

INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA - INPA

PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA

**EFEITOS DA INUNDAÇÃO DA USINA HIDRELÉTRICA DE
SANTO ANTÔNIO SOBRE A ASSEMBLEIA DE PEQUENOS
MAMÍFEROS NÃO VOADORES NO ALTO RIO MADEIRA**

RAYLENNE DA SILVA ARAUJO

Manaus, Amazonas

Agosto, 2023

RAYLENNE DA SILVA ARAUJO

**EFEITOS DA INUNDAÇÃO DA USINA HIDRELÉTRICA DE
SANTO ANTÔNIO SOBRE A ASSEMBLEIA DE PEQUENOS
MAMÍFEROS NÃO VOADORES NO ALTO RIO MADEIRA**

Tese apresentada ao Programa de
Pós-Graduação em Ecologia do
Instituto Nacional de Pesquisas da Amazônia
como requisito para obtenção de título
de Doutora em Biologia (Ecologia)

Orientador: Dr. William E. Magnusson

Coorientador: Dr. Paulo E. D. Bobrowiec

Manaus, Amazonas

Agosto, 2023



PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA

ATA DA DEFESA PÚBLICA DA TESE DE DOUTORADO DO
PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA DO
INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA.

Aos 28 dias do mês de agosto do ano de 2023, às 13h30min, virtualmente pela plataforma zoom, reuniu-se a Comissão Examinadora de Defesa Pública, composta pelos seguintes membros: o Dr. Ricardo Siqueira Bovendorp, da Universidade Estadual de Santa Cruz - UESC, a Drª. Ana Filipa Palmeirim, da University of Porto – UPORTO, a Drª Clarissa Alves da Rosa, do Instituto Nacional de Pesquisas da Amazônia – INPA, a Drª Clarice Borges Matos, da Universidade de São Paulo – USP e o Dr. Marcelo Passamani, da Universidade Federal de Lavras – UFLA, tendo como suplentes a Drª Jussara dos Santos Dayrell, do Instituto Nacional de Pesquisas da Amazônia – INPA e o Dr. Pedro Aurélio Costa Lima Pequeno, da Universidade Federal de Roraima – UFRR, sob a presidência do orientador, a fim de proceder a arguição pública do trabalho de **TESE DE DOUTORADO** de **RAYLENNE DA SILVA ARAÚJO**, intitulado: “**EFEITOS DA INUNDAÇÃO DA USINA HIDRELÉTRICA DE SANTO ANTÔNIO SOBRE A ASSEMBLEIA DE PEQUENOS MAMÍFEROS NÃO VOADORES NO ALTO RIO MADEIRA**”, orientada pelo Dr. William Ernest Magnusson, do Instituto Nacional de Pesquisas da Amazônia – INPA e coorientada pelo Dr. Paulo Estefano Dineli Bobrowiec, do Instituto Tecnológico Vale – ITV.

Após a exposição, a discente foi arguido oralmente pelos membros da Comissão Examinadora, tendo recebido o conceito final:

APROVADO (A)

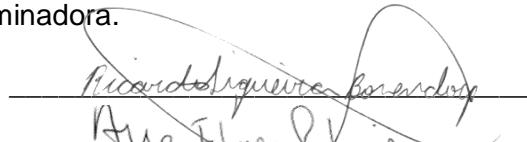
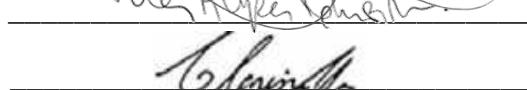
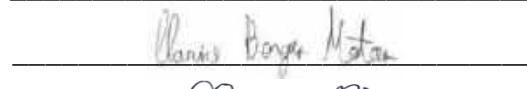
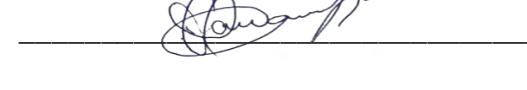
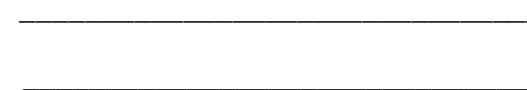
REPROVADO (A)

POR UNANIMIDADE

POR MAIORIA

Nada mais havendo, a presente ata foi lida, lavrada e assinada pelos membros da Comissão Examinadora.

DR. RICARDO SIQUEIRA BOVENDORP

DRª. ANA FILIPA PALMEIRIM

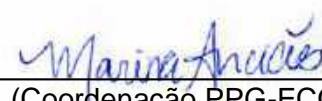
DRª. CLARISSA ALVES DA ROSA

DRª. CLARICE BORGES MATOS

DR. MARCELO PASSAMANI

DRª. JUSSARA DOS SANTOS DAYRELL

DR. PEDRO AURÉLIO COSTA LIMA PEQUENO


(Coordenação PPG-ECO/INPA)

FICHA CATALOGRÁFICA

A663e Araujo, Raylenne da Silva

Efeitos da inundação da Usina Hidrelétrica de Santo Antônio sobre a assembleia de pequenos mamíferos não voadores no alto Rio Madeira / Raylenne da Silva Araujo; orientador William Ernest Magnusson; coorientador Paulo Estefano Dineli Bobrowiec. - Manaus: [s.l.], 2023.

7,0 MB

85p. : il. color.

Tese (Doutorado - Programa de Pós-Graduação em Ecologia) - Coordenação do Programa de Pós-Graduação, INPA, 2023.

1. Reservatório hidrelétrico. 2. Perda de habitat. 3. Avaliação de impacto. I. Magnusson, William Ernest. II. Bobrowiec, Paulo Estefano Dineli. III. Título

CDD 599

À Francisca e ao José (avó e tio, ambos *in memorian*)

AGRADECIMENTOS

Foram quatros anos e meio de trabalho, surpresas, reviravoltas e instabilidade. Por isso, agradeço a Deus, fonte da minha resistência, a quem dedico a minha fé.

À psicoterapia por me ensinar e ajudar a segurar a barra que é a vida adulta e de pós-graduanda no Brasil.

Aos meus pais por serem, acima de tudo, meu porto seguro, minha força e fonte de inspiração. Por sempre me apoiar, mesmo não entendendo quase nada sobre as minhas escolhas profissionais e de vida. Aos *doguinhos*, Darwin e Lucy, pelo suporte emocional e me encherem de alegria nas pausas dessa correria louca. Amo vocês!

Ao orientador Bill Magnusson, que me ensinou tanto e me deu a oportunidade de trabalhar e desenvolver minha pesquisa. Ao coorientador Paulinho Bobrowiec, que foi peça fundamental para o desenvolvimento do meu trabalho e meu crescimento como cientista.

Ao Richard Stevens por ter sido um excelente anfitrião na Texas Tech University e colaborado substancialmente com esta tese, e aos colegas de laboratório pelas trocas científicas. *Thank you all!*

Aos colaboradores dos artigos que compõem esta tese, pelas considerações, revisões, ajuda com R program, compartilhamento de dados.

Aos meus avós Francisca e Lázaro que superam tudo e todos, que abriram o caminho para permitir que hoje eu seja doutora (com doutorado). Aos meus tios e primos maternos por terem sido a rede de apoio que contribuiu para o meu desenvolvimento e educação. Não se chega aonde cheguei sem reconhecer o suporte essencial de vocês!

Aos amigos Wal, Suh e Cássio por terem sido mais que amigos. O que a gente tem juntos não tem explicação e nem preço. A gente ri na cara das estatísticas. Bendita seja nossa amizade e eterna nossa loucura!

À Liegi e Fumiko pela amizade duradoura e sincera, mesmo estando tão longe e passar tanto tempo sem se ver pessoalmente. A Biologia nos honrou com essa relação linda. Saudade de morar perto de vocês!

À Carol Faria e Harumi que me estenderam a mão no momento que mais precisei de apoio e companheirismo, e por me mostrar que é possível construir amizade sincera após os 30.

À Jussara Dayrell, responsável por me convencer a entrar nessa “piscina gelada” que é a pós-graduação, por me ensinar tanto, e por ser meu ponto de equilíbrio em diversos momentos. Bárbara Brum, Dani Prioli, Manô Borges, Isabela Oliveira pela amizade honesta, apoio e cumplicidade.

Aos amigos Pedro Paulo, Amanda Batista e Erasmo por terem compartilhado comigo um lar e a vida em Manaus. Essa Casinha tem história!

Ao pessoal do INPA: Miqueias, Matheus Nunes, Rubana, Jonatas, Augusto, Pilar, Carol Veronese, Jéssica Andrade, Naty Kinap, Elmo, Marina Maximiliano, Rafa Pereira, Carine, Nelson, Ramiro, Raffa di Ponzio, Anaís, Kelly, Laura, Karol Andrade, Ana Clara, Mari Guedes, que estiveram presentes nos melhores e piores momentos em Manaus (*plus* pandemia). Manaus com vocês tem outra cor e sentido!

Ao pessoal de Lubbock (TX): Marina, Amanda, Márcio, Letícia, Jhonatas, Luís, Lorena, Ju Pessoni, Dan, Luísa, Yusa, Bia, Clárisse, PH, Angelina, George, Sammy, Gabi, Lucas, Anastasia e tantos outros que tornaram esse período de doutorado sanduíche nos EUA tão especial e inesquecível. Obrigada pela parceria, companheirismo e aventuras.

Definitivamente, quem tem família e amigos tem TUDO! Eterna gratidão por tudo e por tanto!

“Não é o lugar, e sim as pessoas.”

- *Autor desconhecido*

RESUMO

Em virtude de sua inestimável biodiversidade e potencial econômico, a Amazônia é um dos biomas mais observados do mundo devido ao seu grande território e enorme capacidade de recursos naturais. Concomitantemente, a Amazônia também tem sido alvo de importantes ações humanas, que têm ameaçado a sobrevivência da floresta e o bem-estar das populações humanas e da fauna. A implantação de usinas hidrelétricas em todo território amazônico tem sido apontada como um desses impactos antrópicos, e acende um alerta sobre a necessidade de preservação das áreas naturais atrelado ao crescimento econômico desejado pelos governos locais. Desta forma, nesta tese avalio como a implantação de uma usina hidrelétrica no sudeste da Amazônia interferiu na assembleia de pequenos mamíferos não voadores ao longo do tempo e espaço. No **Capítulo I**, eu e meus coautores buscamos prever como a assembleia de pequenos mamíferos poderia ser afetada após a perda de parte do gradiente ambiental causada pelo reservatório uma usina hidrelétrica, e como essas espécies estavam estruturadas espacialmente de acordo com alguns fatores ambientais com potencial a afetar espécies de pequenos mamíferos. No **Capítulo II**, comparamos alguns parâmetros da diversidade taxonômica, filogenética e traços funcionais de pequenos mamíferos não voadores entre diferentes períodos de amostragem através de dados coletados antes e após o enchimento do reservatório hidrelétrico. As assembleias de pequenos mamíferos se distribuíram de modo diferente entre áreas previstas a serem inundadas e áreas acima do reservatório planejado. Porém, as espécies presentes em áreas baixas também foram observadas nas áreas altas. Além disso, as espécies tiveram relação direta com fatores ambientais relacionados com o solo, a vegetação, e a distância do corpo d'água. Mesmo com o enchimento do reservatório, não houve perda de espécies e tampouco houve perda de linhagens evolutivas. Porém, o número de espécies, abundância, e frequência de traços funcionais aumentaram após o enchimento do reservatório, seguido de queda na maioria desses parâmetros no último ano de amostragem. Esta tese colabora para o conhecimento acerca dos processos ecológicos de pequenos mamíferos não voadores através de diferentes métricas da diversidade, e até que ponto o uso de novos modelos de barragens pode interferir na dinâmica de espécies terrestres, especialmente em regiões tropicais. Espera-se que os resultados aqui apresentados tragam maior entendimento sobre a biodiversidade amazônica, colabore no fomento de novos estudos ecológicos e sirva como embasamento para melhoria das técnicas de avaliação de impactos ambientais.

ABSTRACT

Due to its invaluable biodiversity and economic potential, the Amazon rainforest is one of the most observed biomes in the world due to its vast territory and abundance of natural resources. However, the Amazon has also been the target of significant human actions, which have threatened the forest's survival and the well-being of human and fauna populations. The implementation of hydroelectric power plants throughout the Amazon has been indicated as one of these anthropogenic impacts, raising an alert about the need to preserve natural areas while pursuing the economic growth planned by local governments. In this thesis, I assess how the implementation of a hydroelectric power plant in the southeastern Amazon affected assemblies of non-flying small mammals over time and space. In **Chapter I**, I and my coauthors sought to predict how the assembly of small mammals would be affected after the loss of part of the environmental gradient due to flooding caused by a hydroelectric power plant, and how these species were spatially structured according to some environmental variables expected to affect small-mammal species. In **Chapter II**, we compared some indices of taxonomic diversity, phylogenetics, and functional traits of non-flying small mammals between different sampling periods through data collected before and after the filling of the hydroelectric reservoir. Assemblies of small mammals were distributed differently between areas predicted to be flooded and areas above the planned reservoir. The species were directly related to environmental factors such as soil, vegetation, and distance from the water body, but species present in low areas were also observed in areas individuals in areas expected to be inundated with the filling of the reservoir were eliminated, there would be no loss of species or evolutionary lineages. The number of species, abundance, and frequency of functional traits increased after reservoir filling, followed by a decrease in most of these parameters in the last year of sampling. This thesis contributes to the understanding of ecological processes of non-flying small mammals evaluated through different diversity metrics, and how the use of run-of-the-river dams might interfere with the dynamics of terrestrial species in this tropical region. It hopes that the results presented here will bring greater understanding of Amazonian biodiversity, foster new ecological studies, and serve as basis for improving environmental-impact-assessment techniques.

SUMÁRIO

LISTA DE FIGURAS	x
LISTA DE TABELAS	xi
INTRODUÇÃO GERAL	9
OBJETIVO	11
OBJETIVOS ESPECÍFICOS	11
CAPÍTULO I - The impact of a run-of-the-river hydroelectric dam on a non-volant small- mammal assemblage in Brazilian Amazonia.....	13
CAPÍTULO II - Amazonian dam effects on taxonomic, functional and phylogenetic dimensions of non-flying small mammals	28
SÍNTESE	56
REFERÊNCIAS BIBLIOGRÁFICAS	58
MATERIAL SUPLEMENTAR (CAPÍTULO I).....	61
MATERIAL SUPLEMENTAR (CAPÍTULO II)	75

LISTA DE FIGURAS

Capítulo I

Figura 1. Mapa da área de estudo mostrando os sete módulos de amostragem ao longo das margens do Rio Madeira (TO = Teotônio, MO = Morrinhos, BU = Ilha de Búfalos, PE = Ilha de Pedras, JE = Jirau Margem Esquerda, JD = Jirau Margem Direita e JA = Jaci). O detalhe (à direita) mostra o desenho da amostragem com dois transectos de 3 km e 10 parcelas distribuídas a 0, 500, 1000, 2000 e 3000 metros da margem original do Rio Madeira, Estado de Rondônia, Brasil.

Figura 2. Ordenação da abundância de espécies de pequenos mamíferos não voadores em relação às parcelas alagadas e não alagadas localizadas ao redor do reservatório da Usina Hidrelétrica Santo Antônio, no Rio Madeira, sudoeste da Amazônia brasileira.

Figura 3. Relação entre as duas variáveis latentes geradas pela ordenação bayesiana com base na ocorrência (a) e na abundância com a distribuição binomial negativa (b). Círculo cinza = parcelas previstas a serem alagadas e triângulo preto = parcelas não alagáveis.

Capítulo II

Figura 1. Mapa da área de estudo mostrando os quatro módulos de amostragem ao longo das margens dos Rios Madeira e Jaci-Paraná (TO = Teotônio, BU = Ilha de Búfalos, PE = Ilha de Pedras e JA = Jaci). A caixa à direita mostra o desenho amostral com dois transectos e 10 parcelas localizadas a 0, 500, 1000, 2000 e 3000 m da margem original do Rio Madeira, Brasil.

Figura 2. Primeiras duas variáveis latentes de uma ordenação bayesiana (BORAL) de pequenos mamíferos não voadores de acordo com os períodos de amostragem na área da Usina Hidrelétrica Santo Antônio, Rio Madeira, Brasil.

Figura 3. Frequências médias ponderadas de traços funcionais (CWM) de pequenos mamíferos não voadores registrados antes do enchimento (Pré-enchimento), um ano após o enchimento (Pós-1) e dois anos após o enchimento (Pós-2) na área da Usina Hidrelétrica Santo Antônio, Rio Madeira, Brasil. Círculos pretos representam as médias da frequência dos traços funcionais. * $P < 0.05$ (ver Tabela 3).

LISTA DE TABELAS

Capítulo I

Tabela 1. Números de indivíduos de pequenos mamíferos não voadores de cada espécie registrados em parcelas que seriam inundadas e não inundadas pela Usina Hidrelétrica de Santo Antônio, Rio Madeira, Brasil.

Tabela 2. Mínimo, máximo, média e desvio padrão (SD) das variáveis amostradas em 70 parcelas ao longo das margens do reservatório hidrelétrico da UHE Santo Antônio, sudeste da Amazônia, Brasil.

Tabela 3. Resultados dos testes *manyglm* da associação entre a composição de assembleias de pequenos mamíferos não voadores e variáveis ambientais em parcelas de amostragem ao redor do reservatório da Usina Hidrelétrica de Santo Antônio, sudeste da Amazônia, Brasil.

Capítulo II

Tabela 1. Resultados da análise diversidade beta temporal (TBI) na estrutura de assembleias de pequenos mamíferos não voadores entre os períodos de amostragem próximos ao Reservatório Hidrelétrico de Santo Antônio, Rio Madeira, Brasil. O sinal da mudança indica se os ganhos (+ sinal) ou as perdas (sinal –) dominam em todas as parcelas de amostragem. $P < 0.05$ estão em negrito.

Tabela 2. Resultados das comparações pareadas *post hoc* dos modelos GLMM-TBM para a abundância de espécies, comparando os períodos Pré-enchimento, Pós-1 e Pós-2 ao redor do reservatório da Usina Hidrelétrica de Santo Antônio, Rio Madeira, Brasil. $P < 0.05$ estão em negrito.

Tabela 3. Resultados das comparações pareadas *post hoc* dos modelos GLMM-TBM para cada traço funcional utilizado na análise CWM, comparando os períodos Pré-enchimento, Pós-1 e Pós-2 na área do reservatório da Usina Hidrelétrica de Santo Antônio, Rio Madeira, Brasil. $P < 0.05$ estão em negrito.

INTRODUÇÃO GERAL

O crescimento e desenvolvimento do Brasil têm levado a uma crescente demanda por energia elétrica, o que resulta na implantação de novos empreendimentos relacionados ao setor energético. A matriz energética do país é predominantemente composta por fontes hídricas, representando quase 60% do total, e, aproximadamente 1.105.400 hectares de floresta já foram inundados para viabilizar esses empreendimentos (ECOA, 2012; ANEEL, 2023). A construção de uma barragem e a formação do lago resultam em diversos impactos na área de sua influência, afetando tanto o meio ambiente natural quanto as comunidades humanas presentes na região, tendo efeitos significativos na biologia aquática e terrestre (Giusti, 2005).

A maioria dos estudos sobre áreas amazônicas afetadas por hidrelétricas ainda se concentram em reservatórios que formaram grandes lagos, levando à inundação de extensas áreas florestais, como os exemplos clássicos de Tucuruí e Balbina, nos estados do Pará e Amazonas, respectivamente (Fearnside, 2015). No entanto, as hidrelétricas a fio d'água tem sido o modelo mais difundido recentemente e podem ser operadas sem o armazenamento de grande volume de água a montante; portanto, esse tipo de barragem reduz a área alagada necessária para operar as turbinas (Fearnside, 2014a,b). No entanto, como esse modelo de hidrelétrica a fio d'água não possui grande reservatório de água, se faz necessária a construção de outras barragens adjacentes para conferir maior estabilidade ao sistema (Fearnside, 2014a). A realização de estudos para avaliar os impactos ambientais decorrentes desse tipo de barragem são extremamente necessários (Fearnside, 2014b,c), pois embora seja esperado que os impactos sobre ambientes de terra firme sejam reduzidos, uma vez que não alagam grandes áreas, esse novo modelo de construção ainda pode causar impactos desconhecidos nos ambientes aluviais, e consequentemente, pode afetar todo o ecossistema adjacente.

Assim como em outras partes do bioma amazônico, a bacia do rio Madeira também é considerada uma região com grande biodiversidade, abrangendo praticamente todo o estado de Rondônia (MMA, 2007). Essa área é apontada como uma das regiões zoogeográficas mais ricas em espécies de mamíferos em toda a América (Voss e Emmons, 1996; Rapp Py-Daniel *et al.*, 2007). O crescente ritmo de construção de novas barragens na Amazônia, incluindo a bacia do Rio Madeira, acarreta um maior risco de perdas florestais e representa uma ameaça direta ou indireta a diversas espécies de distribuição restrita, podendo levá-las ao declínio (Lees *et al.*, 2016). No contexto atual, a conservação

efetiva da biodiversidade demanda um conhecimento mínimo sobre as espécies que são alvo desses impactos ambientais (Brito, 2004), o que também se aplica aos pequenos mamíferos não voadores, que representam quase 40% da diversidade de mamíferos no país (Abreu *et al.*, 2022). A utilização dessas espécies é recomendada para diversos estudos, pois esses animais apresentam respondem às alterações do habitat (Alho, 2011; Passamani e Cerboncini, 2013; Palmeirim *et al.*, 2018).

A implantação de hidrelétricas resulta em perdas na complexidade de habitats e alterações na estrutura das comunidades de mamíferos (Alho, 2011; Crosson *et al.*, 1999; Lambert *et al.*, 2003; Mendes-Oliveira *et al.*, 2015). Comumente, variações na abundância de indivíduos, riqueza e composição de espécies podem estar associados a diversos fatores bióticos e abióticos, incluindo perturbações que causam mudanças nos gradientes ambientais ao longo do espaço (Stallings, 1989; Malcolm, 1997; Pardini, 2004). Porém, as investigações sobre os padrões de distribuição da biodiversidade têm historicamente concentrado seus esforços no aspecto taxonômico, enfocando principalmente a riqueza de espécies e abundância de indivíduos (Magurran, 2004). No entanto, a abordagem taxonômica não é suficiente para capturar completamente a diversidade da biodiversidade, mesmo em termos de espécies (Ricotta, 2005). As diferentes espécies possuem características ecológicas que variam entre elas, refletindo respostas, interações e funções ecológicas diversas (Tilman, 2001). Essas variações ecológicas resultam de diversos processos de adaptação e diferenciação ao longo da história evolutiva das espécies, que descrevem uma dimensão da biodiversidade distinta da diversidade taxonômica (Davies & Buckley, 2011). O uso complementar dessas dimensões de diversidade - taxonômica, funcional e filogenética - são de extrema importância para avaliar os efeitos dos impactos da perda e fragmentação de habitat causados por ações antrópicas a exemplo das hidrelétricas.

Esta tese tem como tema principal avaliar os fatores espaço-temporais que estruturam a assembleia de pequenos mamíferos não voadores em seus aspectos taxonômicos, filogenéticos e funcionais no contexto de uma área sob influência de reservatório hidrelétrico na região sul-Oeste da Amazônia brasileira. No **Capítulo I**, eu e meus coautores investigamos como a perda de parte do gradiente ambiental próximo ao rio Madeira e afluentes poderia promover redução de riqueza e abundância das espécies, e, consequentemente, alterando a composição de pequenos mamíferos não voadores. Neste capítulo utilizamos somente dados coletados antes do enchimento do

reservatório, e nele comparamos as assembleias de áreas inundáveis e não-inundáveis e relacionamos esses conjuntos de espécies com variáveis ambientais bióticas e abióticas. No **Capítulo II**, comparamos a riqueza, abundância e composição de espécies, diversidade filogenética e frequência de traços funcionais de 26 espécies de pequenos mamíferos não voadores e avaliamos como essas métricas da diversidade se comportaram após o barramento do Rio Madeira.

OBJETIVO

Avaliar como as assembleias de pequenos mamíferos não voadores são influenciadas por fatores bióticos e abióticos nas áreas previstas as serem inundadas e áreas não inundadas antes do enchimento da barragem da UHE Santo Antônio no alto rio Madeira, e avaliar como o enchimento do reservatório afeta aspectos da diversidade taxonômica, filogenética e traços funcionais das assembleias devido a perda de parte do gradiente ambiental.

OBJETIVOS ESPECÍFICOS

Capítulo I: Avaliar se o enchimento do reservatório da Hidrelétrica de Santo Antônio causa a perda de riqueza e abundância de espécies de pequenos mamíferos não voadores e mudança na composição dessas assembleias, e avaliar como essas espécies se relacionavam com a topografia, vegetação e características do solo.

Capítulo II: Avaliar como diferentes aspectos da diversidade taxonômica, filogenética e traços funcionais de pequenos mamíferos não voadores são afetados pelo enchimento do reservatório da Hidrelétrica de Santo Antônio.

CAPÍTULO I

Araujo, R.S., Bobrowiec, P.E.D., Moura, R.T., Magnusson, W.E. 2022. The impact of a run-of-the-river hydroelectric dam on a non-volant small-mammal assemblage in Brazilian Amazonia. *Austral Ecology* 48: 143-157. <https://doi.org/10.1111/aec.13257>



RESEARCH ARTICLE

The impact of a run-of-the-river hydroelectric dam on a non-volant small-mammal assemblage in Brazilian Amazonia

Raylenne da Silva Araujo¹ | Paulo Estefano Dineli Bobrowiec¹ |
Raquel Teixeira de Moura² | William Ernest Magnusson¹

¹Programa de Pós-graduação em Ecologia, Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Brazil

²Calispictus Consultoria Ambiental, Belo Horizonte, Brazil

Correspondence

Raylenne da Silva Araujo, Francisco Arruda St. 161, C1, Manaus, Amazonas 69083-060, Brazil.
Email: araajo.raylenne@gmail.com

Funding information

American Society of Mastozoology; Conselho Nacional de Desenvolvimento Científico e Tecnológico, Grant/Award Number: PQ - 301873/2016-0; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Grant/Award Number: PROEX 0742/2020; Fundação de Amparo à Pesquisa do Estado do Amazonas, Grant/Award Number: PAPAC 005/2019

Abstract

There are few scientific studies evaluating the impact of the loss of wetlands on the banks of tropical rivers on assemblages of small non-flying mammals. To understand the possible deleterious effects of hydroelectric construction in tropical forests on this group of mammals, we used data from 2 years of monitoring carried out during the period before the filling of a hydroelectric plant reservoir in the Brazilian Amazon, and related them to vegetation, soil and topography. We captured 659 individuals of 20 small-mammal species. The species assemblage composition in the flooded areas was a subset of species that occurred in both floodable and non-floodable areas, and only one species was captured exclusively in the flooded area. Species composition was influenced by the proportion of sand, by soil nutrient concentration and distance from water bodies. We conclude that there is no evidence that the flooding of low-lying areas along the Madeira River would negatively affect the assemblage of non-flying small mammals in the short term because the remaining areas have similar assemblages of small mammals as those destined for flooding. Whether the area lost will be important for population dynamics will depend on the conservation of the remaining areas.

KEY WORDS

dam impact, environmental gradient, small-mammal assembly, tropical forest

RESUMO

Existem poucos estudos científicos avaliando o impacto da perda de áreas úmidas nas margens de rios tropicais sobre as assembleias de pequenos mamíferos não voadores. Para entender os possíveis efeitos deletérios da construção de hidrelétricas em florestas tropicais sobre esse grupo de mamíferos, utilizamos dados de dois anos de monitoramento realizado durante o período anterior ao enchimento de um reservatório de hidrelétrica na Amazônia brasileira e os relacionamos com a vegetação, solo e topografia. Capturamos 659 indivíduos de 20 espécies de pequenos mamíferos. A composição da assembleia de espécies nas áreas alagadas foi um subconjunto das espécies presentes nas áreas não alagáveis, e apenas uma espécie foi capturada exclusivamente na área alagável. A composição de espécies foi influenciada pela proporção de areia, pela concentração de nutrientes no solo e pela distância dos corpos d'água. Concluímos que não há evidências de que a inundação de áreas baixas ao longo do rio Madeira afetaria negativamente a assembleia de pequenos mamíferos não-voadores no curto prazo, pois as áreas remanescentes apresentam assembleias de pequenos mamíferos semelhantes às destinadas a

inundação. Se a área perdida será importante para a dinâmica populacional dependerá da conservação das áreas não inundadas.

INTRODUCTION

Human population growth has increased the demand for electricity, and hydroelectric dams are the main source of electricity in tropical regions (WCD, 2000). Although hydropower generation is claimed to be a more environmentally sustainable energy source than fossil fuels and nuclear energy, the large number of dams built in the last century has altered riverine ecosystems more extensively than any other anthropogenic activity, leaving two-thirds of the world's great rivers fragmented (Ansar et al., 2014; Nilsson et al., 2005). Some 836 hydroelectric dams are in operation or under construction in the world's larger tropical hydrographic basins (Winemiller et al., 2016), which will result in large areas being permanently flooded, and concomitant impacts on terrestrial and aquatic biotas (Anderson et al., 2018; Finer & Jenkins, 2012; Latrubesse et al., 2017).

Permanent flooding of lowlands impacts both aquatic and terrestrial ecosystems, causing the loss of areas with unique vegetation and faunal characteristics, reducing biological diversity and diminishing ecosystem services. River damming also changes the physicochemical characteristics of the water upstream of the reservoir and its tributaries and contributes to the emission of greenhouse gases, such as methane and carbon dioxide (Almeida et al., 2019; Faria et al., 2017; Scherer & Pfister, 2016). Dams also interrupt natural seasonal flood dynamics, producing near-static water levels that compromise seasonal flood pulses and the associated deposition of nutrient-rich sediments on the floodplains. This impacts terrestrial riverbank ecosystems via changes in plant assemblage structure and the composition and productivity of wetlands (Junk et al., 2011; Pitman et al., 2008; Soukaphon et al., 2021).

However, not all dams are the same. Globally, the most common model consists of storage reservoirs that retain and release large amounts of water according to energy consumption and precipitation, and which, depending on the topographic relief, may form islands (IEA, 2012). However, a number of hydroelectric plants built in recent years have been designed to use run-of-river reservoirs, without the need for a large accumulation of water upstream (Baumgartner et al., 2020). A run-of-river reservoir creates little variation in water level and does not flood large portions of terra firme forests, but still floods riverbanks and lowland forests, and alters the natural flow and flood pulse of rivers (Anderson et al., 2015; Fearnside, 2014; Roberts, 1995). Most of the information on the effects of dams on fauna and flora has come from storage reservoirs, with a notable focus on the effects of insularization (Benchimol & Peres, 2020; Cosson et al., 1999). Such studies focus on how biological communities respond to island size, isolation level and island habitat quality (Gibson et al., 2013; Palmeirim et al., 2018). Areas of non-flooded forest are used as a control that presumably represents a pre-dam scenario. However, few studies have evaluated the deleterious effects of run-of-river dams in the tropical region on the complementarity of species compositions between altered areas and remaining areas (Bobrowiec & Tavares, 2017; Dayrell et al., 2021).

Predictive studies based on data collected before the filling of the hydroelectric reservoir are rare, so most impact assessments do not have enough information to assess the real state of biological communities before the installation of the hydroelectric plant (Athayde et al., 2019; Avenant & Kuyler, 2002; Granjon et al., 1996). Studies carried out before dam

construction begins can provide information on which species will be affected, whether the assemblages from the flooded areas can move to adjacent dry areas, how changes in groundwater levels influence changes in vegetation as well as serve as a model to assess temporal changes in the regional biota (Bobrowiec et al., 2021; Dayrell et al., 2021; Melo et al., 2021).

Small non-flying mammals are considered good indicators of environmental quality, as they perform ecosystem functions on the soil, vegetation and mycorrhizal fungi, as well as influencing populations of other vertebrates and invertebrates (Emmons, 1987; Hayward & Phillipson, 1979; Martins & Gribel, 2007). Few studies have combined the evaluation of which environmental factors influence habitat selection by small non-flying mammals with how anthropogenic activities, such as hydroelectric dams, alter the environmental gradients that determine small-mammal assemblage structure in tropical regions (Mendes-Oliveira et al., 2015).

In this study, we assessed the potential immediate effect of flooding of low-lying areas by the Santo Antônio Hydroelectric Dam reservoir in south-eastern Amazonia, Brazil, to eliminate unique small non-volant mammal assemblages. Additionally, we assess how the distributions of small non-flying mammal species respond to topography, vegetation structure and edaphic characteristics at the study site. We predicted that the species composition of areas to be flooded would differ from areas that would not be flooded by the dam due to the influences of vegetation structure, soil nutrient concentration and terrain elevation.

MATERIALS AND METHODS

Study area

The study was carried out in the area surrounding the Santo Antônio Hydroelectric Plant reservoir ($8^{\circ}47'55''$ S, $63^{\circ}53'55''$ W; Figure 1) on the Madeira River, 10 km from the urban centre of the city of Porto Velho, Rondônia State, Brazil. The Madeira River has muddy (white) water and accounts for 15% of sediment discharge from the Amazon River into the

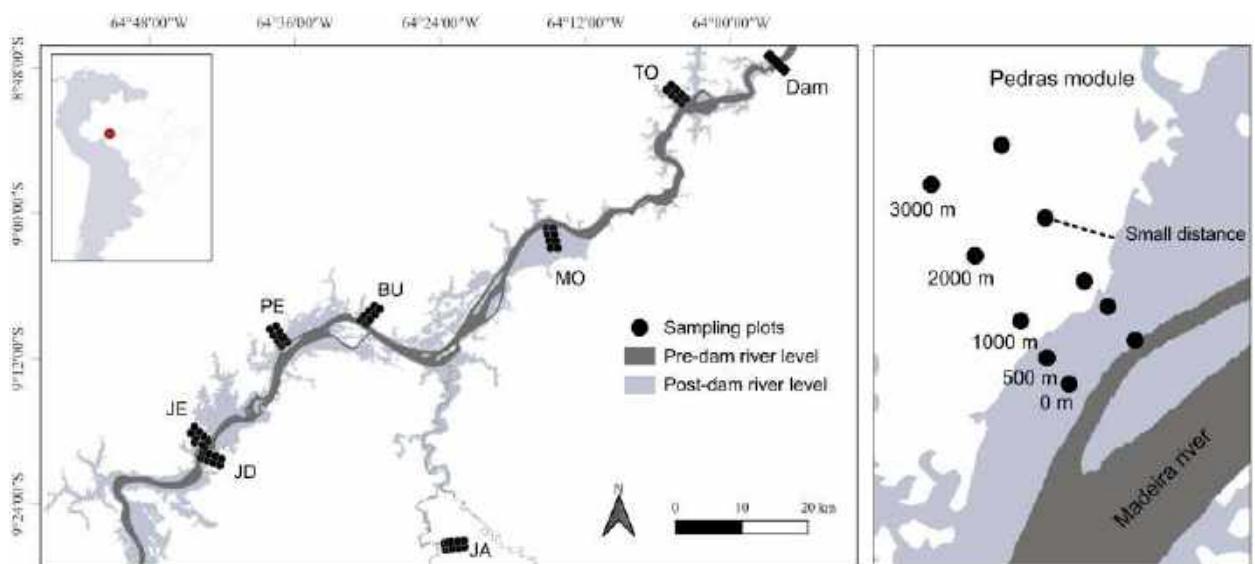


FIGURE 1 Map of the study area showing the seven sampling modules along the two banks of the Madeira River (TO = Teotônio, MO = Morinhas, BU = Ilha de Búfalos, PE = Ilha de Pedras, JE = Jirau Margem Esquerda, JD = Jirau Margem Direita and JA = Jaci). The insert (on the right) shows the sample design with two 3 km transects and 10 plots distributed at 0, 500, 1000, 2000 and 3000 metres from the original bank of the Madeira River, Rondônia State, Brazil.

Atlantic Ocean. The region's rainfall varied between 1400 and 2600 mm/year, with a rainy season from November to April and a dry season from June to September (COGEO/SEDAM, 2010). Regionally, the predominant vegetation is dense terra firme rainforest, and in the vicinity of the Madeira River, the vegetation is open floodable rainforest (IBGE, 2012).

The Santo Antônio Dam has the capacity to generate 3150 MW of electricity and is the fourth-largest hydroelectric plant in Brazil (Fearnside, 2015). The construction dammed the Madeira River in 2012, and the water level subsequently rose 70 m above sea level, flooding an area of 271 km². The dam is a “run-of-river” type that, unlike traditional storage reservoir dams, does not form a large lake (Baumgartner et al., 2020; Fearnside, 2014). However, run-of-river dams on Amazon rivers require new upstream dams to maintain the water supply (Fearnside, 2014). The Jirau hydroelectric dam with a generating capacity of 3750 MW is located 117 km upstream of the Santo Antônio dam.

Small mammal capture methods

Non-volant small mammals were captured in seven sampling modules (Ilha de Pedras, Ilha de Búfalos, Jaci, Teotônio, Morrinhos, Jirau Direita and Jirau Esquerda) distributed along 100 km of the Madeira River, three on the right bank and four on the left bank (Figure 1). One sampling module was located on the Jaci Panará River, a right-bank tributary of the Madeira River (Figure 1). Sampling within the sites followed the RAPELD method (RAP = rapid survey of biological communities; PELD = long-term ecological survey) for standardized fauna and flora monitoring (Magnusson et al., 2005, 2013). Each module contained 10 sampling plots distributed at 0, 500, 1000, 2000 and 3000 m away from the Madeira River bank. We sampled 24 plots predicted to be submerged and 46 plots that would remain dry after the river was dammed, totalling 70 sampling units (Figure 1). Each plot was 250 m long and followed local topography to reduce internal heterogeneity in soil and drainage properties and, consequently, vegetation composition (Magnusson et al., 2013).

The non-volant small mammals were captured using live traps. Each plot had 26 traps that were distributed in pairs, one Sherman® (30 × 8 × 7 cm) and one Tomahawk® (31.5 × 15 × 15 cm) every 20 m, totalling 13 pairs of traps per plot. The live traps were installed alternately on the ground and at a height of 1.5 m, attached to a tree trunk. Each trap was checked daily and baited with pineapple and a sweetened cod liver oil solution. The traps remained in operation for five consecutive nights per plot. Each plot was visited five times between December 2009 and January 2012, totalling 350 capture nights (45 500 trap-nights; one trap-night corresponds to one trap open for one night). Captured small mammals were identified using dichotomous keys and descriptions found in Patton et al. (2000), Wilson and Reeder (2005) and Paglia et al. (2012). Taxonomy follows Abreu et al. (2021).

Vegetation structure, topography and soil characteristics

Vegetation structure was described by understory vegetation density, tree basal area and number of trees. Vegetation density was measured using the point intercept method, which quantifies the number of leaves and branches directly touching a 50-cm-long pole, positioned perpendicularly 50 cm above the ground (Dias-Terceiro et al., 2015). Measurements were taken every 2 m along the 250 m of each plot. The vegetation-density index

was the sum of all touches per plot. The number of trees and the diameter at breast height of trees (DBH) were measured in the 250-m-long plots, with the plot width following DBH hierarchical classes. Using the method described by Costa and Magnusson (2010), plants with DBH ≥ 1 cm were sampled in a 1-m-wide strip on both sides of the plot centre line; plants with DBH < 10 cm were sampled in a 1.5-m-wide strip by Dias-Terceiro et al. (2015); plants with DBH between 10 and 30 cm were sampled in a range of 20 m; and plants with DBH > 30 cm were sampled in 40 m strips. We used the equation $\sum(\pi \text{DBH}^2/4)$ to quantify the basal forest area of each plot.

Terrain topography was described by the slope and elevation of the terrain. The terrain slope was measured using a clinometer every 50 m along each plot (5 points per plot). We used the mean of the 5 points to represent the slope of the plot. We extracted terrain elevation data for each plot from 30-m-resolution raster images provided by The Global Land Cover Facility. Elevation was measured at the starting point of each plot using the 'point sampling' tool of the Quantum Geographic Information System (QGIS) software, version 3.12.1. We calculated the shortest straight-line distance from the plots to the nearest forest streams and to the bank of the Madeira River using shapefile hydrographic images provided by the Instituto Brasileiro de Geografia e Estatística (IBGE).

Soil structure was evaluated using soil samples collected every 50 m along the 250 m of the plot (6 samples per plot) (Dias-Terceiro et al., 2015). Soil fertility was estimated by summing the bases of Ca²⁺, Mg²⁺, K⁺, Fe, Zn and Mn (Quesada et al., 2010). Soil samples were sieved, and the particles were separated according to their vertical suspension in water. The sand and silt fractions were oven dried and weighed to obtain their percentages. Data on vegetation structure, topography and soil characteristics are available in [Supplementary Material S1](#).

Data analysis

We compared the assemblages from plots that would be flooded with plots that would remain dry using generalized linear models (GLM) with negative binomial distribution for multivariate data in the 'manyglm' function of the *mvabund* package (Wang et al., 2012, 2020). This approach considers mean–variance changes without confounding the effect of dispersion and location, which can inflate type I and II errors (Warton et al., 2012). Significance tests were obtained using the 'anova.manyglm' function in the *mvabund* package, based on Wald's statistic, adjusted by the PIT-trap method, and estimated *p* values from 999 bootstrap samples (Warton et al., 2017). Species compositions of the plots that would be flooded and those that would remain dry were described using a Bayesian ordination of multivariate abundance data in ecology (BORDAL) for species abundance and occurrence data. We used t-tests to compare vegetation structure, soil characteristics and topography between plots that would be flooded by the Madeira River dam and plots that would not be inundated. The best residual fits were tested with the 'simulateResiduals' function of the *DHARMa* package (Hartig, 2021) to select the family function most appropriate for the data dispersion. We used generalized linear mixed-effect models, with a negative binomial distribution (Brooks et al., 2017), employing the 'glmmTMB' function of the *glmmTMB* package to compare species' abundances, with more than 10 captures, and species' richness between the floodable and non-flooded plots.

To assay for changes in species composition in relation to topography (terrain slope and elevation, horizontal distance from the Madeira River

and streams), soil characteristics (proportion of sand, silt and soil nutrients) and vegetation structure (number of trees, forest basal area and vegetation density), we used the same ‘manyglm’ function approach described above based on both species’ abundance and occurrence data. We added the seven modules as a random variable in all statistic models to account for potential spatial autocorrelations.

To visually represent the species composition of each plot, we used the first latent variable of a Bayesian ordination generated by the ‘boral’ function of the *boral* package (Hui et al., 2015; Hui & Blanchard, 2021), which allows the adjustment of models using Bayesian Markov chain Monte Carlo (MCMC). Bayesian ordinations were generated with data on species abundance and occurrence (absence/presence). Before running the GLMs, we estimated the variance inflation factor (VIF) to test for multicollinearity between the predictor variables (‘vif’ function of the *vegan* package: Oksanen et al., 2020). Our analyses indicated low multicollinearity ($VIF < 3$); except for the proportion of clay, which was excluded from the analyses. All analyses were done using R software (R Development Core Team, 2020).

RESULTS

We captured 649 individuals from 20 species and three families of small non-volant mammals (Table 1). Most of the captured individuals belonged to the Didelphidae, which represented 74.4% ($n = 483$) of the captures and 50% of the species ($n = 10$ species). *Marmosa demerarae* and *Proechimys cf. gardneri* occurred in more than half of the sampled plots; another seven species occurred in either just one (three species) or two (four species) sampling plots (Table 1), and no species was captured in all 70 plots (Figure 2).

Species composition differed between plots that would be flooded and plots that would remain dry based on both abundance ($Wald = 5.89$; $p = 0.002$) and occurrence ($Wald = 5.40$; $p = 0.003$). Flooded plot assemblages overlapped with non-flooded plots, and the difference between plot types is caused by the more dispersed plots of non-flooded areas, both for abundance and species occurrence data (Figure 3). The total number of species captured per plot ($z = 1.26$; $p = 0.2$) and total abundance of individuals per plot ($z = -0.08$; $p = 0.93$) did not differ between areas that would remain dry and those that would be flooded. Only *Metachirus nudicaudatus* ($z = 2.01$; $p < 0.05$) and *Proechimys* sp. ($z = 2.66$; $p < 0.001$) were more abundant in plots that would remain dry (Figure 2). The other species analysed showed no difference in abundance between plots that would be flooded and those that would remain dry (Figure 2).

The altitude in the plots ranged from 64.6 to 199 m (84.4 ± 20.8 m; mean $\pm SD$), the distance from the bank of the Madeira River ranged from 26 to 3612 m ($1,546 \pm 1082$ m) and the distance to the nearest stream ranged from 0 to 3081 m (880 ± 787 m). Soil nutrients (sum of bases) varied from 0.2 to 0.96 cmolc/dm⁻³ (0.5 ± 0.2 cmol/dm⁻³) and the proportion of sand varied from 14.4% to 72.3% ($26.3\% \pm 10\%$) (Table 2). Four environmental variables differed between plots that would be submerged and those that would remain dry. The plots that would be flooded had lower elevation ($t = -3.30$; $p = 0.01$), were closer to the Madeira River bank ($t = -2.70$; $p = 0.009$) and upland streams ($t = -5.54$; $p < 0.001$) and had higher concentration of nutrients ($t = 2.60$; $p = 0.01$) and a higher proportion of sand ($t = 2.8$; $p = 0.007$).

Based on abundance, species composition was related to proportions of sand, soil nutrients and distance from streams and the Madeira River (Table 3; Supplementary Material S2). Based on occurrence, species

TABLE 1 Numbers of individuals of small non-volant mammals in each species recorded in plots that would be flooded and not flooded by the Santo Antônio hydroelectric dam, Madeira River, Brazil

Family/species	Not flooded plots	Flooded plots	Total
Didelphidae			
<i>Caluromys lanatus</i>	1	1	2
<i>Caluromys philander</i>	9	9	18
<i>Didelphis marsupialis</i>	19	16	35
<i>Marmosa cf. murina</i>	10	4	14
<i>Marmosops cf. noctivagus</i>	7	1	8
<i>Marmosops pinheiroi</i>	6	1	7
<i>Metachirus nudicaudatus</i>	16	1	17
<i>Marmosa demerarae</i>	255	122	377
<i>Monodelphis emiliae</i>	4	0	4
<i>Philander mcilhennyi</i>	1	0	1
Cricetidae			
<i>Euryoryzomys cf. macconelli</i>	1	2	3
<i>Hylaeamys cf. yunganus</i>	2	2	4
<i>Nectomys cf. rattus</i>	1	0	1
<i>Oecomys sp.</i>	3	2	5
<i>Oecomys cf. bicolor</i>	13	4	17
<i>Oecomys cf. rex</i>	0	1	1
<i>Oecomys cf. roberti</i>	2	1	3
<i>Rhipidomys cf. leucodactylus</i>	3	1	4
Echimyidae			
<i>Mesomys cf. hispidus</i>	29	4	33
<i>Proechimys cf. gardneri</i>	87	8	95
Total	469	180	649
Number of species	19	17	20
Number of sampled plots	46	24	70
Sample effort (trap-nights)	29250	14690	43940

composition was related to the number of trees, soil nutrients and distance from the Madeira River (Table 3; Supplementary Material S2).

DISCUSSION

Our study showed that non-volant small-mammal assemblages differed between areas that would be flooded and those that would remain dry, but there was no evidence that the flooding by the Santo Antônio Dam reservoir will negatively influence the small-mammal community in a short term. The areas that would remain dry harboured an assemblage with a number of species and an abundance of individuals similar to the areas that would be flooded, with the latter having no clearly unique species. The only species that was captured exclusively in the flooded area was represented by only one individual. Our results also showed that species composition was structured by the edaphic characteristics and vegetation structure and that the flooding by the dam would probably not change this pattern, as the environmental characteristics of the flooded areas will still be represented in the dry areas, as long as these areas are effectively conserved.

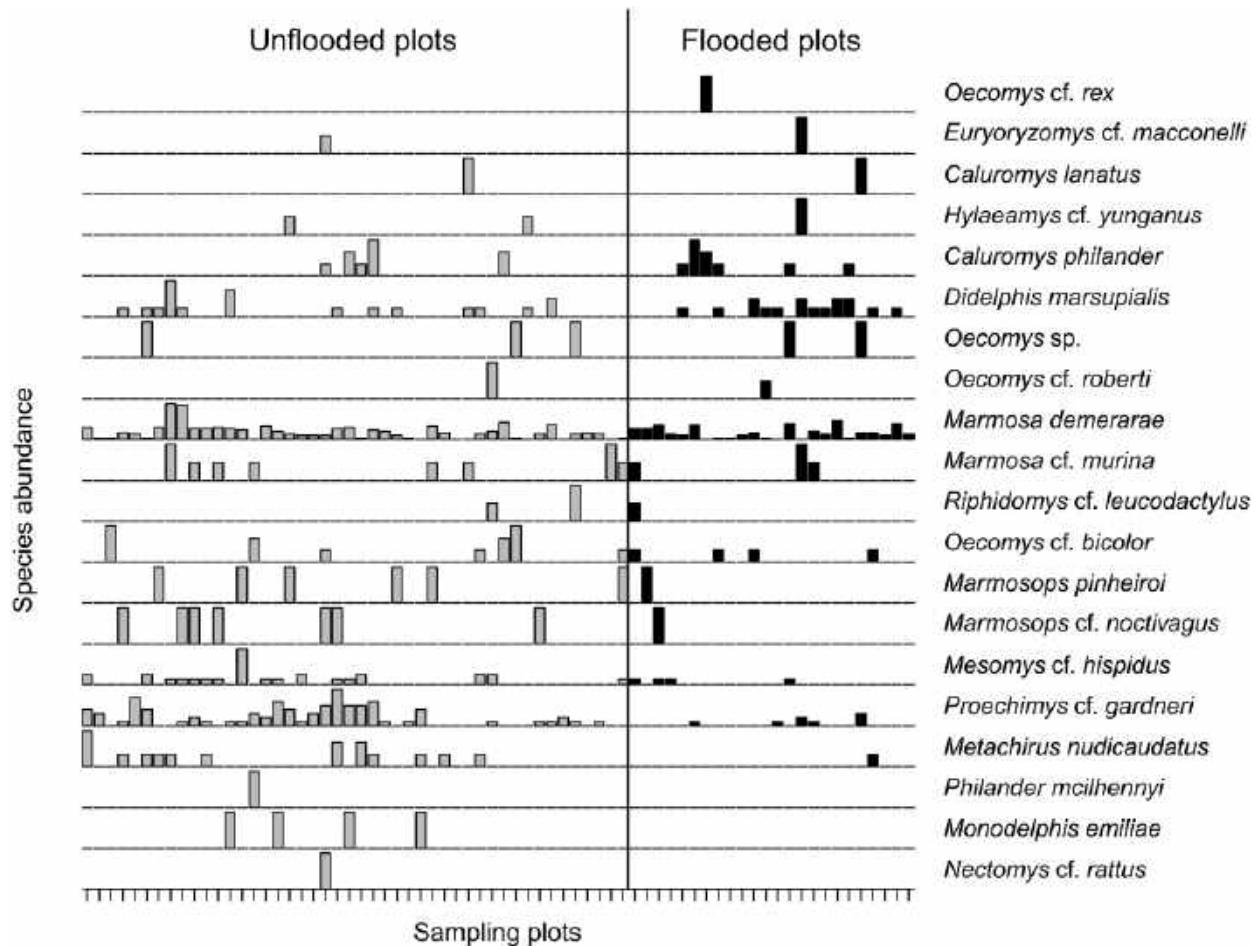


FIGURE 2 Ordination of non-volant small-mammal species abundance in relation to flooded and non-flooded plots located around the reservoir of the Santo Antônio hydroelectric dam on the Madeira River, south-western Brazilian Amazonia.

In the Brazilian Amazon, knowledge of small non-volant mammals is notably poor for the upper Rio Madeira region (Mendes-Oliveira et al., 2015). However, the number of species sampled in our study was similar to other surveys conducted along the middle and upper Rio Madeira (Da Silva et al., 2007). *Marmosops pinheiroi*, *Hylaeamys cf. yunganus*, *Nectomys cf. rattus*, *Oecomys cf. bicolor*, *Oecomys cf. rex*, *Oecomys cf. roberti* and *Rhipidomys cf. leucodactylus* were captured in our study, but not recorded in previous studies. *Marmosops cf. impavidus*, *Sciurillus pusillus* and *Sciurus spadiceus* were recorded by Da Silva et al. (2007), and hence predicted to occur in our study area, but were not captured during the current study. Although our sampling effort was 7.2 times greater than the studies by Da Silva et al. (2007) (6324 night traps), this did not result in a proportionately greater number of species, indicating that a greater effort may not result in the sampling of more species in the region. However, our higher trapping effort captured about five times more individuals, allowing more robust inferences concerning the relationship of assemblages with environmental variables and the potential impacts of anthropic effects on the landscape.

The difference in species composition between areas that would be flooded and those that would remain dry did not indicate an immediate effect of dam construction on the occurrence of assemblages of small non-flying mammals in the region because the assemblage present in the lower areas is represented in the higher areas. *Oecomys cf. rex* was recorded only in the forest that would be submerged. However, only a single

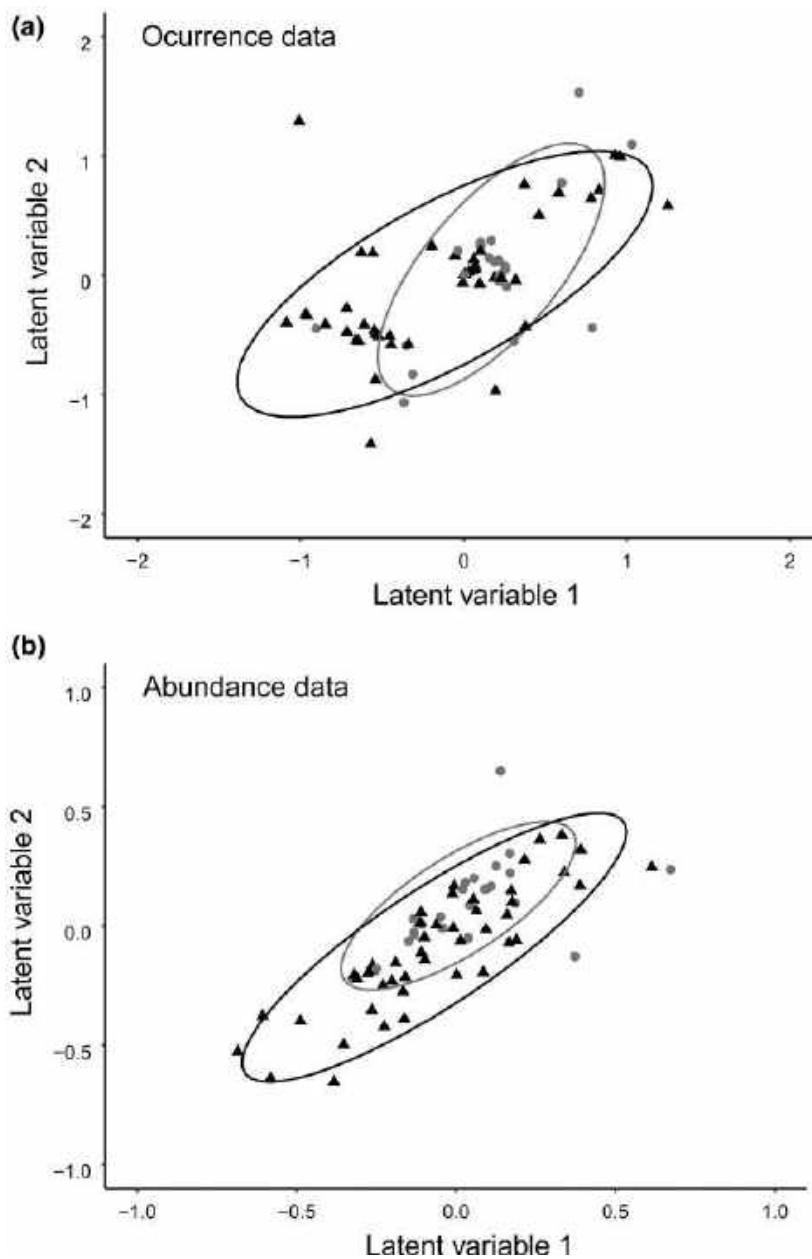


FIGURE 3 Relationship between the two latent variables generated by Bayesian ordination based on occurrence (a) and abundance with the negative binomial distribution (b). Grey circle = floodable plots and black triangle = non-floodable plots.

individual was captured, which makes it impossible to make reliable comments about the local distribution of this species. All other species from the flooded areas were also sampled in the areas not flooded by the dam. Additionally, *M. nudicaudatus* and *P. cf. gardneri* were more abundant or had a higher occurrence in the plots that would not be flooded. These results are in accordance with studies of medium- and large-bodied mammals in flooded forests, which show a greater occupation of species in non-flooded areas (Alvarenga et al., 2018; Haugaasen & Peres, 2005). In contrast, some species of other taxonomic groups, such as frogs (Dayrell et al., 2021) and frugivorous bats (Bobrowiec & Tavares, 2017), were registered mainly or exclusively in forests in the low-lying areas that would be permanently flooded by the dam.



TABLE 2 Minimum, maximum, mean and standard deviation (*SD*) of variables sampled in 70 plots along the banks of the Santo Antônio hydroelectric reservoir, south-eastern Amazon, Brazil

Environmental variables	Minimum	Maximum	Mean	SD
Number of trees	183	613	375.5	85.1
Vegetation density	60	200	113.6	31.9
Basal area of the forest	4.7	32.8	15.7	5.7
Terrain slope	-15.3	12.3	-0.5	4.4
Terrain elevation	64.6	199	84.4	20.8
Sand proportion	14.4	72.3	26.3	10.0
Silt proportion	5.9	19.3	12.0	4.2
Soil nutrients	0.2	0.96	0.5	0.2
Distance from streams	0	3.1	880	797
Distance from Madeira River	26	3.6	1.6	1.1

TABLE 3 Results of the *manyglm* tests of the association between non-volant small-mammal assemblage composition and environmental variables in sampling plots around the Santo-Antônio hydroelectric dam reservoir, south-eastern Amazonia, Brazil

Variable	Abundance data		Occurrence data	
	Wald	p	Wald	p
Flooded × non-flooded plots	5.82	0.004*	5.56	0.001*
Number of trees	5.41	0.07	5.36	0.027*
Vegetation density	3.68	0.68	3.35	0.80
Basal area of the forest	5.05	0.12	4.84	0.09
Terrain slope	4.26	0.39	4	0.42
Terrain elevation	3	0.85	3.5	0.66
Proportion of sand	5.63	0.01*	3.62	0.49
Proportion of silt	2.75	0.15	2.24	0.19
Soil nutrients	5.05	0.02*	5.16	0.01*
Distance from streams	4.70	0.05*	3.9	0.27
Distance from the Madeira River	4.64	0.048*	4.32	0.051*
Module	5.95	0.001*	5.42	0.001*

*means significance of *P* values less than 5% (*P* < 0.05)

The low-lying areas near the course of the Madeira River are occupied by várzea forests, which are seasonally flooded by white waters with high sediment and nutrient contents (Melack & Hess, 2010). Floristic composition and plant phenology in lowland forests are also influenced by seasonal flooding and soil nutrient composition (Moser et al., 2014). The Madeira River flood dynamics possibly exert an influence on the structuring of the regional non-volant small-mammal community, although not all the flood-plains sampled in our study were located in várzea forests and riparian zones. The floodplain on the banks of the Madeira River is narrower than in many parts of the Amazon because of the deep bed and high banks of the Madeira River (Junk et al., 2011; Perigolo et al., 2017). This facilitates the movement of species between the várzea forest and upland, without the need for specialization by forest type. Furthermore, the low abundance of some of the sampled species suggests that these narrow floodplain forests may be suboptimal and not meet the full range of environmental conditions they require, explaining the nested pattern of small non-flying mammal assemblages near the river.



In our study area, soil nutrient levels had the greatest power to predict species composition, followed by sand concentration and the horizontal distance of the plots to the banks of the Madeira River and to streams. Soil edaphic characteristics linked to texture and fertility have been identified as key factors in the structuring of plant assemblages in the tropics (Moulatlet et al., 2014; Schietti et al., 2013). Possibly, assemblages of small non-flying mammals respond indirectly to edaphic characteristics because of the variation in the availability of fruits and phytophagous insects along the nutrient gradient and soil texture (Capaverde Jr. et al., 2018). Vegetation structure also influenced the distribution of small mammals, with species associated with areas of more open or closed vegetation. Areas closer to streams tend to be more open, harbouring species such as *Caluromys lanatus*, *Philander macilhennyi* and *Mesomys hispidus* (Gardner, 2007; Patton & Emmons, 2015).

The construction of new mega hydroelectric dams is still a reality in tropical environments, and our study, which was carried out using data on a regional scale, serves as a basis for conducting large-scale studies that seek to assess the impacts that these future dams will have. Our study also shows the importance—for projects with a potential for high environmental impact—of monitoring biological assemblies before the start of dam construction, as a means of predicting the possible impacts and their magnitudes on the surrounding fauna and flora. This allows the informed proposal of measures of mitigation and environmental compensation before the effects of the installation of the dam.

Unlike what has been reported for other biological groups (bats: Bobrowiec & Tavares, 2017; Bobrowiec et al., 2021; birds: Melo et al., 2021; palm trees: Santos et al., 2020; and frogs: Dayrell et al., 2021), our study showed that the assemblages of non-volant small mammals are not likely to be immediately threatened regionally by the construction of a run-of-the-river dam and the filling to its associated reservoir. Variations in vegetation structure and edaphic characteristics present in the areas that will be submerged will be preserved in some of the unflooded areas, and this may help maintain the original species composition of small non-volant mammals after the dam is filled. Even so, the dam filling can affect the population of small-mammal species in response to changes in interactions with other species of the trophic chain, such as changes in the population of their predators and prey. The importance of the flooded areas to regional population dynamics of the species involved will depend on the conservation of the unflooded areas, and the transport infrastructure associated with dam construction may increase regional deforestation (Fearnside, 2014). Therefore, we recommend conducting long-term studies to monitor the medium- and long-term impacts of hydropower projects and to include analyses of vegetation structure (canopy cover, vegetation obstruction and basal forest area), food availability (fruits and insects) and edaphic structure (soil nutrients, granulometry and water table depth) to understand the environmental mechanisms influencing the distribution and abundance of species in landscapes modified by hydroelectric dams (Castro et al., 2021).

AUTHOR CONTRIBUTIONS

Raylenne da Silva Araujo: Data curation (lead); formal analysis (lead); funding acquisition (lead); investigation (equal); methodology (equal); writing – original draft (lead); writing – review and editing (lead). **Paulo Bobrowiec:** Data curation (equal); formal analysis (equal); funding acquisition (supporting); investigation (supporting); methodology (equal); supervision (equal); writing – original draft (supporting); writing – review and editing (supporting). **Raquel Teixeira Moura:** Data curation (equal); investigation (equal); methodology (supporting); validation (supporting); visualization (supporting); writing – review and editing (supporting). **William Ernest**



Magnusson: Conceptualization (equal); data curation (supporting); formal analysis (equal); funding acquisition (supporting); investigation (equal); methodology (equal); project administration (lead); supervision (lead); validation (equal); visualization (equal); writing – original draft (supporting); writing – review and editing (equal).

ACKNOWLEDGEMENTS

We thank Sete Soluções e Tecnologia Ambiental, Santo Antônio Energia, ICMBio and Instituto Nacional de Pesquisas da Amazônia e Fundação Amazônica de Defesa da Biosfera for providing resources, logistic and general support during this study. We also thank Albertina Lima for making environmental data available; Maria N. da Silva for her help with depositing collected material in the INPA Mammal Collection; and Jussara Dayrell for help with statistical analysis and comments on early versions of the manuscript. We thank American Society of Mastozoology for the Grant-in-Aid of Research. R. Araujo was supported by a doctoral scholarship provided by the CAPES (PROEX 0742/2020), FAPEAM (PAPAC 005/2019) and FAPEAM (POSGRAD 006/2020-Processo: 062.00717/2020); P. Bobrowiec was supported by a post-doctoral scholarship provided by the PNPD/CAPES (#88887.370067/2019-00); William Magnusson was supported by a Productivity Grant (PQ - 301873/2016-0) from the Conselho Nacional de Ciência, Tecnologia e Inovação (CNPq). The experimental design and institutional collaborations were fruits of the Program for Biodiversity Research in Western Amazonia (PPBio-AmOc) and the National Institute for Biodiversity Research in the Amazon (INCT-CENBAM), both supported by CNPq and FAPEAM.

DATA AVAILABILITY STATEMENT

Data available in article supplementary material.

ORCID

Raylenne da Silva Araujo <https://orcid.org/0000-0001-5726-6510>

REFERENCES

- Abreu, E.F., Casali, D., Costa-Araújo, R., Garbino, G.S., Libardi, G., Loretto, D. et al. (2021) Lista de Mamíferos do Brasil (2021-2) [Data set]. Zenodo. Available from: <https://doi.org/10.5281/zenodo.5802047>
- Almeida, R.M., Shi, Q., Gomes-Selman, J.M., Wu, X., Xue, Y., Angarita, H. et al. (2019) Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. *Nature Communications*, 10, 4281.
- Alvarenga, G.C., Ramalho, E.E., Baccaro, F.B., da Rocha, D.G., Ferreira-Ferreira, J. & Bobrowiec, P.E.D. (2018) Spatial patterns of medium and large size mammal assemblages in várzea and terra firme forests, Central Amazonia, Brazil. *PLoS One*, 13, e0198120.
- Anderson, D., Moggridge, H., Warren, P. & Shucksmith, J. (2015) The impacts of 'run-of-river' hydropower on the physical and ecological condition of rivers. *Water and Environment Journal*, 29, 268–276.
- Anderson, E.O., Jenkins, C.N., Heilpern, S., Maldonado-Ocampo, J.A., Carvajal-Vallejos, F.M., Encalada, A.C. et al. (2018) Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Science Advances*, 4, 1–7.
- Ansar, A., Flyvbjerg, B., Budzter, A. & Lunn, D. (2014) Should we build more large dams? The actual costs of hydropower megaproject development. *Energy Policy*, 69, 43–56.
- Athayde, S., Mathews, M., Bohlman, S., Brasil, W., Doria, C.R.C., Dutka-Gianelli, J. et al. (2019) Mapping research on hydropower and sustainability in the Brazilian Amazon: advances, gaps in knowledge and future directions. *Current Opinion in Environmental Sustainability*, 37, 50–69.
- Avenant, N.L. & Kuyler, P. (2002) Small mammal diversity in the Maguga dam inundation area, Swaziland. *South African Journal of Wildlife Research*, 32, 101–108.
- Baumgartner, M.T., Piana, P.A., Baumgartner, G. & Gomes, L.C. (2020) Storage or run-of-river reservoirs: exploring the ecological effects of dam operation on stability and species interactions of fish assemblages. *Environmental Management*, 65, 220–231.

- Benchimol, M. & Peres, C.A. (2020) Determinants of population persistence and abundance of terrestrial and arboreal vertebrates stranded in tropical forest land-bridge islands. *Conservation Biology*, 35, 870–883.
- Bobrowiec, P.E.D., Nobre, C.C. & Tavares, V.C. (2021) Immediate effects of an Amazonian mega hydroelectric dam on phyllostomid fruit bats. *Ecological Indicators*, 132, 108322.
- Bobrowiec, P.E.D. & Tavares, V.C. (2017) Establishing baseline biodiversity data prior to hydroelectric dam construction to monitoring impacts to bats in the Brazilian Amazon. *PLoS One*, 12, e0183036.
- Brooks, M.E., Kristensen, K., van Bentham, K.J., Magnusson, A., Berg, C.W., Nielsen, A. et al. (2017) Package ‘glmmTMB’—balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R Journal*, 9, 378–400.
- Capaverde, U.D., Jr., Pereira, L.G.D.A., Tavares, V.C., Magnusson, W.E., Baccaro, F.B. & Bobrowiec, P. (2018) Subtle changes in elevation shift bat-assemblage structure in central Amazonia. *Biotropica*, 50, 1–10.
- Castro, A.B., Bobrowiec, P.E.D., Castro, S.J., Rodrigues, L.R.R. & Fadini, R.F. (2021) Influence of reduced-impact logging on central Amazonian bats using a before-after-control-impact design. *Animal Conservation*, 25, 311–322. Available from: <https://doi.org/10.1111/acv.12739>
- COGEO/SEDAM [Coordenadoria de Geociências/Secretaria de Estado do Desenvolvimento Ambiental]. (2010) *Boletim Climatológico de Rondônia*, Vol. 12. Porto Velho: COGEO/SEDAM.
- Cosson, J., Ringuet, S., Claessens, O., de Massary, J.C., Dalecky, A. & Villiers, J.F. (1999) Ecological changes in recent land-bridge islands in French Guiana, with emphasis on vertebrate communities. *Biological Conservation*, 91, 213–222.
- Costa, F.R.C. & Magnusson, W.E. (2010) The need for large-scale, integrated studies of biodiversity—the experience of the program for biodiversity research in Brazilian Amazonia. *Natureza & Conservação*, 8, 1–5.
- Da Silva, M.N.F., Arteaga, M.C., Bantel, C.G., Rossoni, D.M., Leite, R. & Pinheiro, P.S. (2007) Mamíferos de pequeno porte (Mammalia: Rodentia & Didelphimorphia). In: *Biodiversidade do médio Madeira: bases científicas para propostas de conservação*, Manaus: INPA, pp. 179–194.
- Dayrell, J.S., Magnusson, W.E., Bobrowiec, P.E.D. & Lima, A.P. (2021) Impacts of an Amazonian hydroelectric dam on frog assemblages. *PLoS One*, 16, e0244580.
- Dias-Terceiro, R.G., Kaefer, I.L., Fraga, R., de Araújo, M.C., Simões, P.I. & Lima, A.P. (2015) A matter of scale: historical and environmental factors structure anuran assemblages from the upper Madeira River, Amazonia. *Biotropica*, 47, 259–266.
- Emmons, L.H. (1987) Comparative feeding ecology of felids in a Neotropical rainforest. *Behavior Ecology and Sociobiology*, 20, 271–283.
- Faria, F.A.M., Davis, A., Severnini, E. & Jaramillo, P. (2017) The local socio-economic impacts of large hydropower plant development in a developing country. *Energy Economics*, 67, 533–544.
- Fearnside, P.M. (2014) Impacts of Brazil's Madeira River dams: unlearned lessons for hydroelectric development in Amazonia. *Environmental Science and Policy*, 38, 164–172.
- Fearnside, P.M. (2015) Hidrelétricas na Amazônia brasileira: questões ambientais e sociais. In: *América Latina, sociedade e meio ambiente: teorias, retóricas e conflitos em desenvolvimento*, Curitiba: UFPR, pp. 7–22.
- Finer, M. & Jenkins, C.N. (2012) Proliferation of hydroelectric dams in the Andean Amazon and implications for Andes-Amazon connectivity. *PLoS One*, 7, 1–9.
- Gardner, A.L. (2007) *Mammals of South America: Marsupials, Xenarthrans, Musaranhos e Bats*, Chicago and London: University of Chicago Press.
- Gibson, L., Lynam, A.J., Bradshaw, C.J.A., He, F., Bickford, D.P., Woodruff, D.S. et al. (2013) Near-complete extinction of native small mammal fauna 25 years after forest fragmentation. *Science Reports*, 341, 1508–1510.
- Granjon, L., Cosson, J.F., Judas, J. & Ringuet, S. (1996) Influence of tropical rainforest fragmentation on mammal communities in French Guiana: short-term effects. *Acta Oecologica*, 17, 673–684.
- Hartig, F. (2021) Package ‘DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models’. Available from: <https://cran.r-project.org/web/packages/DHARMa/vignettes/DHARMa.html> [Accessed 15th August 2021].
- Haugaasen, T. & Peres, C.A. (2005) Mammal assemblage structure in Amazonian flooded and unflooded forests. *Journal of Tropical Ecology*, 21, 133–145.
- Hayward, G.F. & Phillipson, J. (1979) Community structure and functional role of small mammals in ecosystems. In: *Ecology of small mammals*, Berlin: Springer, pp. 135–211.
- Hui, F.K.C. & Blanchard, W. (2021) Package ‘boral—bayesian ordination and regression analysis’. Available from: <https://cran.r-project.org/web/packages/boral/index.html> [Accessed 22nd May 2021].



- Hui, F.K.C., Taskinen, S., Pledger, S., Foster, S.D. & Warton, D.I. (2015) Model-based approaches to unconstrained ordination. *Methods in Ecology and Evolution*, 6, 399–411.
- IBGE [Instituto Brasileiro de Geografia e Estatística]. (2012) *Manual técnico da vegetação brasileira*, 2nd edition. Rio de Janeiro: Ministério do Planejamento, Orçamento e Gestão.
- IEA [International Energy Agency]. (2012) World energy outlook. Available from: <http://www.worldenergyoutlook.org/weo2012/> [Accessed 15th July 2021].
- Junk, W.J., Piedade, M.T.F., Wittmann, F., Schöngart, J. & Parolin, P. (2011) *Amazonian floodplain forests: ecophysiology, biodiversity and sustainable management*, 1st edition. Berlin: Springer.
- Latrubesse, E.M., Arima, E.Y., Dunne, T., Park, E., Baker, V.R., d'Horta, F.M. et al. (2017) Damming the rivers of the Amazon Basin. *Nature*, 546, 363–369.
- Magnusson, W.E., Braga-Neto, R., Pezzini, F., Baccaro, F.B., de Godoy Bergallo, H., Penha, J. et al. (2013) *Biodiversidade e Monitoramento Integrado*. Manaus: Attema Editora.
- Magnusson, W.E., Lima, A.P., Luizão, R., Luizão, F., Costa, F.R.C., Castilho, C.V. et al. (2005) RAPELD: a modification of the gentry method of floristic survey for biodiversity surveys in long-term ecological research sites. *Biota Neotropica*, 2, 1–6.
- Martins, R.L. & Gribel, R. (2007) Polinização de *Caryocar villosum* (Aubl.) Pers. (Caryocaraceae) uma árvore emergente da Amazônia Central. *Revista Brasileira de Botânica*, 30, 37–45.
- Melack, J.M. & Hess, L.L. (2010) Remote sensing of the distribution and extent of wetlands in the Amazon basin. In: *Amazonian floodplain forests: ecophysiology, biodiversity and sustainable management*, Berlin: Springer, pp. 43–59.
- Melo, T.N., Cerqueira, M.C., D'Horta, F.M., Tuomisto, H., Van Doninck, J. & Ribas, C.C. (2021) Impacts of a large hydroelectric dam on the Madeira River (Brazil) on floodplain avifauna. *Acta Amazonica*, 51, 298–310.
- Mendes-Oliveira, A.N., Borges, M.L.O., Lambert, T., Santos-Filho, M., de Godoy Bergallo, H., Ardente, N.C. et al. (2015) Efeitos antrópicos sobre comunidades de pequenos mamíferos não-voadores na Amazônia brasileira. In: *Pequenos mamíferos não-voadores da Amazônia brasileira*, Rio de Janeiro: Sociedade Brasileira de Mastozoologia, pp. 257–274.
- Moser, P., Oliveira, W.L., Medeiros, M.B., Pinto, J.R., Eisenlohr, P.V., Lima, I.L. et al. (2014) Tree species distribution along environmental gradients in an area affected by a hydroelectric dam in southern Amazonia. *Biotropica*, 46, 367–376.
- Mouloulet, G.M., Costa, F.R.C., Rennó, C.D., Emilio, T. & Schietti, J. (2014) Local hydrological conditions explain floristic composition in lowland Amazonian forests. *Biotropica*, 46, 395–403.
- Nilsson, C., Reidy, C.A., Dynesius, M. & Revenga, C. (2005) Fragmentation and flow regulation of the world's large river systems. *Science*, 308, 405–408.
- Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P. & Minchi, P.R. (2020) Package ‘vegan: community ecology’. Available from: <https://cran.r-project.org/web/packages/vegan/index.html> [Accessed 28th April 2021].
- Paglia, A.P., da Fonseca, G.A.B., Rylands, A.B., Herrmann, G., Aguiar, L.M.S., Chiarello, A.G. et al. (2012) *Annotated checklist of Brazilian mammals*, 2nd edition. Arlington: Occasional Papers in Conservation Biology.
- Palmeirim, A.F., Benchimol, M., Vieira, M.V. & Peres, C.A. (2018) Small mammal responses to Amazonian Forest islands are modulated by their forest dependence. *Oecologia*, 187, 191–204.
- Patton, J.L., Da Silva, M.N.F. & Malcolm, J.R. (2000) Mammals of the Rio Juruá and the evolutionary and ecological diversification of Amazonia. *Bulletin of the American Museum of Natural History*, 244, 1–306.
- Patton, J.L. & Emmons, L.H. (2015) Genus *Mesomys* (Wagner, 1845). In: *Mammals of South America: Rodents* Mammals of South America: Rodents, Chicago and London: The University of Chicago Press, pp. 943–950.
- Perigolo, N.A., Medeiros, M.B. & Simon, M.F. (2017) Vegetation types of the upper Madeira River in Rondônia, Brazil. *Brittonia*, 69, 423–446.
- Pitman, N.C.A., Mogollón, H., Dávila, N., Ríos, M., García-Villacorta, R., Guevara, J. et al. (2008) Tree community change across 700 km of lowland Amazonian Forest from the Andean foothills to Brazil. *Biotropica*, 40, 525–535.
- Quesada, C.A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T.R., Czimczik, C. et al. (2010) Variations in chemical and physical properties of Amazon Forest soils in relation to their genesis. *Biogeosciences*, 7, 1515–1541.
- R Core Team. (2020) *R: a language and environment for statistical computing*. Vienna: R Foundation for statistical computing.
- Roberts, T.R. (1995) Mekong mainstream hydropower dams: run-of-river or ruin-of-the-river? *Boletim de História Natural da Siam Society*, 43, 9–19.

- Santos, E.A., Medeiros, B.M., Ferreira, J.L.F., Simon, M.F., Oliveira, W.L. & Costa, F.R.C. (2020) Palm distribution patterns in the southwestern Brazilian Amazon: impact of a large hydroelectric dam. *Forest Ecology and Management*, 463, 118032.
- Scherer, L. & Pfister, S. (2016) Hydropower's biogenic carbon footprint. *PLoS One*, 14, 1–11.
- Schiatti, J., Emilio, T., Rennó, C.D., Drucker, D.P., Costa, F.R.C., Nogueira, A. et al. (2013) Vertical distance from drainage drives floristic composition changes in an Amazonian rainforest. *Plant Ecology & Diversity*, 7, 241–253.
- Soukaphon, A., Baird, I.G. & Hogan, Z.S. (2021) The impacts of hydropower dams in the Mekong River basin: a review. *Water*, 13, 1–18.
- Wang, Y., Naumann, U., Eddelbuettel, D., Wilshire, J., Warton, D., Byrnes, J. et al. (2020) Package ‘Mvabund—statistical methods for analysing multivariate abundance data’. Available from: <https://cran.r-project.org/web/packages/mvabund/index.html> [Accessed 20th May 2021].
- Wang, Y., Naumann, U., Wright, S.T. & Warton, D.I. (2012) Mvabund—An R package for model-based analysis of multivariate abundance data. *Methods in Ecology and Evolution*, 3, 471–474.
- Warton, D.I., Thibaut, L. & Wang, Y.A. (2017) The PIT-trap: a “model-free” bootstrap procedure for inference about regression models with discrete, multivariate responses. *PLoS One*, 12, e0181790.
- Warton, D.I., Wright, S.T. & Wang, Y. (2012) Distance-based multivariate analyses confound location and dispersion effects. *Methods in Ecology and Evolution*, 3, 89–101.
- WCD [World Commission on Dams]. (2000) *Dams and development: a new framework for decision-making*. London: Earthscan Publications Ltd.
- Wilson, D.E. & Reeder, D.M. (2005) *Mammal species of the world: a taxonomic and geographic reference*, 3rd edition. Baltimore: Johns Hopkins University Press.
- Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S. et al. (2016) Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong: basin-scale planning is needed to minimize impacts in mega-diverse rivers. *Science*, 351, 128–129.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article:

Araujo, R.d.S., Bobrowiec, P.E.D., de Moura, R.T. & Magnusson, W.E. (2022) The impact of a run-of-the-river hydroelectric dam on a non-volant small-mammal assemblage in Brazilian Amazonia. *Austral Ecology*, 00, 1–15. Available from: <https://doi.org/10.1111/aec.13257>

CAPÍTULO II

Araujo, R.S., Bobrowiec, P.E.D., Stevens, R.D., Moura, R.T., Sábato, M.A.L., Sábato, E.L., Magnusson, W.E. Amazonian dam effects on taxonomic, functional and phylogenetic dimensions of non-flying small mammals. Manuscrito em preparação para *Environmental Impact Review*

1 **Effects of an Amazonian dam on taxonomic, functional and phylogenetic**
2 **dimensions of biodiversity of non-volant small mammals**

3

4 Raylenne da Silva Araujo^{1,*}, Paulo E. Dineli Bobrowiec^{1,2}, Richard D. Stevens^{3,4},
5 Raquel Teixeira de Moura⁵, Marco Aurélio L. Sábato⁶, Eduardo Lima Sábato⁷, William
6 E. Magnusson¹

7

8 ¹ Programa de Pós-graduação em Ecologia, Instituto Nacional de Pesquisas da
9 Amazônia (INPA), Av. André Araújo 2936, CP 2223, Manaus-AM 69080-971, Brazil

10 ² Instituto Tecnológico Vale, Rua Boaventura da Silva 955, Belém-PA 66055-090, Brazil

11 ³ Department of Natural Resources Management, Texas Tech University, 007D Goddard
12 Hall, Lubbock-TX 79410, USA

13 ⁴ Natural Science Research Laboratory, Museum of Texas Tech University, 3301 4th
14 Street, Lubbock-TX 79415, USA

15 ⁵ Calispictus Consultoria Ambiental, Rua Prof. Pimenta da Veiga 1053/1301, Belo
16 Horizonte-MG 31170-190, Brazil

17 ⁶ RDS Consultoria Ambiental, Rua Ernani Agrícola 420/501, Belo Horizonte-MG
18 30492-040, Brazil

19 ⁷ Sete Soluções e Tecnologia Ambiental Ltda, Av. Contorno 6777, 2nd floor, Belo
20 Horizonte-MG 30110-935, Brazil

21

22 *Correspondent: Av. André Araújo 2936, CP 2223, Manaus-AM 69080-971, Brazil.
23 araujo.raylenne@gmail.com (RSA)

24

25 **ABSTRACT**

26 Hydropower-plant expansion in tropical forests presents environmental and ecological
27 challenges. Our study investigated changes in multiple dimensions of biodiversity of
28 small non-volant mammal assemblages after the construction of a dam in the Brazilian
29 Amazon, where we expected reductions in number of species and abundance, functional
30 traits, and phylogenetic diversity. Our results showed that the number of species and
31 abundance initially increased after reservoir filling but decreased in the second year,
32 reaching levels similar to the pre-filling period. Species composition changed among
33 the three sampling periods, with higher dissimilarity in the first post-filling year.
34 Functional traits related to diet, locomotion, and body mass were affected by the
35 flooding. Frugivorous-omnivorous, terrestrial and larger-bodied species increased in
36 frequency in the first post-filling year, while insectivorous-omnivorous and scansorial
37 species were less frequent in this period. Phylogenetic diversity remained stable
38 throughout the study periods, indicating no significant effect of reservoir filling on this
39 parameter. Our results suggest that dam construction had an immediate impact on small
40 non-volant mammal communities, with changes in species composition and functional
41 traits. However, after two years, non-volant small-mammal assemblages had not fully
42 recovered to pre-filling levels, indicating ongoing adjustments in response to the new
43 environment. Our study highlights the importance of considering taxonomic, functional,
44 and phylogenetic aspects when assessing the ecological effects of large-scale
45 infrastructure projects based on long-term monitoring data.

46 Keywords: hydroelectric, rainforest, diversity, impact, monitoring.

47 RESUMO

48 A expansão de usinas hidrelétricas em florestas tropicais apresenta desafios ambientais e
49 ecológicos. Nossa estudo investigou mudanças nas múltiplas dimensões da
50 biodiversidade de pequenas assembleias de mamíferos não voadores após a construção
51 de uma barragem na Amazônia, onde esperamos as reduções do seu número de espécies
52 e abundância, características funcionais e diversidade filogenética. Nossos resultados
53 mostraram que o número de espécies e a abundância aumentaram inicialmente após o
54 enchimento do reservatório, mas diminuíram no segundo ano, atingindo níveis
55 semelhantes ao período pré-enchimento. A composição de espécies mudou entre os três
56 períodos de amostragem, com maior dissimilaridade no primeiro ano pós-enchimento.
57 Características funcionais relacionadas à dieta, locomoção e massa corporal foram
58 afetadas pela inundação. As espécies frugívoras-onívoras, terrestres e de maior massa
59 corpórea aumentaram de frequência no Pós-1, enquanto as espécies insetívoras-onívoras
60 e escansoriais foram menos frequentes apenas no Pós-1. A diversidade filogenética
61 manteve-se estável ao longo do período de estudo, indicando não haver efeito
62 significativo do enchimento do reservatório sobre este parâmetro. Os resultados
63 sugerem que a construção da barragem teve um impacto imediato nas comunidades de
64 pequenos mamíferos, com mudanças na composição de espécies e características
65 funcionais. No entanto, após dois anos, a assembleia de pequenos mamíferos não
66 voadores não havia recuperado totalmente os níveis anteriores ao enchimento, indicando
67 ajustes em andamento em resposta ao novo ambiente. Nossa estudo destaca a
68 importância de considerar aspectos taxonômicos, funcionais e filogenéticos ao avaliar
69 os efeitos ecológicos de projetos de infraestrutura de grande escala baseados em dados
70 de monitoramento de longa duração.

71 Palavras-chave: hidrelétrica, floresta tropical, diversidade, impacto, monitoramento.

72 **INTRODUCTION**

73 Expansion of hydropower plants brings significant challenges and impacts to
74 local and regional faunas and floras in tropical regions (Fearnside 2014; 2015). Dam
75 construction has altered riparian ecosystems and fragmented rivers worldwide,
76 including in the Amazon, where there are plans to install more than 300 new
77 hydroelectric power plants in the coming years (Nilsson et al. 2005; Ansar et al. 2014;
78 Winemiller et al. 2016). These projects represent substantial financial investments in the
79 construction of hydroelectric plants and significant energy generation potential, but they
80 also raise concerns regarding environmental stemming from their implementation
81 (Gibson et al. 2017; Moran et al. 2018). Because of the extensive river network and
82 great hydroelectric potential for energy generation, millions of hectares of Amazonian
83 forest are at risk of being permanently flooded with enormous consequences for
84 terrestrial and aquatic biota (Winemiller et al. 2016; Latrubblesse et al. 2017; Anderson et
85 al. 2018). While hydropower plants are an important energy source, the expansion of
86 these projects in tropical regions demands a careful balance between energy supply and
87 ecosystem conservation (Nilsson et al. 2005; Winemiller et al. 2016).

88 Construction of reservoir-based hydropower plants, which result from water
89 damming and formation of large lakes, has well-documented significant negative
90 consequences for biota (Lynam 1997; Cosson et al. 1999; Terborgh et al. 2006). These
91 dams alter the landscape, fragment natural habitats, and reduce biological diversity and,
92 consequently, mobile organisms can displace from their original habitats (Passamani &
93 Cerboncini 2013; Winemiller et al. 2016). Studies conducted in various regions of the
94 tropics, including the Brazilian Amazon, have analyzed effects of reservoir-based
95 hydroelectric power plants on biological communities highlight the environmental
96 impacts caused by these dams (Benchimol & Peres 2015; Jones et al. 2016; Palmeirim
97 et al. 2018; Soukaphon et al. 2021). Recently, there has been an increase in
98 construction of run-of-river hydropower plants, whose design does not require the
99 storage of large volumes of water upstream, and the turbines can be operated without
100 significant waterfalls, reducing the need for the formation of large lakes and the
101 flooding of extensive forested areas (Fearnside 2014). Although this approach
102 minimizes impacts on terrestrial environments by not flooding large areas, the impacts
103 of this dam type are unknown for biota and ecosystems (Fearnside 2014; Zarfl et al.
104 2014).

105 Traditionally, research on biodiversity and environmental impact assessment has
106 focused on taxonomic diversity, which refers to the quantity of species and equitability
107 of abundances of individuals present in each environment (Magurran & McGill 2011).
108 However, such a focus is insufficient to capture the full extent of variation in
109 biodiversity and the ecological characteristics of species (Ricotta 2005). Many species
110 have distinct ecological responses, interactions, and morphologies that are not fully
111 characterized by taxonomic diversity measures (Tilman 2001). These other forms of
112 ecological variations result from complex evolutionary processes, so to better
113 understand diversity patterns and their role in ecosystems, it is necessary to complement
114 taxonomic studies with functional and phylogenetic perspectives (Davies & Buckley
115 2011; Stevens & Tello 2014). Phylogenetic diversity describes the variety of
116 evolutionary lineages present in a community (Faith 1992), while functional diversity
117 reflects the variety of morphological, physiological, behavioral, and ecological
118 characteristics of species (Petchey & Gaston 2006). Species, functional traits, and
119 phylogenetic diversity represent different dimensions of biodiversity that are
120 interconnected and complementary (Pavoine & Bonsall 2011; Stevens & Tello 2014).
121 The combination of these three dimensions is crucial for assessing environmental
122 impacts and proposing conservation and mitigation measures, especially in constantly
123 threatened megadiverse tropical regions (Bovendorp et al. 2018; Bobrowiec et al. 2022).

124 Non-volant small mammals play an important role in ecosystem dynamics and
125 are crucial for forest regeneration and maintenance (Mendes-Oliveira & Miranda 2015).
126 They act as population regulators of invertebrates and serve as prey for other animals.
127 They also influence the plant community by participating in the control and
128 maintenance of mycorrhizal fungi, as well as contributing to the diversity and
129 population regulation of seedlings and seed dispersers (Hayward & Phillipson 1979;
130 Martins & Gribel 2007). The presence and activities of non-volant small mammals are
131 fundamental to ecosystem balance, and the loss of these species can lead to a decrease
132 in functional diversity and loss of phylogenetic history that could ultimately
133 compromise forest regeneration (Alho et al. 2011).

134 In this study, we evaluate how different dimensions of biodiversity (taxonomic,
135 functional, and phylogenetic) characterizing assemblages of non-volant small mammal
136 changed over time after construction of a large run-of-river hydroelectric dam in the
137 southeastern Amazon. Our hypothesis is that species richness and abundance, functional
138 traits frequencies and phylogenetic diversity would decrease after the filling of the

139 reservoir caused by the loss of species, functional traits and phylogenetic information.
140 (1) We expected a change in species composition due to decreased species richness and
141 abundance in the years following the reservoir filling due to response to the loss of part
142 of the environmental gradient. This is expected because small mammal individuals are
143 likely to seek areas away from the new riverbank (Passamani & Cerboncini 2013). (2)
144 We also expected a decrease in the frequencies of low body mass species with terrestrial
145 habits, as a reflection of the low mobility of these species in relation to the rapid
146 environmental change after the filling (Cosson et al. 1999). We expected that tree-
147 dwelling species and species with long feet and tails - traits linked to high dispersal
148 capacity - would increase in frequency because they are able to move quickly to non-
149 flooded areas (Szalay 1994; Alroy 2019). (3) We predicted that phylogenetic diversity
150 would decrease as consequence of the loss of species or clades after flooding (Petchey
151 & Gaston 2006).

152

153 MATERIALS AND METHODS

154 Study area

155 Data were collected in the vicinity of the reservoir of the Santo Antônio
156 Hydroelectric Plant ($8^{\circ}47' S$; $63^{\circ}53' W$; Figure 1) situated on the Madeira River, in the
157 city of Porto Velho, Rondônia State, Brazil. The Madeira River has white water and
158 contributes about 15% of the sediment discharge that flows into the Amazon River
159 (Junk et al. 2011). The annual rainfall in the region ranged from 1,400 to 2,600 mm,
160 with a wet season from November to April, and a dry season from June to September
161 (COGEO/SEDAM 2010). The vegetation found in the area is mainly dense *terra firme*
162 rainforest, but it also has *várzea* forests, which are seasonally flooded by white waters
163 with high sediment and nutrient loads (Melack & Hess 2010; IBGE 2012).

164 Santo Antônio Dam has generating capacity of 3,568 MW, and is the fourth-
165 largest hydroelectric plant in Brazil in terms of power output (Fearnside 2015). The dam
166 reservoir was filled up in 2012 and flooded an area of 422 km². Santo Antônio is a "run-
167 of-river" dam, which does not form a large lake and islands, as do conventional storage
168 reservoir dams (Baumgartner et al. 2020; Fearnside 2014).

169

170 Small-mammal sampling

171 We captured non-volant small mammals at four sites (Ilha de Pedras, Ilha de
172 Búfalos, Jaci, Teotônio) located along a 100-kilometer stretch of the Madeira River

173 (Figure 1). One of the sites was situated on the Jaci-Panará River, which is a tributary of
174 the Madeira River (Figure 1). We used the standardized RAPELD method (RAP = rapid
175 survey of biological communities; PELD = long-term ecological survey) proposed for
176 spatially standardized sampling of fauna and flora in long-term studies (Magnusson et
177 al. 2013). At each site, we sampled plots at 0, 500, 1000, 2000, and 3000 meters from
178 the Madeira and Jaci-Paraná riverbanks (Figure 1). Of these, we sampled 34 plots
179 before filling, one year after filling and two years after filling (Figure 1). Each plot was
180 250 meters long and followed the local topography to reduce internal heterogeneity in
181 soil and drainage properties, and vegetation composition (Magnusson et al. 2013).
182 Sampling was conducted before dam filling (hereafter called Pre-filling), one year post-
183 filling (Post-1) and two years after filling (Post-2). Pre-filling sampling was undertaken
184 from December 2009 to August 2012, Post-1 sampling was conducted from August
185 to August 2013, and Post-2 sampling occurred from November 2013 to December
186 2014.

187 We captured non- flying small mammals using live traps. In each plot, we placed
188 26 traps in pairs, one Sherman® trap ($30 \times 8 \times 7$ cm) and one Tomahawk® trap ($31.5 \times$
189 15×15 cm), every 20 meters, resulting in 13 pairs of traps per plot. We installed live
190 traps alternatively on the ground and at a height of 1.5 meters, attached to a tree trunk.
191 We checked each trap daily and baited it with pineapple and a sweetened cod-liver-oil
192 mixture. Traps remained open for five consecutive nights per plot on each sampling
193 occasion. We visited each plot five times per period (Pre-filling, Post-1, Post2), totaling
194 650 capture nights in each period (66,300 trap-nights; one trap-night corresponds to one
195 trap open for one night). We identified captured small mammals using dichotomous
196 keys and descriptions found in Patton et al. (2000), Wilson & Reeder (2005). Taxonomy
197 follows Abreu et al. (2022).

198

199 **Functional traits**

200 We selected traits that may be affected by habitat flooding. We grouped the traits
201 into three categories: foraging habitat (Arboreal, Scansorial, Terrestrial, Semiaquatic),
202 diet reflected by trophic level (Frugivore-Omnivorous, Frugivore-Herbivore, Frugivore-
203 Granivore, Insectivore-Omnivorous), and body measurements associated with
204 locomotion on the ground and in trees (foot length, tail length, body mass) (Table S1).
205 Functional-trait data were obtained from Paglia et al. (2012) and Wilman et al. (2014).

206 The use of different habitats indicates where species spend the most time
207 foraging, and therefore indicates niche differentiation and a possible strategy to avoid
208 interspecific interactions (Püttker et al. 2013). Trophic level is a trait widely used in
209 several studies of non-volant small mammals (Bovendorp et al. 2018; Palmeirim et al.
210 2021), and use of different food resources among cohabiting species can predict niche
211 partitioning and possible interspecific interactions (Galetti et al. 2016). Foot and tail
212 length characterize different modes of locomotion. A larger hind foot indicates a species
213 that jumps, whereas those that creep or walk have smaller relative hind-foot lengths
214 (Alroy 2019). The tail serves as balancing mechanism when moving along tree branches
215 and other vegetation, as well as a swimming aid for semiaquatic species (Szalay 1994).
216 Body mass is considered an important functional trait because it is related to foraging
217 strategies and mobility of species (Cosson et al. 1999).

218

219 **Phylogenetic relationships**

220 To estimate phylogenetic diversity, we constructed a species-level phylogeny of
221 non-volant small mammals using a single 78 base pairs fragment of the mitochondrial
222 Cytochrome-b (Cyt-b) gene obtained from GenBank® (Clark et al. 2016). Genetic
223 sequences were aligned and edited in MEGA11 (Tamura et al. 2011). The maximum-
224 likelihood phylogenetic trees (Table S2) were generated after comparison of model-fit
225 using likelihood ratio tests, to determine the best-fit evolutionary models of sequence
226 evolution based on the lowest Akaike Information Criterion with correction (AICc)
227 (Cadotte & Davis 2016). Phylogenetic pairwise-distance matrices were generated using
228 all species for each sampling period (Pre-filling, Post-1, and Post-2). The pairwise
229 distance matrices were calculated using the Bootstrap method with 1000 replications
230 and the Kimura 2 substitution model, undertaken using the Mega 11 software
231 (Molecular Evolutionary Genetics Analysis; Tamura et al. 2011).

232

233 **Data analysis**

234 We compared abundance and species richness among the three sampling periods
235 (Pre-filling, Post-1 and Post-2) using generalized linear mixed-effect models (GLMM),
236 with a negative binomial distribution, in the ‘glmmTMB’ function from the *glmmTMB*
237 R package (Brooks et al. 2017). Models incorporated sampling sites (Ilha de Pedras,
238 Ilha de Búfalos, Jaci, Teotônio) as random effects to account for potential spatial
239 autocorrelations. We assessed pairwise comparison between sampling periods with the

240 ‘lmeans’ function from the *emmeans* package (Russell et al. 2023). To assess species-
241 level abundance differences between the three sampling periods, we also used GLMM
242 as described above. Species that occurred in <10 samples were excluded, resulting in a
243 total of seventeen species selected for the GLMM analysis.

244 To measure the loss or gain in abundance and richness among plots over time
245 between the Pre-flood, Post-1 and Post-2, we used the Temporal Beta-Diversity Index
246 (TBI) as implemented in the ‘TBI’ function of the *adespatial* package (Legendre 2019;
247 Dray et al. 2020). TBI was computed using the Bray-Curtis dissimilarity index for
248 abundance data (Legendre 2014, 2019). We conducted paired t-tests with 9 999 random
249 permutations to determine whether plots were dominated by species gains or losses and
250 increases or decreases in species abundance.

251 To compare species composition of small-mammal assemblages among
252 sampling periods, we used generalized linear models (GLM) with negative binomial
253 distributions for multivariate data. To avoid confounding effects of dispersion and
254 location of the plots, we used the ‘manyglm’ function of the *mvabund* package (Wang et
255 al. 2012). We obtained significance tests through the ‘anova.manyglm’ function of the
256 *mvabund* package, with Wald's statistic adjusted by the PIT-trap method and estimated
257 p-values from 999 bootstrap samples. A Bayesian ordination of multivariate abundance
258 data in ecology (BORAL) was used to describe species compositions among the three
259 sampling periods.

260 To evaluate if traits were filtered by the dam filling, we examined community-
261 weighted mean trait values (CWM) (Lavorel et al. 2008). The CWM is calculated by
262 taking the average value of each trait, weighted by the abundance of each species, and
263 was computed using the ‘functcomp’ function of the *FD* package (Laliberté et al. 2014).
264 To compare the CWM traits among sampling periods, we employed GLMMs as
265 described previously.

266 To quantify the phylogenetic structure of each assemblage among the three
267 sampling periods we used the mean pairwise distance (MPD) and the mean nearest
268 taxon distance (MNTD) (Webb et al. 2002). MPD is more sensitive to the basal
269 branches of a phylogeny, while MNTD is better suited for detecting clustering in the
270 terminal branches of a phylogenetic tree, so we calculated both MPD and MNTD and
271 inferred significance of differences among sampling periods by examining the overlap
272 of 95% confidence levels. We applied a null model using the standardized effect size
273 (SES) to remove the effect of species richness on MPD and MNTD metrics (Cadotte &

274 Davies 2016). SES was calculated from abundance weighted measures for each plot and
275 by randomizing species across tips of the phylogeny 999 times. Significant positive SES
276 values indicate over-dispersed phylogenetic structure, while significant negative values
277 indicate phylogeny clustering (Cadotte & Davies 2016). To identify significant changes
278 in community structure, we examined if the values for ses.MPD and ses.MNTD were
279 above or below the 97.5% and 2.5% quantiles of the null distribution. Phylogenetic
280 analyses were run using functions ‘mpd’, ‘mtn’, ‘ses.mpd’ and ‘ses.mntd’ from the
281 *picante* R package (Kembel et al. 2010). All analyses were undertaken in R (R Core
282 Team 2020).

283

284 RESULTS

285 We captured 1,437 individuals belonging to 26 species, 16 genera, and three
286 families (Table S3). We recorded 397 individuals from 16 species during the Pre-filling
287 period. In the first year after the reservoir filling (Post-1), 671 specimens of 22 species
288 were recorded, and in the second post-filling year (Post-2), we captured 369 individuals
289 of 21 species (Table S3). Almost half of the species ($n=12$; 46%) were recorded in all
290 periods (Figure S1). One (4%) was recorded only during Pre-filling, one (4%) only in
291 Post-1, and three species (12%) were recorded only in Post-2 (Figure S1).

292 Small-mammal abundance and richness increased in the Post-1 period compared
293 to Pre-filling ($t=3.72$, $P<0.001$; $t=6.27$, $P<0.0001$, respectively), but decreased in the
294 Post-2 period ($t=-4.16$, $P<0.0001$; $t=-4.79$, $P<0.001$, respectively). There was no
295 significant difference in richness and abundance between Pre-filling and Post-2
296 (abundance: $t=0.47$, $P=0.88$; richness: $t=-1.48$, $P=0.30$). According to the TBI analysis,
297 62.7% ($n=23$) of Post-1 plots gained individuals and 73.5% ($n=25$) gained species
298 compared to Pre-filling (Table 1). Most of these plots (individuals data: $n=12$, 52%;
299 species data: $n=15$, 60%) were located within 1000 m of the riverbank. However, in the
300 Post-2 period, 82.4% ($n=28$) of the plots had decreases in abundance and 73.5% ($n=26$)
301 decreased in the number of species captured compared to the Post-1 period (Table 1).
302 There was no difference between the Pre-filling and Post-2 periods in the number of
303 plots with gains and losses in species and abundance (Table 1).

304 Species composition differed between Pre-filling and Post-1 ($Wald=188.21$;
305 $P=0.001$), Post-1 and Post-2 ($Wald=115.45$; $P=0.001$), and Pre-filling and Post-2
306 ($Wald=95.55$; $P=0.001$). Ordination of the species composition revealed that Post-1 had
307 more distinct small mammal assemblages compared to Pre-filling and Post-2, which had

308 greater overlap in species composition (Figure 2). *Metachirus nudicaudatus* showed a
309 strong increase in number of individuals in Post-1, but a very abrupt decrease in Post-2
310 (Figure S2; Tables S3, S4). *Philander mcilhennyi*, *Hylaeamys yunganus*, and *Nectomys*
311 *rattus* also showed abundance increases after flooding, followed by a decrease to levels
312 similar to Pre-filling. Only for *Oecomys bicolor* did abundance increase in both Post-1
313 and Post-2. *Marmosa demerarae* was the only species whose abundance was
314 significantly less in Post-1 than the other periods. Also *M. demerarae* had a slight
315 increase in Post-2, but still showed lower abundance than before flooding (Figure S2;
316 Table S3, S4).

317 The frequency of the functional traits related to diet, locomotion and body mass
318 were altered after flooding (Table 2; Figure 3). In the Post-1 period, there was an
319 increase in the frequency of frugivorous-omnivorous, terrestrial and small mammals
320 with larger body mass, followed by a decrease in the Post-2 period (Figures 5A, D and
321 E). The frequency of insectivorous-omnivorous and scansorial species decreased in
322 Post-1 compared to Pre-filling, but increased in Post-2 (Figures 5B and C). Post-2
323 showed no significant difference in the frequency of any functional traits compared to
324 Pre-filling (Table 2).

325 Phylogenetic diversity of non-volant small mammals did not change in the two
326 years after reservoir filling. Mean pairwise distance (sesMPD; $F=1.00$; $P=0.37$) and
327 mean nearest taxon distance (sesMNTD; $F=1.36$; $P=0.26$) did not differ significantly
328 from the null models among the three sampling periods. There was no significant
329 difference in the number of plots with dispersed ($P<0.975$) or clustered ($P>0.025$)
330 phylogenetic diversity.

331

332 DISCUSSION

333 Our study shows that the assemblages of non-volant small mammals were
334 altered in the years following the filling of the Santo Antônio Hydroelectric Reservoir.
335 Contrary to what has been widely reported for the effects of large infrastructure
336 projects, such as dams, on fauna in the tropical region (Alho 2011; Winemiller et al.
337 2016; Soukaphon et al. 2021), number of species and abundance did not decrease
338 immediately after dam filling. We found that species number and abundance increased
339 immediately after dam construction. However, in the second year of sampling, these
340 parameters tended to decrease, reaching levels similar to those found in the pre-filling
341 period. This contributed to the difference in species composition between the three

342 periods, with a greater dissimilarity in assemblage composition in the first post-filling
343 year and high overlap between pre-filling plots and those sampled in the second year,
344 which means that temporal changes in assemblages were not random among species.
345 Frugivorous-omnivorous, terrestrials, and species with larger body mass increased in
346 frequency in Post-1, while insectivorous-omnivorous and scansorial species were less
347 frequent in Post-1. We also found that phylogenetic diversity remained stable, indicating
348 that there was no differential effect of reservoir filling on evolutionary lineages in non-
349 volant small mammal assemblages.

350 Differences in species composition between the sampling periods indicate an
351 immediate effect of the hydroelectric dam construction. These differences are related to
352 the recording of 10 new species in the post-filling period and a general increase in
353 abundance. Six species recorded in this study showed significant changes in their
354 abundances. The loss of part of the environmental gradient, first due to deforestation of
355 areas that would be flooded, followed by reservoir flooding, may have driven the
356 change in species composition after the damming of the river (Fournier-Chambrillon et
357 al. 2000; Alho 2011). With the loss of lowlands, and part of the *terra firme*, species may
358 have migrated to areas that would not be flooded and concentrate near the new reservoir
359 edge as a means of escaping the inundation, contributing to an increase in species
360 number and abundance (Fournier-Chambrillon et al. 2000; Lambert et al. 2003;
361 Passamani & Cerboncini 2013).

362 Most plots had significant gains in species and individuals during Post-1
363 compared to Pre-filling, and over 70% of plots significantly lost more species and
364 individuals during Post-2 compared to Post-1. These results partially differ from other
365 studies conducted in Santo Antonio Hydroelectric area for anurans and bats. Plots
366 continuously gained frogs species two years after the dam flooded (Dayrell et al. 2021),
367 and there was a significant reduction in bat abundance immediately after reservoir
368 filling (Bobrowiec et al. 2021). This indicates that taxonomic groups with distinct
369 biological characteristics may respond differently to lower intensity flooding by run-of-
370 the-river dams. However, the temporal fluctuation of the number of individuals and
371 species richness that characterize beta diversity of sampling plots suggests that the small
372 mammal assemblages may not have reached an equilibrium and returned to similar
373 spatial patterns as before reservoir filling (Alho 2011). Even two years after the impact,
374 species composition has yet to return to that found pre-filling (Araujo et al. 2022).

We found that, frugivores, large body mass and terrestrial species increased in frequency in Post-1, while insectivorous and scansorial species were negatively affected by flooding. These results follow a similar pattern to those found in some studies that observed an increase in frequency of functional traits of mammal assemblages after an anthropogenic disturbance (Bovendorp et al. 2018; Sancha et al. 2020; Bobrowiec et al. 2022). Variation in functional-trait frequencies correlates with changes in abundances of some species and may be associated with the addition of new species. After flooding, small mammals with terrestrial habit, frugivorous-omnivorous diet, and larger body mass, such as *Philander mcilhennyi* and *Nectomys ratus*, may have had greater dispersal success and thus moved and established in new territories above the new riverbank, indicating a positive effect of disturbance favoring species with these characteristics. As terrestrial species live exclusively on the ground, flooding may have forced them to flee quickly due to the immediate loss of their habitat and migrate to dry areas. Frugivorous-omnivorous species, which mostly had large body masses, may have an advantage by likely encountering new patches of fruit-bearing plants, as well as other complementary food items such as fungi, roots, and seeds during their displacement (Hayward & Phillipson 1979).

Scansorial species have a hybrid mode of locomotion, moving both on the ground and in the understory, and the decrease in frequency of these species indicates that displacement to the new riverbank may have been a costly process, particularly due to their small body size, which could further hinder their success when dispersing to new areas (Pütker et al. 2011). Newly impacted areas often show an increase in insect biomass, promoting an increase in the abundance of insectivorous small mammals (Lambert et al. 2003). However, in our study, the impact of flooding did not positively affect insectivorous small mammals, and the increased availability of food did not counterbalance the apparent physical difficulties during displacement, which appears to be the most important characteristic for these species in a situation of habitat loss such as what occurred on the upper Madeira River. However, in Post-2, functional traits showed a trend of recovery in their frequencies to levels similar to Pre-filling, indicating a possible readjustment of species to the new riverbank and habitat area.

Contrary to taxonomic and functional traits, phylogenetic diversity was not influenced by the dam filling. The addition of species after the river damming also did not change the phylogenetic diversity of assemblages. The similarity in sesMPD and sesMNTD among the three sampling periods may be associated with the close

409 phylogenetic relationship among the species that compose the assemblage (Jansa et al.
410 2013; Barreto et al. 2019). Tropical regions tend to harbor phylogenetically closely
411 related terrestrial-mammal species compared to temperate regions, implying greater
412 phylogenetic stability (Safi et al. 2011; Jansa et al. 2013; Barreto et al. 2019). The
413 extinction of ancient lineages from Pangea, important events of American faunal
414 interchange (Goin et al. 2012), rapid recent evolutionary radiation (Jansa et al. 2013;
415 Marin & Hedges 2016), and low extinction rates of new lineages associated with
416 climate stability (Dynesius & Jansson 2000) may have contributed to close phylogenetic
417 relationships among non-volant small mammals in the Amazon.

418 Taxonomic and functional traits frequencies of non-volant small mammals
419 experienced immediate changes following the closure of the Santo Antônio dam, while
420 phylogenetic diversity remained stable even after the disturbance. However, our results
421 indicate that the assemblage of non-volant small mammals in the Santo Antônio
422 Hydroelectric area is apparently beginning to recover its structure to levels similar to
423 those before the reservoir filling. Although vast areas of floodplain vegetation have
424 permanently disappeared, the Santo Antônio Hydroelectric plant did not cause local
425 extinctions of non-volant small mammals, unlike other studies conducted in land-bridge
426 islands areas (Cosson et al. 1999; Passamani & Cerboncini 2013; Palmeirim et al.
427 2018). The floodplains in this region are narrow compared to other regions of the
428 Amazon (Patton et al. 2000), which may not be sufficient to support specialist animal
429 species in these floodable forests (Araujo et al. 2022). Non-volant small-mammal
430 species are a poorly understood faunal group, although some species are known to be
431 resilient to anthropogenic disturbances (Cosson et al. 1999). However, the lack of data
432 for a period longer than two years and the possibility that other biotic and abiotic
433 characteristics may be affecting structure prevent us from inferring whether the changes
434 were truly benign or not, and whether the apparent return to pre-flooding equilibrium
435 will continue. Our results contradict those found by other studies conducted in the same
436 region for some faunal and floral groups, where there were significant and lasting
437 changes to taxonomic and functional aspects even two years after flooding (trees, Moser
438 et al. 2014; palms, Santos et al. 2020; anurans, Dayrell et al. 2021; bats, Bobrowiec et
439 al. 2022; birds, Melo et al. 2021).

440 Long-term monitoring studies are important tools for the effective assessment of
441 anthropogenic impacts (Magnusson et al. 2013). The advancement of large-scale
442 hydroelectric projects throughout the Amazon region, coupled with the existing impacts

443 in the region for decades, demands greater attention and scientific interest (Fearnside
444 2015). The Madeira River region is known to be part of the "Arc of Deforestation," and
445 between 2011 and 2021 pasture and agriculture cover increased by 27.1% (from
446 340,292 ha to 430,367 ha) within 50 km the Madeira River in the stretch between the
447 Santo Antônio and Jirau dams (PED Bobrowiec pers. obs.). Therefore, it is not enough
448 to maintain long-term monitoring for the assessment of impacts from large-scale
449 projects; it is also necessary to protect the areas surrounding the reservoir, as these
450 remaining areas are important sources for the maintenance and recovery of the
451 assemblage of non-volant small mammals in the Madeira River region.

452

453 **ACKNOWLEDGMENTS**

454 We thank Sete Soluções e Tecnologia Ambiental, Santo Antônio Energia,
455 ICMBio, INPA e Fundação Amazônica de Defesa da Biosfera for providing resources,
456 logistic and general support during this study. We thank Sarah Vaca-Puente for her great
457 contribution to the construction of the phylogenetic trees.

458

459 **FUNDING**

460 This work was supported by the American Society of Mastozoology for the Grant-in-
461 Aid of Research. R. Araujo was supported by a doctoral scholarship provided by the
462 CAPES (PROEX 0742/2020), CAPES (PDSE 10/2022), FAPEAM (PAPAC 005/2019),
463 FAPEAM (POSGRAD 006/2020-Processo: 062.00717/2020); P. Bobrowiec was
464 supported by a postdoctoral scholarship provided by the PNPD/CAPES
465 (#88887.370067/2019-00); William Magnusson was supported by a Productivity Grant
466 (PQ - 301873/2016-0) from CNPq.

467

468 **REFERENCES**

469 Abreu, E.F., Casali, D., Costa-Araujo, R., Garbino, G.S., Libardi, G., Loretto, D. et al.
470 (2022) Lista de Mamíferos do Brasil (2022-1) [Data set]. Zenodo. Available from:
471 <https://doi.org/10.5281/zenodo.7469767>

- 472 Alho, C.J. (2011) Environmental effects of hydropower reservoirs on wild mammals
473 and freshwater turtles in Amazonia: a review. *Oecologia Australis*, 15, 593-604.
- 474 Alroy, J. (2019) Small mammals have big tails in the tropics. *Global Ecology and*
475 *Biogeography*, 28, 1042-1050.
- 476 Anderson, E.O., Jenkins, C.N., Heilpern, S., Maldonado-Ocampo, J.A., Carvajal-
477 Vellejos, F.M., Encalada, A.D., et al. (2018) Fragmentation of Andes-to-Amazon
478 connectivity by hydropower dams. *Science Advances*, 4, 1-7.
- 479 Ansar, A., Flyvbjerg, B., Budzier, A. & Lunn, D. (2014) Should we build more large
480 dams? The actual costs of hydropower mega project development. *Energy Policy*, 69,
481 43–56.
- 482 Araujo, R.S., Bobrowiec, P.E.D., Moura, R.T. & Magnusson, W.E. (2022) The impact of
483 a run-of-the-river hydroelectric dam on a non-volant small-mammal assemblage in
484 Brazilian Amazonia. *Austral Ecology*, 48, 143-157.
- 485 Barreto, E.; Graham, C.H. & Rangel, T.F. (2018) Environmental factors explain the
486 spatial mismatches between species richness and phylogenetic diversity of terrestrial
487 mammals. *Global Ecology and Biogeography*, 28, 1855-1865.
- 488 Baumgartner, M.T., Piana, P.A., Baumgartner, G. & Gomes, L.C. (2020) Storage or run-
489 of-river reservoirs: exploring the ecological effects of dam operation on stability and
490 species interactions of fish assemblages. *Environmental Management*, 65, 220–231.
- 491 Benchimol, M. & Peres, C.A. (2015) Widespread forest vertebrate extinctions induced
492 by a mega hydroelectric dam in lowland Amazonia. *PloS One*, 10,
493 doi:10.1371/journal.pone.0129818.
- 494 Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen,
495 A. et al. (2017) Package ‘glmmTMB’—balances speed and flexibility among packages
496 for zero-inflated generalized linear mixed modeling’. *The R Journal*, 9, 378–400.
- 497 Bobrowiec, P.E.D., Nobre, C.C. & Tavares, V.C. (2021) Immediate effects of an
498 Amazonian mega hydroelectric dam on phyllostomid fruit bats. *Ecological Indicators*,
499 132, 108322.

- 500 Bobrowiec, P.E.D., Farneda, F.Z., Nobre, C.C. & Tavares, V.C. (2022) Taxonomic and
501 functional responses of bats to habitat flooding by an Amazonian mega-dam.
502 *Biodiversity and Conservation*, 31, 1359–1377.
- 503 Bovendorp, R.S., Brum, F.T., McCleery, R.A., Baiser, B., Loyola, R., Cianciaruso, M.
504 V., et al. (2018). Defaunation and fragmentation erode small mammal diversity
505 dimensions in tropical forests. *Ecography*, 42, 23-35.
- 506 Cadotte, M.W. & Davies, T.J. (2016). *Phylogenies in ecology: A guide to concepts and*
507 *methods*. Princeton University Press. USA.
- 508 Clark, K., Karsch-Mizrachi, I., Lipman, D.J., Ostell, J. & Sayers, E.W. (2016) GenBank.
509 *Nucleic Acids Research*, 44, D67-D72.
- 510 COGEO/SEDAM [Coordenadoria de Geociencias/Secretaria de Estado do
511 Desenvolvimento Ambiental]. (2010) *Boletim Climatológico de Rondônia*, Vol. 12.
512 COGEO/SEDAM. Porto Velho, Brazil.
- 513 Cosson, J.F., Ringuet, S., Claessens, O., Massary, J.C., Dalecky, A., Villiers, et al.
514 (1999) Ecological changes in recent land-bridge islands in French Guiana, with
515 emphasis on vertebrate communities. *Biological Conservation*, 91, 213-222.
- 516 Dray, S., Bauman, D., Blanchet, G., Borcard, D., Clappe, S. & Guénard, G. (2020).
517 adespatial: multivariate multiscale spatial analysis. R Package.
- 518 Davies, T.J. & Buckley, L.B. (2011) Phylogenetic diversity as a window into the
519 evolutionary and biogeographic histories of present-day richness gradients for
520 mammals. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366,
521 2414–2425.
- 522 Dayrell, J.S., Magnusson, W.E., Bobrowiec, P.E.D. & Lima, A.P. (2021) Impacts of an
523 Amazonian hydroelectric dam on frog assemblages. *PLoS ONE*, 16, e0244580.
- 524 Dynesius, M. & Jansson, R. (2000) Evolutionary consequences of changes in species'
525 geographical distributions driven by Milankovitch climate oscillations. *Proceedings of*
526 *the National Academy of Sciences USA*, 97, 9115-9120.
- 527 Faith, D.P. (1992) Conservation evaluation and phylogenetic diversity. *Biological*
528 *Conservation*, 61, 1–10.

- 529 Fearnside, P.M. (2014) Impacts of Brazil's Madeira River dams: unlearned lessons for
530 hydroelectric development in Amazonia. *Environmental Science and Policy*, 38, 164–
531 172.
- 532 Fearnside, P.M. (2015) Hidrelétricas na Amazônia brasileira: questões ambientais e
533 sociais. In: América Latina, sociedade e meio ambiente: teorias, retóricas e conflitos em
534 desenvolvimento. pp. 7–22.
- 535 Fournier-Chambrillon, C., Fournier, P., Gaillard, J.M., Genty, C., Hansen, E. & Vié, J.C.
536 (2000) Mammal trap efficiency during the fragmentation by flooding of a neotropical
537 rain forest in French Guiana. *Journal of Tropical Ecology*, 16, 841-851.
- 538 Galetti, M., Rodarte, R.R., Neves, C.L., Moreira, M. & Costa-Pereira, R. (2016) Trophic
539 niche differentiation in rodents and marsupials revealed by stable isotopes. *PLoS ONE*,
540 11, e0152494.
- 541 Gibson, L., Wilman, E.N. & Laurance, W.F. (2017) How green in “green” energy.
542 *Trends in Ecology and Evolution*, 32, 922-935.
- 543 Goin, F.J., Gelfo, J.N., Chornogubsky, L., Woodburne, M.O. & Martin, T. (2012)
544 Origins, radiations, and distribution of South American mammals: from greenhouse to
545 icehouse worlds. In: Bones, clones, and biomes: the history and geography of recent
546 neotropical mammals. pp. 20-50.
- 547 Hayward, G.F. & Phillipson, J. (1979) Community structure and functional role of small
548 mammals in ecosystems. In: *Ecology of small mammals*. pp. 135-211.
- 549 IBGE [Instituto Brasileiro de Geografia e Estatística]. (2012) Manual técnico da
550 vegetação brasileira. 2nd ed. Ministério do Planejamento, Orçamento e Gestão. Rio de
551 Janeiro, Brazil.
- 552 Jansa, S.A., Barker, F.K. & Voss, R.S. (2013) The early diversification history of
553 didelphid marsupials: a window into South America’s “splendid isolation”. *Evolution*,
554 68, 684-695.
- 555 Jones, I., Bunnefeld, N., Jump, A.S., Peres, C.A. & Dent, D.H. (2016) Extinction debt
556 on reservoir land-bridge islands. *Biological Conservation*, 199, 75-83.

- 557 Junk, W.J., Piedade, M.T.F., Wittmann, F., Schöngart, J. & Parolin, P. (2011) Amazonian
558 floodplain forests: ecophysiology, biodiversity and sustainable management, 1st edition.
559 Springer, Germany.
- 560 Kembel, S.W., Cowan, P.D., Helmus, M.R., Cornwell, W.K., Morlon, H., Ackerly, D.D.,
561 et al. (2010). Picante: R tools for integrating phylogenies and ecology. Bioinformatics,
562 26, 1463–1464.
- 563 Laliberté, E., Legendre, P. & Shipley, B. (2014) FD: measuring functional diversity
564 from multiple traits, and other tools for functional ecology. R package version 1:0–12
- 565 Lambert, T.D., Adler, G.H., Riveros, C.M., Lopez, L., Ascanio, R. & Terborgh, J. (2003)
566 Rodents on tropical land-bridge islands. Journal of Zoology, 260, 179-187.
- 567 Latrubesse, E.M., Arima, E.Y., Dunne, T., Park, E., Baker, V.R., d'Hora, F.M. et al.
568 (2017) Damming the rivers of the Amazon Basin. Nature, 546, 363-369.
- 569 Lavorel, S., Grigulis, K., McIntyre, S., Williams, N.S.G., Garden, D., Dorrough, J., et
570 al. (2008) Assessing functional diversity in the field: methodoly matters!. Functional
571 Ecology, 22, 134–147.
- 572 Legendre, P. (2014) Interpreting the replacement and richness difference components of
573 beta diversity. Global Ecology and Biogeography, 23, 1324-1334.
- 574 Legendre, P. (2019) A temporal beta-diversity index to identify sites that have changed
575 in exceptional ways in space–time surveys. Ecology and Evolution, 9, 3500-3514.
- 576 Lynam, A.J. (1997) Rapid decline of small mammals' diversity in monsoon evergreen
577 forest fragments in Thailand. In: Tropical forest remnants: ecology, management and
578 conservation of fragmented communities. pp. 222-240.
- 579 Magnusson, W.E., Braga-Neto, R., Pezzini, F., Baccaro, F.B., de Godoy Bergallo, H.,
580 Penha, J. et al. (2013) Biodiversidade e Monitoramento Integrado. Attema Editora
581 Brazil.
- 582 Magurran, A.E., & McGill, B.J. (2011) Biological diversity: Frontiers in measurement
583 and assessment. Oxford University Press, UK.
- 584 Marin, J. & Hedges, S.B. (2016) Time best explains global variation in species richness
585 of amphibians, birds and mammals. Journal of Biogeography, 43, 1069-1079.

- 586 Martins, R.L & Gribel, R. (2007) Polinização de *Caryocar villosum* (Aubl.) Pers.
587 (Caryocaraceae) uma árvore emergente da Amazônia Central. Revista Brasileira de
588 Botânica, 30, 37-45.
- 589 Melack, J.M. & Hess, L.L. (2010) Remote sensing of the distribution and extent of
590 wetlands in the Amazon basin. In: Amazonian floodplain forests: ecophysiology,
591 biodiversity and sustainable management. pp. 43–59.
- 592 Melo, T.N., Cerqueira, M.C., D’Horta, F.M., Tuomisto, H., Doninck, J.V. & Ribas, C.C.
593 (2021) Impacts of a large hydroelectric dam on the Madeira River (Brazil) on floodplain
594 avifauna. Acta Amazonica, 51, 298 – 310.
- 595 Mendes-Oliveira, A.N., Lima, M.G.M., Santos-Filho, M. & Lima, R.C.S. (2015)
596 Estrutura de comunidades de pequenos mamíferos não-voadores na Amazônia. In:
597 Pequenos mamíferos não-voadores da Amazônia brasileira. pp. 213-256.
- 598 Moran, E.F., Lopez, M.C., Moore, N., Müller, N. & Hyndman, D. W. (2018) Sustainable
599 hydropower in the 21st century. PNAS, 115, 11891-11898.
- 600 Moser, P., Oliveira, W.L., Medeiros, M.B., Pinto, J.R., Eisenlohr, P.V., Lima, I.L. et al.
601 (2014) Tree species distribution along environmental gradients in an area affected by a
602 hydroelectric dam in southern Amazonia. Biotropica, 46, 367–376.
- 603 Nilsson, C., Reidy, C. A., Dynesius, M. & Revenga, C. (2005) Fragmentation and flow
604 regulation of the world’s large river systems. Science, 308, 405–408.
- 605 Paglia, A.P., da Fonseca, G.A.B., Rylands, A.B., Herrmann, G., Aguiar, L.M.S.,
606 Chiarello, A.G. et al. (2012) Annotated checklist of Brazilian mammals, 2nd edition.
607 Occasional Papers in Conservation Biology, USA.
- 608 Palmeirim, A.F., Benchimol, M., Vieira, M.V. & Peres, C.A. (2018) Small mammal
609 responses to Amazonian forest islands are modulated by their forest dependence.
610 Oecologia, 187, 191-204.
- 611 Palmeirim, A.F. Farneda, F.Z., Vieira, M.V. & Peres, C.A. (2021) Forest area predicts all
612 dimensions of small mammal and lizard diversity in Amazonian insular forest
613 fragments. Landscape Ecology, 36, 3401–3418.

- 614 Passamani, M. & Cerboncini, R.A.S. (2013) The effects of the creation of a
615 hydroelectric dam on small mammals' communities in central Brazil. *Neotropical*
616 *Biology and Conservation*, 8, 9-16.
- 617 Patton, J.L., Da Silva, M.N.F. & Malcolm, J.R. (2000) Mammals of the Rio Juruá and
618 the evolutionary and ecological diversification of Amazonia. *Bulletin of the American*
619 *Museum of Natural History*, 244, 1–306.
- 620 Pavoine, S. & Bonsall, M.B. (2011) Measuring biodiversity to explain community
621 assembly: a unified approach. *Biological Reviews*, 86, 792–812.
- 622 Petchey, O.L. & Gaston, K.J. (2006) Functional diversity: back to basics and looking
623 forward. *Ecological Letters*, 9, 741–758.
- 624 Pütkker, T., Bueno, A.A., Barros, C.S., Sommer, S. & Pardini, R. (2011) Immigration
625 rates in fragmented landscapes – empirical evidence for the importance of habitat
626 amount for species persistence. *PLoS ONE*, 6, e27963.
- 627 R Core Team. (2020) R: a language and environment for statistical computing. Vienna:
628 R Foundation for statistical computing.
- 629 Ricotta, C. (2005) Through the jungle of biological diversity. *Acta Biotheoretica*, 53,
630 29–38.
- 631 Russell, V.L., Ben, B., Paul, B., Iago, G.V., Maxime, H., Maarten, J., et al. (2023)
632 Package ‘emmeans’. Available from: <https://cran.r-project.org/web/packages/emmeans/emmeans.pdf> [Accessed 08th November 2022].
- 633 Safi, K.; Cianciaruso, M.V.; Loyola, R.D.; Brito, D.; Armour-Marshall, K. & Diniz-
634 Filho, J.A. (2011) Understanding global patterns of mammalian functional and
635 phylogenetic diversity. *Philosophical Transactions of the Royal Society B*, 366, 2536-
636 2544.
- 637 Sancha, N.U., Maestri, R., Bovendorp, R.S. & Higgis, C.L. (2020) Disentangling
638 drivers of small mammal diversity in a highly fragmented forest system. *Biotropica*, 52,
639 182-195.
- 640 Santos, E.A., Medeiros, B.M., Ferreira, J.L.F., Simon, M.F., Oliveira, W.L. & Costa,
641 F.R.C. (2020) Palm distribution patterns in the southwestern Brazilian Amazon: impact
642 of a large hydroelectric dam. *Forest Ecology and Management*, 463, 118032.

- 644 Soukaphon, A., Baird, I.G. & Hogan, Z.S. (2021) The Impacts of Hydropower Dams in
645 the Mekong River Basin: A Review. *Water*, 13, 1-18.
- 646 Stevens, R.D. & Tello, J.S. 2014. On the measurement of dimensionality of biodiversity.
647 *Global Ecology and Biogeography*, 23, 1115-1125.
- 648 Szalay, F.S. (1994) Evolutionary history of the marsupials and an analysis of
649 osteological characters. Cambridge University Press, USA.
- 650 Tamura, K., Stecher, G. & Kumar, S. (2011) MEGA11: Molecular Evolutionary
651 Genetics Analysis (MEGA) software version 11. *Molecular Biology and Evolution*, 38,
652 3022–3027.
- 653 Terborgh, J., Feeley, K., Silman, M., Nuñez, P. & Balukjian, B. (2006) Vegetation
654 dynamics of predator-free land-bridge islands. *Journal of Ecology*, 94, 253-263.
- 655 Tilman, D. (2001) Functional diversity. In: *Encyclopedia of Biodiversity*. pp. 109–120.
- 656 Wang, Y., Naumann, U., Wright, S.T. & Warton, D.I. (2012) Mvabund—An R package
657 for model-based analysis of multivariate abundance data. *Methods in Ecology and
658 Evolution*, 3, 471–474.
- 659 Webb, C.O.; Ackerly, D.D.; McPeek, M.A. & Donoghue, M.J. (2002) Phylogenies and
660 community ecology. *Annual Review of Ecology, Evolution, and Systematics*, 33, 475-
661 505.
- 662 Wilman, H., Belmaker, J., Simpson, J., de la Rosa, C., Rivadeneira, M.M. & Jetz, W.
663 (2014) EltonTraits 1.0: species-level foraging attributes of the world's birds and
664 mammals. *Ecology*, 95, 2027–2027
- 665 Wilson, D.E. & Reeder, D.M. (2005) Mammal species of the world: a taxonomic and
666 geographic reference, 3rd edition. Johns Hopkins University Press, USA.
- 667 Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam,
668 S. et al. (2016) Balancing hydropower and biodiversity in the Amazon, Congo, and
669 Mekong: basin-scale planning is needed to minimize impacts in mega-diverse rivers.
670 *Science*, 351, 128-129.
- 671 Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L. & Tockner, K. (2014) A global
672 boom in hydropower dam construction. *Aquatic Sciences*, 77, 161-170.

TABLES

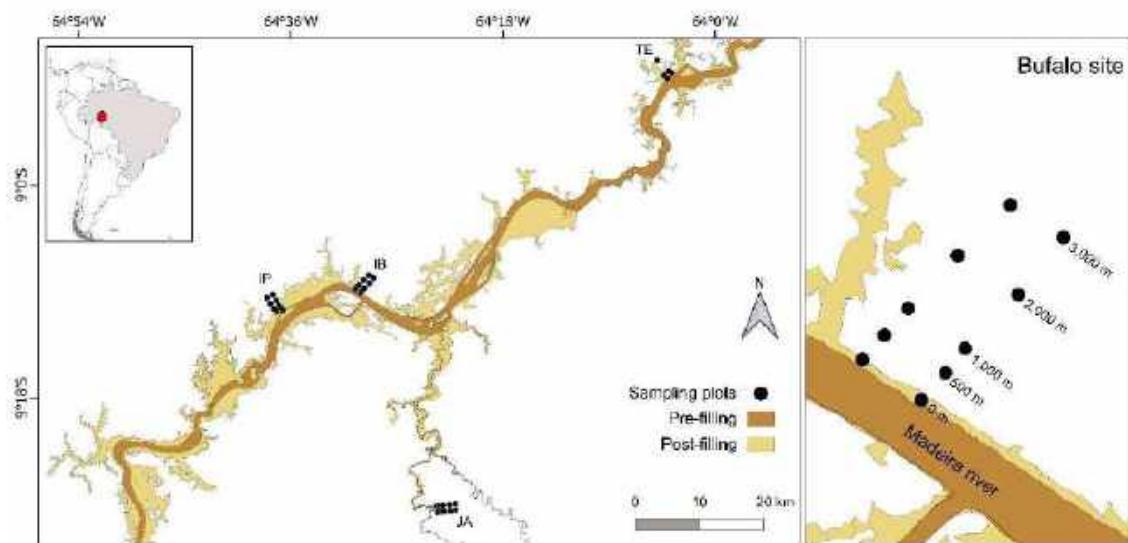
Table 1. Results of analysis of temporal beta diversity (TBI) statistics on the structure of non-volant small mammal assemblages between sampling periods near the Santo Antônio Hydroelectric Reservoir, Madeira River, Brazil. The sign of change indicates if gains (+ sign) or losses (– sign) dominate across all sampling plots. $P < 0.05$ are in bold.

Assemblages	TBI	<i>P</i>	Change	Plots	Plots	Plots (gains=losses)
				(Gain)	(Losses)	
Abundance						
Pre × Post-1	0.21	0.003	+	23	9	2
Post-1 x Post-2	-0.26	<0.001	-	6	28	0
Pre × Post-2	-0.06	0.28	0	14	19	1
Richness						
Pre × Post-1	0.21	<0.001	+	25	1	8
Post-1 x Post-2	-0.16	0.001	-	2	25	7
Pre × Post-2	0.04	0.37	0	16	12	6

673

Table 2. Results of post-hoc pairwise comparisons of the GLMM-TBM models for each functional trait used in the CWM analysis comparing the Pre-filling, Post-1 and Post-2 periods in the reservoir area of the Santo Antônio Hydroelectric, Madeira River, Brazil. $P < 0.05$ are in bold.

Traits	Pre × Post-1		Post-1 × Post-2		Pre × Post-2	
	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>
Frugivore-granivore	-0.95	0.61	-0.59	0.82	-1.55	0.27
Frugivore-herbivore	0.00	0.00	0.00	0.00	0.00	0.00
Frugivore-omnivorous	3.32	0.01	-2.84	0.004	-0.49	0.87
Insectivorous-omnivorous	-3.96	<0.001	-1.92	0.13	2.05	0.10
Arboreal	-2.05	0.11	0.34	0.94	-1.73	0.20
Semiaquatic	-1.86	0.15	0.54	0.85	-0.21	0.97
Scansorial	-4.29	<0.001	2.09	0.09	2.21	0.07
Terrestrial	2.80	0.01	1.64	0.23	-1.17	0.47
Body Mass	2.82	0.01	-3.22	0.004	0.41	0.91
Tail Length	1.55	0.27	-0.62	0.81	0.94	0.62
Foot Length	-1.92	0.14	0.32	0.95	-1.62	0.24

674 **FIGURES**

675

676 Figure 1. Map of the study area showing the four sampling modules along the banks of
677 the Madeira and Jaci-Paraná Rivers (TO = Teotônio, BU = Ilha de Búfalos, PE = Ilha de
678 Pedras and JA = Jaci). Right box shows the sample design with two transects and 10
679 plots located at 0, 500, 1000, 2000 and 3000 meters from the original bank of the
680 Madeira River, Brazil.

681

682

683

684

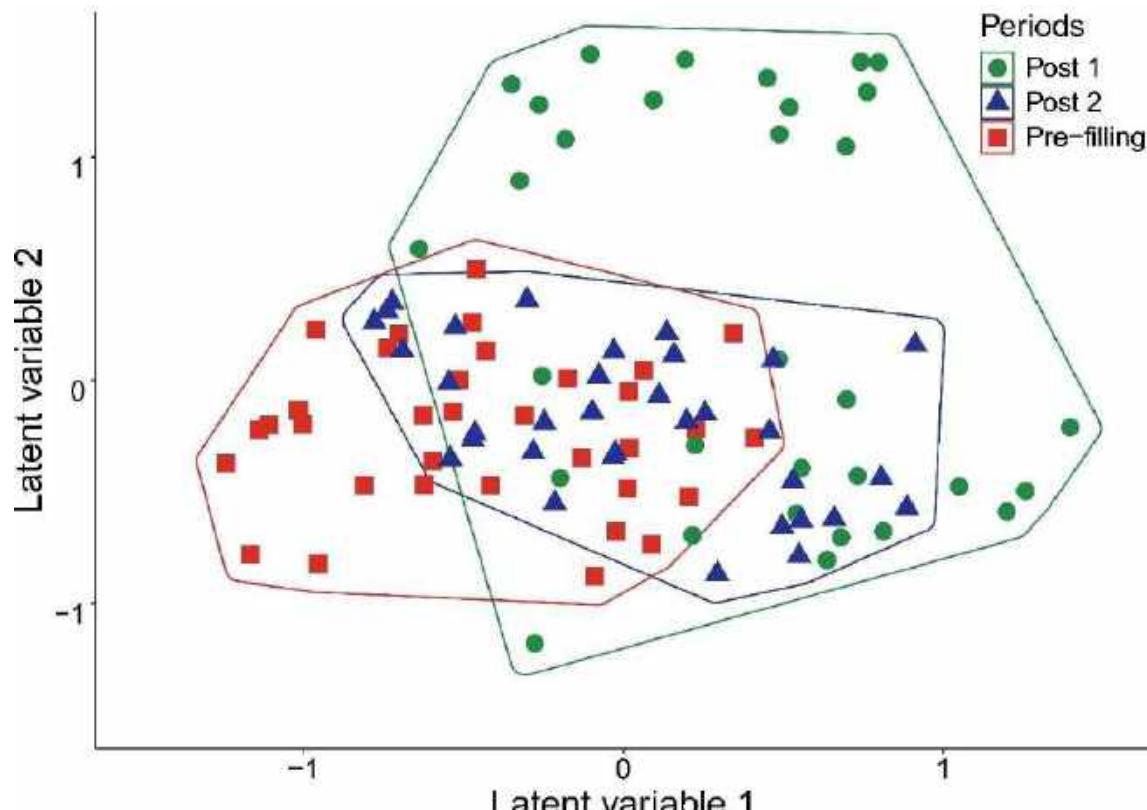
685

686

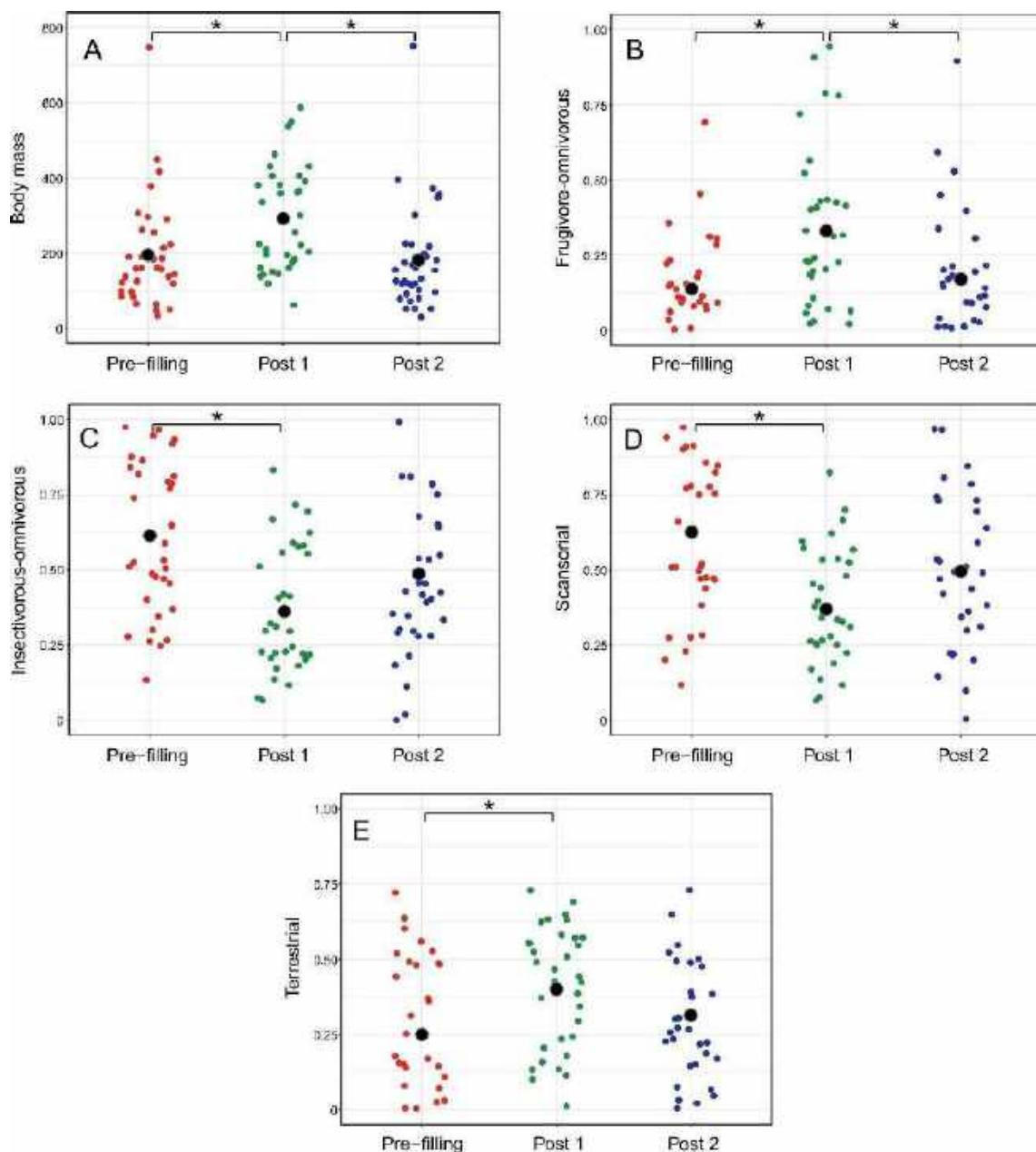
687

688

689



690
691 Figure 2. First two latent variables of a Bayesian (BORAL) analysis of non-volant small
692 mammals according to sampling periods around the Santo Antônio Hydroelectric,
693 Madeira River, Brazil.
694
695
696
697
698
699
700
701
702
703



704

705 Figure 3. Community-weighted mean trait frequencies (CWM) of non-volant small
 706 mammals sampled before filling (Pre-filling), one-year post filling (Post-1) and two
 707 years post filling (Post-2) in the Santo Antônio Hydroelectric area, Madeira River,
 708 Brazil. Black circles represent the means of the trait frequency. * $P < 0.05$ (see Table 2).

SÍNTESE

Nesta tese avaliamos quais os possíveis efeitos poderiam da instalação de uma usina hidrelétrica no sudeste da Amazônia brasileira sobre as espécies de pequenos mamíferos não voadores. Investigamos como a assembleia de pequenos mamíferos não voadores se distribuíam áreas previstas a serem inundadas e áreas fora da inundação às margens do alto Rio Madeira, e como diversos fatores ambientais bióticos e abióticos influenciavam a distribuição dessas espécies. Avaliamos também como as espécies se comportaram através de diferentes dimensões da diversidade após a mudança da margem do rio causada pelo alagamento do reservatório hidrelétrico.

Dentre fatores ambientais e espaciais avaliados, analisamos as assembleias de pequenos mamíferos em áreas que não seriam inundadas e áreas mais próximas ao corpo d'água, que seriam inundadas. Portanto, no **Capítulo I**, eu e meus coautores investigamos a distribuição das assembleias de pequenos mamíferos não voadores em áreas previstas a serem inundadas e áreas não inundadas e observamos que o conjunto de espécies presentes nas áreas não inundáveis e áreas inundáveis era diferente. Porém, essa diferença foi atribuída ao fato da assembleia de espécies em áreas inundáveis ser um subconjunto da assembleia de espécies presentes nas áreas não inundáveis. Portanto, não houve o registro de espécies estritamente especialistas nessas áreas que seriam alagadas, o que confere menor risco de perda local de espécies. Além disso, os pequenos mamíferos não voadores dessa região apresentam forte relação com ambientes cujas características do solo apresentavam maiores taxas de nutrientes, maior concentração de areia e com maior número de árvores, além de manterem sua composição distinta entre áreas próximas ou distantes do Rio Madeira e seus afluentes.

No **Capítulo II**, analisamos os efeitos do enchimento do reservatório da Hidrelétrica Santo Antônio por meio da comparação da assembleia de pequenos mamíferos não voadores registrados ao longo de dois anos antes e dois anos após o alagamento. Após o enchimento do reservatório, houve mudança significativa da composição, e aumento do número de espécies e abundância de indivíduos, além de mudanças na frequência de traços funcionais relativos a tamanho do corpo, locomoção e dieta. Porém, assim como previsto no Capítulo I, não houve perda de espécies e tampouco perda de linhagens filogenéticas. Após dois anos do alagamento, as métricas taxonômicas e frequências de traços funcionais mostraram tendência a retornar aos mesmos patamares de antes do impacto causado pelo reservatório.

Esta tese providenciou conhecimento e produtos inéditos sobre a diversidade e ecologia de pequenos mamíferos não voadores do alto Rio Madeira. Mostramos que características edáficas e da vegetação são importantes preditores da distribuição desses mamíferos amazônicos, seja em áreas próximas ou mais distantes das margens de rios e riachos. Na região estudada, o uso de diferentes dimensões da diversidade ajuda a compreender melhor como as espécies respondem aos impactos oriundos do alagamento permanente causado por uma hidrelétrica a fio d'água. Assim, espera-se que esta tese sirva como fonte para novos estudos mais detalhados sobre a ecologia e diversidade de pequenos mamíferos não voadores da Amazônia e demais florestas tropicais, além de poder contribuir para proposição de novas alternativas de medição de impactos ambientais.

REFERÊNCIAS BIBLIOGRÁFICAS

- Agência Nacional de Energia Elétrica (ANEEL), 2023. Banco de Informações de Geração (<https://app.powerbi.com/view?r=eyJrIjoiNjc4OGYyYjQtYWM2ZC00YjllLWJIYmEtYzdkNTQ1MTc1NjM2IiwidCI6IjQwZDZmOWI4LWVjYTctNDZhMi05MmQ0LWVhNGU5YzAxNzBlMSIsImMiOjR9>). Acesso: 14/06/2023.
- Alho, C.J.R. 2011. Environmental effects of hydropower reservoirs on wild mammals and freshwater turtles in Amazonia: A review. *Oecologia Australis*, 15: 593-604.
- Brito, D. 2004. Lack of adequate taxonomic knowledge may hinder endemic mammal conservation in the Brazilian Atlantic Forest. *Biodiversity and Conservation*, 13: 2135-2144.
- Crosson, J.F.; Ringuet, S.; Claessens, O.; Massary, J.C.; Dalecky, A.; Villiers, J.F.; Granjon, L.; Pons, J.M. 1999. Ecological changes in recente land-bridge islands in French Guiana, with emphasis on vertebrate communities. *Biological Conservation*, 91: 213-222.
- Davies, T.J.; Buckley, L. B. 2011. Phylogenetic diversity as a window into the evolutionary and biogeographic histories of present-day richness gradients for mammals. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366: 2414–2425.
- Ecologia em Ação (ECOA). 2012. International Rivers and Fundacion Proteger, Dams in Amazonia. (<http://www.dams-info.org/en>). Acesso: 10/11/2018.
- Fearnside, P.M. 2014a. Impacts of Brazil's Madeira River dams: unlearned lessons for hydroelectric development in Amazonia. *Environmental Science & Policy*, 38: 164–172.
- Fearnside, P.M. 2014b. Barragens do Rio Madeira- Revés para a política. (<https://amazoniareal.com.br/barragens-do-rio-madeira-reves-para-a-politica-3-impactos-e-beneficios/>) Acesso: 08/07/2023.
- Fearnside, P. M. 2014c. Barragens do Rio Madeira-Impactos 7: Impactos sociais e hidrovia. (<https://amazoniareal.com.br/barragens-do-rio-madeira-impactos-7-impactos-sociais-e-hidrovia/>). Acesso: 08/07/2023
- Fearnside, P.M. 2015. Hidrelétricas na Amazônia brasileira: Questões ambientais e sociais. In: Floriani, D. & Hevia, A.E. (eds.) América Latina Sociedade e Meio Ambiente: Teorias, Retóricas e Conflitos em Desenvolvimento. Editora da Universidade Federal do Paraná, Curitiba, PR, BRA. 348pp.

- Giusti, M.C.H. 2005. *Conflictos ambientales en la gestión del santuario histórico de Machupicchu: el caso de la instalación y manejo de la Central Hidroeléctrica Machupicchu*. Tese de doutorado, Escuela Andina de Post-Grado Maestría en Gestión Ambiental y Desarrollo. Cusco, Peru. 189 pp.
- Lambert, T.D.; Adler, G.H.; Riveros, L.M.; Lopez, L.; Ascanio, R.; Terborgh, J. 2003. Rodents tropical land-bridge islands. *Journal of Zoology*, 260: 179-187.
- Lees, A.C.; Peres, C.A.; Fearnside, P.M.; Schneider, M; Zuanon, JA.S. 2016. Hydropower and the future of Amazonian biodiversity. *Biodiversity and Conservation*, 25: 451-466.
- Magurran, A.F. 2004. *Measuring biological diversity*. Wiley-Blackwell, Oxford, UK. 264 pp.
- Malcolm, J.R. 1997. Biomass and diversity of small mammals in forest fragments. In: Laurance, W.F. & Bierregaard Jr., R.O. (Eds). *Tropical Forest Remnants: Ecology, management and conservation of fragmented communities*. University of Chicago Press, Illinois. p. 207-221.
- Mendes-Oliveira, A.N.; Borges, M.L.O.; Lambert, T.; Santos-Filho, M.; Bergallo, H.; Ardente, N.; Maria, S.L.S.; Malcom, J. 2015. Efeitos antrópicos sobre comunidades de pequenos mamíferos não-voadores na Amazônia brasileira. In: Mendes-Oliveira, A.N.; Miranda, C. L. Eds) *Pequenos mamíferos não-voadores da Amazônia brasileira*. SBMz, Rio de Janeiro, Rio de Janeiro. p. 257-274.
- Ministério do Meio Ambiente (MMA). 2007. *Portaria MMA nº 09, de 23 de janeiro de 2007 – “Áreas Prioritárias para a Conservação, Uso Sustentável e Repartição de Benefícios da Biodiversidade Brasileira”*. MMA, Brasília. 327pp.
- Palmeirim, A.F.; Benchimol, M.; Vieira, M.V.; Peres, C.A. 2018. Small mammal responses to Amazonian forest islands are modulated by their forest dependence. *Oecologia*, 187: 191-204.
- Pardini, R. 2004. Effects of forest fragmentation on small mammals in an Atlantic Forest landscape. *Biodiversity and Conservation*, 13: 2567-2586.
- Passamani, M.; Cerboncini, R.A.S. 2013. The effects of the creation of a hydroelectric dam on small mammals' communities in central Brazil. *Neotropical Biology and Conservation*, 8: 9-16.

- Rapp Py-Daniel, L.; Deus, C.P.; Henriques, A.L.; Pimpão, D.M. & Ribeiro, O.M. 2007. Biodiversidade do médio Madeira: bases científicas para propostas de conservação. Instituto Nacional de Pesquisas da Amazônia, Manaus, Amazonas. 244pp.
- Ricotta, C. 2005. Through the jungle of biological diversity. *Acta Biotheoretica*, 53: 29–38.
- Stallings, J.R. 1989. Small mammals inventories in an eastern Brazilian park. *Bulletin Florida State Museum*, 34: 153-200.
- Tilman, D. 2001. Functional diversity. In: *Encyclopedia of Biodiversity*. Levin, S.A.(Ed). Academic Press, San Diego, CA. p. 109–120.
- Voss, R.S. & Emmons, L.H. 1996. Mammalian diversity in Neotropical lowland rainforests: a preliminary assessment. *Bulletin of the American Museum of Natural History*. n. 230, 115pp.

MATERIAL SUPLEMENTAR (CAPÍTULO I)

“The impact of a run-of-the-river hydroelectric dam on a non-volant small- mammal assemblage in Brazilian Amazonia”

Table S1. Environmental variables of vegetation, topography, soil and distance from water collected in Santo Antônio Hydroelectric area, Madeira River, Brazil.

module	sample	latitu de	longitu de	area	n_ tree s	vegetati on _density	area – bas al	slop e	heigh t	clay_ %	sand_ %	silt_ %	soil_ nutrien ts	dist_ madei ra	dist – wat er
Ilha_da_Ped ra	IP_T1_0	3221 87	898465 0	Flooded	438	71	23.1	2.9	72	70.6	17.4	12	0.25	308.7	266
Ilha_da_Ped ra	IP_T1_500	3219 07	898498 1	Flooded	506	185	26.9	0.2	75.2	72.1	19.5	8.4	0.43	743.6 7	671
Ilha_da_Ped ra	IP_T1_100	3215 77	898544 7	Unflood ed	369	68	19.7	0.8	84.2	70.5	20.5	9	0.45	1326. 75	119 8
Ilha_da_Ped ra	IP_T1_200	3209 98	898627 1	Unflood ed	373	84	20.4	2.1	84.5	71	22	7	0.66	2341. 43	212 3
Ilha_da_Ped ra	IP_T1_300	3204 43	898717 0	Unflood ed	350	101	26.7	0.3	85.5	69.1	23.4	7.5	0.83	3419. 4	263 8

Ilha_da_Pedra	IP_T2_0	3230 16	898520 9	Flooded	247	139	5.6	- 3	73.7 6	59.3	30.5	10.2	0.4	39.03	0
Ilha_da_Pedra	IP_T2_500	3226 69	898563 6	Flooded	329	92	32.8	- 8	75.3 1	58	29	13	0.3	589.6 6	550
Ilha_da_Pedra	IP_T2_100	3223 73	898595 7	Unflooded	337	105	22.3	1.7 5	84.8	59.2	32	8.8	0.36	1023. 69	986. 3
Ilha_da_Pedra	IP_T2_200	3218 77	898675 4	Unflooded	457	136	18.2	- 2.5 8	79.0 9	59.8	31.1	9.1	0.44	1954. 97	191 9
Ilha_da_Pedra	IP_T2_300	3213 25	898767 5	Unflooded	408	83	12.3	- 1.1 7	91	64.2	28	7.8	0.54	3027. 3	299 9
Ilha_do_Bufalo	IB_T1_0	3341 31	898858 8	Unflooded	301	81	17.5	0.8	79.1	77.7	14.4	7.9	0.51	116.3 1	86.5
Ilha_do_Bufalo	IB_T1_500	3344 38	898893 5	Unflooded	346	60	13.6	1.2	80	74.8	15	10.2	0.24	572.3 5	537. 5
Ilha_do_Bufalo	IB_T1_100	3347 75	898931 8	Unflooded	372	72	16	0.7	77.7	70.4	22	7.6	0.41	1087. 1	430

Ilha_do_Buf alo	IB_T1_200 0	3354 73	899007 2	Unflood ed	361	88	10.3	0	84.6	72.8	19.8	7.4	0.33	2119. 23	465
Ilha_do_Buf alo	IB_T1_300 0	3362 11	899079 1	Unflood ed	447	131	19	0.9	84.8	75.4	17.6	7	0.29	3143. 23	561
Ilha_do_Buf alo	IB_T2_0 67	3349 67	898801 5	Unflood ed	346	112	11.9	- 0.9 2	79.5 9	69	19.3	11.7	0.25	61.33	20
Ilha_do_Buf alo	IB_T2_500 07	3353 07	898840 4	Unflood ed	452	71	11.4	- 2.0 8	77.7 7	62.2	18.5	19.3	0.36	581.4 4	262
Ilha_do_Buf alo	IB_T2_100 0	3355 82	898875 3	Unflood ed	613	103	14	- 0.3 3	77.6 8	70.4	18.8	10.8	0.23	1024. 87	40
Ilha_do_Buf alo	IB_T2_200 0	3363 32	898952 1	Unflood ed	503	130	10.1	- 0.7 5	84.4 1	70.4	16.6	13	0.46	2110. 45	141. 6
Ilha_do_Buf alo	IB_T2_300 0	3369 64	899033 6	Unflood ed	452	104	14.1	0.4 2	82.8 2	64.1	19.3	16.6	0.57	3124. 79	194

Jaci	JA_T1_0	3471 30	895372 3	Unflood ed	354	157	12	- 0.7 5	100. 29	56.6	31.4	12	0.47	254.1 5	848
Jaci	JA_T1_50 0	3476 28	895383 6	Unflood ed	347	99	13.7	- 2.0 8	99.0 4	54	28	18	0.41	766.4 8	127 8
Jaci	JA_T1_10 00	3481 22	895391 4	Unflood ed	353	143	17	- 1.2 5	100. 03	53.2	30.8	16	0.6	1267. 11	174 4
Jaci	JA_T1_20 00	3491 18	895399 6	Unflood ed	353	137	24.3	- 1.0 8	99.5 6	55.4	29.6	15	0.5	2260. 73	209 1
Jaci	JA_T1_30 00	3499 46	895415 9	Unflood ed	579	130	25.6	-6.5	87.7 6	58.9	29.7	11.4	0.45	3100. 69	138 4
Jaci	JA_T2_0	3469 04	895469 4	Unflood ed	464	165	17.5	0.9	100. 6	62.7	27	10.3	0.48	104.0 4	530
Jaci	JA_T2_50 0	3473 96	895480 4	Unflood ed	292	120	16.2	0.5	99.2	49.9	31.1	19	0.39	610.4 8	102 4
Jaci	JA_T2_10 00	3479 40	895486 8	Unflood ed	425	123	22.9	0.3	98.8	58	27.5	14.5	0.4	1157. 33	158 1

Jaci	JA_T2_20 00	3489 33	895496 4	Unflood ed	429	94	20.2	0.9	99.1	55.4	28	16.6	0.37	2151. 4	180 0
Jaci	JA_T2_30 00	3498 75	895507 8	Unflood ed	410	114	13.7	2.5	99.4	54.8	28	17.2	0.39	3089. 46	870. 6
Morrinhos	MO_T1_0	3621 38	900268 8	Flooded	387	91	13.3	0.8 3	69.3 4	41.5	39.5	19	0.73	133.8	122
Morrinhos	MO_T1_5 00	3622 67	900220 0	Flooded	425	90	28.2	1.8 3	70.8 7	42	51	7	0.55	637.6 6	644
Morrinhos	MO_T1_1 000	3623 72	900174 5	Flooded	379	72	21.4	- 5.1 7	69.1 2	47	47.1	5.9	0.82	1114. 54	110 0
Morrinhos	MO_T1_2 000	3626 10	900166 4	Flooded	433	131	15.9	- 0.8 7	70.4 7	41.4	42	16.6	0.75	2116. 38	631
Morrinhos	MO_T1_3 000	3628 10	899973 6	Flooded	526	112	21.9	0.1 7	69.5 8	37	49.6	13.4	0.77	3178. 78	271
Morrinhos	MO_T2_0	3631 53	900268 9	Flooded	306	119	17.1	0.2	70.7	55.4	26.6	18	0.72	182.7 7	146. 6
Morrinhos	MO_T2_5 00	3632 87	900215 2	Flooded	416	151	32	0.1	71.8	52.8	29.7	17.5	0.76	753.8 2	696. 5

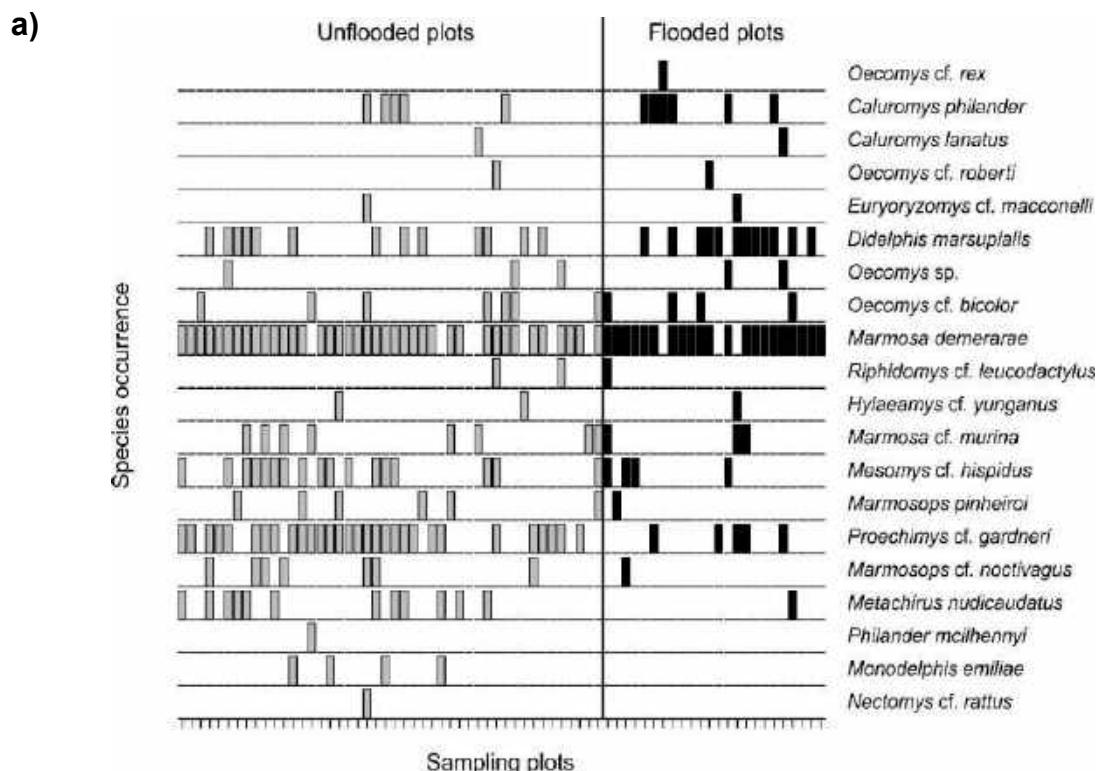
Morrinhos	MO_T2_1 000	3633 99	900175 6	Flooded	350	113	17.3	2.7	69.8	49	34.4	16.6	0.62	1158. 55	640. 8
Morrinhos	MO_T2_2 000	3636 13	900071 5	Flooded	418	200	14.7	0.9	69.6	43.2	38.1	18.7	0.68	2208. 97	238
Morrinhos	MO_T2_3 000	3638 19	899973 3	Flooded	486	144	16	0.9	70.1	42	39	19	0.96	3241. 51	107
Teotonio	TE_T1_0	3825 05	902179 7	Unflood ed	407	190	0	- 1.4 2	100. 2	70.5	22	7.5	0.41	709.5	295
Teotonio	TE_T1_50 0	3821 36	902214 5	Unflood ed	144	347	0	3.8	79.1 4	70.8	18.8	10.4	0.48	1224. 12	500
Teotonio	TE_T1_10 00	3817 69	902247 6	Flooded	456	143	8.1	1.5	64.5 9	47	40.2	12.8	0.78	1685. 7	129. 3
Teotonio	TE_T1_20 00	3810 32	902316 1	Flooded	588	107	0	- 1.5 8	65.5 9	75.2	17	7.8	0.33	2715. 73	63
Teotonio	TE_T1_30 00	3802 94	902384 1	Unflood ed	0	0	0	0	0	0	0	0	0	3788. 21	696. 5
Teotonio	TE_T2_0	3831 92	902252 9	Unflood ed	276	137	9.6	0.3	101. 9	72.3	21.5	6.2	0.41	629.0 8	323

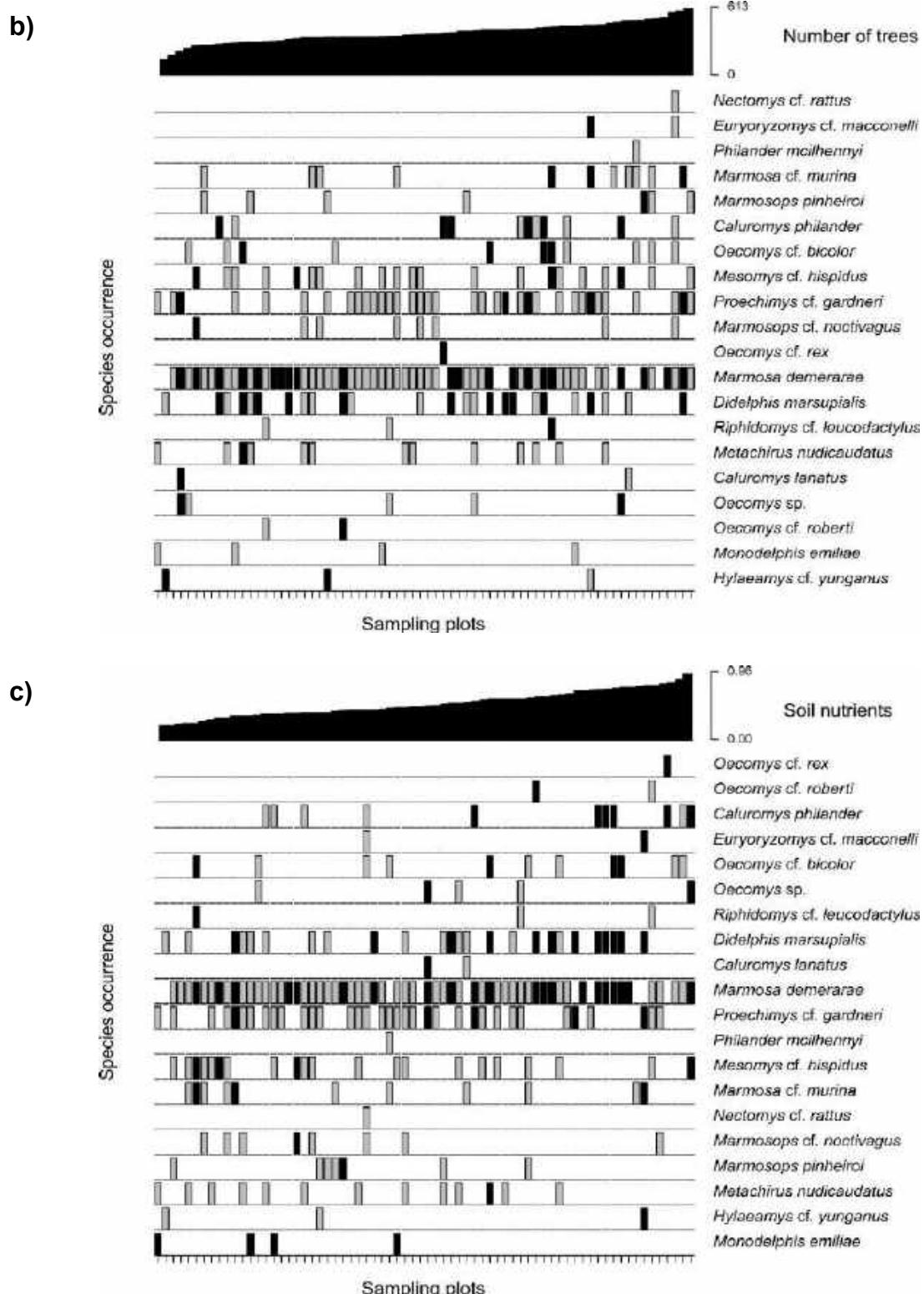
Teotonio	TE_T2_50 0	3828 24	902286 5	Unflood ed	364	82	8.9	3	82.6	73.3	19	7.7	0.6	1139. 26	756. 5
Teotonio	TE_T2_10 00	3824 71	902318 7	Flooded	419	96	16.1	1.5	66.9	75.2	18.6	6.2	0.45	1601. 66	106 5
Teotonio	TE_T2_20 00	3817 19	902388 5	Unflood ed	519	108	18.1	1.8	82.9	75.1	17.9	7	0.49	2607. 59	996. 5
Teotonio	TE_T2_30 00	3809 83	902457 0	Unflood ed	502	179	20.3	2.7	82.4	73.7	18.8	7.5	0.54	3611. 79	142 8
Jir_MD	JD_T1_0	3100 83	896752 8	Flooded	318	85	16.1	-3.3	84.1 3	66	20.5	13.5	0.53	193.6 1	146
Jir_MD	JD_T1_50 0	3105 38	896735 1	Flooded	283	133	16.9	4.4	83.7 3	65	27	8	0.74	675.7 7	639
Jir_MD	JD_T1_10 00	31111 0	896715 1	Unflood ed	286	100	7.5	- 15. 3	87.4 2	67.4	18.6	14	0.65	1283. 34	125 7
Jir_MD	JD_T1_20 00	3119 62	896681 8	Unflood ed	304	101	20.4	-4.2	88.3	70.7	20.2	9.1	0.79	2198. 73	181 4
Jir_MD	JD_T1_30 00	3129 62	896644 8	Unflood ed	451	157	13.4	-3.6	85.0 2	61	29.1	9.9	0.88	3267. 35	266 0

Jir_MD	JD_T2_0	3104 39	896846 2	Flooded	183	107	4.7	-9.7	84.2 1	66.4	23	10.6	0.49	305.8 9	88
Jir_MD	JD_T2_50	3109 91	896828 8	Flooded	296	82	17.1	-1.4	81.7 7	66.4	19.9	13.7	0.59	889.7 3	257. 6
Jir_MD	JD_T2_10	3113 32	896814 3	Flooded	310	196	13.6	9.4	85.3 8	60.4	29.2	10.4	0.64	1256. 1	333
Jir_MD	JD_T2_20	3123 44	896775 5	Unflooded	221	105	9.1	-6.6	83.3 2	18.1	72.3	9.6	0.36	2336. 51	954
Jir_MD	JD_T2_30	3132 24	896741 2	Unflooded	0	0	0	0	0	0	0	0	0	3283. 57	177 2
Jir_ME	JE_T1_0	3106 76	896920 0	Flooded	302	96	20.4	-	84.9 11.9	52.6	30.8	16.6	0.64	25.74	0
Jir_ME	JE_T1_500	3103 21	896956 4	Unflooded	378	90	20.9	-	199 13. 9	61.7	22.5	15.8	0.79	540.0 2	338
Jir_ME	JE_T1_100	3090 98	896994 0	Unflooded	352	89	16.5	12.	172. 3 55	54.5	27	18.5	0.6	982.2 5	491
Jir_ME	JE_T1_200	3093 01	897058 8	Unflooded	416	107	17.9	0.9	100. 44	63.2	19.8	17	0.72	1987. 85	139 1

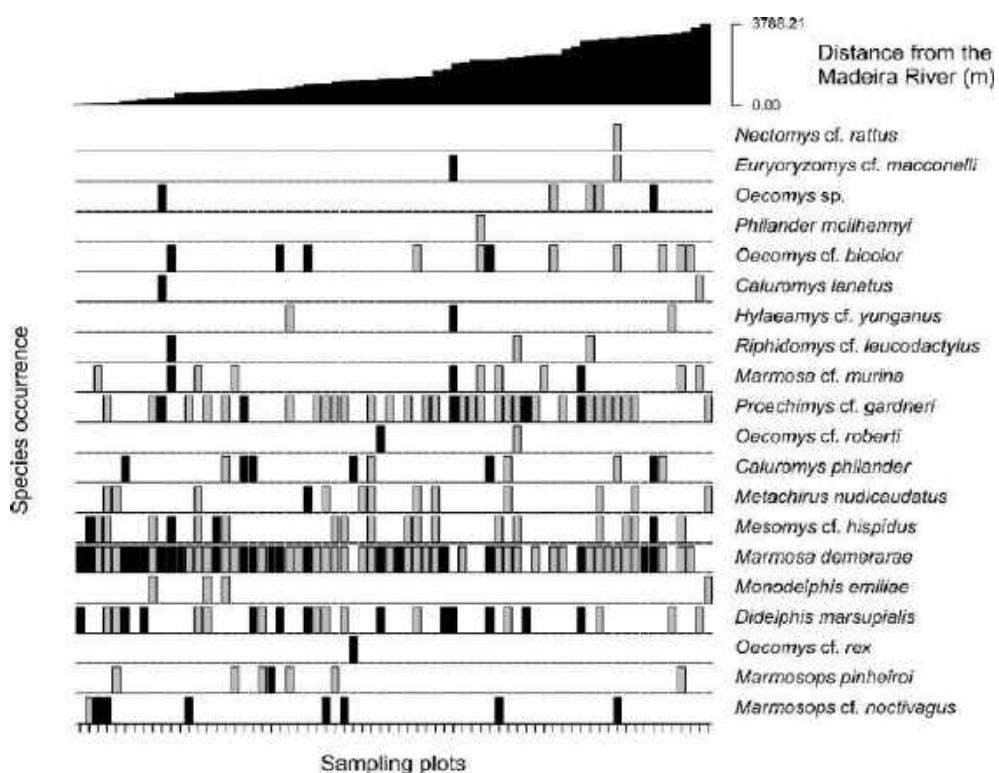
Jir_ME	JE_T1_3000	308582	8971309	Unflooded	356	102	17.6	-1.3	93.83	69.5	17.5	13	0.6	2999.33	2337
Jir_ME	JE_T2_0	311118	8970098	Flooded	388	71	16.2	-4.3	85.93	60.4	26.6	13	0.39	339.39	256
Jir_ME	JE_T2_500	310831	8970473	Unflooded	282	78	17.6	7.4	99.47	49.2	31.8	19	0.23	807.54	594
Jir_ME	JE_T2_1000	310485	8970820	Unflooded	353	120	18.4	-1	98.83	58.1	27.4	14.5	0.45	1317.4	1075
Jir_ME	JE_T2_2000	309787	8971554	Unflooded	478	101	13.5	-1.5	93.57	52.3	30.5	17.2	0.77	2305.25	2060
Jir_ME	JE_T2_3000	309067	8972272	Unflooded	514	122	14.5	1.2	93.2	49.2	32	18.8	0.6	3324.99	3081

Figure S1. Species composition based on species occurrence (a) and abundance related to the number of trees (b), soil nutrients (c, f), proportion of sand (e), distance from stream (g) and distance from the Madeira River (d, h), Brazil. Legend: black bars = flooded plots, gray bars = unflooded plots.

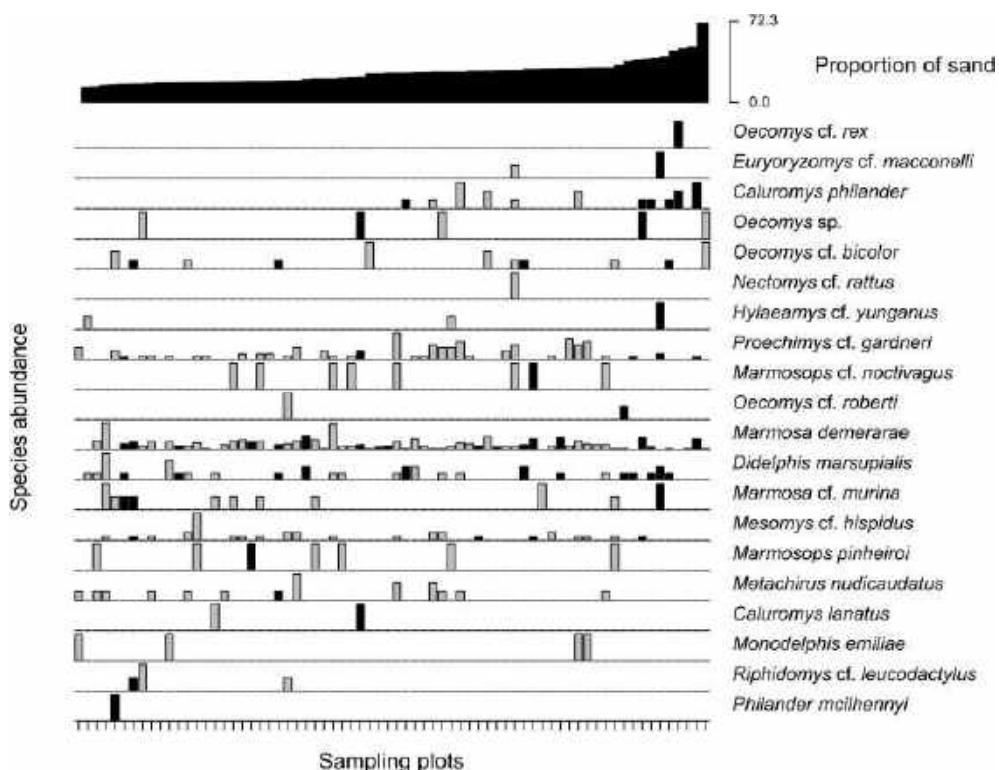


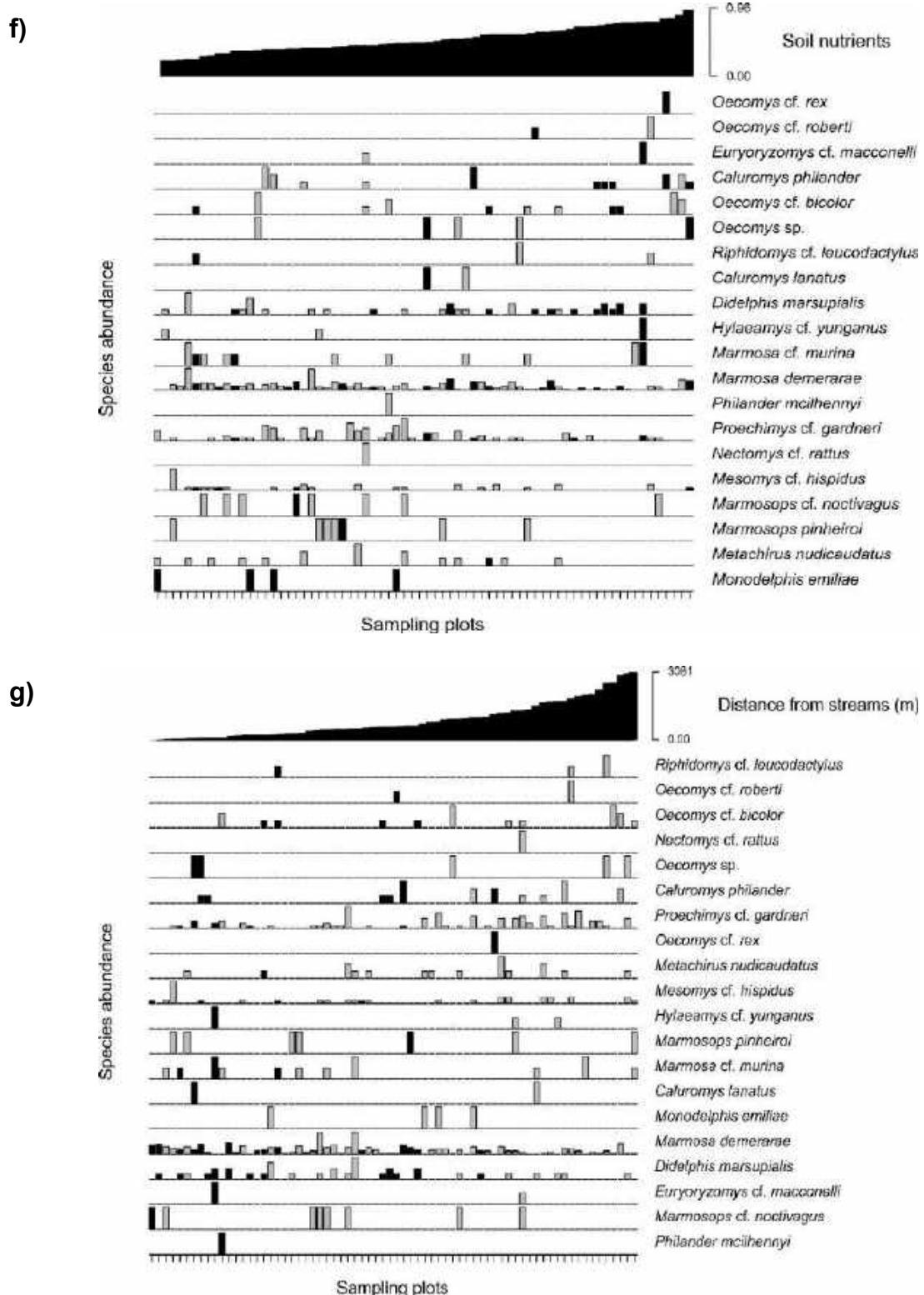


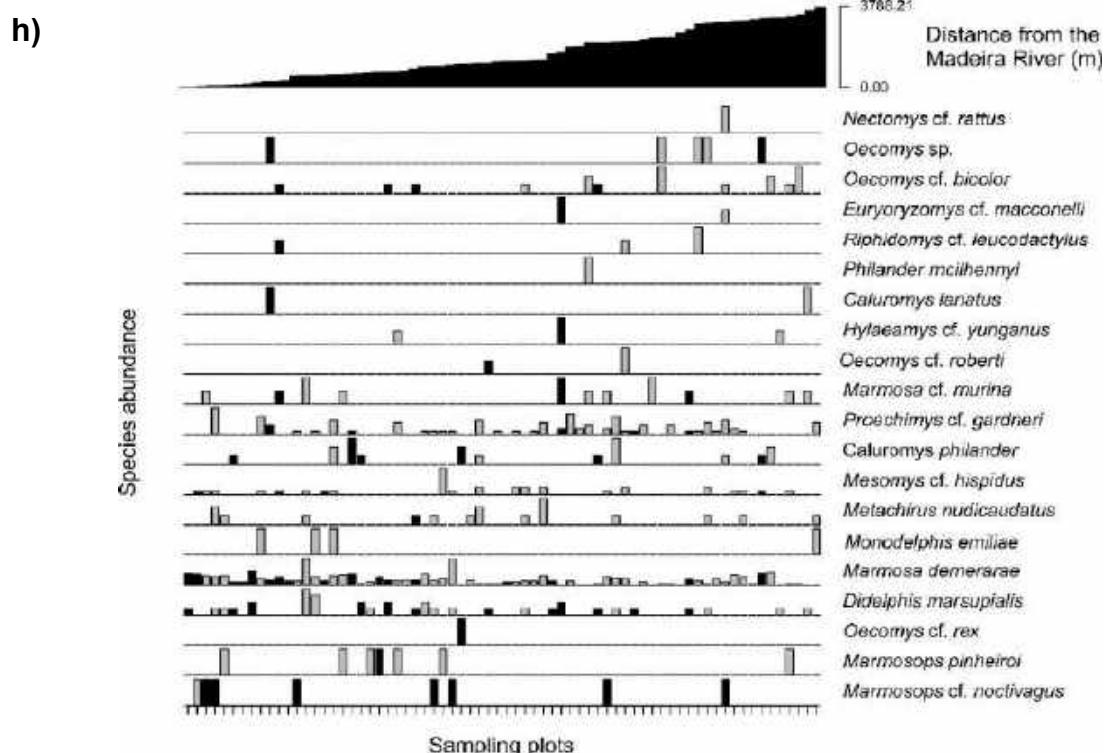
d)



e)







MATERIAL SUPLEMENTAR (CAPÍTULO II)

Effects of an Amazonian dam on taxonomic, functional and phylogenetic dimensions of biodiversity of non-volant small mammals

Raylenne da Silva Araujo, Paulo Estefano Dineli Bobrowiec, Richard D. Stevens, Raquel Teixeira de Moura, Marco Aurélio Sábato, Eduardo Lima Sábato, William Ernest Magnusson

Table S1. Functional-trait data of non-volant small mammals recorded in the area of the Santo Antônio Hydroelectric Power Plant, Madeira River, Brazil.

Taxon	Body Mass (g)	Tail (mm)	Feet (mm)	Diet	Habitat
Didelphidae					
<i>Caluromys lanatus</i>	520	446	51	Frugivore-Omnivorous	Arboreal
<i>Caluromys philander</i>	390	410	40	Frugivore-Omnivorous	Arboreal
<i>Didelphis marsupialis</i>	1700	497	66	Frugivore-Omnivorous	Scansorial
<i>Marmosa demerarae</i>	150	287	34	Frugivore-Omnivorous	Arboreal
<i>Marmosa lepida</i>	23	142	16	Insectivore-Omnivorous	Scansorial
<i>Marmosa murina</i>	52	212	24	Insectivore-Omnivorous	Scansorial
<i>Marmosops noctivagus</i>	60	202	23	Insectivore-Omnivorous	Scansorial
<i>Marmosops parvidens</i>	31	160	17	Insectivore-Omnivorous	Scansorial
<i>Marmosops pinheiroi</i>	33	160	18	Insectivore-Omnivorous	Scansorial
<i>Metachirus nudicaudatus</i>	480	342	47	Insectivore-Omnivorous	Terrestrial
<i>Monodelphis emiliae</i>	60	70	24	Insectivore-Omnivorous	Terrestrial

<i>Monodelphis glirina</i>	50	106	26	Insectivore-Omnivorous	Terrestrial
<i>Philander mcilhennyi</i>	400	377	46	Frugivore-Omnivorous	Scansorial
Cricetidae					
<i>Euryoryzomys macconnelli</i>	80	161	38	Frugivore-Granivore	Terrestrial
<i>Holochilus sciureus</i>	80	174	44	Frugivore-Herbivore	Semiaquatic
<i>Hylaeamys megacephalus</i>	60	130	31	Frugivore-Granivore	Terrestrial
<i>Hylaeamys yunganus</i>	53	120	32	Frugivore-Granivore	Terrestrial
<i>Neacomys spinosus</i>	31	107	25	Frugivore-Granivore	Terrestrial
<i>Nectomys ratus</i>	350	201	47	Frugivore-Omnivorous	Semiaquatic
<i>Oecomys bicolor</i>	28	130	24	Frugivore-Granivore	Arboreal
<i>Oecomys concolor</i>	32	160	29	Frugivore-Granivore	Arboreal
<i>Oecomys rex</i>	60	138	28	Frugivore-Granivore	Arboreal
<i>Oecomys roberti</i>	240	177	31	Frugivore-Granivore	Arboreal
<i>Rhipidomys leucodactylus</i>	159	235	39	Frugivore-Granivore	Arboreal
Ecnimyidae					
<i>Mesomys hispidus</i>	220	203	33	Frugivore-Omnivorous	Arboreal
<i>Proechimys gardneri</i>	270	152	45	Frugivore-Granivore	Terrestrial

Table S2. Phylogenetic likelihood trees of non-volant small mammals recorded in the area of the Santo Antônio Hydroelectric Power Plant, Madeira River, Brazil.

Maximum Likelihood Tree (Pre-filling) - GTR+G model

(((((Didelphis_marsupialis:0.13119662,Philander_mcilhennyi:0.12694352):0.27049951,Monodelphis_emiliae:0.33010761):0.12129805,(Metachirus_nudicaudatus:0.47978238,(Marmosa_demerarae:0.32288447,Marmosa_murina:0.36320269):0.04082356):0.02326955):0.04761581,(Marmosops_noctivagus:0.34025117,Marmosops_pinheiroi:0.34573357):0.08883521):0.09562817,(Caluromys_lanatus:0.17238984,Caluromys_philander:0.21438116):0.12532013):0.25028317,(Euryoryzomys_macconnelli:0.13693028,(Oecomys_bicolor:0.17453578,(Hylaeamys_yunganus:0.21355768,Nectomys_rattus:0.22810085):0.05523784):0.06983702):0.38109965,(Mesomys_hispidus:0.41869266,Proechimys_gardineri:0.19957702):0.69454823);

Maximum Likelihood Tree (Post-filling 1) - GTR+G model

((((((((Marmosa_demerarae:0.28126619,Marmosa_lepida:0.30009255):0.08504514,Marmosa_murina:0.40070201):0.02987055,(Caluromys_lanatus:0.20745216,Caluromys_philander:0.22431198):0.22023257):0.02048214,Metachirus_nudicaudatus:0.48889605):0.06194918,(Monodelphis_emiliae:0.32097044,Monodelphis_glirina:0.41109410):0.12369254):0.04029287,(Didelphis_marsupialis:0.13418253,Philander_mcilhenn

yi:0.13886464):0.31925148):0.10996173,Marmosops_parvidens:0.42346253):0.10236120,Marmosops_noctivagus:0.22672263):0.31807236,(Mesomys_hispidus:0.44554045,Proechimys_gardineri:0.22859754):0.63976155,(Neacomys_spinosus:0.29147478,((Oecomys_bicolor:0.13376267,Oecomys_roberti:0.07299414):0.06964913,Euryoryzomys_macconnelli:0.21484792):0.05410856,((Holochilus_sciureus:0.21446141,Nectomys_rattus:0.16308664):0.08360167,(Hylaeamys_yunganus:0.21477579,Rhipidomys_leucodactylus:0.54272586):0.05783297):0.03158091):0.08577025):0.48218574);

Maximum Likelihood Tree (Post-filling 2) - GTR+G+I model

((((((Oecomys_bicolor:0.06277203,Oecomys_concolor:0.03464565):0.02759590,Oecomys_rex:0.08757834):0.03346304,(Hylaeamys_megacephalus:0.09335765,Hylaeamys_yunganus:0.09874367):0.03855925):0.01522566,(Euryoryzomys_macconnelli:0.10596576,(Holochilus_sciurus:0.09230765,Rhipidomys_leucodactylus:0.21932621):0.03602260):0.00845245):0.05055242,Neacomys_spinosus:0.12899768):0.12559075,(Mesomys_hispidus:0.16394992,Proechimys_gardineri:0.11816993):0.21167183,(Marmosops_parvidens:0.20576766,((Marmosa_demerarae:0.11731823,Marmosa_lepida:0.13998371):0.01921304,((Marmosa_murina:0.14734411,Metachirus_nudicaudatus:0.20844680):0.02219500,((Caluromys_lanatus:0.12035364,Caluromys_philander:0.09757806):0.04570923,(Didelphis_marsupialis:0.14885309,(Monodelphis_emiliae:0.14454489,Monodelphis_glirina:0.16673717):0.00246774):0.05890241):0.05434184):0.02034255):0.04057161):0.13139434);

Table S3. Species abundance of non-volant small mammals recorded in 34 plots sampled before filling (Pre-filling), one-year post filling (Post-1) and two years post filling (Post-2) in the Santo Antônio Hydroelectric area, Madeira River, Brazil.

Taxon	Pre-filling	Post 1	Post 2	Total
Didelphidae				
<i>Caluromys lanatus</i>	1	7	1	9
<i>Caluromys philander</i>	7	2	3	12
<i>Didelphis marsupialis</i>	15	17	13	45
<i>Marmosa demerarae</i>	225	81	125	431
<i>Marmosa lepida</i>	0	10	1	11
<i>Marmosa murina</i>	7	12	11	30
<i>Marmosops noctivagus</i>	7	16	0	23
<i>Marmosops parvidens</i>	0	29	18	47
<i>Marmosops pinheiroi</i>	6	0	0	6
<i>Metachirus nudicaudatus</i>	14	113	9	136
<i>Monodelphis emiliae</i>	3	8	2	13
<i>Monodelphis glirina</i>	0	10	6	16
<i>Philander mcilhennyi</i>	1	87	0	88
Cricetidae				
<i>Euryoryzomys macconnelli</i>	1	2	2	5
<i>Holochilus sciureus</i>	0	2	1	3
<i>Hylaeamys megacephalus</i>	0	0	1	1
<i>Hylaeamys yunganus</i>	1	21	8	30
<i>Neacomys spinosus</i>	0	13	7	20
<i>Nectomys rattus</i>	1	17	0	18
<i>Oecomys bicolor</i>	6	40	30	76
<i>Oecomys concolor</i>	0	0	1	1
<i>Oecomys rex</i>	0	0	3	3
<i>Oecomys roberti</i>	0	9	0	9
<i>Rhipidomys leucodactylus</i>	0	1	4	5
Echimyidae				
<i>Mesomys hispidus</i>	26	66	39	131
<i>Proechimys gardineri</i>	76	108	84	268
Total abundance	397	671	369	1437
Richness	16	22	21	26

Table S4. Results of post hoc pairwise comparisons of the GLMM-TBM models for species-level abundance comparing Pre-filling, Post-1 and Post-2 periods around the reservoir of the Santo Antônio Hydroelectric, Madeira River, Brazil. $P < 0.05$ are in bold.

Taxon	Pre x Post-1		Post-1 x Post-2		Pre x Post-2	
	t	P	t	P	t	P
Didelphidae						
<i>Caluromys philander</i>	1.47	0.31	-0.42	0.91	1.13	0.49
<i>Didelphis marsupialis</i>	-0.25	0.96	0.53	0.85	0.28	0.95
<i>Marmosa demerarae</i>	-4.84	< 0.0001	2.33	0.06	-2.61	0.03
<i>Marmosa lepida</i>	0.00	1.00	2.17	0.08	0.00	1.00
<i>Marmosa murina</i>	0.94	0.61	0.01	1.00	0.92	0.63
<i>Marmosops noctivagus</i>	0.57	0.83	0.002	1.00	-0.002	1.00
<i>Marmosops parvidens</i>	0.002	1.00	1.24	0.43	0.002	1.00
<i>Metachirus nudicaudatus</i>	4.92	< 0.001	-5.40	< 0.001	-0.83	0.68
<i>Monodelphis emiliae</i>	1.45	0.32	1.75	0.19	-0.44	0.89
<i>Monodelphis glirina</i>	0.01	1.00	0.99	0.59	0.01	1.00
<i>Philander mcilhennyi</i>	3.97	< 0.001	0.002	1.00	-0.002	1.00
Cricetidae						
<i>Hylaeamys yunganus</i>	2.97	0.01	2.32	0.06	1.96	0.13
<i>Neacomys spinosus</i>	0.002	1.00	1.14	0.49	0.002	1.00
<i>Nectomys rattus</i>	2.61	0.02	0.00	1.00	-0.001	1.00
<i>Oecomys bicolor</i>	3.37	0.003	0.56	0.84	2.95	0.01
Echimyidae						
<i>Mesomys hispidus</i>	2.12	0.09	1.46	0.31	0.68	0.77
<i>Proechimys gardneri</i>	0.88	0.65	0.23	0.97	0.64	0.79

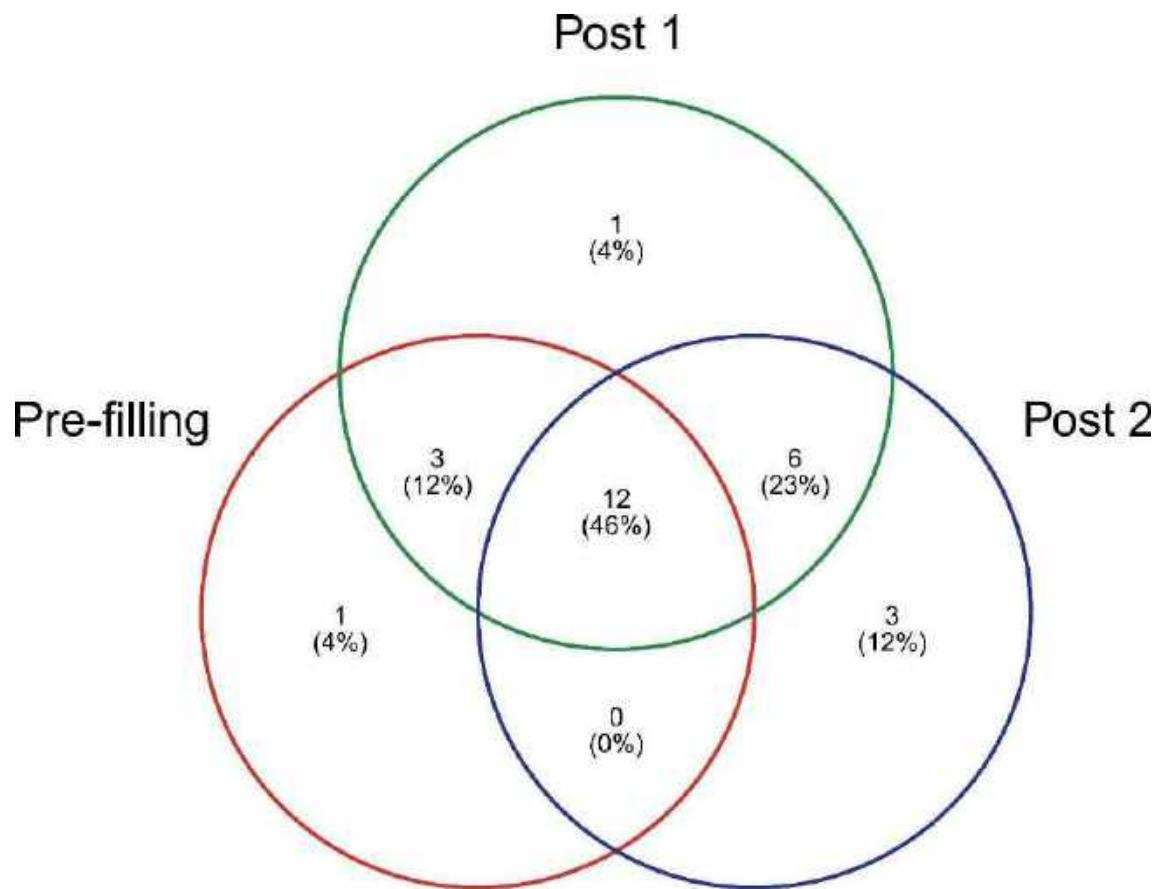


Figure S1. Venn diagram showing species sharing and exclusivity of non-flying small mammals in the Pre-filling, Post-1 and Post-2 periods sampled around the Santo Antônio Hydroelectric, Madeira River, Brazil.

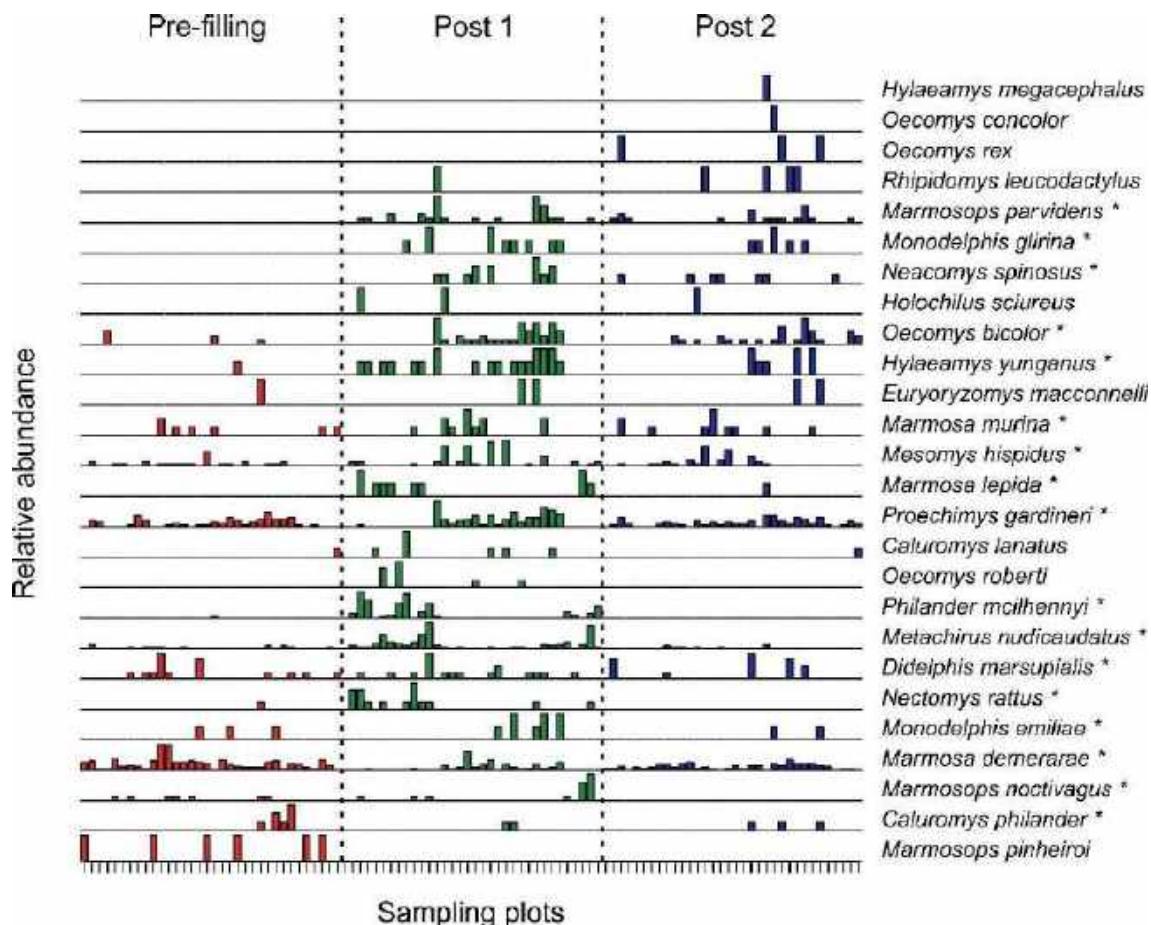


Figure S2. Plots organized by capture frequency of non-flying small mammals in relation to sampling periods around the Santo Antônio Hydroelectric Reservoir, Madeira River, Brazil. Red = Pre-filling, green = Post-1, blue = Post-2. * indicates species whose abundances were compared among the three periods (see details in Tables S3 and S4).