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ORIGINAL ARTICLE

Impacts of a large hydroelectric dam on the Madeira River (Brazil) on floodplain avifauna

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ABSTRACT

Hydroelectric dams represent an important threat to seasonally flooded environments in the Amazon basin. We aimed to evaluate how a dam in the Madeira River, one of the largest tributaries of the Amazonas River, affected floodplain avifauna. Bird occurrence was recorded through simultaneous passive acoustic monitoring in early successional vegetation and floodplain forest downstream from the dam and upstream in sites impacted by permanent flooding after dam reservoir filling. Species were identified through manual inspection and semi-automated classification of the recordings. To assess the similarity in vegetation between downstream and upstream sites, we used Landsat TM/ETM+ composite images from before (2009-2011) and after (2016-2018) reservoir filling. Downstream and upstream floodplain forest sites were similar before, but not after dam construction. Early successional vegetation sites were already different before dam construction. We recorded 195 bird species. While species richness did not differ between upstream and downstream sites, species composition differed significantly. Ten species were indicators of early successional vegetation upstream, and four downstream. Ten species were indicators of floodplain forest upstream, and 31 downstream. Seven of 24 floodplain specialist species were detected by the semi-automated classification only upstream. While we found some bird species characteristic of early successional vegetation in the upstream sites, we did not find most species characteristic of tall floodplain forest. Predominantly carnivorous, insectivorous, and nectarivorous species appear to have been replaced by generalist and widely distributed species.

KEYWORDS: Amazon; ecoacoustics; indicator species; passive acoustic monitoring

Impacto de uma grande usina hidroelétrica sobre a avifauna de várzea do Rio Madeira (Brasil)

RESUMO

Barragens hidroelétricas representam uma importante ameaça a ambientes sazonalmente alagados na Amazônia. Avaliamos como uma barragem no Rio Madeira, um dos maiores tributários do Rio Amazonas, afetou a comunidade de aves de várzea. A ocorrência de aves foi registrada através de monitoramento acústico passivo simultâneo em vegetação em estágio sucessional inicial e floresta de várzea a jusante e em áreas a montante alagadas permanentemente após a formação do reservatório. Espécies foram identificadas por inspeção manual e classificação semi-automática das gravações. Para acessar a similaridade entre a vegetação a jusante e montante, utilizamos composições de imagens Landsat TM/ETM+ de antes (2009-2011) e após (2016-2018) a formação do reservatório. Sítios de floresta de várzea foram similares antes, mas não após o reservatório. Sítios de vegetação sucessional inicial já diferiam antes do reservatório. Registramos 195 espécies de aves. A riqueza de espécies não diferiu entre os sítios a jusante e montante, mas a composição de espécies diferiu significativamente. Dez espécies foram indicadoras de vegetação sucessional inicial a montante e quatro a jusante. Dez espécies foram indicadoras de floresta de várzea a montante e 31 a jusante. Sete de 24 espécies especialistas de várzea foram detectadas apenas a montante pelas classificações semi-automáticas. Encontramos algumas espécies típicas de vegetação sucessional inicial a montante, porém não encontramos a maioria de espécies típicas the floresta alta de várzea. Predominantemente, aves carnívoras, insetívoras e nectarívoras aparentam ter sido substituídas por espécies generalistas e amplamente distribuídas.

PALAVRAS-CHAVE: Amazônia; ecoacústica; espécies indicadoras; monitoramento acústico passivo

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INTRODUCTION

The growing human demand for electricity has led to an unprecedented increase in both construction and planning of new hydroelectric dams in emerging economies (Zarfl *et al.* 2015), with the Amazon basin being considered a hotspot for future projects (Winemiller *et al.* 2016; Forsberg *et al.* 2017; Latrubesse *et al.* 2017; Almeida *et al.* 2019). Currently, 158 dams already exist in Amazonia (68 in Brazil), and 351 more are planned, most of them (213) in Brazil (Almeida *et al.* 2019).

The immediate and most evident impact upstream of dams is the loss of natural floodplain habitats due to permanent flooding, which causes the death of the vegetation adapted to the Amazonian flood pulse cycle (Assahira *et al.* 2017) and eliminates specific microhabitats, such as rock outcrops, rapids and sand beaches (Lees *et al.* 2016; Cochrane *et al.* 2017; Forsberg *et al.* 2017). Impacts downstream of the dams are characterized by a reduction in the concentration of fine suspended sediments and nutrients (Forsberg *et al.* 2017; Rivera *et al.* 2019) and these effects are cumulative along drainages (Latrubesse *et al.* 2017; 2020).

Amazonian seasonally flooded environments harbor unique bird communities (Remsen and Parker III 1983). Many bird species are restricted to these habitats, but little is known about their ecology and genetic and phenotypic variation along the basin (Remsen and Parker III 1983; Laranjeiras *et al.* 2019). Recent studies suggest that many unrecognized independent evolutionary lineages are present at different interfluves (Thom *et al.* 2018; 2020). The distribution limits and population sizes of these floodplain specialist species have never been estimated, which means that many species have not received an adequate threat status from IUCN and regional Red Lists (Vale *et al.* 2008; Bird *et al.* 2012). Dam construction and operation decrease habitat availability and ecological connectivity for floodplain species, and therefore can be a significant driver of local extinction and population fragmentation (Vale *et al.* 2008; Latrubesse *et al.* 2020).

We evaluated the effect of the Santo Antonio dam on the Madeira River (one of the largest tributaries of the Amazonas River) on bird communities associated with two contrasting types of floodplain habitats. To achieve this objective, we: (a) used Landsat imagery to determine similarities in vegetation between sampling sites upstream and downstream from the dam both before and after dam reservoir filling; (b) characterized bird species richness and composition at each site; and (c) identified which bird species and guilds were most impacted by permanent flooding. This study provides the first assessment of which floodplain habitat-specific bird fauna is most affected by dams in the southwestern Amazon.

MATERIAL AND METHODS

Study area

The Madeira River is the longest tributary of the Amazon River, with a total length of 3,600 km, contributing to 15% of the discharge and approximately 50% of the sediment load to the Amazon River (Goulding *et al.* 2003). The Madeira River basin covers 1,400,000 km^2, which corresponds to 23% of the Amazon basin (Rivera *et al.* 2019). Average rainfall throughout the basin ranges from 2,000 to 2,500 mm, with a rainy season between December and April and the downstream flood peak between March and April (Rivera *et al.* 2021). The amplitude of the flood pulse in this region varies, on average, from 10.8 to 12.4 m between the lowest and the highest water levels (Goulding *et al.* 2003).

During the low water season, the exposed river banks are colonized by early successional vegetation composed of grasses, such as *Echinochloa* spp. and patches of *Gynerium sagittatum*. In the higher intermediate zone, trees and shrubs adapted to prolonged flooding predominate, such as *Tessaria integrifolia*, *Cecropia* sp., *Inga* sp., and *Muntingia calabura*. In the highest areas, which are flooded for a shorter period, the vegetation is tall floodplain forest that has a higher diversity of plant species, a well-developed understory and a canopy height of ca. 15-20 m, including emergent trees of up to 25-30 m (Perigolo *et al.* 2017).

Two large hydroelectric dams, Santo Antônio and Jirau, have been in operation on the Madeira River since 2012. These run-of-the-river dams employ a horizontal bulb turbine system that causes permanent flooding, mostly of previously seasonally flooded habitats along a large stretch of the river upstream of the dams but maintain water flow downstream (Li *et al.* 2020). The Santo Antonio dam permanently inundated an area of 271 km2 in which most of the floodplain forest trees died (Fearnside 2015; Cochrane *et al.* 2017; Li *et al.* 2020). The newly flooded areas between the Santo Antonio and Jirau dams increased by 47.2% after dam construction (Li *et al.* 2020).

Sampling design

The selection of sampling sites occurred in 2017, based on inspection of satellite images in Google Earth and subsequent inspection in the field. Selection criteria were the presence of key vegetation elements (e.g. *Cecropia* trees in early successional vegetation or presence of mature floodplain forest prior to the reservoir) and ease of access.

We sampled 19 sites, nine located upstream (90 to 105 km from the Santo Antonio dam) in the area that has been permanently flooded by the reservoir, and ten sites downstream (50 to 57 km from the dam) (Figure 1). We treated the downstream sites as control sites, as the flooding regime and vegetation cover have not changed significantly since reservoir filling (Li *et al.* 2020). We chose five upstream sampling sites in floodplain forest area on the left bank of the river where the rise of the groundwater table caused the death of most trees of species that are not adapted to the increased flooding, while still keeping more resistant vegetation, mainly shrubs, palms, and grasses (Figure 1c,e; Supplementary Material, sites

U1-U5 in Table S1, Figure S1c,d). Four upstream sites were located on a river island (Figure 1c,e), covered by vegetation that appears resistant to prolonged flooding, of which two were dominated by *Cecropia* trees (Urticaceae), and two by *Tessaria* shrubs (Asteraceae), with the understory dominated by grasses (Supplementary Material, sites U6-U9 in Table S1, Figure S1a,b). Six downstream sites were located on the left bank of the river in tall floodplain forest areas, with a well developed and diverse understory (Figure 1d,f; Supplementary Material, sites D5-D10 in Table S1, Figure S1f). Four downstream sites were also located on a river island dominated by *Cecropia* trees and mostly herbaceous plants in the understorey (Figure 1d,f; Supplementary Material, sites D1-D4 in Table S1, Figure S1e).

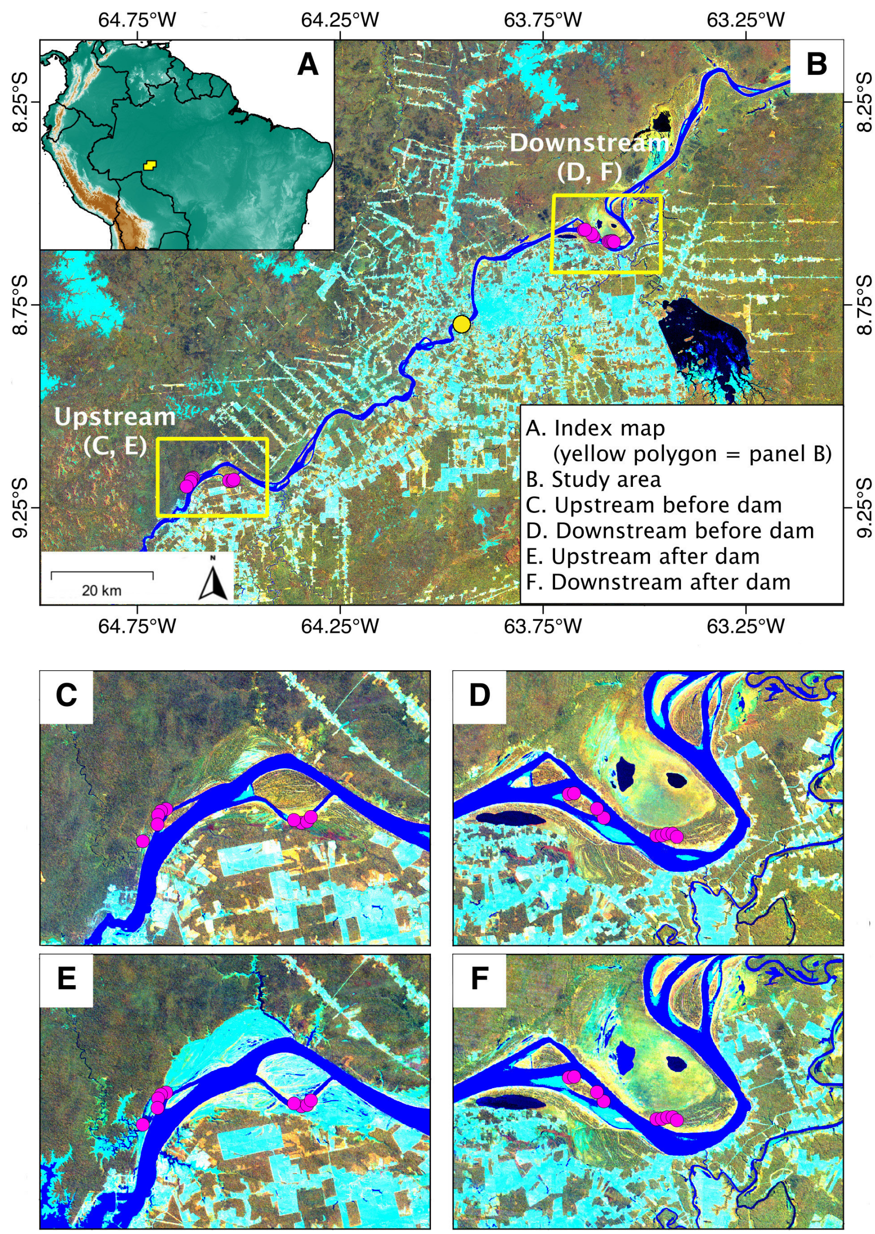

Figure 1. A – Location of the study area (yellow spot); B – Location of the Santo Antônio dam (yellow circle) and upsteam and downstream bird sampling sites (pink circles) along the upper Madeira River, Rondônia state, Brazil; B-F – Landsat TM/ETM+ composite images in background false color with bands 4, 5, and 3 assigned to the red, green, and blue color channels, respectively. Distinctions in the composite imagens before and after the dam construction and downstream and upstream of the dam are shown (C, D, E, F). Light blue color represents non-forest vegetation, including young successional vegetation along the rivers and deforested areas now under cultivation or pasture. C – Upstream sampling sites before reservoir filling; D – Downstream sampling sites before reservoir filling; E – Upstream sites after reservoir filling; F – Downstream sites after reservoir filling. This figure is in color in the electronic version.

The upstream river island is larger than the downstream island, and the latter had a taller vegetation, with a more developed understory than former (as corroborated by the presence of forest species such as *Monasa nigrifrons* and *Myrmotherula assimilis* as indicator species). Despite the heterogeneity of Amazonian river islands (Rosenberg 1990), which makes them difficult to compare, we chose sampling sites on islands because Amazonian river islands are known to harbour specialist bird species (Borges *et al.* 2019).

Habitat characterization

As standardized samplings before dam construction were not available, we used a space-for-time substitution approach to assess changes in bird communities associated with the dam construction (Blois *et al.* 2013). An essential prerequisite for this approach is that the sites representing the conditions before and after the impact are otherwise similar enough, so that current differences in bird communities can be assumed to be effects of the dam. After the bird samplings (see below), we used Landsat satellite images to assess habitat differences between the areas upstream and downstream from the dam, both before and after reservoir filling, as surface reflectance are good predictors of floristic and environmental variation in Amazonia (Higgins *et al.* 2011; Tuomisto *et al.* 2003; 2019; Van Doninck and Tuomisto 2018). We assumed that, if surface reflectance of the sites were similar before reservoir filling, the environments and their associated bird communities were also similar, as the occurrence of bird species is related to vegetation characteristics (Parker III *et al.* 1996).

We generated Landsat TM/ETM+ image composites for two 3-year periods: 2009-2011, for vegetation before dam reservoir filling, and 2016-2018, for vegetation after the start of the Santo Antônio dam operations. Each composite used all Landsat 5 and Landsat 7 images that were available for the relevant years and had less than 60% cloud cover. Directional effects were normalized following the methods described in Van Doninck and Tuomisto (2017a). Each pixel's reflectance value was selected from the available observations using the medoid method (Van Doninck and Tuomisto 2017b).

An unsupervised k-means clustering with visual assessment of the clusters was used to classify the pixels into forest, non-forest, and water classes. For numerical analyses, spectral values were extracted for a window of 15 x 15 pixels (450 m x 450 m) centered on each sampling site. For each sampling site window, the number of pixels in each of the three ground cover classes was registered together with the median reflectance value, for each ground cover class separately, of Landsat bands 2 (green), 3 (red), 4 (near-infrared), 5 (shortwave infrared 1) and 7 (shortwave infrared 2).

To estimate the spectral similarity among sites before and after reservoir filling, we summarized the reflectance data using principal component analysis (PCA; based on a correlation matrix) separately for each time period. Three separate PCA runs were done: one only with the pixels classified as forest, one only with the pixels classified as non-forest vegetation, and one with both classes combined. Pixels classified as water were excluded from all PCAs, and the differences were estimated by visual inspection of the PCA ordination. The *princomp* function of the *stats* package in R version 3.6.1 (R Core Team 2019) was used.

Bird sampling

Bird communities at all sites were sampled by autonomous recorders in four periods of 20 days each, for a total of 80 days per sampling site. The sampling periods were distributed over the four phases of the Madeira River flood pulse: September 2017 (low water level), December 2017 (rising water level), March 2018 (maximum water level), and June/July 2018 (decreasing water level). We used one recorder per site, totalizing 19 recorders. An advantage of using autonomous recorders is the standardization of sampling effort in different habitat types, avoiding the bias of easier visual detection in more open habitats (Kulaga and Budka 2019).

Each recorder consisted of a LG smartphone protected by a water-resistant case, connected to a Monoprice external condenser microphone. The recorders were programmed to record 1 minute every 10 minutes, totalizing 144 minutes of recording per day, at a sampling rate of 44.1 kHz, during the same days in all sites. Microphones had a flat response between 50 Hz to 20 kHz and a sensitivity of -45 dB ± 2 dB. The recorders were separated by a minimum distance of 400 m and placed in trees at an average height of 1.80 m above either the ground or the water surface, depending on the water level during the sampling period. A previous test using the same recorder model found that most bird species are detected up to a distance of ~100 m, so the minimum distance between sites was sufficient to guarantee sample independence (Campos-Cerqueira *et al.* 2019).

To build species lists for each site, we randomly selected three sampling days from each site and sampling period for acoustic inspection. We listened to all morning chorus recordings made between 05h40 and 09h00 and to ten randomly selected recordings from the time interval between 10h00 and 23h50, totaling 31 1-minute recordings per site and day and 93 1-minute recordings per site and sampling period, totaling 7,068 recordings. A matrix was generated containing the species recorded by minute, site, and sampling period. All species identifications were made by TNM. Congeneric species with very similar vocalizations were identified only to genus level (*Ardea* sp., *Ara* sp., *Brotogeris* sp., and *Psarocolius* sp.) and were not included in the statistical analyses. Species nomenclature followed the taxonomy by the Handbook of the Birds of the World and BirdLife International (2020). All recordings are permanently archived on the RFCx-ARBIMON platform (https://arbimon.rfcx.org/project/birds-of-madeira-flooded-habitats/dashboard).

Analysis of bird communities

We compared bird species richness between habitat type (early successional vegetation and floodplain forest) and between upstream (flooded) and downstream (control) sites with the non-parametric Wilcoxon-Mann-Whitney test. We also used the first order Jackknife estimator to estimate total species richness. Non-parametric multidimensional scaling (NMDS) ordination was used to visualize similarity patterns in bird species composition based on presence-absence data (Jaccard index). We used the permutational analysis of variance (PERMANOVA) to test the significance of the dissimilarity in species composition, as determined by the Jaccard index, comparing sites within habitat downstream and upstream. The tests were carried out using the *vegan* package in R (Oksanen *et al*. 2019).

We considered species that occur primarily or exclusively in seasonally flooded Amazonian habitats as floodplain specialists (Remsen and Parker III 1983; Parker III *et al*. 1996; Billerman *et al*. 2020). To identify which functional groups appear to be most affected by the dam, we classified species into guilds adapted from Wilman *et al*. (2014). We classified species on the basis of their degree of sensitivity to environmental disturbance (low, medium, and high) following Parker III *et al*. (1996).

To better characterize habitat use by the birds, we performed an indicator species analysis to identify which species are characteristic of each of the two habitat types (early successional vegetation and floodplain forest) upstream and downstream of the dam. This analysis calculates for each species an indicator value that varies between 0 and 1, where 0 indicates no association with a habitat and 1 indicates that the species occurs only in that habitat, in all sampled sites (Dufrêne and Legendre 1997). Species were considered statistically significant indicators when the probability of finding as high an indicator value in 10,000 random permutations was < 0.05. We used the *indval* function of the R package *labdsv* (Roberts 2019).

To analyze the occurrence of floodplain specialist species in the upstream sites, we used automated classification algorithms in the RFCx-ARBIMON platform to determine the presence or absence of 24 floodplain specialists (diurnal birds) in 93,435 audio recordings (between 05h00 to 18h00). Species-specific identification models allow the detection and analysis of target species in a large dataset and have been successfully used in several groups of organisms (Corrada-Bravo *et al*. 2017; LeBien *et al*. 2020).

All recording classifications were based on a template-matching procedure (one model per species, using the territorial song as a template). This procedure searches through audio data for acoustic signals and detects regions with a high correlation with a user's template. Regions of interest (ROIs) with values above a correlation threshold are presented as potential detections (see LeBien *et al*. 2020 for more details).

Template choice was based on a previous analysis of the most common type of vocalization present in the recordings and based on the best available recording (high signal-to-noise ratio). We selected the threshold of 0.1, which increases the number of false positives, and may capture variations in the call type. We used the score filter on all matches resulting from the automated classification to validate the results, marking only the true positives as present. The score filter groups the highest-scoring matches in descending order, optimizing the time to find true positives with manual inspection. This procedure ensured that the final dataset only included expert-verified detections, without false positives.

RESULTS

Vegetation cover before and after reservoir filling

Surface reflectance values of the Landsat data (Supplementary Material, Table S2) showed that many of the upstream sites, that were mostly or entirely forested before reservoir filling, had lost forest cover in 2016-2018 and consisted mostly of non-forest vegetation (Figure 2), as great part of the trees died and only more resistant vegetation persistted, such as palm trees, shrubs, and grasses (Supplementary Material, Figure S1). The corresponding PCA ordinations confirmed that the forests in the upstream sites were spectrally similar to the forests in the downstream sites before reservoir filling, but that spectral characteristics changed in upstream sites after filling and became clearly different from the downstream sites (Figure 2). The PCA indicated that early successional vegetation sites differed between the islands before reservoir filling, and become slightly more similar after filling (Figure 2).

Impacts on bird communities

The final data set included 16,780 detections of 195 species, and the first order Jackknife richness estimate was 220 species (Figure 3; Supplementary Material, Table S1). The number of detections at each site ranged from 456 to 1145 (mean = 883, SD = 178) (Supplementary Material, Table S3). Among all species, 66 (33.8%) were detected only downstream, 35 (17.9%) only upstream, and 30 (15.4%) were specialists that are restricted to or primarily associated with Amazonian seasonally flooded habitats (Supplementary Material, Table S1).

Species richness per site ranged from 44 to 92 (Supplementary Material, Table S3), and did not differ significantly between upstream and downstream sites for early successional vegetation (Wilcoxon's W = 4.5, p = 0.38) nor forest (Wilcoxon's W = 6.5, p = 0.14) (Figure 4a). Considering only floodplain specialists, however, species richness differed significantly for both habitat types. There were more specialist species in early successional sites upstream (Wilcoxon's W = 1, p = 0.05) and forest sites downstream (Wilcoxon's W = 29.5, p = 0.01) (Figure 4b).

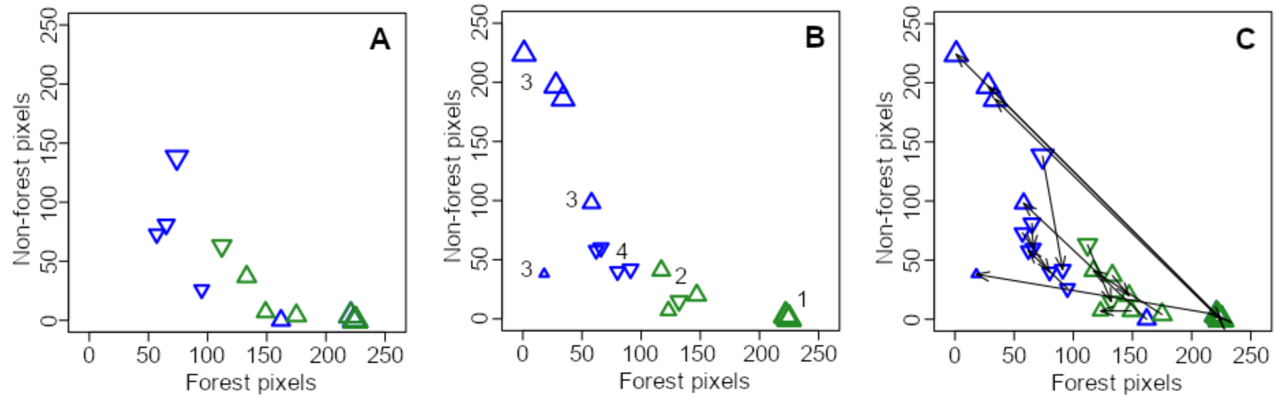

Figure 2. Scatterplots of the sampling sites downstream and upstream from the Santo Antônio dam on the Madeira River resulting from PCA showing how many pixels in a 15 by 15 pixel window centered over the sampling site in a Landsat TM/ETM+ composite image were classified as forest and how many as non-forest vegetation. A – before reservoir filling (based on surface reflectances from 2009-2011); B – after reservoir filling (2016-2018). Numbers indicate: 1- sites in floodplain forest downstream, 2 - successional vegetation downstream, 3 - drowned floodplain forest upstream, 4 - successional vegetation upstream; C – combined data (arrows indicate how individual sites have changed). Sites with > 50% forest pixels before reservoir filling are shown with upward-pointing triangles and other sites with downward-pointing triangles. Upstream sites are shown in blue, downstream sites in green. Symbol size increases according to the percentage of land pixels in the window. This figure is in color in the electronic version.

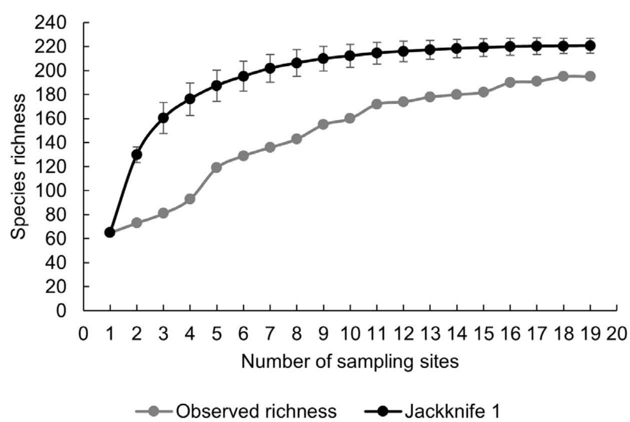

Figure 3. Species accumulation curves of observed and estimated (first order Jackknife estimator) species richness for floodplain avifauna sampled at 19 sites along the upper Madeira River.

Early successional sites did not differ significantly in the proportion of species per trophic guild, except for invertebrate generalists, which contained more upstream species (Wilcoxon's W = 1, $p = 0.05$) (Figure 5g). Downstream forest sites had about twice as many carnivore (Wilcoxon's W = 26, $p = 0.05$) and nectarivore (Wilcoxon's W = 29.5, $p < 0.01$) species than upstream forest sites (Figure 5a and f). In turn, upstream forest sites had more open habitat species, such as piscivores (Wilcoxon's W = 0, $p < 0.01$), invertebrate generalists (Wilcoxon's W = 1.5, $p = 0.01$), and granivores (Wilcoxon's W = 6, $p = 0.05$) (Figure 5e, g,h; Supplementary Material, Table S4).

More than 60 species, mostly insectivore passerine birds with medium and high sensitivity to habitat disturbance, were only detected downstream. In contrast, more than half of all species detected upstream have low sensitivity (Supplementary Material,

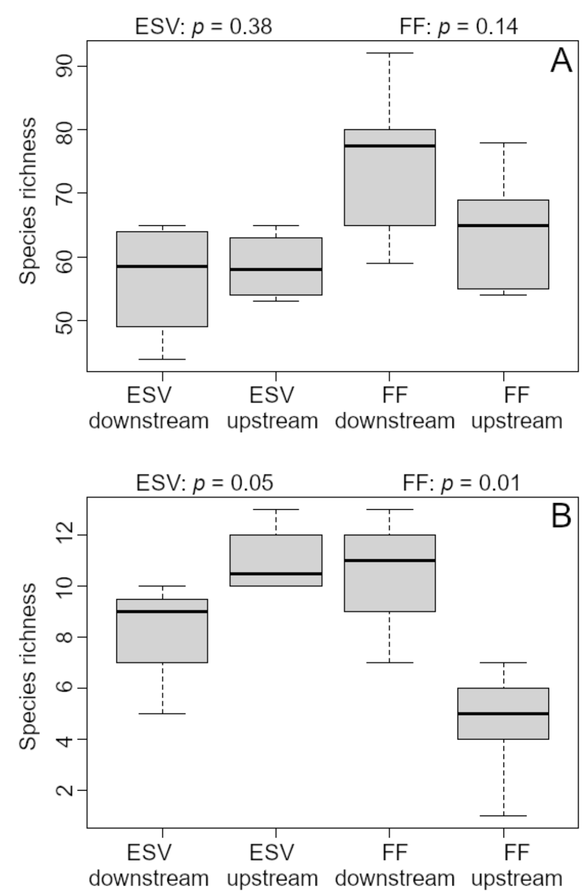

Figure 4. Species richness for all bird species (A), and floodplain specialists (B) in floodplain forest (FF) and early successional vegetation (ESV) sampling sites upstream and downstream from Santo Antônio dam on the Madeira River. The significance level of the Wilcoxon-Mann-Whitney test is shown. Lines are the average, boxes the standard deviation and bars the range.

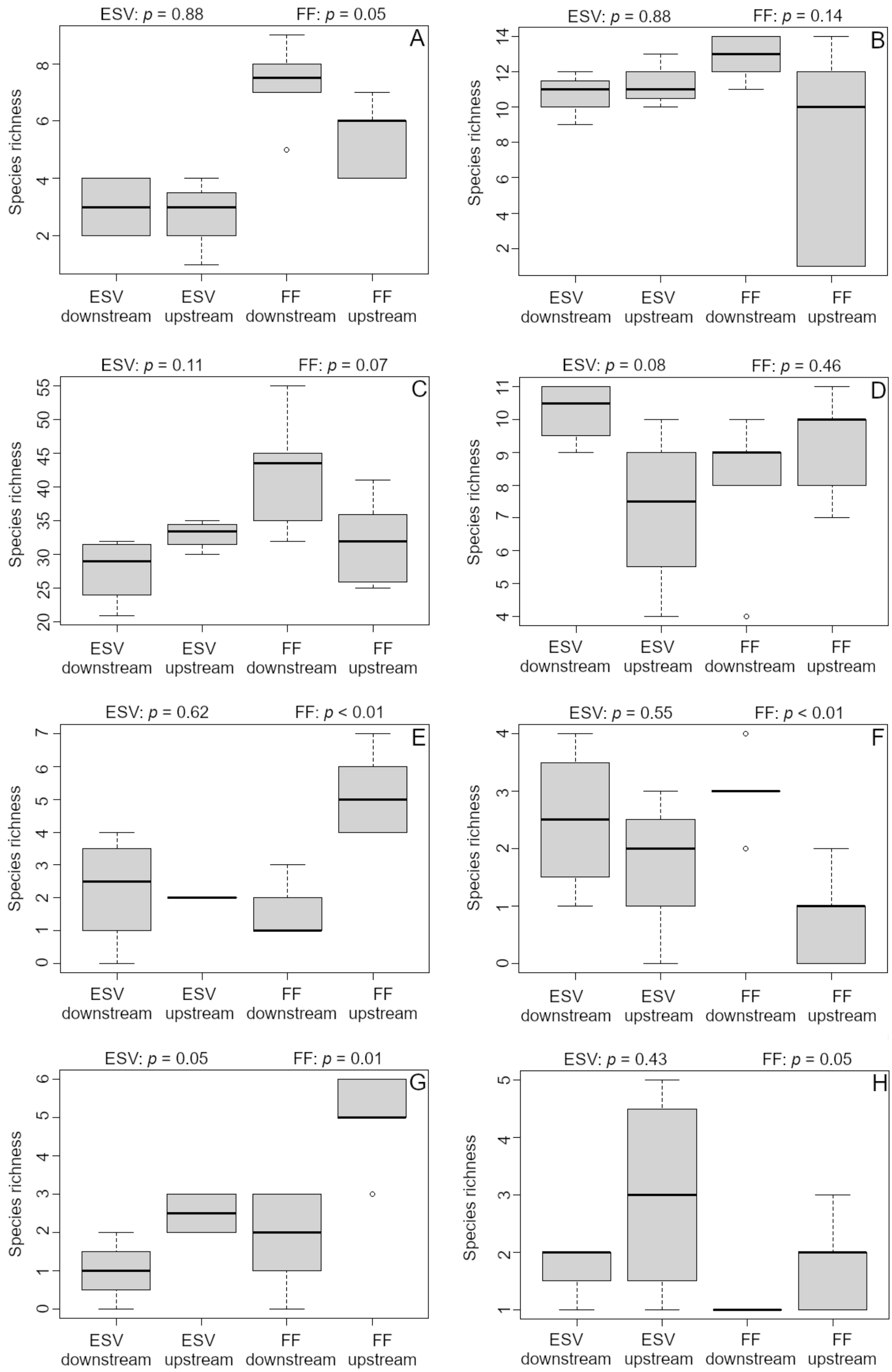

Figure 5. Species richness of different bird trophic guilds in floodplain forest (FF) and early successional vegetation (ESV) sampling sites upstream and downstream from Santo Antônio dam on the Madeira River. A – carnivores; B – frugivores; C – insectivores; D – omnivores; E – piscivores; F – nectarivores; G – invertebrate generalists; H – gramnivores. The significance level of the Wilcoxon-Mann-Whitney test is shown. Lines are the average, boxes the standard deviation and bars the range.

Table S3). Downstream forest sites had significantly more species with high (Wilcoxon's W = 30, $p < 0.01$) and medium sensitivity to impacts (Wilcoxon's W = 30, $p < 0.01$) (Figure 6b,c) than upstream forest sites, which had more species with low sensitivity (Wilcoxon's W = 0, $p < 0.01$) (Figure 6a). In addition, the downstream early successional sites also had more species with high sensitivity than the upstream sites (Wilcoxon's W = 16, $p < 0.05$).

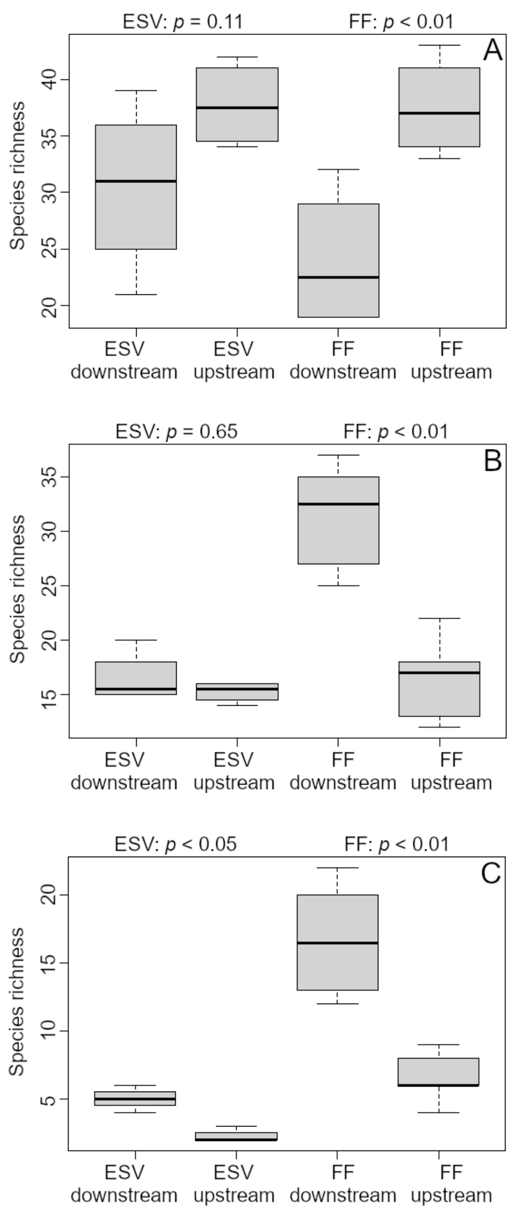

Figure 6. Species richness of birds in different levels of sensitivity to environmental disturbance in floodplain forest (FF) and early successional vegetation (ESV) sampling sites upstream and downstream from Santo Antônio dam on the Madeira River. A – low; B – medium; C – high sensitivity. The significance level of the Wilcoxon-Mann-Whitney test is shown. Lines are the average, boxes the standard deviation and bars the range.

Species composition differed significantly between upstream and downstream forest sites (PERMANOVA, pseudo-F = 5.05, r^2 = 0.45, $p < 0.05$) (Figure 7a), and between upstream and downstream early successional sites (PERMANOVA, pseudo-F = 5.05, r^2 = 0.35, $p < 0.01$) (Figure 7b). The differences between upstream and downstream sites in composition were also significant when considering only specialist species in forest (PERMANOVA, pseudo-F = 5.25, r^2 = 0.37, $p < 0.01$) and early successional vegetation (PERMANOVA, pseudo-F = 8.54, r^2 = 0.59, $p < 0.05$) (Figure 7d). The avifauna in the dead floodplain forest was composed of widely distributed open area generalist and aquatic species with low sensitivity to habitat disturbance such as *Volatinia jacarina*, *Donacobius atricapilla*, and *Jacana jacana*. More tolerant floodplain specialists, such as *Synallaxis gujanensis* and *Cantorchilus leucotis*, were also recorded in these sites, although they had more detections in upstream early successional sites (Figure 5; Table 1).

The indicator species analysis identified 54 species, of which 11 were floodplain specialists. Thirty-one species were indicators of floodplain forest downstream, 10 of floodplain forest upstream, four of early successional vegetation downstream, and 10 of early successional vegetation upstream (Table 1).

Semi-automated classification models for 24 floodplain specialist birds yielded 7,414 positive detections (Supplementary Material, Table S5) after approximately 34 h of manual validation. Five species had considerably more detections, and 11 were detected on more sites on manual inspection. Seven floodplain specialists were detected only in upstream sites, ten only in downstream sites, and eight in both. *Myrmochanes hemileucus*, *Mazaria propinqua*, *Cranioleuca vulpecula*, *Elaenia pelzelni*, *Furnarius minor*, *Stigmatura napensis*, and *Cantorchilus leucotis* were detected only upstream. However, in the manual inspection, *C. leucotis* was also detected downstream.

DISCUSSION

As the Landsat data suggested that vegetation cover of all forest sites was similar before dam filling, similar bird communities would be expected in all sites. Accordingly, all forest species that we recorded downstream, except *Sakesphorus luctuosus*, were recorded upstream of the dam before the reservoir filling (Sábato *et al.* 2014; Supplementary Material, Table S2). The early successional sites, however, already differed downstream and upstream before reservoir filling. Thus, the differences observed in the bird communities on the island sites can also be related to other factors than the dam impact, such as the differences in size, successional stage of the vegetation or the formation history of the islands (Borges *et al.* 2019). These results reinforce that the occurrence of bird species in floodplains can be conditioned by differences among islands or vegetation size (Rosenberg 1990).

Table 1. Indicator value (IndVal) for each indicator species by habitat type in the upper Madeira River floodplain in southwestern Amazonia. FS = Species restricted or that occur primarily in Amazonian floodplain habitats (Remsen and Parker 1983; Parker III *et al*. 1996; Billerman *et al*. 2020). ** P < 0.01, * P < 0.05. Numbers in parentheses are the number of detections.

Family	Species	Early successional vegetation		Floodplain forest	
		Upstream	Downstream	Upstream	Downstream
Galbulidae	*Galbula ruficauda*	1.0** (32)	--	--	--
Furnariidae	*Mazaria propingua* (FS)	1.0** (384)	--	--	--
Furnariidae	*Xenops minutus*	--	--	--	1.0** (14)
Thamnophilidae	*Myrmochanes hemileucus* (FS)	1.0** (297)	--	--	--
Thamnophilidae	*Isleria hauxwelii*	--	--	--	1.0** (81)
Thamnophilidae	*Thamnophilus schistaceus*	--	--	--	1.0** (114)
Tyrannidae	*Knipolegus orenocensis* (FS)	1.0** (57)	--	--	--
Tyrannidae	*Elaenia pelzelni* (FS)	1.0** (22)	--	--	--
Tyrannidae	*Lathrotriccus euleri*	--	--	--	1.0** (174)
Trochilidae	*Amazilia cyanus*	--	--	--	0.83** (20)
Dendrocolaptidae	*Dendrocincla fuliginosa*	--	--	--	0.83** (61)
Dendrocolaptidae	*Dendrocolaptes certhia*	--	--	--	0.83** (37)
Dendrocolaptidae	*Dendrocolaptes picumnus*	--	--	--	0.83** (14)
Thamnophilidae	*Hypocnemis peruviana*	--	--	(11)	0.83** (517)
Thamnophilidae	*Epinecrophylla amazonica*	--	--	--	0.83** (26)
Tyrannidae	*Attila spadiceus*	--	--	--	0.83** (44)
Polioptilidae	*Ramphocaenus melanurus*	--	--	--	0.83** (48)
Trogonidae	*Trogon viridis*	--	(4)	--	0.80** (20)
Thamnophilidae	*Myrmoborus leucophrys* (FS)	--	(3)	--	0.80** (184)
Eurypygidae	*Eurypyga helias*	--	--	0.80** (18)	--
Jacanidae	*Jacana jacana*	(3)	--	0.80** (240)	--
Alcedinidae	*Chloroceryle amazona*	(1)	--	0.80** (35)	--
Donacobiidae	*Donacobius atricapilla*	--	--	0.80** (75)	--
Thraupidae	*Volatinia jacarina*	--	--	0.80** (62)	--
Furnariidae	*Cranioleuca vulpecula* (FS)	0.75** (97)	--	--	--
Tyrannidae	*Stigmatura napensis* (FS)	0.75** (45)	--	--	--
Tyrannidae	*Myiozetetes similis*	0.71** (218)	--	(3)	--
Tinamidae	*Tinamus major*	--	--	--	0.66** (13)
Caprimulgidae	*Nyctidromus albicollis*	(3)	--	0.66** (14)	--
Accipitridae	*Spizaetus tyrannus*	--	--	--	0.66** (9)
Tyrannidae	*Tyrannulus elatus*	--	--	0.66** (6)	(2)
Rhynchocyclidae	*Todirostrum chrysocrotaphum*	--	--	--	0.66** (43)
Thraupidae	*Eucometis penicillata*	--	--	--	0.66** (9)
Trogonidae	*Trogon melanurus*	--	--	--	0.64* (23)
Rhynchocyclidae	*Hemitriccus minor* (FS)	--	--	--	0.64** (90)
Dendrocolaptidae	*Sittasomus griseicapillus*	--	--	--	0.62** (41)
Ardeidae	*Butorides striata*	--	--	0.60* (16)	--
Rallidae	*Porphyrio flavirostris*	--	--	0.60* (5)	--
Ramphastidae	*Ramphastos vitellinus*	--	--	--	0.60** (85)
Picidae	*Celeus flavus* (FS)	--	--	--	0.58** (30)
Trochilidae	*Glaucis hirsutus*	--	--	--	0.57** (88)
Thraupidae	*Nemosia pileata*	--	0.56* (24)	--	--
Rallidae	*Laterallus exilis*	0.55* (41)	--	--	--
Dendrocolaptidae	*Xiphorhynchus guttatoides*	--	--	--	0.55** (215)
Cuculidae	*Piaya cayana*	--	--	--	0.52* (22)
Thamnophilidae	*Phlegopsis nigromaculata*	--	--	--	0.50* (3)
Thamnophilidae	*Myrmotherula axillaris*	--	--	--	0.50* (7)
Tyrannidae	*Philohydor lictor*	0.50* (20)	--	0.50* (23)	--
Pipridae	*Pipra fasciicauda* (FS)	--	--	--	0.50* (158)

Table 1. Continued

Family	Species	Early successional vegetation		Floodplain forest	
		Upstream	Downstream	Upstream	Downstream
Rhynchocyclidae	*Myiornis ecaudatus*	--	--	--	0.46* (62)
Thamnophilidae	*Myrmotherula brachyura*	--	0.45* (20)	--	--
Bucconidae	*Monasa nigrifrons* (FS)	--	0.44* (36)	--	--
Ramphastidae	*Pteroglossus castanotis*	--	0.41** (37)	--	--
Picidae	*Campephilus melanoleucus*	--	--	--	0.35* (22)

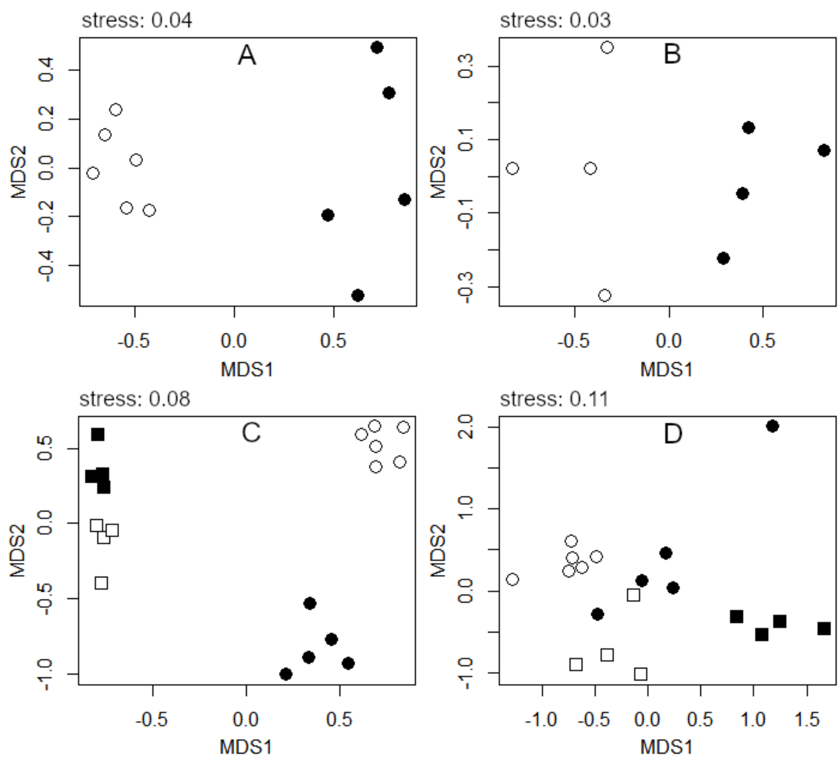

Figure 7. NMDS ordination of bird species composition based on presence/absence data for floodplain forest (A), early successional vegetation (B), all sites combined (C), and only floodplain specialist species (D) upstream and downstream from Santo Antônio dam on the Madeira River. White symbols = downstream sites, black symbols = upstream sites, circles = floodplain forest, squares = early successional vegetation.

A significant result from a conservation perspective was the presence of several specialist species at the early successional vegetation sites on the upstream island. Considering the generally small area of river islands across the Amazon basin, species restricted to these habitats are potentially the most threatened by dam impacts (Borges *et al.* 2019). Even five years after Santo Antonio began operations, these highly specialized species continued to occur upstream of the dam, probably because the key plant species of this habitat type (*Tessaria integrifolia*), which is important for some floodplain bird species (Rosenberg 1990), is highly tolerant to flooding and persisted in these sites (Wittmann *et al.* 2002; 2004). Therefore, these upstream river-island habitats should be monitored in the long term to assess whether their vegetation and its associated fauna withstand the flooding regime of the dam reservoir in the future.

The impact associated with dam construction is significant for floodplain forest specialists that do not occur in the adjacent upland forest or in other kinds of floodplain habitats, such as *Myrmoborus leucophrys*, *Cranioleuca gutturata*, *Hemitriccus minor*, and *Pipra fasciicauda* (all with detections only in the downstream floodplain forest) or species that occur in forest and other advanced stage succession vegetation, like *Myrmotherula assimilis* (Billerman *et al.* 2020). Although these species were recorded in surveys after the reservoir filling (Sábato *et al.* 2014), possibly most of their suitable habitat was lost. Forest species may have ecological and behavioral limitations that prevent them from crossing large areas of open habitats (Less and Peres

2009). Also, floodplain forest species seem to avoid upland forests, maybe due to competition with related upland species (Rowedder *et al.* 2021). However, these limitations vary among species. Therefore the loss of seasonally flooded forests associated with dams can cause gaps in the distribution of these species, affecting connectivity among populations and consequently their genetic diversity (Thom *et al.* 2020).

As expected, changes in the floodplain forest also altered the functional attributes of the bird community. Models that simulate habitat loss and degradation in tropical forests suggest that the most significant loss of bird diversity is likely to affect frugivores, insectivores, and nectarivores (Newbold *et al.* 2014). We did not observe a loss in frugivorous bird diversity in dead floodplain forests, probably due to that the numerous dead trees provide nesting sites that attract parrots, macaws, and toucans to use these area as resting and breeding sites. Many studies, mostly in upland forests, show that most Amazonian insectivorous birds are dependent on forested areas and are sensitive to environmental impacts (Canaday 1996; Parker III *et al.* 1996; Stratford and Stouffer 1999; Ferraz *et al.* 2003; Haugaasen *et al.* 2003; Laurance *et al.* 2004; Stouffer *et al.* 2009; 2011). Our study showed similar results in floodplain forest.

CONCLUSIONS

The presence of several floodplain specialists at the upstream sites in early successional vegetation, but not in the forest, indicates that the impact of the dam on the bird community depends on the habitat affinity of each species. The most significant concern is the loss and degradation of floodplain forests and the local extinction of forest specialists. During the licensing process of the Santo Antônio dam, surveying and monitoring efforts usually were more concentrated on upland forests and aquatic habitats (Sábato *et al.* 2014). Since floodplain forests are distributed linearly along the river margins, these habitats are disproportionately affected by river damming, even with run-of-the-river reservoirs, as is the case with the Madeira River dams, inevitably causing degradation and loss of these biological communities, in addition to connectivity loss between upstream and downstream populations. Therefore, we recommend special attention be given in future studies to the environmental impact of Amazonian dams to these habitats. A more careful and intensive survey of the occurrence of bird species restricted to floodplain forests is necessary, as well as the long-term monitoring of species with restricted distribution, especially those considered specialists in river islands.

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SUPPLEMENTARY MATERIAL (only available in the electronic version)

Melo *et al*. Impacts of a large hydroelectric dam on the Madeira River (Brazil) on floodplain avifauna

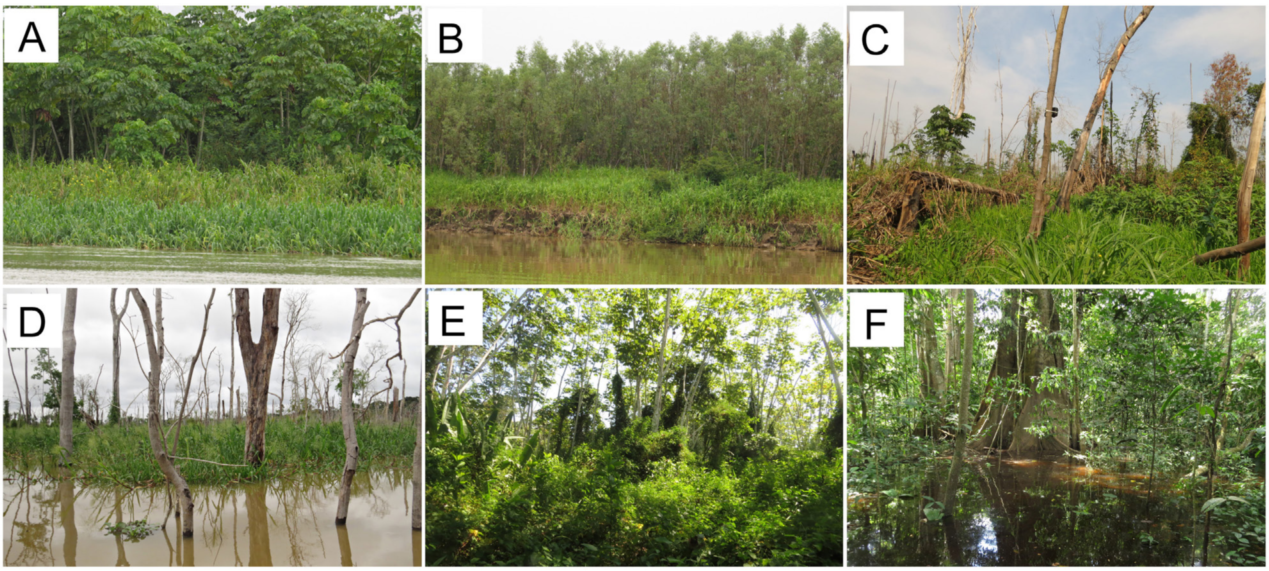

Figure S1. Sampling habitats in the upper Madeira River. Upstream (after the Santo Antônio dam reservoir filling): A – early successional vegetation dominated by *Cecropia* trees; B – early successional vegetation dominated by *Tessaria integrifolia*; C – dead floodplain forest in the dry season (September); D – dead floodplain forest in the rainy season (March). Downstream: E – early successional vegetation dominated by *Cecropia* trees; F – floodplain forest in the rainy season (March). This figure is in color in the electronic version.

Table S1. Habitat type at 19 sampling sites before reservoir filling (2009-2011) of the Santo Antônio dam on the upper Madeira River in the southwestern Brazilian Amazon, as predicted by Landsat TM/ETM+ images, and after reservoir formation (2016-2018). The number of bird species and number of detections are also shown for each site. *C. membranacea* = *Cecropia membranacea* (Urticaceae); *T. integrifolia* = *Tessaria integrifolia* (Asteraceae).

Site	Habitat prior to reservoir	Current habitat	Location	Species richness	Detections
U1	floodplain forest	dead floodplain forest	upstream	69	992
U2	floodplain forest	dead floodplain forest	upstream	54	620
U3	floodplain forest	dead floodplain forest	upstream	78	989
U4	floodplain forest	dead floodplain forest	upstream	55	934
U5	floodplain forest	dead floodplain forest	upstream	65	864
U6	early successional vegetation	early successional vegetation dominated by *C. membranacea*	upstream	55	975
U7	early successional vegetation	early successional vegetation dominated by *C. membranacea*	upstream	61	814
U8	early successional vegetation	early successional vegetation dominated by *T. integrifolia*	upstream	63	1075
U9	early successional vegetation	early successional vegetation dominated by *T. integrifolia*	upstream	53	1145
D1	early successional vegetation	early successional vegetation dominated by *C. membranacea*	downstream	65	1076
D2	early successional vegetation	early successional vegetation dominated by *C. membranacea*	downstream	44	456
D3	early successional vegetation	early successional vegetation dominated by *C. membranacea*	downstream	54	1072
D4	early successional vegetation	early successional vegetation dominated by *C. membranacea*	downstream	63	947
D5	floodplain forest	floodplain forest	downstream	80	963
D6	floodplain forest	floodplain forest	downstream	59	795
D7	floodplain forest	floodplain forest	downstream	65	676
D8	floodplain forest	floodplain forest	downstream	75	730
D9	floodplain forest	floodplain forest	downstream	92	912
D10	floodplain forest	floodplain forest	downstream	80	744

Table S2. Number of pixels in each class (forest, non-forest and water) and canopy reflectance values (Bands 2, 3, 4, 5, 7) for each sampling site before (2009-2011) and after (2016-2018) reservoir filling of the Santo Antônio dam on the upper Madeira River in the southwestern Brazilian Amazon based on Landsat TM/ETM + composite images. U1-U9 = Upstream sites; D1-D9 = Downstream sites.

	2009-2011 composite image												
	Pixel class			Reflectance values									
Site	Forest	Non-forest	Water	Band2 forest	Band2 non-forest	Band3 forest	Band3 non-forest	Band4 forest	Band4 non-forest	Band5 forest	Band5 non-forest	Band7 forest	Band7 non-forest
U1	224	0	1	428	-	278.5	-	3028	-	1388	-	490	-
U2	225	0	0	429	-	278	-	2963	-	1381	-	492	-
U3	225	0	0	445	-	296	-	2921	-	1386	-	504	-
U4	162	0	63	457.5	-	308	-	3087.5	-	1427.5	-	516	-
U5	221	4	0	438	688.5	303	581.5	3081	3319.5	1427	2235	501	1081.5
U6	65	81	79	546	1262	388	1395	3657	2602	1760	2079	736	1599
U7	74	138	13	615.5	1104	456.5	1234	3460	2475.5	1723.5	2006.5	768	1402
U8	57	73	95	612	1348	420	1461	3047	2423	1518	2090	620	1699
U9	95	26	104	537	896	330	812.5	3684	2481	1653	1785	628	1019.5
D1	133	37	55	552	871	361	815	3640	2668	1680	1965	673	989
D2	112	63	50	491	1013	324.5	974	3520.5	2448	1558.5	1850	560.5	1203
D3	175	4	46	489	779.5	316	643	3483	3252	1527	2077	580	1034
D4	149	7	69	476	721	319	603	3429	3296	1471	1889	546	852
D5	221	4	0	463	660	307	496.5	3186	3684	1451	2330.5	540	1136
D6	225	0	0	458	-	306	-	3210	-	1465	-	532	-
D7	225	0	0	463	-	301	-	3243	-	1489	-	543	-
D8	225	0	0	454	-	294	-	3188	-	1472	-	539	-
D9	225	0	0	441	-	291	-	3130	-	1435	-	531	-
	2016-2018 composite image												
U1	34	186	5	541	638	403	586	1591.5	2352.5	1400.5	2165	764.5	1226.5
U2	28	197	0	524	643	472.5	587	1679.5	2511	1305.5	2159	746	1172
U3	1	224	0	546	631	438	542	2663	2745	1803	2100	873	1099.5
U4	58	98	69	636.5	656.5	537.5	567.5	2226	2544.5	1392.5	2038	672	1074
U5	18	38	169	561	612	496.5	529.5	1383.5	2210.5	1247	2055	725.5	1089.5
U6	66	60	99	585.5	679	444	528	3190.5	3305.5	1699	2194.5	708	1049
U7	91	42	92	608	627	404	459	3745	3538	1941	2115.5	806	937.5
U8	80	40	105	710	708.5	562.5	522	3099	3422	1639	2084.5	739	929
U9	62	58	105	716.5	705.5	558	546	2879.5	3246	1635	2016.5	742	944.5
D1	147	20	58	555	724.5	356	604.5	3649	3015	1690	1948	661	895
D2	132	15	78	483	729	317	602	3475.5	3159	1536	1926	566	851
D3	117	41	67	558	1195	381	1310	3814	2545	1936	2122	790	1331
D4	123	7	95	551	692	375	545	3535	3489	1801	1959	737	891
D5	225	0	0	503	-	331	-	3433	-	1683	-	654	-
D6	222	3	0	494.5	551	335	422	3253	3174	1543	1922	586	812
D7	225	0	0	479	-	319	-	3217	-	1478	-	548	-
D8	223	2	0	463	559.5	303	413.5	3160	3077.5	1502	1883	564	828
D9	225	0	0	458	-	301	-	3116	-	1514	-	571	-

Table S3. Number of detections (and number of sampling sites where the species was detected) of all bird species recorded in the manual inspection of the recordings by habitat type upstream and downstream of the Santo Antônio dam on the upper Madeira River, Rondônia, Brazil. Values after the vegetation type indicate number of sampling sites. FS = species restricted or that occurs primarily in floodplain habitats in Amazonia according to Remsen and Parker III (1983), Parker III *et al.* (1996) and Billerman *et al.* (2020). Asterisks (*) indicate species that were previously recorded upstream from the Santo Antônio dam (Sábato *et al.* 2014). Sensitivity to habitat disturbance follows Parker III *et al.* (1996). Trophic guild adapted from Wilman *et al.* (2014): CAR = carnivore, FRU = frugivore, INS = insectivore, INV = invertebrate generalist, NEC = nectarivore, OMN = omnivore, PIS = piscivore. Species nomenclature follows the BirdLife International's taxonomy (Handbook of the Birds of the World and BirdLife International 2020).

			Downstream sites		Upstream sites	
Species	**Sensitivity**	**Guild**	Floodplain forest (6)	Early successional vegetation (4)	(Dead) floodplain forest (5)	Early successional vegetation (4)
Tinamidae						
*Tinamus major**	Medium	OMN	13 (4)	0	0	0
*Crypturellus cinereus**	Low	FRU	2 (2)	0	0	0
*Crypturellus undulatus**	Low	FRU	307 (6)	7 (2)	0	36 (4)
*Crypturellus parvirostris**	Low	GRA	0	0	0	1
Anatidae						
*Dendrocygna autumnalis**	Low	GRA	0	0	0	35 (4)
Cracidae						
*Aburria cumanensis**	High	FRU	0	0	1 (1)	2 (1)
*Ortalis guttata**	Low	FRU	31 (5)	0	1 (1)	2 (2)
Ardeidae						
*Tigrisoma lineatum**	Medium	PIS	0	2 (1)	0	0
*Butorides striata**	Low	PIS	0	0	16 (3)	0
Ardea sp.*	Low	PIS	0	2 (1)	69 (5)	0
*Egretta thula**	Low	PIS	0	0	8 (1)	1 (1)
Threskiornithidae						
*Mesembrinibis cayennensis**	Medium	INV	3 (3)	3 (1)	1 (1)	0
Pandionidae						
*Pandion haliaetus**	Medium	PIS	0	1 (1)	4 (3)	0
Accipitridae						
*Leptodon cayanensis**	Medium	CAR	5 (3)	0	1 (1)	1 (1)
*Elanoides forficatus**	Medium	INS	0	1 (1)	0	0
*Harpagus bidentatus**	Medium	CAR	1 (1)	0	0	0
*Ictinia plumbea**	Medium	INS	1 (1)	0	0	0
*Busarellus nigricollis**	Low	PIS	0	0	1 (1)	1 (1)
Helicolestes hamatus (FS)*	Medium	INV	4 (4)	4 (2)	4 (2)	1 (1)
Buteogallus schistaceus (FS)*	High	CAR	6 (1)	1 (1)	0	0
*Buteogallus urubitinga**	Medium	CAR	2 (2)	0	1 (1)	0
*Rupornis magnirostris**	Low	CAR	5 (4)	43 (3)	48 (5)	18 (4)
*Leucopternis kuhli**	High	CAR	3 (1)	0	0	0
*Buteo nitidus**	Medium	CAR	1 (1)	0	8 (2)	0
*Buteo brachyurus**	Medium	CAR	5 (1)	1 (1)	0	0
*Spizaetus tyrannus**	Medium	CAR	9 (4)	0	0	0
Eurypygidae						
*Eurypyga helias**	Medium	INV	0	0	18 (2)	0
Aramidae						
*Aramus guarauna**	Medium	INV	2 (2)	1 (1)	0	1 (1)
Rallidae						
*Aramides cajanea**	High	OMN	1 (1)	0	0	1 (1)
*Laterallus exilis**	Low	INV	0	0	53 (4)	41 (4)
*Porzana albicollis**	Medium	INV	0	0	2 (1)	0
Porphyrio flavirostris	Medium	OMN	0	0	5 (3)	0
Charadriidae						
*Vanellus chilensis**	Low	INV	0	1 (1)	18 (4)	40 (4)

Table S3. Continued

Species	Sensitivity	Guild	Downstream sites		Upstream sites	
			Floodplain forest (6)	Early successional vegetation (4)	(Dead) floodplain forest (5)	Early successional vegetation (4)
Jacanidae						
*Jacana jacana**	Low	INV	0	0	240 (5)	3 (1)
Sternidae						
*Phaetusa simplex**	High	PIS	0	19 (3)	42 (4)	7 (2)
Columbidae						
*Patagioenas cayennensis**	Medium	FRU	1 (1)	1 (1)	0	0
*Leptotila rufaxilla**	Medium	GRA	63 (6)	52 (4)	2 (1)	29 (3)
Cuculidae						
*Coccycua minuta**	Low	INS	15 (3)	19 (4)	13 (2)	8 (3)
*Piaya cayana**	Low	INS	22 (5)	1 (1)	0	1 (1)
*Crotophaga major**	Medium	INS	13 (5)	32 (4)	12 (3)	24 (4)
*Crotophaga ani**	Low	INS	0	1 (1)	157 (5)	29 (4)
Strigidae						
*Megascops choliba**	Low	INS	0	0	7 (1)	2 (2)
*Megascops watsonii**	High	INS	2 (1)	0	0	0
*Lophostrix cristata**	High	CAR	6 (2)	0	0	0
*Pulsatrix perspicillata**	Medium	CAR	6 (1)	0	0	0
Strix sp.*	-	CAR	27 (3)	0	0	0
*Glaucidium hardyi**	High	CAR	5 (2)	0	0	0
*Glaucidium brasilianum**	Low	CAR	13 (4)	2 (2)	0	0
Nyctibiidae						
*Nyctibius grandis**	Medium	INS	9 (4)	4 (1)	3 (2)	0
*Nyctibius griseus**	Low	INS	0	0	0	3 (1)
Caprimulgidae						
*Nyctidromus albicollis**	Low	INS	0	0	14 (5)	3 (2)
*Caprimulgus parvulus**	Low	INS	0	0	2 (2)	1 (1)
Apodidae						
*Chaetura viridipennis**	Medium	INS	1 (1)	0	15 (3)	0
*Chaetura brachyura**	Low	INS	4 (2)	2 (1)	44 (3)	1 (1)
Trochilidae						
*Glaucis hirsutus**	Low	NEC	88 (6)	4 (3)	0	0
Phaethornis hispidus (FS)*	Medium	NEC	175 (6)	36 (4)	10 (2)	24 (3)
Polytmus theresiae	Low	NEC	1 (1)	0	2 (1)	3 (2)
*Amazilia cyanus**	Medium	NEC	20 (5)	0	0	0
*Amazilia fimbriata**	Low	NEC	0	1 (1)	1 (1)	6 (2)
Trogonidae						
*Trogon melanurus**	Medium	OMN	23 (5)	1 (1)	0	0
*Trogon viridis**	Medium	OMN	20 (6)	4 (1)	0	0
Alcedinidae						
*Megaceryle torquata**	Low	PIS	18 (6)	66 (3)	25 (5)	15 (4)
*Chloroceryle amazona**	Low	PIS	0	0	35 (5)	1 (1)
*Chloroceryle aenea**	Medium	PIS	5 (2)	0	0	0
*Chlorceryle inda**	Medium	PIS	1 (1)	0	0	0
Galbulidae						
*Galbula ruficauda**	Low	INS	0	0	0	32 (4)
*Galbula cyanescens**	Low	INS	7 (1)	0	13 (2)	0
*Galbula dea**	Medium	INS	6 (2)	0	0	0
*Jacamerops aureus**	High	INS	1 (1)	0	0	0

Table S3. Continued

Species	Sensitivity	Guild	Downstream sites		Upstream sites	
			Floodplain forest (6)	Early successional vegetation (4)	(Dead) floodplain forest (5)	Early successional vegetation (4)
Bucconidae						
Bucco tamatia (FS)*	Medium	INS	5 (3)	0	1 (1)	0
Monasa nigrifrons (FS)*	Medium	INS	10 (4)	36 (4)	3 (3)	0
Capitonidae						
*Capito auratus**	Medium	OMN	2 (1)	0	0	0
Ramphastidae						
*Ramphastos tucanus**	High	OMN	197 (6)	6 (3)	20 (4)	0
*Ramphastos vitellinus**	High	OMN	85 (6)	1 (1)	2 (2)	0
*Pteroglossus castanotis**	High	OMN	43 (5)	37 (4)	6 (3)	0
Picidae						
*Picumnus aurifrons**	Medium	INS	1 (1)	1 (1)	0	8 (3)
*Melanerpes cruentatus**	Low	OMN	91 (5)	6 (2)	4 (2)	0
*Venilionis passerinus**	Low	INS	0	4 (2)	3 (1)	1 (1)
*Colaptes punctigula**	Low	INS	4 (2)	18 (3)	47 (5)	7 (3)
*Celeus grammicus**	High	OMN	1 (1)	0	0	0
Celeus flavus (FS)*	Medium	OMN	30 (6)	4 (2)	0	0
*Dryocopus lineatus**	Low	INS	6 (4)	2 (2)	54 (5)	7 (3)
*Campephilus melanoleucus**	Medium	INS	22 (6)	8 (3)	8 (4)	5 (2)
Falconidae						
*Daptrius ater**	Low	CAR	1 (1)	0	0	0
*Ibycter americanus**	High	INV	8 (4)	1 (1)	10 (4)	0
*Milvago chimachima**	Low	CAR	0	5 (3)	2 (2)	1 (1)
*Herpetotheres cachinnans**	Low	CAR	8 (4)	0	9 (4)	0
*Falco rufigularis**	Low	CAR	7 (3)	0	21 (4)	2 (2)
Psittacidae						
Ara sp.*	Medium/High	FRU	46 (6)	39 (4)	69 (5)	22 (4)
*Ara severus**	Medium	FRU	72 (6)	106 (4)	57 (5)	75 (4)
*Orthopsittaca manilatus**	Medium	FRU	0	1 (1)	43 (4)	13 (2)
*Psittacara leucophthamus**	Low	FRU	4 (2)	2 (1)	6 (2)	2 (2)
*Aratinga weddellii**	Low	FRU	26 (6)	146 (4)	136 (5)	59 (4)
*Pyrrhura snethlaegae**	High	FRU	4 (2)	0	0	0
Brotogeris sp.*	-	FRU	3 (2)	123 (4)	67 (5)	2 (2)
*Pionites leucogaster**	High	FRU	0	1 (1)	21 (3)	1 (1)
*Pionus mestruus**	Low	FRU	22 (6)	29 (4)	6 (3)	1 (1)
*Amazona farinosa**	Medium	FRU	93 (6)	15 (3)	139 (5)	14 (4)
*Amazona ochrocephala**	Medium	FRU	21 (5)	128 (4)	18 (4)	1 (1)
Thamnophilidae						
*Pygiptila stellaris**	High	INS	2 (1)	0	0	0
*Epinecrophylla amazonica**	High	INS	26 (5)	0	0	0
Myrmochanes hemileucus (FS)*	Medium	INS	0	0	0	297 (4)
*Myrmotherula brachyura**	Low	INS	23 (3)	20 (3)	0	0
*Myrmotherula axillaris**	Medium	INS	7 (3)	0	0	0
Myrmotherula assimilis (FS)*	Medium	INS	0	9 (2)	0	0
*Isleria hauxwelli**	High	INS	81 (6)	0	0	0
*Thamnomanes satuninus**	High	INS	5 (2)	0	0	0
*Thamnomanes caesius**	High	INS	21 (2)	0	0	0
Sakesphorus luctuosus (FS)	Medium	INS	1 (1)	0	0	0
*Thamnophilus doliatus**	Low	INS	2 (1)	1 (1)	20 (3)	60 (4)
*Thamnophilus schistaceus**	High	INS	114 (6)	0	0	0
*Thamnophilus aethiops**	High	INS	3 (2)	0	0	0

Table S3. Continued

Species	Sensitivity	Guild	Downstream sites: Floodplain forest (6)	Downstream sites: Early successional vegetation (4)	Upstream sites: (Dead) floodplain forest (5)	Upstream sites: Early successional vegetation (4)
*Cymbilaimus linatus**	Medium	INS	1 (1)	0	0	0
*Taraba major**	Low	INS	1 (1)	0	0	6 (1)
*Sclateria naevia**	Medium	INS	77 (2)	0	19 (2)	0
Myrmoborus leucophrys (FS)*	Medium	INS	184 (6)	3 (1)	0	0
*Hypocnemis peruviana**	Medium	INS	517 (6)	0	11 (1)	0
*Phlegopsis nigromaculata**	Medium	INS	3 (3)	0	0	0
*Oneillornis salvini**	High	INS	1 (1)	0	0	0
Dendrocolaptidae						
*Dendrocincla fuliginosa**	High	INS	61 (5)	0	0	0
*Sittasomus griseicapillus**	Medium	INS	41 (6)	0	8 (3)	0
*Xiphorhynchus obsoletus**	Medium	INS	0	0	3 (2)	0
*Xiphorhynchus guttatoides**	Low	INS	215 (6)	0	47 (4)	0
*Dendroplex picus**	Low	INS	9 (3)	116 (4)	131 (5)	55 (4)
Dendroplex kienerii (FS)*	High	INS	1 (1)	0	0	0
Nasica longirostris (FS)*	High	INS	42 (5)	5 (1)	48 (4)	0
*Dendrexetastes rufigula**	High	INS	42 (5)	0	44 (4)	0
*Dendrocolaptes certhia**	High	INS	37 (5)	0	0	0
*Dendrocolaptes picumnus**	High	INS	14 (5)	0	0	0
Furnariidae						
*Xenops minutus**	Medium	INS	14 (6)	0	0	0
*Berlepschia rikeri**	Medium	INS	0	0	1 (1)	0
Furnarius minor (FS)*	Medium	INS	0	0	0	9 (2)
*Philydor pyrrhodes**	High	INS	2 (2)	0	0	0
Mazaria propinqua (FS)*	Medium	INS	0	0	0	384 (4)
Synallaxis gujanensis (FS)*	Low	INS	0	60 (4)	44 (2)	202 (4)
Cranioleuca vulpecula (FS)*	Medium	INS	0	0	0	97 (3)
Thripophaga gutturata (FS)*	High	INS	11 (2)	0	0	0
Pipridae						
Pipra fasciicauda (FS)*	Medium	FRU	158 (3)	0	0	0
Tityridae						
*Pachyramphus castaneus**	Medium	INS	0	2 (1)	1 (1)	1 (1)
*Pachyramphus polychopterus**	Low	INS	33 (4)	50 (4)	0	18 (4)
Rhynchocyclidae						
*Tolmomyias sulphurescens**	Medium	INS	117 (6)	113 (4)	5 (2)	6 (2)
*Tolmomyias poliocephalus**	Medium	INS	34 (6)	27 (3)	2 (1)	4 (2)
*Tolmomyias flaviventris**	Low	INS	6 (3)	0	4 (1)	0
*Todirostrum maculatum**	Low	INS	0	679 (4)	44 (2)	525 (4)
*Todirostrum chysocrotaphum**	Medium	INS	43 (4)	0	0	0
*Myiornis ecaudatus**	Medium	INS	62 (5)	1(1)	14 (2)	0
*Hemitriccus minor (FS)**	High	INS	90 (5)	2 (1)	0	0
Stigmatura napensis (FS)*	Medium	INS	0	0	0	45 (3)
Tyrannidae						
*Camptostoma obsoletum**	Low	INS	2 (1)	120 (4)	66 (5)	75 (4)
Elaenia pelzelni (FS)*	Medium	INS	0	0	0	22 (3)
*Myiopagis gaimardii**	Medium	INS	38 (5)	34 (4)	32 (2)	12 (2)
*Tyrannulus elatus**	Low	INS	2 (1)	0	6 (4)	0
Attila cinnamomeus (FS)*	High	INS	74 (5)	33 (4)	9 (3)	9 (4)
*Attila spadiceus**	Medium	INS	44 (5)	0	0	0
*Legatus leucophaius**	Low	INS	25 (3)	5 (1)	0	0

Table S3. Continued

Species	Sensitivity	Guild	Downstream sites		Upstream sites	
			Floodplain forest (6)	Early successional vegetation (4)	(Dead) floodplain forest (5)	Early successional vegetation (4)
*Myiarchus tuberculifer**	Low	INS	3 (2)	0	2 (1)	0
*Myiarchus ferox**	Low	INS	1 (1)	19 (4)	7 (2)	15 (3)
*Pitangus sulphuratus**	Low	OMN	29 (5)	48 (4)	105 (5)	375 (4)
*Philohydor lictor**	Low	INS	0	0	23 (5)	20 (4)
*Myiodynastes maculatus**	Low	OMN	1 (1)	0	0	0
*Megarynchus pitangua**	Low	OMN	0	0	2 (1)	0
*Myiozetetes similis**	Low	OMN	0	0	3 (2)	218 (4)
*Tyrannus albogularis**	Low	INS	0	0	2 (1)	0
*Tyrannus melancholicus**	Low	INS	0	68 (4)	47 (5)	5 (3)
*Cnemotriccus fuscatus**	Low	INS	4 (2)	32 (3)	0	15 (3)
*Lathrotriccus euleri**	Medium	INS	174 (6)	0	0	0
Knipolegus orenocensis (FS)*	Medium	INS	0	0	0	57 (4)
Hirundinidae						
Progne sp.*	-	INS	0	81 (3)	105 (5)	9 (3)
Tachycineta albiventer (FS)*	Low	INS	0	1 (1)	6 (3)	3 (2)
Troglodytidae						
*Troglodytes musculus**	Low	INS	2 (1)	174 (4)	964 (5)	19 (3)
*Campylorhynchus turdinus**	Low	INS	11 (4)	23 (3)	26 (2)	0
Cantorchilus leucotis (FS)*	Low	INS	79 (5)	7 (1)	51 (4)	309 (4)
Donacobiidae						
*Donacobius atricapilla**	Medium	INS	0	0	75 (4)	0
Polioptilidae						
*Ramphocaenus melanurus**	Low	INS	48 (5)	0	0	0
Turdidae						
*Turdus hauxwelli**	High	OMN	20 (4)	0	25 (1)	0
Turdus sanchezorum (FS)	-	OMN	0	2 (2)	0	0
Turdus ignobilis (FS)*	Low	OMN	0	0	0	14 (2)
Passerellidae						
*Ammodramus aurifrons**	Low	GRA	0	107 (3)	39 (3)	149 (4)
Icteridae						
Psarocolius sp.*	-	OMN	32 (5)	39 (4)	5 (3)	2 (2)
*Cacicus cela**	Low	OMN	92 (6)	39 (4)	21 (3)	82 (3)
Thraupidae						
Paroaria gularis (FS)*	Low	INS	0	1 (1)	0	1 (1)
*Tangara mexicana**	Medium	OMN	0	6 (3)	5 (1)	2 (1)
*Tangara episcopus**	Low	OMN	0	41 (4)	57 (5)	12 (4)
*Tangara palmarum**	Low	OMN	0	41 (4)	57 (5)	12 (4)
Nemosia pileata	Low	INS	0	24 (3)	0	1 (1)
Conirostrum margaritae (FS)*	Medium	INS	0	11 (2)	0	0
*Volatinia jacarina**	Low	GRA	0	0	62 (4)	0
*Eucometis penicillata**	Medium	INS	9 (4)	0	0	0
*Ramphocelus carbo**	Low	OMN	32 (4)	374 (4)	213 (5)	70 (3)
*Coereba flaveola**	Low	FRU	0	2 (2)	0	0
*Sporophila castaneiventris**	Low	GRA	0	0	0	7 (2)
*Sporophila angolensis**	Low	GRA	0	0	24 (1)	0
*Saltator coerulescens**	Low	OMN	0	46 (2)	38 (2)	86 (4)
Fringillidae						
*Euphonia laniirostris**	Low	FRU	10 (4)	36 (3)	17 (4)	10 (1)
*Euphonia chrysopasta**	Medium	OMN	2 (2)	0	5 (2)	0

Table S4. Number and percentage (in parentheses) of bird species per guild and sensitivity category recorded in sampling sites upstream and downstream from the Santo Antônio dam on the upper Madeira River in the southwestern Brazilian Amazon. Values are presented overall and per habitat type.

	Location relative to dam		Habitat			
	Downstream	Upstream	Floodplain forest downstream	Floodplain forest upstream	Early successional vegetation downstream	Early successional vegetation upstream
Ecological guild						
Carnivore	21 (13%)	10 (7.6%)	19 (14.4%)	10 (9.2%)	8 (8.6%)	5 (5.5%)
Frugivore	22 (13.6%)	16 (12.1%)	19 (14.4%)	15 (13.7%)	14 (15%)	15 (16.5%)
Insectivore	86 (53.1%)	67 (50.8%)	74 (56%)	52 (47.7%)	43 (46.2%)	45 (49.4%)
Invertebrate generalist	2 (1.2%)	4 (3%)	1 (0.8%)	4 (3.7%)	2 (2.2%)	3 (3.3%)
Nectarivore	6 (3.7%)	3 (2.3%)	4 (3%)	3 (2.8%)	4 (4.3%)	3 (3.3%)
Omnivore	17 (10.5%)	18 (13.6%)	11 (8.3%)	14 (12.8%)	16 (17.2%)	11 (12.1%)
Piscivore	7 (4.3%)	8 (6.1%)	3 (2.3%)	8 (7.3%)	5 (5.4%)	5 (5.5%)
Granivore	1 (0.6%)	6 (4.5%)	1 (0.8%)	3 (2.8%)	1 (1.1%)	4 (4.4%)
Sensitivity						
Low	61 (37.6%)	73 (53.8%)	42 (31.8%)	58 (53.2%)	48 (51.6%)	58 (63.7%)
Medium	66 (40.8%)	49 (37.1%)	58 (44%)	40 (36.8%)	34 (36.5%)	28 (30.8%)
High	35 (21.6%)	12 (9.1%)	32 (24.2%)	11 (10%)	11 (11.9%)	5 (5.5%)

Table S5. Total number of detections resulting from semi-automated classification models (total number of sampling sites where the species was detected) of floodplain specialist bird species per habitat and location relative to the Santo Antônio dam on the upper Madeira River in the southwestern Brazilian Amazon. Values after the vegetation type indicate number of sampling sites.

Floodplain specialist species	Downstream sites		Upstream sites	
	Floodplain forest (6)	Early successional vegetation (4)	Floodplain forest (5)	Early successional vegetation (4)
Myrmoborus leucophrys	366 (4)	0	0	0
Thripophaga gutturata	9 (2)	0	0	0
Pipra fasciicauda	1361 (4)	0	0	0
Hemitriccus minor	19 (2)	0	0	0
Sclateria naevia	328 (2)	0	50 (1)	0
Nasica longirostris	45 (6)	0	22 (4)	0
Attila cinnamomeus	100 (5)	19 (3)	15 (3)	32 (2)
Myrmotherula assimilis	0	32 (2)	0	0
Conirostrum margaritae	0	8 (1)	0	0
Synallaxis gujanensis	0	139 (4)	211 (3)	383 (4)
Cantorchilus leucotis	0	0	106 (1)	679 (3)
Myrmochanes hemileucus	0	0	0	1332 (4)
Furnarius minor	0	0	0	10 (2)
Mazaria propinqua	0	0	0	1511 (4)
Cranioleuca vulpecula	0	0	0	373 (4)
Stigmatura napensis	0	0	0	17 (1)
Elaenia pelzelni	0	0	0	16 (3)
Sakesphorus luctuosus	2 (2)	0	0	0
Celeus flavus	47 (6)	5 (4)	0	0
Phaethornis hispidus	48 (5)	7 (1)	0	8 (2)
Monasa nigrifrons	17 (4)	36 (4)	10 (3)	0
Helicolestes hamatus	0	10 (2)	11 (1)	3 (2)
Buteogallus schistaceus	8 (1)	0	0	0
Dendroplex kienerii	2 (2)	0	0	0

Table S6. Number of detections (and total number of sampling sites where the species was detected) of 17 floodplain specialist bird species resulting from manual inspection of recordings and from semi-automated classification models. Data for 19 sampling sites upstream and downstream from the the Santo Antônio dam on the upper Madeira River in the southwestern Brazilian Amazon. N false positives = number of false positives from the semi-automated classification.

Species	Manual detections	Semi-automated classification	N false positives
Mazaria propinqua	384 (4)	1511 (4)	38,796
Pipra fasciicauda	158 (3)	1361 (4)	71,167
Myrmochanes hemileucus	297 (4)	1332 (4)	53,486
Cantorchilus leucotis	446 (14)	785 (4)	69,257
Synallaxis gujanensis	306 (10)	733 (11)	52,246
Sclateria naevia	100 (4)	378 (3)	24,817
Cranioleuca vulpecula	97 (3)	373 (4)	78,956
Myrmoborus leucophrys	187 (8)	366 (4)	18,036
Attila cinnamomeus	125 (16)	166 (13)	38.974
Nasica longirostris	95 (10)	67 (8)	8,547
Myrmotherula assimilis	9 (2)	32 (2)	17,495
Hemitriccus minor	92 (7)	19 (2)	87,834
Stigmatura napensis	45 (3)	17 (1)	69,461
Elaenia pelzelni	22 (3)	16 (3)	68,270
Furnarius minor	9 (2)	10 (2)	42,766
Thripophaga gutturata	11 (3)	9 (2)	45,094
Conirostrum margaritae	11 (2)	8 (1)	7,913
Sakesphorus luctuosus	1 (1)	2 (2)	6,113
Celeus flavus	35 (8)	52 (10)	26,836
Phaethornis hispidus	245 (15)	63 (8)	64,456
Monasa nigrifrons	49 (11)	63 (11)	23,142
Helicolestes hamatus	13 (9)	24 (5)	31,977
Buteogallus schistaceus	7 (2)	8 (1)	14,633
Dendroplex kienerii	1 (1)	2 (2)	16,517