Biodiversity and Conservation
https://doi.org/10.1007/s10531-022-02396-8

ORIGINAL PAPER

Taxonomic and functional responses of bats to habitat flooding by an Amazonian mega-dam

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Received: 14 September 2021 / Revised: 10 January 2022 / Accepted: 21 February 2022

Abstract

Hydroelectric dams are among the main cause of anthropogenic impacts in tropical environments. Damming interrupts the continuity of the river and produces the flooding of adjacent terrestrial ecosystems. Despite the negative effects on terrestrial and aquatic biodiversity, studies of the impacts of hydroelectric dams on species and community functional responses to flooding are scarce. Here, we evaluated the effects of river damming on taxonomic and functional diversity of phyllostomid bats sampled before (flooded sites) and after (unflooded sites) the construction of a mega hydroelectric dam in the southwestern of the Brazilian Amazon. The flooding of the lowlands significantly increased the taxonomic and functional α-diversity, as well as the species- and the community-level functional uniqueness of the bat assemblages, reflecting a reduction in the abundance of functional redundant species. Based on functional trait composition, we detected an increase in the frequency of animalivorous bats, and a reduction in phytophagous bats. Pre- and post-dam temporal differences show that functional β-diversity shifts were more determined by replacement of traits weighted by species abundance than by the loss or gain of traits. Functional traits linked to trophic level, body mass, and diet proved to be powerful indicators of the bat community's responses to temporal changes caused by run-of-the-river dams, which degrade riparian and *várzea* forests. Plans to expand the electric power matrix in Brazil include the construction of several dams, potentially flooding large areas of *várzea* forests. We demonstrate the importance of the *várzea* and the riparian forests to phytophagous bats to guarantee the ecological functions they perform.

Keywords Functional diversity · Functional traits · Functional uniqueness · River damming · Run-of-the-river reservoir · Temporal dynamics

Communicated by Anurag chaurasia.

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Introduction

Hydropower development is among the significant anthropogenic impacts in natural environments, with well-documented negative effects on terrestrial and aquatic biodiversity and ecosystems (e.g., Gibson et al. 2013; Palmeirim et al. 2017; Anderson et al. 2018; Benchimol & Peres 2020). These effects are associated with a uniformly hostile open-water matrix that imposes a barrier to species' mobility and limits the use of resources in fragments (Farneda et al. 2020a; Benchimol & Peres 2020). Hydropower corresponds to ~80% of electricity in Brazil (Zarfl et al. 2015), and 334 new hydroelectric dams are with construction planned in the Amazon Basin (Winemiller et al. 2016). Although hydropower generation is claimed to be environmentally sustainable, until 2012, approximately 1.1 million ha of forest in the Brazilian Amazon has been completely flooded (Forsberg et al. 2017), resulting in significant impacts on ecological services and ecosystem functioning through the extinction and replacement of species.

Most of the existing knowledge about the impacts of hydroelectric dams on the biota comes from storage reservoirs (Baumgartner et al. 2020), traditionally used worldwide (International Energy Agency 2012). This type of reservoir retains large amounts of water, causing the interruption of the natural flood level regime (Baumgartner et al. 2020) and creating several islands that may have different sizes and degrees of isolation (Benchimol & Peres 2020). Conversely, run-of-the-river reservoirs have become increasingly common in planning the expansion of the electric power matrix. Because run-of-the-river hydroelectric dams are based on the building of smaller lakes with limited water storage, they have been considered a priori less detrimental (Almeida et al. 2019), but their effects on the biota are scarcely known. New hydroelectric dams call for new perspectives of environmental impact studies, addressing multiple dimensions of diversity to better understand the river damming effects on communities.

Ecologists have traditionally attempted to estimate the effects of environmental disturbance based primarily on examining the taxonomic dimension, including analyses of species composition, richness, and relative abundance (Mackey & Currie 2001). However, these descriptors consider the species to be independent units, ignoring the functional similarities between them (Cadotte et al. 2011; Gagic et al. 2015). The different species' responses to human-made disturbances are limited by their morphology, physiology, and behavior (McGill et al. 2006; Mouillot et al. 2013; Gagic et al. 2015; Weiss & Ray 2019). Thus, studies based on functional traits offer a promising alternative approach to taxonomic diversity (McGill et al. 2006; Mouillot et al. 2013; Gagic et al. 2015; Ricotta et al. 2016). Functional traits can be directly affected by the environmental disturbance, even in events where there is no change in the total number of species or composition (Flynn et al. 2009; Cadotte et al. 2011; Beiroz et al. 2018).

Bats have been progressively used as models to assess the effects of anthropogenic landscape changes on functional diversity (e.g., García-Morales et al. 2016; Gonçalves et al. 2017; Pereira et al. 2018; Farneda et al. 2018; 2020a; Carvalho et al. 2020). In particular, Neotropical bats from the family Phyllostomidae form species-rich assemblages that are highly diverse for functional traits and promote a variety of functions in ecosystems. Ecosystem services offered by bats include functional traits associated with seed dispersal, plant pollination and insect population control (Castillo-Figueroa 2020). Additionally, certain functional traits of bats, such as trophic level and body mass, have been identified as sensitive to environmental disturbance, and larger animalivores species to have a minor chance of survival after the disturbance (Fenton et al. 1992; Farneda et al. 2015; 2018; 2020b). Frugivorous bats are associated with waterways and may be sensitive to loss of flooded and riparian forests (Bobrowiec et al. 2014; Capaverde et al. 2018). However, the knowledge about the effects of hydropower development on the functional diversity of bats comes from studies conducted in insularized landscapes generated by storage reservoirs (Cosson et al. 1999; Meyer et al. 2008; Farneda et al. 2020a; Zortéa et al. 2021).

Here, we evaluate the effects of river damming on the taxonomic and functional diversity of phyllostomid bats in areas that would be flooded and not flooded before and after the construction of the Santo Antônio Hydroelectric dam, located in southwestern Brazilian Amazon. Additionally, we investigate how bat functional traits are affected by river damming and how the flooding of lowlands contributes to changes in functional β-diversity. Our hypothesis is that functional and taxonomic α-diversity, and functional uniqueness at the communities and species-level decrease after the river damming due to assemblages functionally similar and simplified. We predicted that after dam filling:

1. functional and taxonomic α-diversity and community-level functional uniqueness would decrease based on negative species responses to environmental changes.
2. species-level functional uniqueness would increase for phytophagous species because of their positive association with the lowlands that would be flooded (Bobrowiec et al. 2014).
3. functional traits associated with phytophagous species would be negatively affected because these species are more abundant in lowland forests (Capaverde et al. 2018).
4. temporal differences in functional β-diversity would be mainly determined by the replacement of functional traits than by the gain of traits.

Materials and methods

Study area

We captured bats in the surrounding areas to the Santo Antônio Hydroelectric reservoir (08°48’S; 63°57’W; Fig. 1). The hydroelectric dam was built on the upper Madeira River, located to ~5 km upstream from the city of Porto Velho, Rondônia State, southern Brazilian Amazonia (Fig. 1), and started operating in March 2012, with generating capacity of 3150 MW. The dam is a run-of-the-river project with bulb-type turbines that allow for the formation of smaller reservoirs. Despite that, the reservoir reached 70 m above the river’s maximum natural flood level. The Madeira River originates in the Andes, receiving nutrient-rich waters bounding from the left margin, and tributaries on the right-side carry nutrient-poor waters from the western Amazon plateau. The region’s vegetation is characterized by dense tropical forests, including *terra firme* upland forests, *várzea* forest on the river banks and patches of *campinarana* and *campina* (Moser et al. 2014). The climate is tropical humid hyperthermic (Cochrane & Cochrane 2010). The average annual precipitation varies from 1700 to 2000 mm (Sombroek 2001), with a rainy season between November and April and a dry season between June and September (Santos et al. 2020).

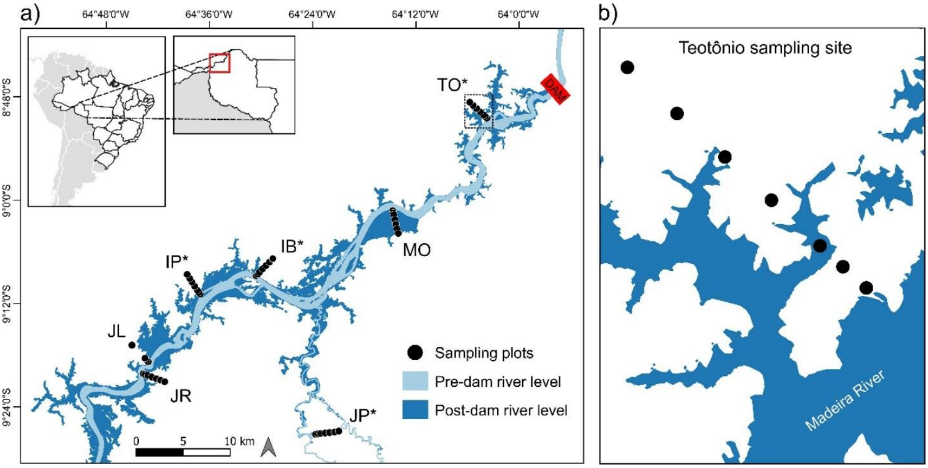

Fig. 1 Map of the study area downstream of the Santo Antônio Hydroelectric in the upper Madeira River, Southwestern Brazilian Amazonia. (a) Light blue indicates the area occupied by the original river before dam construction, the dark blue indicates the extent of the reservoir after the full dam flooding. (b) Illustration of the plot's distribution in the one site in relation to the post-dam Madeira River level. The sampling sites are: TO = Teotônio, MO = Morrinhos, IB = Ilha dos Búfalos, IP = Ilha das Pedras, JL = Jirau Left Bank, JR = Jirau Right Bank, JP = Jaci-Paraná. Sampling sites that were sampled after the river damming are indicated by asterisk (*)

Bat sampling

We captured bats in seven sampling sites with seven plots in each, totaling 46 sampling plots (Fig. 1, Table S1). Six sites were located on the Madeira River and one on the Jaci-Paraná River (Fig. 1). The plots were distributed 50, 500, 1000, 2000, 3000, 4000, and 5000 m away from the riverbank on a trail perpendicular to the river bank (Fig. 1). The sample design followed the RAPELD method (RAP = rapid survey of biological communities; PELD = long-term ecological research) for standardized surveys of fauna and flora in the Amazon (Magnusson et al. 2005). The RAPELD system consists of 250 m long and 40 m wide plots that follow the topographic contour to minimize internal heterogeneity in soil properties and drainage.

We sampled the plots in two stages (Table S1): Pre-dam stage = 12 plots located in areas that were going to be flooded by the reservoir (pre-flooded plots), and 34 plots that were going to remain dry (pre-unflooded plots) (June 2010 to September 2011); and Post-dam stage = 25 pre-unflooded plots resampled after the flooding of the reservoir (post-dam plots) (June 2013 to June 2014).

We captured bats using eight ground-level mist-nets (12 × 2.5 m, 36 mm mesh, Ecotone Inc, Poland) per plot. The mist-nets were opened between 18:00 and 00:00 and inspected at 15-minute intervals. Each plot was visited for 3–4 non-consecutive nights in both phases of the dam filling, totaling 290 sampling nights (13,920 mnh; 1 mist-net hour, mnh, equals one 12-m net open for 1 h; Table S2). Species were identified following Charles-Dominique et al. (2001), Lim and Engstrom (2001), and Gardner (2007). Taxonomy follows Garbino et al. (2020).

Species traits

We selected five functional traits (Table 1 and S3) related to the variability of diets and movement ability of bats. These traits have been used to predict the response of bats to anthropogenic environmental changes (Castillo-Figueroa & Pérez-Torres 2021) and may be defined as follows:

Body mass – this trait has been widely used in bat functional studies (Farneda et al. 2015; Castillo-Figueroa & Pérez-Torres 2021) and was obtained during our fieldwork using a balance with 0.5 g of precision.

Wing morphology – the shape of the wings of a bat constraint its flying mode and performance and may be described in two functional traits: relative wing loading and aspect ratio (Norberg & Rayner 1987). Wings with a high aspect ratio and relative wing loading are suitable for high-speed flights, little maneuverability in obstructed habitats, but advantageous for foraging in open spaces (Norberg & Rayner 1987; Tavares 2013; Marinello & Bernard 2014). Values of relative wing loading and aspect ratio of 41 species sampled in our study were obtained from Marinello & Bernard (2014) and Farneda et al. (2015). For the other seven species, we estimated the values of relative wing loading and aspect ratio using the equation of linear regressions of these traits with body mass (Relative wing loading: $t = -1.94$, $P = 0.06$, $r^2 = 0.088$, $RWL = -0.069 \times (\text{body mass}) + 39.5$; Aspect ratio: $t = 1.15$, $P = 0.26$, $r^2 = 0.034$, $AR = 0.0035 \times (\text{body mass}) + 6.13$) (Table S3).

Trophic level – we divided this trait into two main categories: phytophagous phyllostomids (which consume fruits, seeds, nectar, leaves, and flowers), and animalivorous phyllostomids (including insects, small rodents, frogs, and blood in their diets) (Giannini & Kalko 2004).

Diet – this trait conveys a more detailed scale of trophic level and represents the main food item eaten by bats. We ranked the diet of bat species according to the classification found in the literature (Giannini & Kalko 2004), including the categories as follows: frugivores, nectarivores, gleaning insectivores, carnivores, omnivores and sanguinivores.

Data analysis

We calculated the taxonomic and functional α-diversity, and the community-level functional uniqueness following the methodological approach proposed by Ricotta et al. (2016), which

Table 1 List and description of the bat functional traits used in taxonomic and functional analyses at Santo Antonio Hydroelectric, Southwestern Amazonia, Brazil. Table S3 shows the values of each functional trait

Trait	Scale	Description	Source
Body mass	Continuous	Average body mass of each species (excluding pregnant females and juveniles)	Our capture data
Wing morphology	Continuous	Relative wing loading and aspect ratio	Marinello & Bernard (2014); Farneda et al. (2015)
Trophic level	Categorical	Phytophagues and animalivores	Our capture data
Diet	Categorical	Based on the main food item consumed by each species (i.e., frugivores, nectarivores, gleaning insectivores, carnivores, omnivores and sanguinivores)	Our capture data

consists of using Simpson index D for taxonomic diversity and Rao's index Q for functional diversity. Simpson D considers all species functionally similar, but taxonomically different, and Rao's Q takes the species dissimilarities into account to calculate of functional diversity. Based on these two indices, we were further able to estimate the functional uniqueness U, which consists of the ratio between the two diversity indices: U=Q / D. This approach has been widely applied to compare taxonomic and functional diversity in recent ecological studies on a variety of taxa (e.g., Doxa et al. 2020; Farneda et al. 2018; 2020b). Both indexes consider the relative species abundance and, therefore, are good indicators of early warning of disturbances as they do not only need species extinctions to change (Mouillot et al. 2013). We also calculate the index of functional richness (Fric) that does not consider the abundance of species (Villéger et al. 2008). Fric is the total amount of functional space filled by the community and increases by adding functionally unique species to the assemblage, but remains unchanged with the addition of functionally redundant species (Villéger et al. 2008). We compared each index (D, Q, U, Fric) between the pre- (pre-unflooded+pre-flooded; Table S1) and post-dam plots, and also between the three categories of plots (pre-unflooded, pre-flooded, post-dam; Table S1) using a Generalized Linear Mixed Model (GLMM) in *lme4* package (Brooks et al. 2017). Pre-dam plots account for all plots sampled before filling the reservoir, both pre-flooded and pre-unflooded plots (Table S1). Thus, we can understand how pre-dam plots differ from post-dam plots. The models incorporated the sampling sites and plots as random effects to account for potential spatial autocorrelations. We assessed pairwise comparison among pre-unflooded, pre-flooded, and post-dam with the 'glht' function from *multcomp* package (Hothorn et al. 2008).

To evaluate the relevance of each species in a particular function about the river damming, we calculated the species-level functional uniqueness $\bar{K_i}$, which is also based on the relative species abundance. $\bar{K_i}$ varies between 0 and 1, and high values are associated with rare species linked to less common functional traits in the community. We compared the $\bar{K_i}$ values between pre- and post-dam periods for phytophagous and animalivorous bats using permutational paired *t*-tests with 9999 randomizations in the *broman* package (Broman 2020). For this, we used only the species that were recorded in both periods. We also compared the $\bar{K_i}$ values between animalivorous and phytophagous bat species before and after the dam construction using permutational *t*-tests with 9999 randomizations (*RVAideMemoire* package, Hervé 2020). We calculated the Q, D, U and $\bar{K_i}$ indices using the 'uniqueness' function of the *adiv* package (Pavoine 2020), based on Gower's functional dissimilarity that allows including categorical and quantitative traits (*gawdis* package, de Bello et al. 2021). We used 'functcomp' function from *FD* package (Laliberté et al. 2014) to perform the Fric index.

To understand how each functional trait respond to the river damming, we calculated the community-weighted mean trait values (CWM; Lavorel et al. 2008). The CWM employs the average value of each trait weighted by the abundance of each species (Violle et al. 2007). We calculated the CWM traits using the 'functcomp' function of the *FD* package (Laliberté et al. 2014). For each functional trait, comparisons between plots of the three categories (pre-flooded, pre-unflooded, and post-dam) and two categories (pre- and post-dam) were performed using GLMMs as previously described.

Temporal changes for functional structure of communities before and after disruption can be assessed by calculating the functional β-diversity (Mouillot et al. 2013). Total functional β-diversity (βtotal) is represented by replacement (turnover of species functional traits, βrepl) and difference in species richness (loss or gain of traits, βrich). We use the Cardoso et al. (2015) approach that predicts that βtotal corresponds to the sum of the replacement component with the richness difference component (βtotal = βrepl + βrich). The βtotal and its components were calculated using the 'beta' function of the *BAT* package (Cardoso et al. 2020), based on a site × species matrix with species occurrence data and Jaccard dissimilarity, a tree of the functional traits and rarefaction of species with 1000 runs. The functional tree was based on a matrix of species × traits, submitted to a hierarchical clustering procedure using UPGMA with Gower distance (Cardoso et al. 2015). We used a rarefaction for the same abundance as the plot with the least individuals sampled (argument raref = 1). The functional β-diversity of bat assemblages was calculated between pre- and post-dam periods with all plots (pre-dam × post-dam), and between pre-unflooded plots and post-dam (without pre-flooded plots). All analyses were performed in R (R Core Team 2020).

Results

We captured 2981 bats belonging to 48 species (Table S2). Post-dam plots had higher taxonomic (D) and functional diversity (Q), and higher functional uniqueness (U) than pre-dam plots (pre-unflooded + pre-flooded), but functional richness (Fric) was similar to the pre-unflooded stage (Table 2; Fig. 2). When we contrasted post-dam with pre-flooded and pre-unflooded plots, we observed that post-dam had higher taxonomic diversity (D) and functional diversity (Q) compared to pre-unflooded plots, but were similar to pre-flooded plots for D and Q (Table 3; Fig. S1).

Table 2 Results of the GLMM for the taxonomic (D) and functional (FRic, Q and U) diversity indices, and for each functional trait used in community-weighted mean (CWM) analyses. Comparisons were made between pre-dam (pre-flooded and pre-unflooded combined) and post-dam plots. $P < 0.05$ are in bold

	Pre-dam × Post-dam	
Indices	***t***	***P***
Simpson D	**2.29**	**0.031**
Functional richness FRic	-1.01	0.35
Rao's Q	**2.41**	**0.022**
Functional Uniqueness U	**2.05**	**0.048**
Traits		
Body mass	0.19	0.85
Relative wing load	1.52	0.13
Aspect ratio	-0.06	0.96
Trophic level:		
phytophagues	**2.17**	**0.034**
animalivores	**-2.18**	**0.033**
Diet:		
frugivores	**3.29**	**0.002**
nectarivores	-1.28	0.21
gleaning insectivores	-1.69	0.09
carnivores	-1.14	0.26
omnivores	-1.11	0.27
sanguinivores	-1.67	0.09

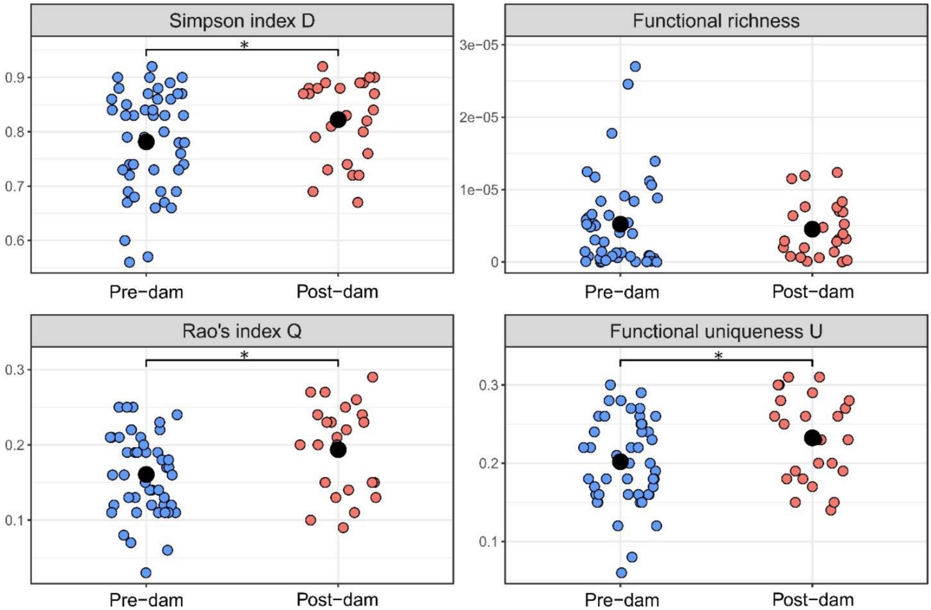

Fig. 2 Taxonomic diversity (Simpson index D), functional diversity (Functional richness and Rao's index Q), and functional uniqueness U of the bat assemblages sampled pre-dam (blue circles) and post-dam (red circles) at Santo Antonio Hydroelectric, Southwestern Amazonia, Brazil. Black circles represent the means of the functional indexes values. * $P<0.05$ (see Table 2). Pre-dam represent pre-flooded and pre-unflooded plots combined

We recorded relevant changes for bat species-level functional uniqueness ($\overline{K}_i$). For example, $\overline{K}_i$ of seven species (14.5% of all species) of animalivorous bats (e.g., *Diphylla ecaudata*, *Chrotopterus auritus*, *Micronycteris megalotis*) decreased with dam construction. In contrast, $\overline{K}_i$ increased for 15 species (31.3%) of phytophagous bats (e.g., *Rhinophylla fischerae*, *Platyrrhinus brachycephalus*, *Uroderma bilobatum*) (Fig. 3). The mean functional uniqueness of all bat species increased following the river damming (paired t-test: t = -2.37; P=0.019) mainly for phytophagous bats (paired t-test: t = -3.13; P=0.007), and remained similar in animalivorous (paired t-test: t = -0.12; P=0.86). Species-level functional uniqueness of animalivorous bats during the periods pre- (t-test: t=8.01; P<0.0001) and post-dam (t-test: t=8.23; P<0.0001) were, in average, 1.9 and 1.7 times greater than that of phytophagous bats, respectively (Fig. S2).

Changes in functional traits composition were associated with the effects of river damming, as demonstrated by the community-weighted mean trait values (CWM). The traits that revealed significant changes in CWM after the construction of the dam were trophic level, diet, and body mass (Tables 2 and 3). The CWM trait values of animalivores increased significantly (P=0.033) after the dam construction, while for phytophagous bats (P=0.034) represented mainly by the frugivores (P=0.002) it decreased (Table 2; Fig. 4). Frugivorous bats were less frequent (P=0.003) in the post-dam plots compared to pre-unflooded and pre-flooded plots (Table 3; Fig. S3). Animalivorous bats were more frequent in pre-unflood and post-dam plots than pre-flooded plots (Table 3; Fig. S3). Body mass was higher in pre-flooded plots than pre-unflooded and post-dam plots (Table 3; Fig. S3).

Table 3 Results of the GLMM for the taxonomic (D) and functional (FRic, Q and U) diversity indices, and for each functional trait used in community-weighted mean (CWM) analyses. Comparisons were made between pre-flooded, pre-unflooded, and post-dam plots. P<0.05 are in bold

	Pre-flood × Pre-unflood		Pre-flood × Post-dam		Pre-unflood × Post-dam	
Indices	***t***	***P***	***t***	***P***	***t***	***P***
Simpson D	**-2.39**	**0.041**	-0.84	0.67	**2.66**	**0.020**
Functional richness FRic	0.31	0.95	-0.4	0.91	-1.03	0.55
Rao's Q	-0.85	0.66	0.67	0.77	**2.52**	**0.029**
Functional Uniqueness U	-0.40	0.91	0.91	0.62	2.08	0.09
Traits						
Body mass	**-2.84**	**0.012**	**2.49**	**0.032**	-0.21	0.97
Relative wing load	-1.49	0.29	2.12	0.08	1.21	0.44
Aspect ratio	-2.15	0.08	1.59	0.25	-0.59	0.82
Trophic level:						
phytophagues	-0.82	0.68	1.77	0.17	1.62	0.23
animalivores	0.82	0.68	-1.78	0.17	-1.63	0.22
Diet:						
frugivores	-0.78	0.71	**2.58**	**0.03**	**3.06**	**0.006**
nectarivores	-1.27	0.40	0.38	0.92	-1.43	0.31
gleaning insectivores	2.07	0.09	**-2.69**	**0.02**	-1.28	0.39
carnivores	-0.95	0.61	-0.09	0.99	-1.37	0.35
omnivores	0.17	0.98	-0.81	0.69	-1.04	0.54
sanguinivores	-0.31	0.95	-0.93	0.62	-1.68	0.21

The differences in functional βtotal (0.089) between pre- and post-dam bat assemblages was mostly explained by the replacement of species traits (βrepl=0.067; 75.3% of the βtotal) compared to loss or gain of traits (βrich=0.017; 19.1%) (Fig. 5). When we removed the pre-flooded plots from the analysis, βrich slightly increased (Fig. 5).

Discussion

Hydroelectric dams have become one of the main drivers of changes in tropical biota (Winemiller et al. 2016; Jones et al. 2016). Identifying the functional traits that explain species' responses to river damming may help to choose management practices that restore ecosystem functions (Spasojevic et al. 2018). Contrary to our expectations, the flooding of lowland areas of the Madeira River increased the taxonomic and functional α-diversity and functional uniqueness of the bat assemblages. We also found strong evidence for a shift in functional traits after river damming, with an increase in the frequency of animalivorous bats and a reduction of phytophagous. Our data show that total β-diversity results from replacing functional traits (i.e., the substitution of functional traits weighted by the species abundance) and not by the loss or gain of traits.

In scenarios of recent and extensive environmental disturbances, such as the implementation of dams, the species need to adapt to new conditions until the equilibrium is found (Dayrell et al. 2021). Indices of functional diversity and uniqueness are very sensitive to species abundance (de Bello et al. 2007). The increase in functional α-diversity and functional uniqueness, as demonstrated by our data, is likely a result of the influx of individuals

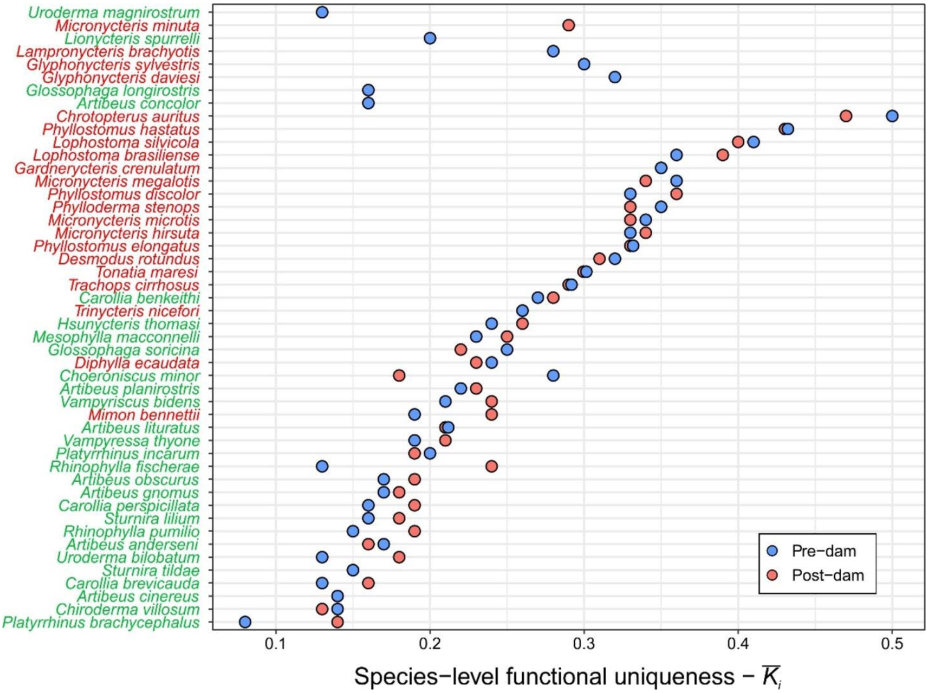

Fig. 3 Species-level functional uniqueness of the bat species sampled pre-dam (blue circles) and post-dam (red circles) at Santo Antonio Hydroelectric, Southwestern Amazonia, Brazil. Species names in green represent phytophagous bats, and names in red represent animalivorous bats. Pre-dam represent pre-flooded and pre-unflooded plots combined

from the areas lost to the remaining landscape. Contrary to our prediction 1, the taxonomic diversity (D), functional diversity (Q), and functional uniqueness (U) increased in magnitude after the disturbance caused by the dam due to the reduction in the abundance of the functional redundant bat species. On the other hand, the functional richness was similar between the three categories of habitats (pre-flooded, pre-unflooded, and post-dam), indicating that the flooding of the reservoir did not affect the number of functionally unique species. An increase in functional diversity after human-induced impacts has also been observed in Amazonian and Atlantic Forest for ants (Zhao et al. 2020), birds (Ding et al. 2013), fish (Stegmann et al. 2019), and mammals (Bovendorp et al. 2019; Sancha et al. 2020), including bats (Farneda et al. 2018; Carvalho et al. 2020).

The functional uniqueness of bat species from the Madeira riverside communities ($\bar{K_i}$) increased in the post-dam period. Following prediction 2, this increment of $\bar{K_i}$ was driven by the input of several species of phytophagous bats, mainly frugivores, that declined in abundance (e.g., *Rhinophylla pumilio*, *Vampyriscus bidens*, *Carollia perspicillata*, *Uroderma bilobatum*). Functional uniqueness in animalivorous bats did not change, although it remained greater than phytophagous bats. So, the increase in the functional uniqueness of the post-dam assemblages resulted from the combination of the large abundance of frugivorous bats, that became less dominant, and the animalivorous bats with unique traits. Unique assemblages selected after human disturbance may be of special concern for the

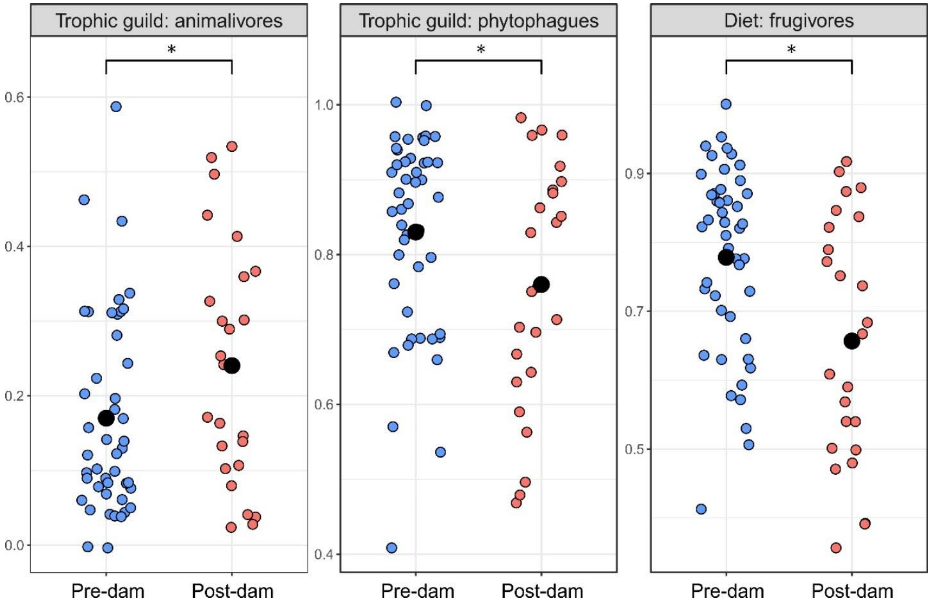

Fig. 4 Community-weighted mean (CWM) trait values for statistically significant functional traits: Trophic guild: animalivores and phytophagues, and Diet: frugivores. Bat assemblages were sampled during pre-dam (blue circles) and post-dam (red circles) at Santo Antonio Hydroelectric, Southwestern Amazonia, Brazil. Black circles represent the means of the CWM trait values. * $P<0.05$ (see Table 2). Pre-dam represent pre-flooded and pre-unflooded plots combined

conservation of ecosystems as they may lack essential functions and services (Biggs et al. 2020). These effects can be temporarily worsened if the abundance of fruit bats does not increase in the future.

Under prediction 3, our results from the CWM analyses revealed that phytophagous bats, most of them frugivores, and large bats were negatively affected by the construction of the dam. At the same time, animalivorous species responded positively to changes imposed by the dam. Similar results have been found in a small hydroelectric dam in the Brazilian Cerrado (Zortéa et al. 2021). Several studies have shown that frugivorous bats benefit from converting the original undisturbed forest to secondary vegetation (Bobrowiec & Gribel 2010; Rocha et al. 2017). However, fruit bats are the most vulnerable to permanent loss of *várzea* and riparian forests, which constitute the larger part of the flooded area lost in the Santo Antonio dam (Santos et al. 2020). *Terra firme* upland forests, *várzea* and riparian forests have distinct bat assemblages influenced mainly by the seasonal flooding of the *várzea* and water-table level (Pereira et al. 2009; Bobrowiec et al. 2014; Pereira et al. 2019). Frugivorous bats are more abundant in *várzea* and riparian zones (Pereira et al. 2009; Bobrowiec et al. 2014, Capaverde et al. 2018, Zortéa et al. 2021). Moreover, we found assemblages with large bats in *várzea*, mainly due to the greater abundance of large-bodied species such as *Artibeus lituratus*, a pattern like those found in other Amazonian regions (Pereira et al. 2009; Bobrowiec et al. 2014). Nutrient-rich *várzea* forests have a high fruit production that attracts many frugivorous bats (Pereira et al. 2010). Plants of the genus *Piper* are common in the riparian forest and are exploited for food by frugivorous bats (Zortéa et al. 2021). The frequency reduction of frugivorous bats in post-dam areas compared to pre-unflooded areas

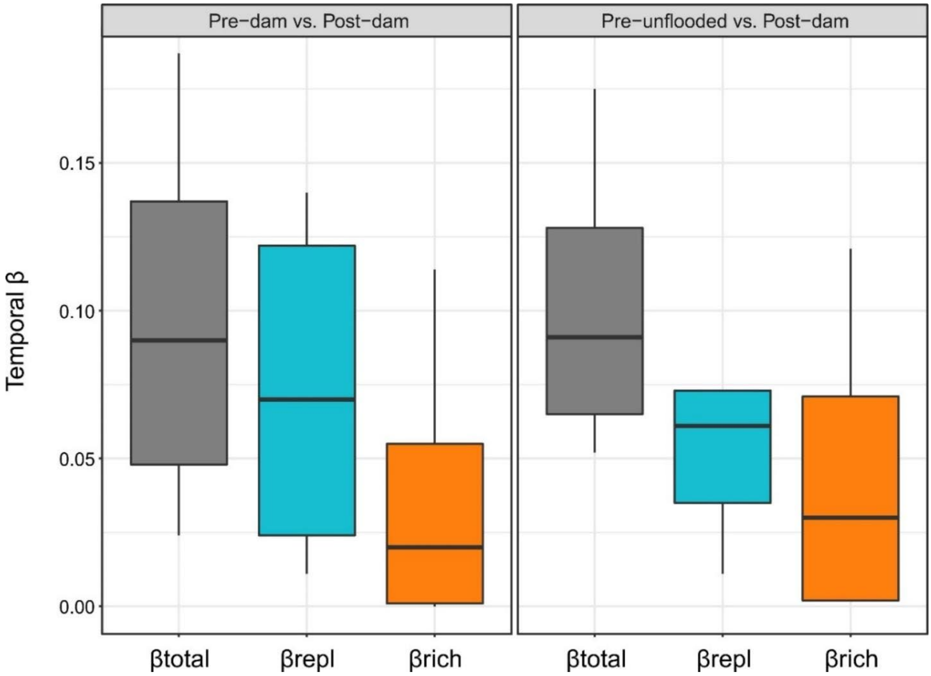

Fig. 5 Results of the rarefaction for components of bat functional β diversity between pre- (flooded and unflooded plots combined) and post-dam with all data set (left boxplots) and between pre-unflooded and post-dam data set (excluding pre-flooded data; right boxplots) at Santo Antonio Hydroelectric, Southwestern Amazonia, Brazil. βtotal functional diversity (grey) was partitioned in the components βrepl (blue; replacement of species functional traits) and βrich (orange; loss or gain of traits). Values represent means (horizontal lines) ± 95% confidence levels (colored bars) and maximum and minimum (vertical lines)

indicates that these bats may have moved to other forests with suitable food supply and thus reduced upland fruit bat populations. The Jirau/Santo Antônio hydroelectric complex flooded 800 km^2 of lowland forests along 245 km of the Madeira River, of which 118 km^2 were *várzea* forests (Cochrane et al. 2017). The loss of *várzea* forests can damage important ecological functions provided by frugivorous bats, such as the gene flow of plants via seed dispersal and pollination. As frugivores account for 77.5% of the phyllostomid bats sampled, the loss of ecosystem services may be more severe in assemblies with a lower frugivore abundance than the original.

On the other hand, the CWM results showed that river damming positively affected animalivorous bats. The frequency increase of animalivorous bats after dam filling indicates that these bats seem to have moved from flooded to non-flooded habitat. Animalivorous phyllostomids, represented mainly by carnivores, insectivorous gleanings and omnivores are dependent on the mature forest and are overall sensitive to environmental disturbances in response to the scarcity of food and roost (Klingbeil & Willig 2009; Farneda et al. 2015; Gonçalves et al. 2017). Areas that remained unflooded did not change the environmental conditions required by bats with these traits in the first two years of Santo Antônio hydroelectric dam operation. However, the integrity of the remaining forests over time is likely essential to mitigate the harmful effects of river damming (Benchimol & Peres 2020).

In accordance with prediction 4, our findings regarding β-diversity suggest that species traits replacement is the most important component of temporal functional total β diversity. The prevalence of diversity components related to the replacement of functional traits is expected for forests with less severe anthropogenic disturbances (Farneda et al. 2018; Carvalho et al. 2020). At the time of our study, the remaining vegetation in the Madeira riverside close to the Santo Antônio dam has a similar structural complexity as in the pre-dam period. However, the loss of *várzea* and riparian forests increased the influence of functional diversity due to richness and inversely decreased the diversity due to the replacement of functional traits. This indicates that *várzea* and riparian forests support high taxonomic and functional diversity of ecosystems (Pereira et al. 2009; Bobrowiec et al. 2014) because they harbor species with functions that are not shared within unflooded *terra firme* forests. The loss of species signifies a loss of functions with possible implications for ecosystem preservation (Leitão et al. 2016).

The Santo Antônio dam changed the taxonomic and functional α-diversity and the functional uniqueness of bat assemblages in a short time, while the long-term consequences remain unknown. The two years of the Santo Antônio dam flooding may not have been long enough to change in the vegetation, affected by the rise in the water table level in the areas close to the new banks of the Madeira River and streams. The vegetation change process is not yet over and the reaction of flora and fauna to the changed conditions is probably still ongoing. The loss of *várzea* forest is permanent and the new margins of the reservoir will not replicate the same alluvial habitats that previously existed (Almeida et al. 2019). Evidence indicates that changes in taxonomic diversity caused by the Santo Antônio dam will continue in the region, as observed in anurans (Dayrell et al. 2021) and birds (Henriques et al. 2021). The abundance of frugivorous bat species in several plots has decreased (Bobrowiec et al. 2021), which may increase the functional uniqueness of the assemblages and the contribution of functional richness (βrich) if rare species are prone to local extinction over time. If declines in frugivorous bats abundance continue, a potential cascading impact on ecosystems is also expected, including a reduction in vegetation regeneration potential via seed dispersal. The main problem seems to be that ecosystems that harbor fewer functionally redundant species are less resilient to environmental changes (Díaz & Cabido 2001; Bovendorp et al. 2019; Biggs et al. 2020). Therefore, the continuous monitoring of large-scale environmental impacts, as in the case of hydroelectric dams, is required to understand the direction and magnitude of changes in functional and taxonomic diversity and to estimate when the communities may reach a new equilibrium (Dayrell et al. 2021; Souza & Fernandes 2021).

Conservation implications

River damming by a run-of-the-river hydroelectric dam quickly changed the taxonomic and functional diversity of Phyllostomidae bat assemblages from Madeira riverside lowlands. Those changes were driven mainly by the replacement of traits rather than the loss or gain of traits. Due to their frequency reduction in assemblages, functional traits linked to the trophic level, diet, and body mass are powerful indicators of the responses of the bat communities to the temporal changes caused by run-of-the-river dams that putatively degrade mainly lowland, riparian and *várzea* forests in the Amazonia River systems. Therefore, studies that consider functional diversity are promising in identifying communities that may be prone to temporal changes in the human-modified landscapes (Brandl et al. 2016; Farneda et al. 2018).

Run-of-the-river hydroelectric dams negatively affect large-body phytophagous bats by flooding *várzea* forests and riparian zones. Species with larger body sizes have been identified as a good indicator of species vulnerability (Farneda et al. 2015; 2020b). The use of bats as bioindicators is auspicious, but this property is seldom tested in the field (Russo et al. 2021). Our study provides evidence that frugivorous bats are sensitive to river damming and can be used as bioindicator. Conserving the *várzea* and riparian forests is essential to ensure ecological functions performed by phytophagous bats (frugivores and nectarivores) to ensure ecosystem functionality (Assahira et al. 2017; Forsberg et al. 2017, Santos et al. 2020; Schöngart et al. 2021). New dams are planned to be built in the Amazon with the potential to flood large areas of *várzea* forests (Lees et al. 2016; Forsberg et al. 2017). For these reasons, we emphasize the importance of creating a category of protected area as standard compensation conditioning the hydroelectric dam development, including *várzea* forests. We also suggest that the energy companies should be responsible for safeguarding these reserves.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10531-022-02396-8.

Acknowledgements We are thankful to the Santo Antônio Energia, Instituto Chico Mendes de Conservação da Biodiversidade, Instituto Nacional de Pesquisas da Amazônia, Fundação Amazônica de Defesa da Biosfera, and to Eduardo L. Sábato from SETE Soluções e Tecnologia Ambiental for providing facilities to the development of this study. P. Bobrowiec was supported by a postdoctoral scholarship provided by the Fundação de Amparo à Pesquisa do Estado do Amazonas/Programa de Apoio à Fixação de Doutores no Amazonas (FAPEAM/FIXAM) and Programa Nacional de Pós-Doutorado/Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (PNPD/CAPES), V. Tavares was supported by postdoctoral scholarships Fundação de Amparo à Pesquisa do Estado do Amazonas/Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (PRO-DPD/AM - PPGSS) and PNPD/CAPES, and F. Z. Farneda was supported by a postdoctoral scholarship from Programa Institucional de Internacionalização (PrInt/CAPES). V. Tavares is grateful to Fernando A. Perini (Universidade Federal de Minas Gerais) and Pedro C. Estrela (Universidade Federal da Paraíba) for housing her at their labs during different stages dedicated to this research. We are very grateful to several people involved in different stages of fieldwork. We thank to anonymous reviewers for commenting on drafts of the paper.

Author contributions **Paulo E. D. Bobrowiec**: Conceptualization, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing. **Fábio Z. Farneda**: Formal analysis, Writing - Original Draft, Writing - Review & Editing. **Carla C. Nobre**: Investigation. **Valéria C. Tavares**: Conceptualization, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing.

Funding This work was supported by Instituto Nacional de Pesquisas da Amazonia, Santo Antônio Energia, Fundação Amazônica de Defesa da Biosfera, Fundação de Amparo à Pesquisa do Estado do Amazonas. All funding of this research were closed when the manuscript was submitted to the journal Biodiversity and Conservation.

Availability of data and material The data and metadata of the species captured are deposited in the public repository of the Brazilian Biodiversity Research Program (PPBio): https://ppbiodata.inpa.gov.br/metacatui/#view/PPBioAmOc.87.4. The data can be accessed by title "Bat species (Chiroptera) captured in 49 sampling plots in the upper River Madeira - Rondonia, Brazil" or key words "Chiroptera", "Madeira River", and "Rondônia".

Code Availability Not applicable.

Declarations

Conflicts of interest/Competing interests (include appropriate disclosures) The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Additional declarations for articles in life science journals that report the results of studies involving humans and/or animals This study was undertaken under licenses for scientific purposes (capture, collection, and transport of specimens) from Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) (Procedure number 02001.000965/2008-83, Permit number 259/2009).

Ethics approval Experienced investigators handled all captured bats. We followed the guidelines approved by the American Society of Mammalogists in our procedures (Sikes & Gannon 2011).

Consent to participate (include appropriate statements) Not applicable.

Consent for publication (include appropriate statements) Not applicable.

References

Almeida RM, Hamilton SK, Rosi EJ, Arantes JD, Barros N, Boemer G, Gripp A, Huszar VLM, Junger PC, Lima M, Pacheco F, Carvalho D, Reisinger AJ, Silva LHS, Roland F (2019) Limnological effects of a large Amazonian run-of-river dam on the main river and drowned tributary valleys. Sci Rep 9:1–11

Anderson EP, Jenkins CN, Heilpern S, Maldonado-Ocampo JA, Carvajal-Vallejos FM, Encalada AC, Rivadeneira JF, Hidalgo M, Cañas CM, Ortega H, Salcedo N, Maldonado M, Tedesco PA (2018) Fragmentation of Andes-to-Amazon connectivity by hydropower dams. Sci Adv 4:1–8

Assahira C, Piedade MTF, Trumbore SE, Wittmann F, Cintra BBL, Batista ES, Resende AF, Schöngart J (2017) Tree mortality of a flood-adapted species in response of hydrographic changes caused by an Amazonian river dam. For Ecol Manag 396:113–123

Baumgartner MT, Piana PA, Baumgartner G, Gomes LC (2020) Storage or run-of-river reservoirs: exploring the ecological effects of dam operation on stability and species interactions of fish assemblages. Environ Manage 65:220–231

Beiroz W, Sayer E, Slade EM, Audino L, Braga RF, Louzada J, Barlow J (2018) Spatial and temporal shifts in functional and taxonomic diversity of dung beetles in a human-modified tropical forest landscape. Ecol Ind 95:518–526

Benchimol M, Peres CA (2020) Determinants of population persistence and abundance of terrestrial and arboreal vertebrates stranded in tropical forest land-bridge islands. Conserv Biol 35:870–883

Biggs CR, Yeager LA, Bolser DG, Bonsell C, Dichiera AM, Hou Z, Keyser SR, Khursigara AJ, Lu K, Muth AF, Negrete B, Erisman BE (2020) Does functional redundancy affect ecological stability and resilience? A review and meta-analysis. Ecosphere 11:e03184

Bobrowiec PED, Gribel R (2010) Effects of different secondary vegetation types on bat community composition in Central Amazonia, Brazil. Anim Conserv 13:204–216

Bobrowiec PED, Rosa L dos, Gazarini S, Haugaasen J T (2014) Phyllostomid bat assemblage structure in amazonian flooded and unflooded forests. Biotropica 46:312–321

Bobrowiec PED, Nobre CC, Tavares VC (2021) Immediate effects of an Amazonian mega hydroelectric dam on phyllostomid fruit bats. Ecol Ind 132:108322

Bovendorp RS, Brum FT, McCleery RA, Baiser B, Loyola R, Cianciaruso MV, Galetti M (2019) Defaunation and fragmentation erode small mammal diversity dimensions in tropical forests. Ecography 42:23–35

Brandl SJ, Emslie MJ, Ceccarelli DM, Richards ZT (2016) Habitat degradation increases functional originality in highly diverse coral reef fish assemblages. Ecosphere 7:e01557

Broman KW (2020) broman: Karl Broman's R code. R package version 0.71-6

Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Maechler M, Bolker BM (2017) glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. R J 9:378–400

Cadotte MW, Carscadden K, Mirotchnick N (2011) Beyond species: functional diversity and the maintenance of ecological processes and services. J Appl Ecol 48:1079–1087

Capaverde UD, Pereira LGA, Tavares VC, Magnusson WE, Baccaro FB, Bobrowiec PED (2018) Subtle changes in elevation shift bat-assemblage structure in Central Amazonia. Biotropica 50:674–683

Cardoso P, Rigal F, Carvalho JC (2015) BAT–Biodiversity Assessment Tools, an R package for the measurement and estimation of alpha and beta taxon, phylogenetic and functional diversity. Methods Ecol Evol 6:232–236

Cardoso P, Mammola S, Rigal F, Carvalho JC (2020) BAT: biodiversity assessment tools. R package version 2.4.1

Carvalho WD, Meyer CFJ, Xavier B, da S, Mustin K, de Castro IJ, Silvestre SM, Pathek DB, Capaverde UD, Hilário R, Toledo JJ (2020) Consequences of replacing native savannahs with acacia plantations for the taxonomic, functional, and phylogenetic α- and β-diversity of bats in the Northern Brazilian Amazon. Front Ecol Evol 8:1–12

Castillo-Figueroa D (2020) Why bats matters: a critical assessment of bat-mediated ecological processes in the Neotropics. Eur J Ecol 6:77–101

Castillo-Figueroa D, Pérez-Torres J (2021) On the development of a trait-based approach for studying Neotropical bats. Papéis Avulsos de Zoologia 61:1–27

Charles-Dominique P, Brosset A, Jouard S (2001) Atlas dês chauvessouris de Guyane. Patrimoines Naturels 49:1–172

Cochrane SMV, Matricardi EAT, Numata I, Lefebvre PA (2017) Landsat-based analysis of mega dam flooding impacts in the Amazon compared to associated environmental impact assessments: Upper Madeira River example 2006–2015. Remote Sens Applications: Soc Environ 7:1–8

Cochrane TT, Cochrane TA (2010) Amazon forest and Savanna lands: A guide to the climates, vegetation, landscapes and soils of central tropical South America. Charleston, Amazon Publishing

Cosson J, Pons J, Masson D (1999) Effects of forest fragmentation on frugivorous and nectarivorous bats in French Guyana. J Trop Ecol 15:515–534

Dayrell JS, Magnusson WE, Bobrowiec PED, Lima AP (2021) Impacts of an Amazonian hydroelectric dam on frog assemblages. PLoS ONE 16:e0244580

de Bello F, Bott-Dukat Z, Leps J, Fibich P (2021) Towards a more balanced combination of multiple traits when computing functional differences between species. Methods Ecol Evol 12:443–448

de Bello F, Lepš J, Lavorel S, Moretti M (2007) Importance of species abundance for assessment of trait composition: an example based on pollinator communities. Community Ecol 8:163–170

Díaz S, Cabido M (2001) Vive la différence: Plant functional diversity matters to ecosystem processes. Trends in Ecology and Evolution 16:646–655

Ding Z, Feeley KJ, Wang Y, Pakeman RJ, Ding P (2013) Patterns of bird functional diversity on land-bridge island fragments. J Anim Ecol 82:781–790

Doxa A, Devictor V, Baumel A, Pavon D, Médail F, Leriche A (2020) Beyond taxonomic diversity: revealing spatial mismatches in phylogenetic and functional diversity facets in Mediterranean tree communities in southern France. For Ecol Manag 474:118318

Farneda FZ, Grelle CEV, Rocha R, Ferreira DF, López-Baucells A, Meyer CFJ (2020a) Predicting biodiversity loss in island and countryside ecosystems through the lens of taxonomic and functional biogeography. Ecography 43:97–106

Farneda FZ, Meyer CFJ, Grelle CEV (2020b) Effects of land-use change on functional and taxonomic diversity of Neotropical bats. Biotropica 52:120–128

Farneda FZ, Rocha R, López-Baucells A, Sampaio EM, Palmeirim JM, Bobrowiec PED, Grelle CEV, Meyer CFJ (2018) Functional recovery of Amazonian bat assemblages following secondary forest succession. Biol Conserv 218:192–199

Farneda FZ, Rocha R, López-Baucells A, Groenenberg M, Silva I, Palmeirim JM, Bobrowiec PED, Meyer CFJ (2015) Trait-related responses to habitat fragmentation in Amazonian bats. J Appl Ecol 52:1381–1391

Fenton MB, Acharya L, Audet D, Hickey MBC, Merriman C, Obrist MK, Syme DM, Adkins B (1992) Phyllostomid bats (Chiroptera: Phyllostomidae) as indicators of habitat disruption in the Neotropics. Biotropica 24:440–446

Flynn DFB, Gogol-Prokurat M, Nogeire T, Molinari N, Richers BT, Lin BB, Simpson N, Mayfield MM, DeClerck F (2009) Loss of functional diversity under land use intensification across multiple taxa. Ecol Lett 12:22–33

Forsberg BR, Melack JM, Dunne T, Barthem RB, Goulding M, Paiva RCD, Sorribas MV, Silva UL, Weisser S (2017) The potential impact of new Andean dams on Amazon fluvial ecosystems. PLoS ONE 12:e0182254

Gagic V, Bartomeus I, Jonsson T, Taylor A, Winqvist C, Fischer C, Slade EM, Steffan-Dewenter I, Emmerson M, Potts SG, Tscharntke T, Weisser W, Bommarco R (2015) Functional identity and diversity of animals predict ecosystem functioning better than species-based indices. Proceedings of the Royal Society B: Biological Sciences 282:20142620

Garbino GST, Gregorin R, Lima IP, Loureiro L, Moras LM, Moratelli R, Nogueira MR, Pavan AC, Tavares VC, Nascimento MC, Peracchi AL (2020) Updated checklist of Brazilian bats: version 2020. Comitê da Lista de Morcegos do Brasil-CLMB. Sociedade Brasileira para o Estudo de Quirópteros (SBEQ). https://www.sbeq.net/lista-de-especies

García-Morales R, Moreno CE, Badano EI, Zuria I, Galindo-González J, Rojas-Martínez AE, Ávila-Gómez ES (2016) Deforestation impacts on bat functional diversity in tropical landscapes. PLoS ONE 11:e0166765

Gardner AL (2007) Mammals of South America: marsupials, xenarthrans, shrews, and bats. The University of Chicago Press, Chicago

Giannini NP, Kalko EKV (2004) Trophic structure in a large assemblage of phyllostomid bats in Panama. Oikos 105:209–220

Gibson L, Lynam AJ, Bradshaw CJA, He F, Bickford DP, Woodruff DS, Bumrungsri S, Laurance WF (2013) Near-complete extinction of native small mammal fauna 25 years after forest fragmentation. Science 341:1508–1510

Gonçalves F, Fischer E, Dirzo R (2017) Forest conversion to cattle ranching differentially affects taxonomic and functional groups of Neotropical bats. Biol Conserv 210:343–348

Henriques LMP, Dantas S, Santos LB, Bueno AS, Peres CA (2021) Avian extinctions induced by the oldest Amazonian hydropower mega dam: evidence from museum collections and sighting data spanning 172 years. PeerJ 9:e11979

Hervé M (2020) RVAideMemoire: testing and plotting procedures for biostatistics. R package version 0:9–78

Hothorn T, Bretz F, Westfall P (2008) Simultaneous inference in general parametric models. Biom J 50:346–363

International Energy Agency (2012) World energy outlook. http://www.worldenergyoutlook.org/weo2012/

Jones IL, Bunnefeld N, Jump AS, Peres CA, Dent DH (2016) Extinction debt on reservoir land-bridge islands. Biol Conserv 199:75–83

Klingbeil BT, Willig MR (2009) Guild-specific responses of bats to landscape composition and configuration in fragmented Amazonian rainforest. J Appl Ecol 46:203–213

Laliberté E, Legendre P, Shipley B (2014) FD: measuring functional diversity from multiple traits, and other tools for functional ecology. R package version 1:0–12

Lavorel S, Grigulis K, McIntyre S, Williams NSG, Garden D, Dorrough J, Berman S, Quétier F, Thébault A, Bonis A (2008) Assessing functional diversity in the field -. Methodol matters! Funct Ecol 22:134–147

Lees AC, Peres CA, Fearnside PM, Schneider M, Zuanon JA (2016) Hydropower and the future of Amazonian biodiversity. Biodivers Conserv 25:451–466

Leitão RP, Zuanon J, Villéger S, Williams SE, Baraloto C, Fortunel C, Mendonça FP, Mouillot D (2016) Rare species contribute disproportionately to the functional structure of species assemblages. Proceedings of the Royal Society B: Biological Sciences 283:20160084

Lim BK, Engstrom MD (2001) Species diversity of bats (Mammalia: Chiroptera) in Iwokrama Forest, Guyana, and the Guianan subregion: implications for conservation. Biodivers Conserv 10:613–657

Mackey RL, Currie DJ (2001) The diversity-disturbance relationship: is it generally strong and peaked? Ecology 82:3479–3492

Magnusson WE, Lima AP, Luizão R, Luizão F, Costa FR, Castilho CVD, Kinupp VF (2005) RAPELD: a modification of the Gentry method for biodiversity surveys in long-term ecological research sites. Biota Neotrop 5:19–24

Marinello MM, Bernard E (2014) Wing morphology of Neotropical bats: a quantitative and qualitative analysis with implications for habitat use. Can J Zool 92:141–147

McGill BJ, Enquist BJ, Weiher E, Westoby M (2006) Rebuilding community ecology from functional traits. Trends Ecol Evol 21:178–185

Moser P, Oliveira WL, Medeiros MB, Pinto JR, Eisenlohr PV, Lima IL, Silva GP, Simon MF (2014) Tree species distribution along environmental gradients in an area affected by a hydroelectric dam in Southern Amazonia. Biotropica 46:367–376

Mouillot D, Graham NAJ, Villéger S, Mason NWH, Bellwood DR (2013) A functional approach reveals community responses to disturbances. Trends in Ecology and Evolution 28:167–177

Norberg UM, Rayner JM (1987) Ecological morphology and flight in bats (Mammalia; Chiroptera): wing adaptations, flight performance, foraging strategy and echolocation. Philosophical Trans Royal Soc Lond B Biol Sci 316:335–427

Palmeirim AF, Vinícius M, Peres CA (2017) Non-random lizard extinctions in land-bridge Amazonian forest islands after 28 years of isolation. Biol Conserv 214:55–65

Pavoine S (2020) adiv: analysis of diversity. R package version 2.0.1

Pereira LGA, Capaverde UD, Tavares VC, Magnusson WE, Bobrowiec PED, Baccaro FB (2019) From a bat's perspective, protected riparian areas should be wider than defined by Brazilian laws. J Environ Manage 232:37–44

Pereira MJR, Fonseca C, Aguiar LMS (2018) Loss of multiple dimensions of bat diversity under land-use intensification in the Brazilian cerrado. Hystrix 29:25–32

Pereira MJR, Marques JT, Palmeirim JM (2010) Ecological responses of frugivorous bats to seasonal fluctuation in fruit availability in Amazonian forests. Biotropica 42:680–687

Pereira MJR, Marques T, Santana J, Santos CD, Valsecchi J, Queiroz HL, Beja P, Palmeirim JM (2009) Structuring of Amazonian bat assemblages: the roles of flooding patterns and floodwater nutrient load. J Anim Ecol 78:1163–1171

R Core Team (2020) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Ricotta C, de Bello F, Moretti M, Caccianiga M, Cerabolini BEL, Pavoine S (2016) Measuring the functional redundancy of biological communities: a quantitative guide. Methods Ecol Evol 7:1386–1395

Rocha R, López-Baucells A, Farneda FZ, Groenenberg M, Bobrowiec PED, Cabeza M, Palmeirim JM, Meyer CFJ (2017) Consequences of a large-scale fragmentation experiment for Neotropical bats: disentangling the relative importance of local and landscape-scale effects. Landscape Ecol 32:31–45

Russo D, Salinas-Ramos VB, Cistrone L, Smeraldo S, Bosso L, Ancillotto L (2021) Do we need to use bats as bioindicators? Biology 10:693

Sancha NU, Maestri R, Bovendorp RS, Higgins CL (2020) Disentangling drivers of small mammal diversity in a highly fragmented forest system. Biotropica 52:182–195

Santos EA, Medeiros MB, Ferreira EJL, Simon MF, Oliveira WL, Costa FRC (2020) Palm distribution patterns in the southwestern Brazilian Amazon: impact of a large hydroelectric dam. For Ecol Manag 463:118032

Schöngart J, Wittmann F, Resende AF, Assahira C, Lobo GS, Neves JRD, Rocha M, Mori GB, Quaresma AC, Demarchi LO, Albuquerque BW, FeitosaYO, Costa GS, Feitoza GV, Durgante FM, Lopes A, Trumbore SE, Silva TSF, ter Steege H, Val AL, Junk WJ, Piedade MTF (2021) The shadow of the Balbina dam: a synthesis of over 35 years of downstream impacts on floodplain forests in Central Amazonia. Aquatic Conservation: Marine and Freshwater Ecosystems 2021:1–19

Sikes RS, Gannon WL (2011) Guidelines of the American Society of Mammalogists for the use of wild mammals in research. J Mammal 92:235–253

Sombroek W (2001) Spatial and temporal patterns of Amazon rainfall. AMBIO: A Journal of the Human Environment 30:388–396

Souza JLP, Fernandes IO (2021) Do spatial and temporal scales affect the efficiency of surrogates in ant monitoring on the hydroelectric power-plant area in Brazilian. Amazon? Ecol Indic 121:107158

Spasojevic MJ, Catano CP, LaManna JA, Myers JA (2018) Integrating species traits into species pools. Ecology 99:1265–1276

Stegmann LF, Leitão RP, Zuanon J, Magnusson WE (2019) Distance to large rivers affects fish diversity patterns in highly dynamic streams of Central Amazonia. PLoS ONE 14:e0223880

Tavares VDC (2013) Phyllostomid bat wings from Atlantic Forest bat ensembles: an ecomorphological study. Chiropt Neotropical 19:57–70

Villéger S, Mason NW, Mouillot D (2008) New multidimensional functional diversity indices for a multifaceted framework in functional ecology. Ecology 89:2290–2301

Violle C, Navas M-L, Vile D, Kazakou E, Fortunel C, Hummel I, Garnier E (2007) Let the concept of trait be functional! Oikos 116:882–892

Weiss KCB, Ray CA (2019) Unifying functional trait approaches to understand the assemblage of ecological communities: synthesizing taxonomic divides. Ecography 42:2012–2020

Winemiller KO, McIntyre PB, Castello L, Fluet-Chouinard E, Giarrizzo T, Nam S et al (2016) Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science 351:128–129

Zarfl C, Lumsdon AE, Berlekamp J, Tydecks L, Tockner K (2015) A global boom in hydropower dam construction. Aquat Sci 77:161–170

Zhao Y, Dunn RR, Zhou H, Si X, Ding P (2020) Island area, not isolation, drives taxonomic, phylogenetic and functional diversity of ants on land-bridge islands. J Biogeogr 47:1627–1637

Zortéa M, de Souza Gomes K, Tomaz LAG, Palmeirim JM, Lima-Ribeiro MS (2021) Impacts of a hydroelectric power plant on the bat community in central Brazil. Mammal Res 66:509–518

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