Conservation Biology
DOI: https://doi.org/10.1111/cobi.14033

SUPPORTING INFORMATION

Effects of Amazonian flying rivers on frog biodiversity and populations in the Atlantic rainforest

Lucas Ferrante[1], Augusto Getirana[2,3], Fabricio Beggiato Baccaro[4], Jochen Schöngart[1], Ana Cristina Monteiro Leonel[5], Renato Gaiga[6], Michel Varajão Garey[7] & Philip Martin Fearnside[1]

[1]Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Brazil.
[2]Science Applications International Corporation, Maryland, USA.
[3]Hydrological Sciences Laboratory, NASA Goddard Space Flight Center, Maryland, USA.
[4]Univertisdade Federal do Amazonas (UFAM), Manaus, Brazil.
[5]Programa de Pós-Graduação em Oceanografia (PPGO), Universidade de São Paulo (USP), São Paulo Brazil.
[6]Biotropica Consultoria Ambiental, Poços de Caldas, Brazil.
[7]Universidade Federal da Integração Latino-Americana (UNILA), Foz do Iguaçu, Brazil.
E-mail: lucasferrante@hotmail.com

Conservation Biology

DOI: https://doi.org/10.1111/cobi.14033

Appendix S1 Vouchers and individuals analyzed.

Vouchers used in morphological comparisons and analyses were: (Célio F. B. Haddad Amphibian Collection - CFBH: 38882, 38883, 39919, 39920, 39921, 39922, 39922); (Alfred Russel Wallace Collection – Unifal/MG only for Areado: CHARW A 2549, CHARW A 2550, CHARW A 2551, CHARW A 2552, CHARW A 2553, CHARW A 2554, CHARW A 2690); (Coleção de Anfíbios da Universidade Federal da Integração Latino-Americana only for Poços de Caldas: CA-UNILA 272, CA-UNILA 273, CA-UNILA 274, CA-UNILA 275, CA-UNILA 276, CA-UNILA 277, CA-UNILA 280).

Appendix S2. Extent of occurrence for *Hylodes sazimai*.

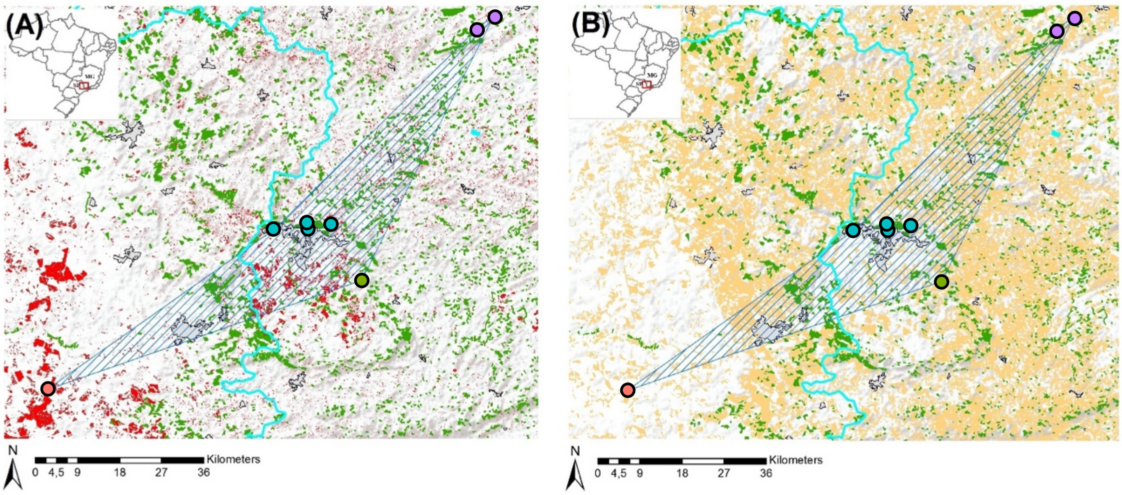

Fig. S1. Known extent of occurrence for *Hylodes sazimai* delimited by polygon and locality for each of the populations according to genetic inferences (See. Figure 1 in the main text): Campinas = red point; Caldas = green point; Poços de Caldas = blue points; Areado = purple points. (A) The red polygon represents natural forest loss from 2008 to 2018 according INPE images. (B) The orange area represents pasture.

The new habitats included seasonal semi-deciduous Atlantic Forest fragments and ombrophilous high Montane Atlantic Forest fragments. According to our visual and auditory observations, *H. sazimai* is the most abundant species in the interior of primary and conservation forests, the number of vocalizing males decreasing near the edges of forests and in areas with less forest cover. The species occurs in ombrophilous high Montane Atlantic Forest in the Serra de São Domingos and Serra do Selado hills in Poços de Caldas municipality and in semideciduous forest fragments in Areado municipality.

Conservation Biology
DOI: https://doi.org/10.1111/cobi.14033

Fig S2. Habitat and vocalization sites of *Hylodes sazimai*: (a,b,c,d) Poços de Caldas locality; (e) and (f) Caldas locality; (g) Areado locality.

DOI: https://doi.org/10.1111/cobi.14033

Appendix S3 A gap in monitoring threats to Brazilian amphibians.

Both observed and projected climate change should be considered in extinction risk assessments for species in Brazil's Atlantic Forest, which is an area of climate instability (Main text, Fig. 3e). The Atlantic Forest biome is severely fragmented and isolated (Ribeiro et al., 2009; Rosa et al., 2021), as are populations of strict-forest frogs (Dixo et al., 2009) and even populations of habitat generalists (Telles et al., 2007). This is partly due to changes in land cover for agricultural activities and the consequent increased use of pesticides in the agricultural landscape (Ferrante et al., 2019), which has caused local mutations and extinctions in amphibians in Brazil (Ferrante & Fearnside, 2020c). The agricultural matrix around forest fragments has become impassable and inhospitable to many species (Ferrante et al., 2017). Our results show that the climatic stress (Fig. 4e) and climate anomalies in these areas (Main text, Fig. 5) may be one of the factors causing anuran population fragmentation, since open areas and agricultural crops have lower humidity and higher temperature, making them inhospitable to many species of amphibians.

Based on local studies that show the inhospitality of the landscape to anuran communities and populations (Ferrante et al., 2017; 2019), together with genetic data that show population isolation (Telles et al., 2007; Dixo et al., 2009), "Criterion B" of the red-list evaluation methodology ("Restricted geographic distribution, fragmentation, continued decline or extreme fluctuations") should be used for endemic species whose area of occupation or range of occurrence is wholly or partially within this zone of climatic instability (Main text, Fig. 4e). Significant reductions in the areas of occurrence and occupation for endemic species in this area have already been reported, classifying them as "at risk of extinction," as is the case of *Scinax caldarum* (EN) (Ferrante et al., 2019).

In the assessment of threatened species by the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), which is the Brazilian authority responsible for fauna and flora, several researchers evaluating amphibians in the Atlantic Forest have argued that many endemic species would be protected because they are abundant, are located in protected areas or because they do not have any apparent threat (ICMbio, 2022). An analogy was even created comparing extinction risk for some species with the risk of a catastrophic meteor impact like the one that extinguished the dinosaurs. However, our results suggest that ongoing climate change is an extinction event for the species that are endemic to these areas. This means that that the red list of threatened species in the Atlantic Forest is underestimated and that there is high probability of a silent loss of species in the coming years.

References

ICMbio. (2022). Portaria MMA No 148, de 7 de junho de 2022. https://www.in.gov.br/en/web/dou/-/portaria-mma-n-148-de-7-de-junho-de-2022-406272733

Conservation Biology
DOI: https://doi.org/10.1111/cobi.14033

Dixo, M., Metzger, J. P., Morgante, J. S. & Zamudio, K. R. (2009). Habitat fragmentation reduces genetic diversity and connectivity among toad populations in the Brazilian Atlantic Coastal Forest. *Biological Conservation,* 142, 1560– 1569 DOI: https://doi.org/10.1016/j.biocon.2008.11.016

Ferrante, L., Baccaro, F. B., Ferreira, E. B., Sampaio, M. F. O., Santos, T., Justino, R. C., Angulo, A. (2017). The matrix effect: how agricultural matrices shape forest fragment structure and amphibian composition. *Journal of Biogeography,* 44, 1911-1922. DOI: https://doi.org/10.1111/jbi.12951

Ferrante, L., Leonel, A. C. M., Gaiga, R., Kaefer, I. L. & Fearnside, P. M. (2019). Local extinction of *Scinax caldarum*, a treefrog in Brazil's Atlantic Forest. *Herpetological Journal,* 29, 295-298. DOI: https://doi.org/10.33256/hj29.4.295298

Ribeiro, M. C., Metzger, J. P., Martensen, A. C., Ponzoni, F, J. & Hirota, M. M. (2009). The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for conservation. *Biological Conservation,* 142, 1141–1153 DOI: https://doi.org/10.1016/j.biocon.2009.02.021

Rosa, M.R., Brancalion, P. H. S., Crouzeilles, R., Tambosi, L. R., Piffer, P. R., Lenti, F. E. B., Hirota, M., Santiami, E., Metzger, J. P. (2021). Hidden destruction of older forests threatens Brazil’s Atlantic Forest and challenges restoration programs. *Science Advances,* 7, 4. DOI: https://doi.org/10.1126/sciadv.abc4547

Telles, M. P. C., Diniz-Filho, J. A. F., Bastos, R. P., Soares, T. N., Guimarães, L D. & Lima, L. P. (2007). Landscape genetics of *Physalaemus cuvieri* in Brazilian Cerrado: Correspondence between population structure and patterns of human occupation and habitat loss. *Biological Conservation,* 139, 37-46. DOI: https://doi.org/10.1016/j.biocon.2007.06.003

Conservation Biology
DOI: https://doi.org/10.1111/cobi.14033

Appendix S4 Threats to the locations of Amazonian high-pressure cells.

The southern portion of Amazonia, which is an area with high levels of deforestation, has the highest proportion of vapor-pressure cells to be exported from Amazonia to the studied locations in southeastern Brazil (Main text, Fig. 2). Worryingly, this is also one of the areas with the highest concentrations of climatic anomalies (Main text, Fig. 5). Climatic anomalies due to land-use change have occurred mainly in the arc of deforestation (Main text, Fig. 5), which has expanded to the interfluve between the Purus and Madeira Rivers along Highway BR-319 (Manaus-Porto Velho), a road that is serving as spearhead to provide access for land grabbing and deforestation for this portion of the Amazon (Ferrante et al., 2021b). This road gives access to one of the most preserved blocks of Amazon rainforest today and is a part of the center-western Amazonia area that has some of the high vapor-pressure cells that are responsible for rainfall in the locations we studied in the Atlantic Forest (Main text, Fig. 2).

The “middle section” of Highway BR-319 has deforestation rates up to 2.5 times higher than the average for the Brazilian Amazon as a whole (Ferrante et al., 2021b). The planned reconstruction of Highway BR-319 is linked to plans for side roads that would open the vast area of intact forest west of the Purus River to the entry of deforesters (Fearnside & Graça, 2006; Fearnside, 2021; 2022). Our results support the conclusion that these areas in the Amazon play a fundamental role in the rainfall in southeastern Brazil. The increase in deforestation in these areas would expand the frontiers of climatic anomalies linked to the land-use change that is currently concentrated in the arc of deforestation, expanding this deforestation to central and western Amazonia (Main text, Fig. 5). In fact, giving deforesters access to these forest areas by reconstructing Highway BR-319 and building associated side roads (Ferrante & Fearnside, 2020a) has the potential not only to cause the collapse of ecosystems and biodiversity in Amazonia (Ferrante et al., 2021a), but also to cause these same impacts in southeastern Brazil and threaten water supply to the human population in one of the most populous areas in the country.

The area along Highway BR-319 has a complete lack of governance to contain deforestation, even including irregular actions by some inspection agencies facilitating illegal deforestation and land grabbing (Andrade et al., 2021; Ferrante et al., 2021b). Deforestation in this area is surging due to the promises by politicians that BR-319 will soon be reconstructed, together with a “maintenance” program since 2015 that has gradually made the road, which had been abandoned since 1988, marginally passable in the dry season. The BR-319 reconstruction project has been shown to be both environmentally and economically unfeasible (Ferrante & Fearnside, 2020a; Ferrante et al., 2021a; 2021b), with projected impacts that both negatively impact biodiversity in the Amazon (dos Santos et al., 2019) and contribute to loss of the critical water recycling function of the western part of Brazilian Amazonia (Fearnside, 2022). As shown by the results of the present study, these changes would also impact the rainfall regime of southeastern Brazil and consequently the biodiversity of the Atlantic Forest.

Brazil must rapidly alter its policies affecting deforestation, not only rebuilding its largely dismantled environmental institutions and enforcing regulations governing

DOI: https://doi.org/10.1111/cobi.14033

land occupation and land use, but also immediately suspending any infrastructure projects that contribute to the advance of deforestation, such as the BR-319 highway (Ferrante et al., 2021a). Failure to do so can be expected to result in the emergence of climate anomalies, such as the climate instability cell formed in southeastern Brazil (Main text, Fig. 4e), thus causing a silent collapse of biodiversity in forests beyond the borders of the Amazon biome. Brazilian authorities, including the judiciary, have already been alerted to the need to suspend activities that have increased deforestation in the BR-319 highway area and of the consequences of the project for the loss of ecosystem services of the Amazon rainforest; however, none of these activities have been suspended (Ferrante & Fearnside, 2020a; Ferrante et al., 2021a). The effects beyond the borders of the Amazon region add to the need for Brazil's Federal Public Ministry, as well as politicians in the affected areas such as southeastern Brazil, to mobilize to stop this deforestation.

Deforestation in Amazonia, specifically in the area affected by BR-319, not only affects the "flying rivers" but also contributes to global warming, which, in turn, brings the region closer to the tipping point tolerated by the Amazon Forest (Wunderling et al., 2020) and by the Atlantic Ocean itself (Wunderling et al., 2021). The advance of Amazon degradation in the eastern portion of the region and other parts of the arc of deforestation is already causing the forest in these areas to emit more carbon than it absorbs, which feeds global climate change and, in turn, alters the water cycle that depends on the oceans and on the Amazon Forest (Gatti et al., 2021). Projections of carbon emission due to degradation, deforestation and fragmentation of the Amazon Forest indicate that up to 22.63 Gt CO_2 could be emitted by 2050 (Assis et al., 2022), which would have catastrophic implications for the hydrological cycles described in the present study (Main text, Figs. 2 and 3).

References:

Andrade, M., Ferrante, L. & Fearnside, P. M. (2021). Brazil's Highway BR-319 demonstrates a crucial lack of environmental governance in Amazonia. *Environmental Conservation,* 48, 161-164. DOI: https://doi.org/10.1017/S0376892921000084

Assis, T. O., Aguiar, A. P. D., Von Randow, C. & Nobre, C. A. (2022). Projections of future forest degradation and CO_2 emissions for the Brazilian Amazon. *Science Advances*, 8, eabj3309. DOI: https://doi.org/10.1126/sciadv.abj3309

dos Santos Júnior, M., Yanai, A. M., Sousa Junior, F. O., de Freitas, I. S., Pinheiro, H. P., de Oliveira, A. C. R., da Silva, F. L., Graça, P. M. L. A. & Fearnside, P. M. (2019). *BR-319 Como Propulsora de Desmatamento: Simulando o Impacto da Rodovia Manaus-Porto Velho*. IDESAM, Manaus. https://bityl.co/4skH

Fearnside, P. M. & Graça, P. M. L. A. (2006). BR-319: Brazil's Manaus-Porto Velho Highway and the potential impact of linking the arc of deforestation to central

Conservation Biology
DOI: https://doi.org/10.1111/cobi.14033

Amazonia. *Environmental Management,* 38, 705-716. DOI: https://doi.org/10.1007/s00267-005-0295-y

Fearnside, P. M. (2022). Amazon environmental services: Why Brazil's Highway BR-319 is so damaging. *Ambio.* DOI: https://doi.org/10.1007/s13280-022-01718-y

Ferrante, L. & Fearnside, P. M. (2020a). Amazon's road to deforestation. *Science,* 369, 634. DOI: https://doi.org/10.1126/science.abd6977

Ferrante, L., Andrade, M. B. T. & Fearnside, P. M. (2021b). Land grabbing on Brazil's Highway BR-319 as a spearhead for Amazonian deforestation. *Land Use Policy,* 108, 105559. DOI: https://doi.org/10.1016/j.landusepol.2020.104548

Ferrante, L., Andrade, M. B. T., Leite, L., et al. (2021a). Brazils Highway BR-319: The road to the collapse of the Amazon and the violation of indigenous rights. *Die Erde – Journal of the Geographical Society of Berlin,* 152, 65-70. DOI: https://doi.org/10.12854/erde-2021-552

Gatti, L. V., Basso, L. S., Miller, J. B. et al. (2021). Amazonia as a carbon source linked to deforestation and climate change. *Nature*, 595, 388–393. https://doi.org/10.1038/s41586-021-03629-6

Wunderling, N., Staal, A., Sakschewski, B., et al. (2020). Network dynamics of drought-induced tipping cascades in the Amazon rainforest. *Research Square* (preprint). DOI: https://doi.og/10.21203/rs.3.rs-71039/v1

Wunderling, N., Donges, J. F., Kurths, J. & Winkelmann, R. (2021). Interacting tipping elements increase risk of climate domino effects under global warming. *Earth System Dynamics,* 12, 601–619. DOI: https://doi.org/10.5194/esd-12-601-2021

Conservation Biology

DOI: https://doi.org/10.1111/cobi.14033

Appendix S5. *Hylodes sazimai* threat status.

The torrent frog *Hylodes sazimai* can be considered endangered according our assessment following the premises of the IUCN Red List, even considering the new populations reported here (EN B1ab (ii+iii)). This species has a distribution range smaller than of 5000 km^2, with the known extent of occurrence totaling only 1837 km^2 (Fig. S1, Supporting Information Appendix S1). The assessment shows that the population is severely fragmented (See. Fig. 1, Main manuscript) and area of habitat in the known range of the species is continuing to decline (recent deforestation, See. Fig. S1a in Supporting Information Appendix S1) and habitat quality is also declining (See. Fig. 3e in the Main manuscript). A large part of the known range of the species is occupied by sugarcane and cattle pasture (Supporting Information Appendix S1, Fig. S1b), which contributes to habitat quality loss in the interiors of the forest fragments (See. Ferrante et al. 2017). These land uses impact the quality of the Atlantic Forest fragments and of their anuran assemblages, causing local extirpations, including for *H. sazimai* (Ferrante et al. 2017). This species is dependent on the quality and size of forest remnants, experiencing local extinctions in very small fragments or in those with depleted vegetation (Ferrante et al. 2017). This strictly forest species has suffered a reduction of vegetation cover over the last 10 years throughout its range (Fig. S1a, Supporting Information Appendix S1). Given the level of endemism in the region, many other species would be classified as threatened.

Conservation Biology
DOI: https://doi.org/10.1111/cobi.14033

Appendix S6 Conservation gaps in Brazil.

Our data are especially important because they show that environmental agencies should consider potential environmental damage of proposed infrastructure projects at locations far away from the projects themselves. Our data suggest that deforestation in the Amazon can affect a species more than 3000 km away due to the disruption of the rainfall cycle on which this species depends. Environmental threats that may cause impacts at distant locations must be considered both by ICMbio and IUCN in the assessment of the red lists of threatened species, as well as by IBAMA when evaluating environmental impact assessments of large projects in the Amazon. Environmental licensing has been increasingly weakened in Brazil (Ruaro et al., 2021; 2022), requiring a quick reversal to maintain biodiversity and ecosystem services. The climate that maintains biodiversity in the Atlantic Forest depends on conservation of the Amazon. Brazil's policies for expansion of agribusiness are accelerating biodiversity loss (Ferrante & Fearnside, 2018), both by intensifying anthropogenic climate change and by destruction of habitat. The tools for species conservation in Brazil, such as updating the red lists, are advancing at a much slower pace than are the threats that are driving species to extinction, demanding an urgent change in the policies that now drive biodiversity loss.

References:

Ferrante, L. & Fearnside, P. M. (2018). Amazon sugarcane: A threat to the forest. *Science,* 359, 1472. DOI: https://doi.org/10.1126.aat4208

Ruaro, R., Ferrante, L. & Fearnside, P.M. (2021). Brazil's doomed environmental licensing. *Science,* 372, 1049-1050. DOI: https://doi.org/10.1126/science.abj4924

Ruaro, R., Zaia Alves, G. H., Tonella, L., Ferrante, L., & Fearnside, P. M. (2022). Loosening of environmental licensing threatens Brazilian biodiversity and sustainability. *Die Erde,* 153, 60-64. DOI: https://doi.org/10.12854/erde-2022-614