decreasing in size over a 34-year period. Amazon forest class transitions were limited to a few stages, mainly from Core forests to Connector classes, then to anthropogenic areas. Analyzing fragmentation trajectories helps target actions to prevent negative scenarios and improve connectivity in fragmented or degraded areas.

The Central Amazon's intermediate fragmentation requires immediate attention to align forest use with conservation. Focus should be on preserving Core and Connector classes to prevent severe fragmentation, as seen in the Eastern Amazon. This study highlights how understanding fragmentation dynamics can improve conservation and restoration strategies, as rapid class changes often render existing approaches outdated, leading to resource loss and unmet goals.

Conservation strategies should prioritize enhanced connectivity, utilizing protected areas, private forests, undesignated public forests, and secondary forests to mitigate fragmentation and maintain ecosystem function. We also advocate for a shift toward sustainable development, as increasing fragmentation demands greater scientific and political focus.

CRediT authorship contribution statement

Pedro Trejo: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Claudia Azevedo-Ramos:** Writing – review & editing, Formal analysis. **Felipe Lenti:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors report no competing interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2025.04.001.

References

Assis, L.F.F.G., Ferreira, K.R., Vinhas, L., Maurano, L., Almeida, C., Carvalho, A., Rodrigues, J., Maciel, A., Camargo, C., 2019. TerraBrasilis: a spatial data analytics infrastructure for large-scale thematic mapping. ISPRS Int. J. Geo Inf. 8, 513. https://doi.org/10.3390/ijgi8110513.
Barbosa, S.G., Spletozer, A.G., Roque, M.P.B., Ferreira Neto, J.A., Dias, H.C.T., Ramos, M. P., Bonilla, M.A.C., Ribeiro, W.S., Alcántara-De La Cruz, R., Zanuncio, J.C., 2018. Geotechnology in the analysis of forest fragments in northern Mato Grosso, Brazil. Sci. Rep. 8, 3959. https://doi.org/10.1038/s41598-018-22311-y.
Batistella, M., Robeson, S., Moran, E.F., 2003. Settlement design, forest fragmentation, and landscape change in rondônia, amazônia. Photogramm. Eng. Remote Sens. 69, 805–812. https://doi.org/10.14358/PERS.69.7.805.
Becker, B.K., 2005. Geopolítica da amazônia. Estud. Avançados 19, 71–86. https://doi.org/10.1590/S0103-40142005000100005.

Brito, B., Barreto, P., 2020. Nota técnica sobre Medida Provisória n.º 910/2019.

Cabral, A.I.R., Saito, C., Pereira, H., Laques, A.E., 2018. Deforestation pattern dynamics in protected areas of the Brazilian Legal Amazon using remote sensing data. Appl. Geogr. 100, 101–115. https://doi.org/10.1016/j.apgeog.2018.10.003.

Carrero, G.C., Fearnside, P.M., do Valle, D.R., de Souza Alves, C., 2020. Deforestation trajectories on a development frontier in the Brazilian amazon: 35 years of Settlement colonization, policy and economic shifts, and Land accumulation. Environ. Manage. 66, 966–984. https://doi.org/10.1007/s00267-020-01354-w.

Cochran, W.G., 1977. Sampling Techniques. John Wiley & Sons, New York.

Coutinho, J. da S., 2019. Uso de geotecnologias para análise da fragmentação florestal, em uma área do município de Capitão Poço-Pa. 64f. Orientadora: Dr.a Paula Nepomuceno Campos Coorientador: MSc. Bruno Monteiro Ferreira. Trabalho de Conclusão de Curso (Bacharelado em Ciências Biológicas) - Universidade Federal Rural da Amazônia.

Ewers, R.M., Didham, R.K., 2006. Confounding factors in the detection of species responses to habitat fragmentation. Biol. Rev. Camb. Philos. Soc. 81, 117–142. https://doi.org/10.1017/S1464793105006949.

FAO, 2020. The State of the World' Forests 2020. FAO and UNEP, Rome. https://doi.org/10.4060/ca8642en.

Gabadinho, A., Ritschard, G., Müller, N.S., Studer, M., 2011. Analyzing and visualizing state sequences in R with TraMineR. J. Stat. Softw. 40, 1–37. https://doi.org/10.18637/jss.v040.i04.

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., Klaus, F., Riechers, M., Rosa, J., Tiede, J., Udy, K., Westphal, C., Wurz, A., Tscharntke, T., 2019. Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. People Nat. 1. https://doi.org/10.1002/pan3.21.

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sexton, J.O., Austin, M.P., Collins, C.D., Cook, W.M., Damschen, E.I., Ewers, R.M., Foster, B.L., Jenkins, C.N., King, A.J., Laurance, W.F., Levey, D.J., Margules, C.R., Melbourne, B.A., Nicholls, A.O., Orrock, J.L., Song, D.-X., Townshend, J.R., 2015. Habitat fragmentation and its lasting impact on earth's ecosystems. Sci. Adv. 1, 1–9. https://doi.org/10.1126/sciadv.1500052.

He, H.S., DeZonia, B.E., Mladenoff, D.J., 2000. An aggregation index (AI) to quantify spatial patterns of landscapes. Landsc. Ecol. 15, 591–601. https://doi.org/10.1023/A:1008102521322.

Hernández, A., Miranda, M.D., Arellano, E.C., Dobbs, C., 2016. Landscape trajectories and their effect on fragmentation for a Mediterranean semi-arid ecosystem in Central Chile. J. Arid Environ. 127, 74–81. https://doi.org/10.1016/j.jaridenv.2015.10.004.

Jesus, J.B. de, Gama, D.C., Nascimento Jr, J.M. do, Fernandes, M.M.M.R. de M., Fernandes, M.M.M.R. de M., 2019. Fragmentação florestal em região semiárida no Nordeste do Brasil. Pesqui. Florest. Bras. 39. https://doi.org/10.4336/2019.pfb.39e201801683.

Laurance, W.F., Camargo, J.L.C., Fearnside, P.M., Lovejoy, T.E., Williamson, G.B., Mesquita, R.C.G., Meyer, C.F.J., Bobrowiec, P.E.D., Laurance, S.G.W., 2018. An Amazonian rainforest and its fragments as a laboratory of global change. Biol. Rev. 93, 223–247. https://doi.org/10.1111/brv.12343.

Lisboa, L.S., Almeida, A.S. de, Lameira, W.J., 2019. Análise temporal da fragmentação florestal no leste da Amazônia legal. Novos Cad. NAEA 22, 141–156. https://doi.org/10.5801/ncn.v22i3.6571.

Mas, J.F., Vasconcelos, R.N., Franca-Rocha, W., 2019. Analysis of high temporal resolution land use/land cover trajectories. Land 8, 30. https://doi.org/10.3390/land8020030.

McGarigal, K., Cushman, S.A., Ene, E., 2015. FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps.

Michalski, F., Peres, C.A., Lake, I.R., 2008. Deforestation dynamics in a fragmented region of southern Amazonia: evaluation and future scenarios. Environ. Conserv. 35, 93–103. https://doi.org/10.1017/S0376892908004864.

Mitchell, M.G.E., Suarez-Castro, A.F., Martinez-Harms, M., Maron, M., McAlpine, C., Gaston, K.J., Johansen, K., Rhodes, J.R., 2015. Reframing landscape fragmentation's effects on ecosystem services. Trends Ecol. Evol. 30, 190–198. https://doi.org/10.1016/j.tree.2015.01.011.

Montibeller, B., Kmoch, A., Virro, H., Mander, Ü., Uuemaa, E., 2020. Increasing fragmentation of forest cover in Brazil's Legal Amazon from 2001 to 2017. Sci. Rep. 10, 5803. https://doi.org/10.1038/s41598-020-62591-x.

Moutinho, P., Azevedo-Ramos, C., 2023. Untitled public forestlands threaten Amazon conservation. Nat. Commun. 14, 1152. https://doi.org/10.1038/s41467-023-36427-x.

Müller-Hansen, F., Cardoso, M.F., Dalla-Nora, E.L., Donges, J.F., Heitzig, J., Kurths, J., Thonicke, K., 2017. A matrix clustering method to explore patterns of land-cover transitions in satellite-derived maps of the Brazilian Amazon. Nonlinear Process. Geophys. 24, 113–123. https://doi.org/10.5194/npg-24-113-2017.

Ng, C.N., Xie, Y.J., Yu, X.J., 2013. Integrating landscape connectivity into the evaluation of ecosystem services for biodiversity conservation and its implications for landscape planning. Appl. Geogr. 42, 1–12. https://doi.org/10.1016/j.apgeog.2013.04.015.

Nunes, S., Oliveira, L., Siqueira, J., Morton, D.C., Souza, C.M., 2020. Unmasking secondary vegetation dynamics in the Brazilian Amazon. Environ. Res. Lett. 15, 034057. https://doi.org/10.1088/1748-9326/ab76db.

Pinheiro, P.F.V., 2019. Fragmentação florestal em áreas protegidas na Amazônia maranhense e conservação da biodiversidade. Orientadora: Maria de Lourdes Pinheiro Ruivo, 2019. 150 f. Tese (Doutorado em Biodiversidade e Biotecnologia da Rede BIONORTE) - Universidade Federal do Pará, Belém.

Skole, D., Tucker, C., 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. Science (80-.) 260, 1905–1910. https://doi.org/10.1126/science.260.5116.1905.

Souza, C.M., Shimbo, J.Z., Rosa, M.R., Parente, L.L., Alencar, A.A., Rudorff, B.F.T., Hasenack, H., Matsumoto, M., Ferreira, L.G., Souza-Filho, P.W.M., de Oliveira, S.W., Rocha, W.F., Fonseca, A.V., Marques, C.B., Diniz, C.G., Costa, D., Monteiro, D., Rosa, E.R., Vélez-Martin, E., Weber, E.J., Lenti, F.E.B., Paternost, F.F., Pareyn, F.G.C., Siqueira, J.V., Viera, J.L., Neto, L.C.F., Saraiva, M.M., Sales, M.H., Salgado, M.P.G., Vasconcelos, R., Galano, S., Mesquita, V.V., Azevedo, T., 2020. Reconstructing three decades of land use and land cover changes in Brazilian biomes with landsat archive and earth engine. Remote Sens. 12, 2735. https://doi.org/10.3390/rs12172735.

Trejo, P., Azevedo-Ramos, C., 2020. La experiencia de la Reserva Legal en Brasil: una opción de conservación en propiedades rurales. Hist. Ambient. Latinoam. Caribeña Rev. la Solcha 10, 300–318. https://doi.org/10.32991/2237-2717.2020v10i3.p300-318.

Trejo, P., Azevedo-Ramos, C., Szlafasztein, C.F., 2021. La dinámica de la fragmentación forestal en la Amazonia brasileña. In: Ravena, N., Acevedo Marin, R.E. (Eds.), Amazônia: As Ameaças Das Politicas Desenvolvimentistas. NAEA, Belém, Brasil, pp. 183–205.

Trindade Jr., S.-C.C., 2013. Uma Floresta Urbanizada? Legado e Desdobramentos de uma Teoria sobre o Significado da Cidade e do Urbano na Amazônia. Espaço Aberto 3, 89–108. https://doi.org/10.36403/espacoaberto.2013.2117.

Vedovato, L.B., Fonseca, M.G., Arai, E., Anderson, L.O., Aragão, L.E.O.C., 2016. The extent of 2014 forest fragmentation in the Brazilian Amazon. Reg. Environ. Chang. 16, 2485–2490. https://doi.org/10.1007/s10113-016-1067-3.

Vogt, P., Riitters, K., 2017. GuidosToolbox: universal digital image object analysis. Eur. J. Remote Sens. 50, 352–361. https://doi.org/10.1080/22797254.2017.1330650.

Vogt, P., Riitters, K.H., Estreguil, C., Kozak, J., Wade, T.G., Wickham, J.D., 2007. Mapping spatial patterns with morphological image processing. Landsc. Ecol. 22, 171–177. https://doi.org/10.1007/s10980-006-9013-2.

Wang, Y., Ziv, G., Adami, M., Almeida, C.Ade, Antunes, J.F.G., Coutinho, A.C., Esquerdo, J.C.D.M., Gomes, A.R., Galbraith, D., 2020. Upturn in secondary forest clearing buffers primary forest loss in the Brazilian Amazon. Nat. Sustain. 3, 290–295. https://doi.org/10.1038/s41893-019-0470-4.