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Padrões de uso de habitat e o efeito do alagamento permanente sobre a avifauna de várzea afetada pela UHE Santo Antônio no Rio Madeira

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Manaus, Amazonas

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Tese apresentada ao Programa de Pós-Graduação em Zoologia, da Universidade Federal do Amazonas/Instituto Nacional de Pesquisas da Amazônia, como parte dos requisitos para obtenção do título de Doutor em Zoologia.

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Resumo

As várzeas são ambientes altamente produtivos e com uma rica diversidade de espécies que são bem adaptadas as mudanças sazonais na paisagem, decorrente dos pulsos de inundação. Em relação as aves, estima-se que 15% das espécies na Amazônia sejam associadas as várzeas. Historicamente, porém, as várzeas sempre foram menos estudadas que as florestas de terra firme e atualmente sofrem diversos tipos de impactos, como o planejamento e implantação de usinas hidroelétricas em diversas bacias hidrográficas na Amazônia. A crescente pressão que esses ambientes enfrentam contrasta com a falta de conhecimento sobre alguns aspectos de sua avifauna. A presente tese, organizada em dois capítulos, investigou o impacto da barragem da usina hidroelétrica de Santo Antônio e os padrões de ocupação de espécies de aves de várzea no rio Madeira, no município de Porto Velho, Estado de Rondônia, Brasil. O **primeiro capítulo** descreve como a comunidade de aves de várzea respondeu ao alagamento permanente causado pelo enchimento do reservatório da usina. O **segundo capítulo** trata da relação entre variáveis ambientais que são consideradas importantes para a ocorrência de aves na várzea e os padrões de ocupação e detectabilidade da resposta dessas espécies ao pulso de inundação. Os resultados mostram quais grupos de aves são potencialmente mais ameaçados pelo impacto causado por barragens e apresenta informações inéditas que contribuem para o conhecimento da ecologia de algumas espécies de várzea.

Palavras-chave: ecoacústica; monitoramento acústico passivo; impacto ambiental; ocupação de habitat; pulso de inundação.

Abstract

Floodplains are highly productive environments with a rich diversity of species adapted to seasonal changes in the landscape, resulting from flood pulses. It is estimated that 15% of bird species in the Amazon are associated with floodplains. Historically, however, floodplains have always been less studied than upland forests (*terra firme*) and currently suffer from different types of impacts, such as the planning and implementation of hydroelectric plants in several hydrographic basins in the Amazon. The growing pressure these environments face contrasts with the lack of knowledge about some aspects of their avifauna. This thesis, organized in two chapters, investigated the impacts of the Santo Antonio hydroelectric power plant on the varzea associated avifauna, and the occupation patterns of floodplain bird species along the Madeira River in the municipality of Porto Velho, State of Rondônia, Brazil. The **first chapter** describes how the floodplain bird community responded to flooding due to the filling of the Santo Antônio hydroelectric plant reservoir. The **second chapter** deals with the relationship between environmental variables that are considered important for the occurrence of birds in the floodplain and the patterns of occupation and detectability of the response of these species to the flood pulse. The results show which groups of birds are potentially more threatened by the impact caused by hydroelectric plants and present new information that contributes to understanding the ecology of some floodplain species.

Keywords: ecoacoustics; passive acoustic monitoring; environmental impact; habitat occupancy; flood pulse.

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Introdução geral

No mundo, nenhum habitat criado nas planícies alagáveis de rios ocupa áreas tão extensas quanto na Amazônia, correspondendo a 14% da área total do bioma (Hess et al. 2015). A amplitude natural de flutuação no nível dos rios pode inundar áreas que variam de alguns metros a quilômetros, tornando as espécies que vivem nesses locais adaptadas ou mesmo dependentes desse processo, resultando em uma composição de espécies diferente dos habitats adjacentes (Remsen e Parker III 1983). Os ambientes sazonalmente alagáveis promovem uma grande diversidade de habitats ao longo de sua extensão e desempenham um importante papel na evolução da biota amazônica (Sioli 1984, Tundisi et al. 2014).

Os ambientes aluviais na Amazônia, tradicionalmente, são classificados pela coloração da água e por seus atributos físico-químicos, reunindo, principalmente, as várzeas e igapós (Sioli 1984, Junk et al. 2011). Os igapós são as formações vegetais que se desenvolvem sobre os terrenos aluviais, marginais aos rios de águas pretas ou claras. Por outro lado, as várzeas são aquelas formações que se desenvolvem nas áreas sob influência das inundações sazonais por rios de origem andina, com água branca ou barrenta, ricas em sedimentos e nutrientes (Figure 1; Sioli 1984, Junk et al. 2011). Além dos atributos físico-químicos, as diferenças na cor da água são determinantes das diferenças na estrutura das comunidades, composição de espécies, produtividade primária e, em alguns casos, na biomassa e história de vida dos organismos, tanto de ambientes aquáticos como aluviais (Junk et al. 2011, Laranjeiras et al. 2019).

Figure 1. Várzea no rio Madeira (A); Igapó no rio Negro (B).

A extensão média da área alagada nos sistemas aquáticos da Amazônia depende da precipitação, descarga e topografia da região, variando ao longo do curso do rio (Wittmann et al. 2006). A bacia amazônica possui um pronunciado período de alta precipitação e um período de seca, cuja duração e intensidade variam geograficamente. Esses processos acarretam mudanças no nível da água dos sistemas aquáticos, caracterizando um pulso de inundação natural, responsável, no caso dos rios de água branca, pela alta produtividade dos ambientes de várzea, devido a água rica em nutrientes (Junk et al. 1989). Os pulsos de inundação tornam as várzeas ambientes muito dinâmicos em razão dos processos de erosão e deposição de sedimentos. Esse intenso dinamismo causado pela constante destruição e criação de substrato sobre o qual a várzea se desenvolve criam paisagens de grande complexidade, onde são registradas formações vegetais dos diferentes estágios do processo de sucessão primária. As formações que caracterizam os estágios iniciais desse processo são dominadas por uma ou poucas espécies de plantas (Junk et al. 2011). No outro extremo do processo de sucessão registram-se formações caracterizadas pela grande diversidade de espécies.

Nessas áreas é possível observar gradientes de transformação da estrutura e composição das formações vegetais entre a margem do rio e a terra firme, influenciadas pela topografia, duração e altura da inundação (Wittmann et al. 2010). Devido a esses gradientes, diversos tipos de várzea podem ser identificados, e variam na composição, riqueza de espécies e estrutura da vegetação (Junk et al. 2011). Após a deposição inicial de sedimentos, ocorre rápida colonização de vegetação herbácea (Wittmann et al. 2010, Junk et al. 2011). Após o estabelecimento de gramíneas, espécies de arbustos (*e.g*. *Tessaria integrifolia* ou *Salix hunbolditiana*) e árvores pioneiras (*e.g*. *Cecropia latiloba*) se desenvolvem, formando aglomerados monoespecíficos, denominados oranal e embaubal, respectivamente (Figura 2). Nesse ponto, o estabelecimento dessa vegetação arbórea reduz o impacto do alagamento, estabiliza o substrato e sombreia o ambiente, favorecendo o estabelecimento de espécies secundárias (Wittmann et al. 2010, Junk et al. 2011). Nos locais mais altos, que possuem curto período de alagamento é encontrada a típica floresta de várzea (Figura 3). Esse ambiente possui sub-bosque desenvolvido e maior diversidade de espécies arbóreas de grande porte (Wittmann et al. 2002).

Figura 2. Diferentes habitats formados pelos estágios da sucessão da vegetação na várzea do rio Madeira. A primeira linha de vegetação é dominada por gramíneas, em seguida uma faixa de *Tessaria integrifolia* (oranal) e mais distante da margem as árvores do gênero *Cecropia* (embaubal).

Figura 3. Floresta de várzea no rio Madeira.

Esses habitats possuem uma fauna característica e especializada, cujas assembleias variam ao longo do ciclo hidrológico, de acordo com as flutuações no nível da água (Stotz et al. 1996; Haugaasen e Peres 2005, Cohn-Haft et al. 2007a, Beja et al. 2010). Em relação as aves, mais de 400 espécies ocorrem nas várzeas e mais de 100 aparentemente são restritas a esse ambiente (Remsen e Parker III 1983, Stotz et al. 1996, Cohn-Haft et al. 2007b), tornando esses ambientes fundamentais para a manutenção da riqueza desse grupo na Amazônia (Remsen e Parker III 1983). Algumas espécies de aves de várzea estão associadas a certos microhabitats, ou seja, às condições ambientais e elementos da estrutura da vegetação específicos (Rosenberg 1990, North 1996). *Conirostrum margaritae* (Thraupidae), por exemplo, é estritamente relacionado a extensos aglomerados de *Cecropia* (Figure 4; Hilty 2011, Melo et al. 2020), já *Ochthornis littoralis* (Tyrannidae) ocorre apenas em troncos, barrancos e outros materiais acumulados na margem dos rios (Figura 5; Fitzpatrick 2004).

Figura 4. Figuinha-da-amazônia (*Conirostrum margaritae*).

Figure 5. Maria-da-praia (*Ochthornis littoralis*).

Apesar de sua importância, do ponto de vista ornitológico, as várzeas são um ambiente ainda muito pouco estudado na Amazônia, cujo foco, historicamente, foram as aves de terra firme (Cohn-Haft et al. 2007a). Embora seja conhecido que espécies de aves de várzea sejam associadas de forma categórica a tipos específicos de habitats (Remsen e Parker III 1983, Stotz et al. 1996), os padrões de ocupação de aves de várzea em tipos diferentes de nunca foram quantificados.

Devido aos seus solos produtivos, à facilidade de acesso e à maior concentração de populações humanas, as várzeas sempre foram alvo de extração de recursos e de exploração agrícola e pecuária (Padoch 1996). Mesmo atividades econômicas consideradas sustentáveis, como o cultivo comercial de açaí, também podem causar perda na estrutura das florestas de várzea (Weinstein e Moegenburg 2004). Além da pressão decorrente das atividades agropastoris e extrativistas mal planejadas, a bacia amazônica se tornou uma fronteira em virtude da política energética do Brasil e de outros países amazônicos, e da crescente demanda internacional por esse insumo (Manyari e Carvalho Jr. 2007, Tundisi et al. 2014, Lees et al. 2016, Forsberg et al. 2017, Latrubesse et al. 2017). A crescente demanda por energia, com a implementação recente de usinas hidroelétricas na Amazônia e o planejamento futuro de novas barragens é hoje um dos maiores problemas ambientais desse bioma (Forsberg et al. 2017, Latrubesse et al. 2017). Situação que contrasta com a falta de conhecimento sobre as espécies diretamente impactadas por esses empreendimentos. Por exemplo, estima-se que as alterações no nível e regime de flutuação natural dos rios na Amazônia, que afetem as espécies restritas aos ambientes aluviais, podem reduzir até 13% da riqueza de aves no bioma (Remsen e Parker III 1983).

As usinas hidroelétricas necessitam de alto investimento para sua implantação e acarretam grande dano ambiental e social (Fearnside 2006, Manyari e Carvalho Jr. 2007, Lees et al. 2016). Embora grandes usinas já se encontrem implantadas ou em implantação na Amazônia, segundo o planejamento energético dos países sul-americanos, o bioma ainda guarda um enorme potencial de geração de energia a partir de seu sistema hidrográfico. Além do rio, os danos mais significativos ocorrem nas áreas de várzea ou igapó, em que milhares de hectares são alagados permanentemente (Cochrane et al. 2017, Li et al. 2020). Em anos recentes aumentaram os debates sobre os problemas relacionados às usinas hidroelétricas, embora muitos dos impactos ambientais e sociais, decorrentes da implantação e operação desses empreendimentos não sejam levados em consideração pelo governo, ilustrando a falta de consenso entre o setor energético e as agências responsáveis pelo licenciamento (Manyari e Carvalho Jr. 2007, Fearnside 2015).

Considerando esse cenário, a construção dos novos reservatórios aumentará os impactos em larga escala no ciclo hidrológico, prejudicando ecossistemas terrestres e aquáticos, além de contribuírem com a emissão de gases do efeito estufa (Tundisi et al. 2014). Em um estudo recente, Latrubesse et al. (2017), propuseram um Índice de Vulnerabilidade Ambiental as Barragens (DEVI, em inglês). Para o cálculo são levados em conta parâmetros que avaliam o quanto a bacia é vulnerável a mudanças no uso da terra, erosão e poluição, a dinâmica do transporte de sedimentos e pulso de inundação e o quanto o sistema é ou será afetado por hidroelétricas. Caso o planejamento de novas usinas na Amazônia seja levado adiante, os impactos serão cumulativos e irreversíveis, incluindo alterações hidrofísicas e bióticas na Bacia Amazônica, nos estuários, em ambientes marinhos ao longo da costa nordeste da América do Sul, além de afetar o clima regional (Latrubesse et al. 2017). De acordo com o DEVI, a bacia do rio Madeira, em razão de suas características ambientais, é a sub-bacia mais vulnerável da Amazônia.

As usinas no rio Madeira usam modelo de reservatório, do tipo fio d'água, com um reservatório pequeno em relação a capacidade instalada, que contrasta com modelos tradicionais, como Balbina ou Tucuruí (Fearnside 2015). Porém o modelo de reservatório fio d'água concentra o impacto do alagamento permanente nos ambientes de várzea/igapó, eliminando o pulso natural de inundação, afetando grandes extensões desses ambientes à montante da barragem, devido ao alagamento permanente e a médio e longo prazo. Os impactos também se manifestam à jusante, devido, principalmente, às mudanças na sazonalidade do alagamento e no aporte de sedimentos. O Rio Madeira é responsável por 50% do transporte de sedimentos para rio Amazonas. Após a construção das usinas, foi detectada uma redução de 20% na concentração média de sedimentos em suspenção a jusante de Santo Antônio (Latrubesse et al. 2017).

No rio Madeira, duas grandes usinas hidroelétricas estão em operação desde 2012, Santo Antônio, com 3150 MW de capacidade instalada e Jirau, com 3750 MW (Fearnside 2015), ambas no estado de Rondônia. A Usina Hidroelétrica de Santo Antônio está localizada abaixo de Porto Velho, enquanto Jirau localiza-se a 117 km rio acima, a cerca de meio caminho entre Porto Velho e Abunã, município na fronteira entre Brasil e Bolívia (Fearnside 2015). Assim como outras barragens implantadas ou planejadas na Amazônia, o processo de licenciamento das usinas do rio Madeira foi acelerado por pressão política, a despeito das inúmeras críticas, do posicionamento contrário da equipe técnica do IBAMA e de metas descumpridas pelas proponentes dos projetos (Fearnside 2015).

Recentemente, Cochrane et al. (2017) comprovaram que o dano provocado pelas usinas no rio Madeira é maior do que o previsto pelo Estudo de Impacto Ambiental (EIA). A área conjunta alagada pelos reservatórios de Santo Antônio e Jirau, prevista em 2005, no EIA, era de 529 km^2. Em 2015 a área alagada era 64,5% maior que a prevista, com 870 km^2. O impacto foi além das fronteiras nacionais e a área alagada no trecho do rio Madeira em território boliviano aumentou em 28 km^2 (15,3%). O impacto ainda pode aumentar nos próximos anos, caso o volume de água no entorno dos reservatórios continue aumentando. O impacto nas áreas de várzea foi completamente negligenciado no EIA. Até 2015, 89 km^2 de várzeas a montante de Santo Antônio foram permanentemente alagados. O impacto do alagamento permanente na várzea ainda é desconhecido, porém as espécies de várzea dependem do pulso natural de inundação e a mortalidade da vegetação nas florestas de várzea é evidente (Figure 6; Junk et al. 1989, Cochrane et al. 2017).

Figura 6. Floresta de várzea impactada pelo alagamento permanente a montante da usina de Santo Antônio, no rio Madeira.

Em relação a fauna, os impactos mais expressivos das usinas hidroelétricas são a perda e fragmentação de habitats. No mundo, são relatados impactos negativos em diversos vertebrados, como peixes (Raymond 1979, Neraas e Spruell 2001, Torrent-Vilara et al. 2011), anfíbios (Welsh Jr. e Wilson, 1996, Brandão e Araújo 2008, Dayrell et al. 2021), mamíferos (Santos et al. 2008, Benchimol e Venticinque 2014, Benchimol e Peres 2015, Bobrowiec et al. 2021) e aves (Kingsford e Thomas 1995, Reitan e Thingstad 1999, Aurélio-Silva et al. 2016). Na Amazônia, com relação as aves, poucos estudos relatam o impacto de hidroelétricas, com foco em espécies de terra firme, conduzidos nos reservatórios das usinas de Balbina e Tucuruí (Aurélio-Silva et al. 2016, Henriques et al. 2021). Em Balbina, menos de 10% das 3546 ilhas do reservatório continham uma assembleia de aves de terra firme que representava significativamente a avifauna regional

(Aurélio-Silva et al. 2016). Embora as aves típicas dos ambientes ripários não tenham sido o foco, os autores não registraram espécies restritas a esses ambientes, anteriormente registradas no local.

Nesse contexto, conhecer as características ecológicas dessas espécies permite entender por que determinadas espécies declinam e outras proliferam, frente a alterações antropogênicas no ambiente. Esse tipo de informação pode ser usada para prever impactos de intervenções humanas e o risco de extinção para populações e espécies (Lees e Peres 2008). Portanto, se torna fundamental conhecer como as espécies de aves de várzea usam o ambiente, e quais as espécies mais sensíveis às alterações de habitat causadas por hidroelétricas. O estudo da resposta da comunidade de aves às alterações no habitat provocadas pela implantação de uma usina no rio Madeira é uma oportunidade inédita de entender como certas espécies restritas a ambientes de várzea estão sendo impactadas, colaborando na previsão e mitigação do impacto em futuras barragens.

A presente tese investigou a resposta da comunidade de aves de várzea no rio Madeira à implantação e operação da usina hidroelétrica de Santo Antônio e os padrões de ocupação e detectabilidade de espécies de aves de várzea em relação a seleção de habitat e ao pulso de inundação do rio Madeira. Os resultados estão organizados em dois capítulos:

- **Capítulo 1** aborda a resposta da comunidade de aves de várzea do rio Madeira à implantação e operação da usina hidroelétrica de Santo Antônio.
- **Capítulo 2** trata dos padrões de ocupação e detectabilidade de 10 espécies de aves consideradas especialistas em várzea no rio Madeira.

CAPÍTULO 1

Tomaz Nascimento de Melo, Marconi Campos-Cerqueira, Fernando Mendonça d'Horta, Hanna Tuomisto, Jasper Van Doninck, Camila Cherem Ribas. **Impacts of a large hydroelectric dam on the floodplain avifauna of the Madeira River (Brazil).** Manuscrito aceito para publicação no periódico Acta Amazônica em 08 de outubro de 2021.

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

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

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 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

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).

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 (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).

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, 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, $p < 0.05$).

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 eraly 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 the floodplains can be conditioned by differences in the island or vegetation size (Rosenberg 1990).

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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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
Furnariidae	*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)
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)

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)
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)

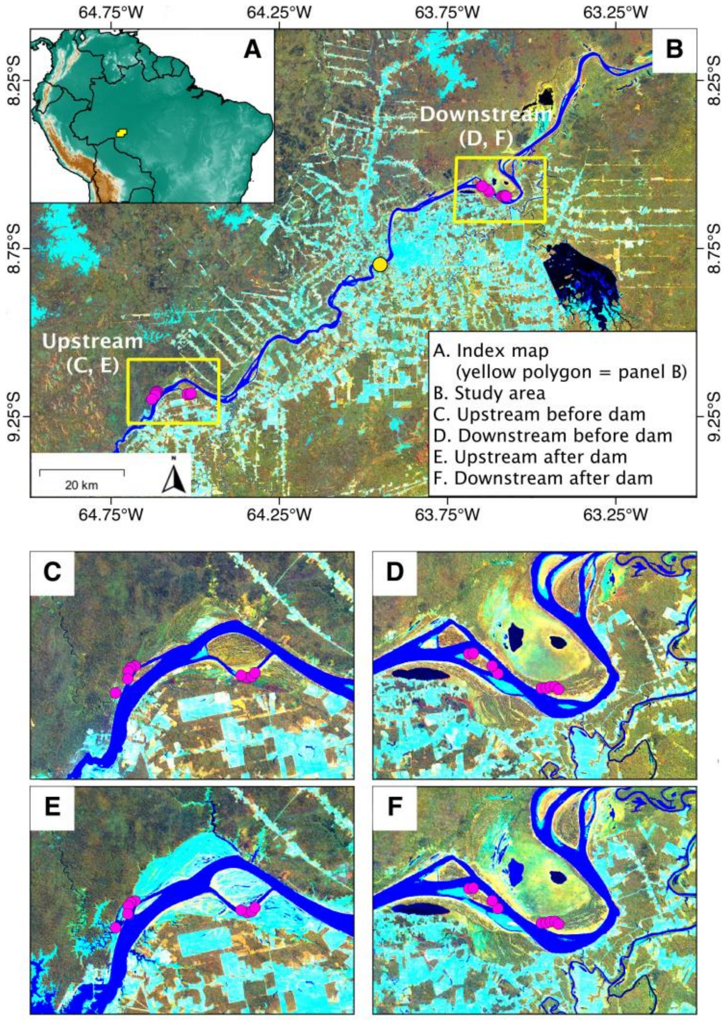

Figure 1. A – Location of the study area (yellow spot); B – Location of the Santo Antônio dam (yellow circle) and upsteam and downstream bird sampling sites (pink circles) along the upper Madeira River, Rondônia state, Brazil; B-F – Landsat TM/ETM+ composite images in background false color with bands 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.

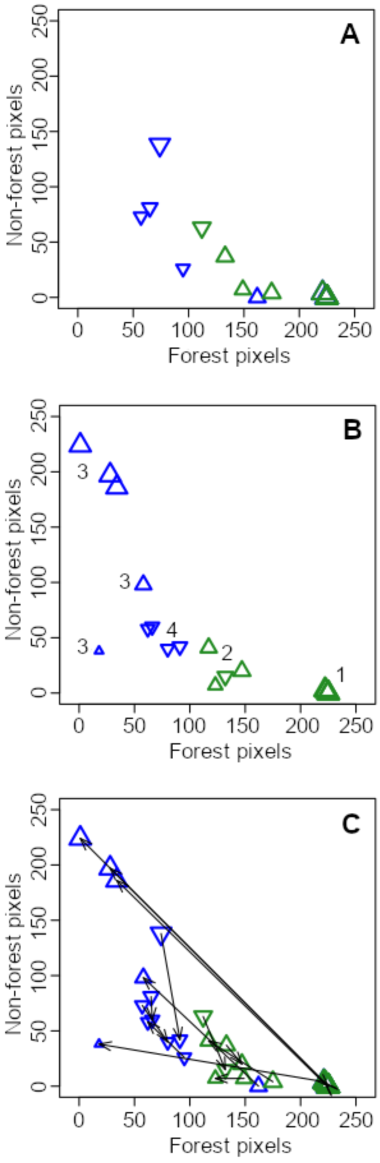

Figure 2. Scatterplots of the sampling sites downstream and upstream from the Santo Antônio dam on the Madeira River resulting from PCA showing how many pixels in a 15 by 15 pixel window centered over the sampling site in a Landsat TM/ETM+ composite image were classified as forest and how many as non-forest 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.

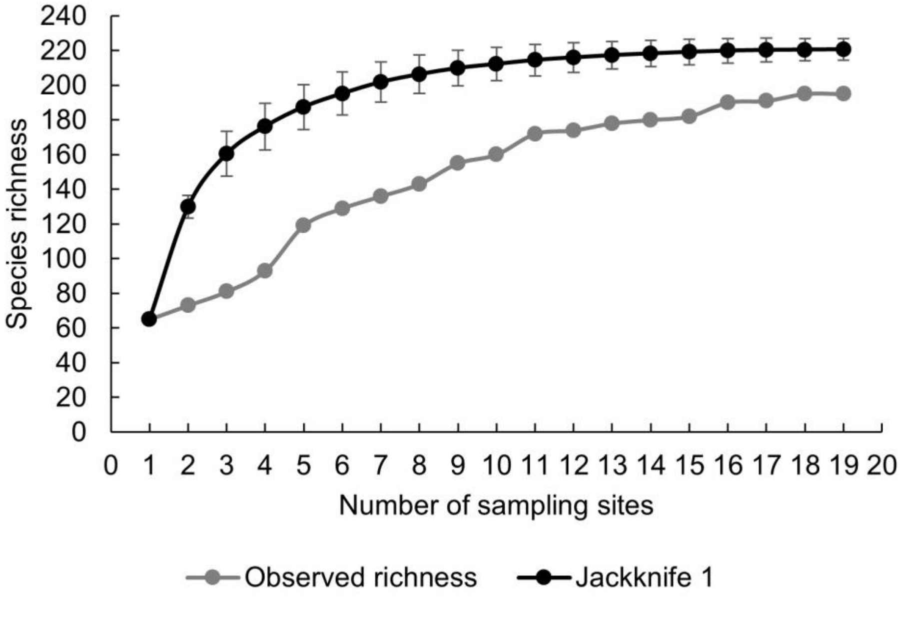

Figure 3. Species accumulation curves of observed and estimated bird species richness by fist order Jackknife.

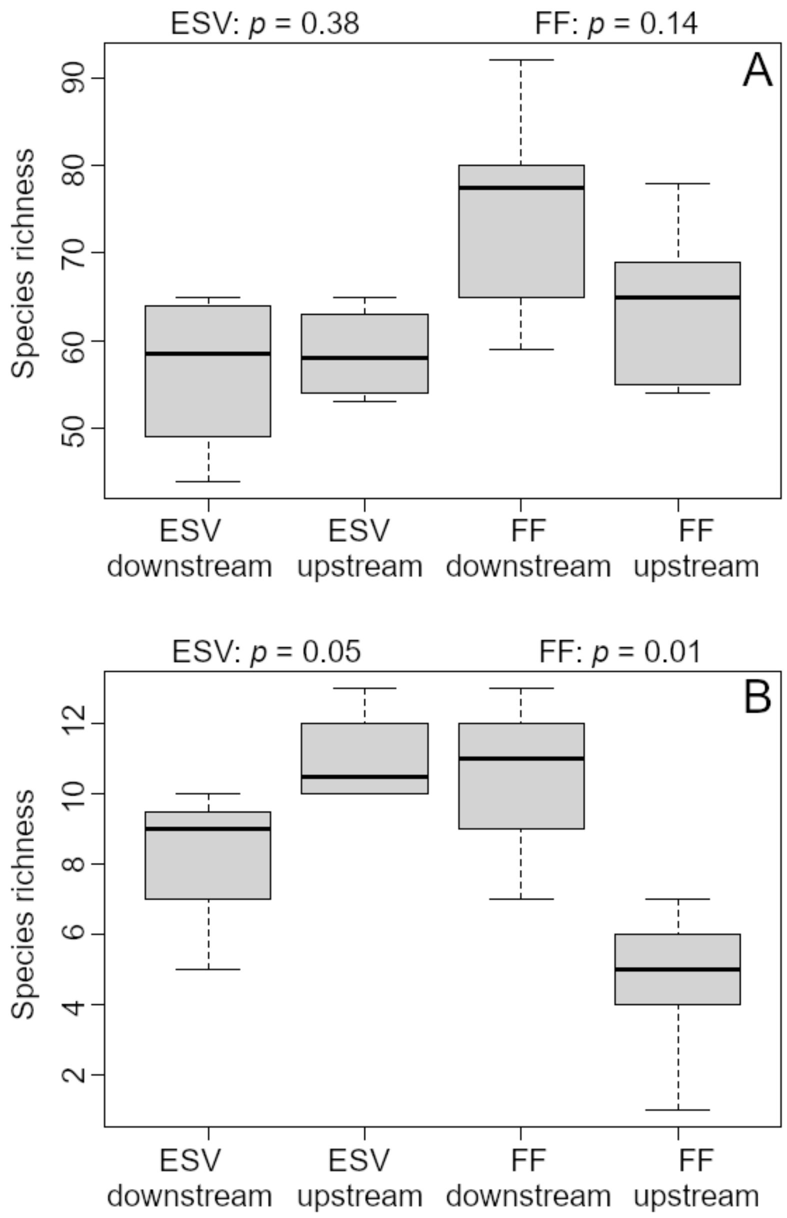

Figure 4. Species richness for all bird species (A), and floodplain specialists (B) in floodplain forest (FF) and early successional vegetation (ESV) sampling sites upstream and downstream from Santo Antônio dam on the Madeira River. The significance level of the Wilcoxon-Mann-Whitney test is shown.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

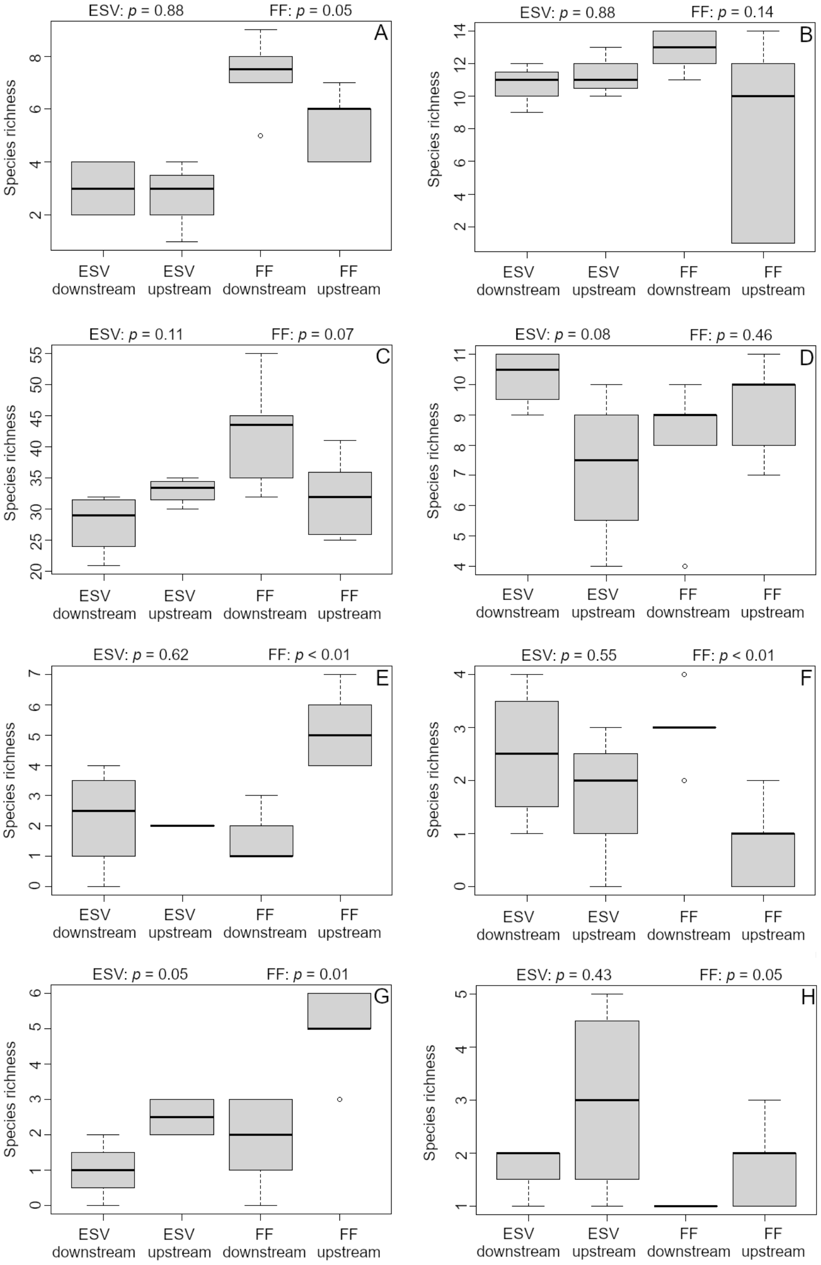

Figure 5. Species richness of different bird trophic guilds in floodplain forest (FF) and early successional vegetation (ESV) sampling sites upstream and downstream from Santo Antônio dam on the Madeira River. A – carnivores; B – frugivores; C – insectivores; D – omnivores; E – piscivores; F – nectarivores; 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.

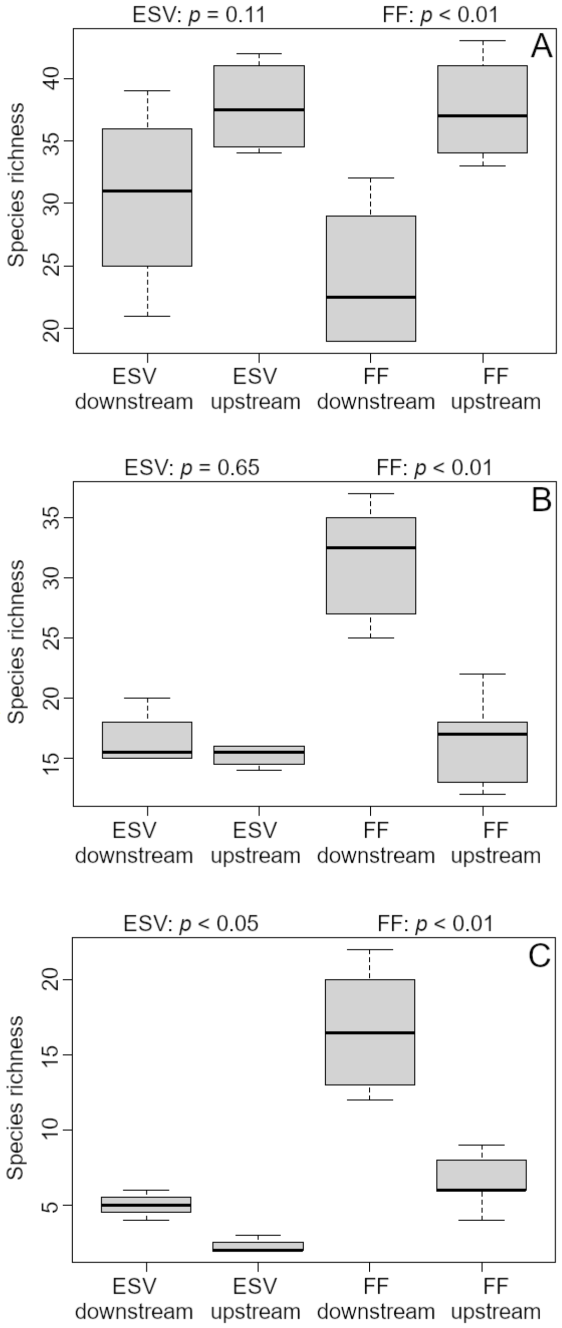

Figure 6. Species richness of birds in different level of sensitivity to environmental disturbance in floodplain forest (FF) and early successional vegetation (ESV) sampling

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.

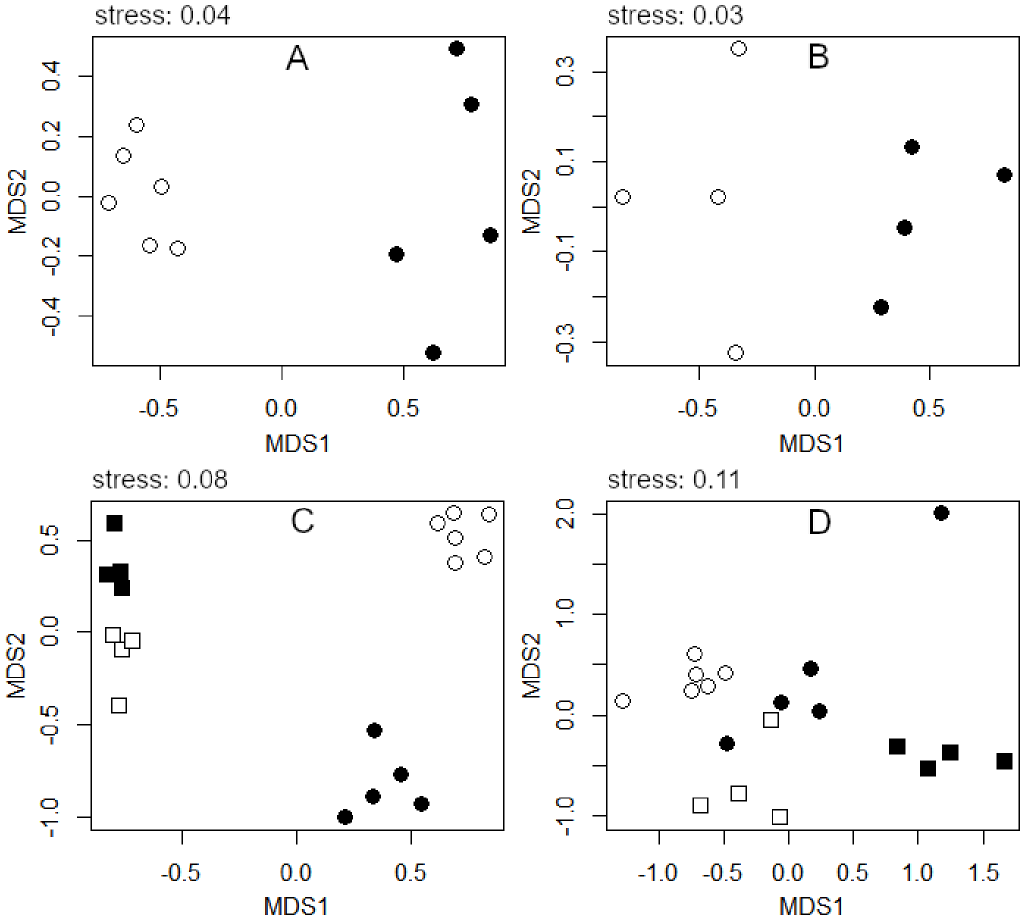

Figure 7. NMDS ordination of bird species composition based on presence/absence data for floodplain forest (A), early successional vegetation (B), all sites combined (C), and only floodplain specialist species (D) upstream and downstream from Santo Antônio dam on the Madeira River. White symbols = downstream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

Supplementary Material

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 per species are also shown for each site. *Cecropia membranacea* (Urticaceae) = *C. membranacea*; *Tessaria integrifolia* (Asteraceae) = *T. integrifolia*.

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. Upstream sites = U1-U9; Downstream sites = D1-D9.

2009-2011 composite image													
	Pixel class			**Reflectance values**									
Site	**Forest**	**Non-forest**	**Water**	**Band2 forest**	**Band2 non-forest**	**Band 3 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. FS = species restricted or that occur primarily in floodplain habitats in Amazonia, identified through a review of the information available in 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**	**Early successional**	**(Dead) floodplain**	**Early successional**

			(6)	**vegetation (4)**	**forest (5)**	**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)
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
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
*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
*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.

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

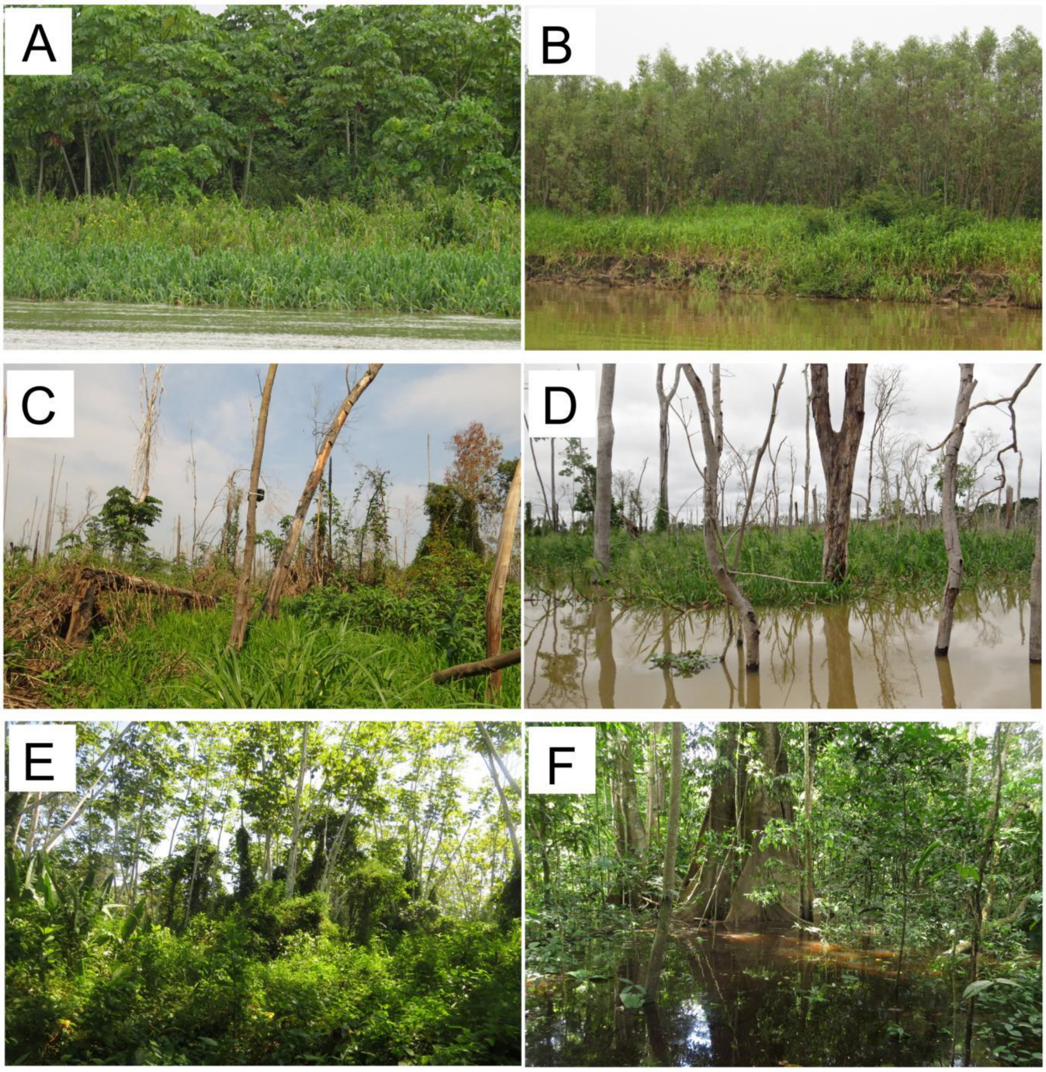

Figure S1. Sampling habitats in the upper Madeira River. Upstream (after the Santo Antônio dam reservoir filling): A – early successional vegetation dominated by *Cecropia* trees; B – early successional vegetation dominated by *Tessaria integrifolia*; C – dead floodplain forest in the dry season (September); 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.

CAPÍTULO 2

Tomaz Nascimento de Melo, Marconi Campos-Cerqueira, Fernando Mendonça d'Horta, Camila Cherem Ribas. **Understanding the occupancy patterns of Amazon floodplain birds.** Manuscrito aceito para publicação no periódico The Wilson Journal of Ornithology em 2 de março de 2022.

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RH: *Melo et al.* • Occupancy patterns of floodplain birds

Understanding the occupancy patterns of Amazon floodplain birds

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ABSTRACT—In the Amazon basin, several species are restricted or occur primarily in habitats along rivers. However, little is known about habitat occupancy over time and how seasonal fluctuations in the level of rivers affect bird species occurrence in floodplains. In this study, we verified if the occupancy and detection probability of 10 floodplain bird specialist species are related to 3 environmental variables considered to be important for floodplain birds: the number of *Tessaria shrubs,* the number of *Cecropia* trees, and the number of other tree species. We also tested if occupancy and detection probabilities changed among flood pulse seasons. Our study was conducted at 19 sampling sites in the Madeira River floodplain in Rondônia, Brazil, including sites impacted by the Santo Antonio dam. Sampling was done with autonomous recorders and subsequent development of semi-automatic identification models for each species. The best occupancy models show that the number of *Tessaria shrubs* was positively related to occupancy probability for 4 species: Black-and-white Antbird (*Myrmochanes hemileucus*), Parker's Spinetail (*Cranioleuca vulpecula),* White-bellied Spinetail (*Mazaria propinqua),* and Plain-crowned Spinetail (*Synallaxis gujanensis).* The number of *Cecropia* trees was positively correlated with the occupancy of a single species, the Spotted Tody-Flycatcher (*Todirostrum maculatum*). The number of other trees was positively correlated for White-browed Antbird (*Myrboborus leucophrys),* Peruvian Warbling-Antbird (*Hypocnemis peruviana),* and Band-tailed Manakin (*Pipra fasciicauda).* Occupancy probability is similar among sampling periods, which indicates that species remain onsite. The detection probability, however, varied in 9 of the 10 species, probably related to seasonal variation in vocal activity. This variation in detectability needs to be considered in bird surveys in floodplains. In addition, the classification of floodplain species according to the type of habitat specialization can help define the species most vulnerable to environmental changes, such as those caused by hydroelectric plants in the Amazon.

Key words: Amazon dams, automated identification models, Madeira River, passive acoustic monitoring, pattern matching, riparian, vegetation structure.

Entendendo os padrões de ocupação das aves de várzea na Amazônia

RESUMO (Portuguese)—Na Bacia Amazônia, diversas espécies são restritas ou ocorrem primariamente em habitats ao longo dos rios. Entretanto, pouco se conhece sobre a ocupação do habitat ao longo do tempo e como as flutuações sazonais no nível dos rios afeta as espécies de aves que ocorrem nas várzeas. Nesse estudo, nós verificamos se a ocupação e a probabilidade de detecção de 10 espécies de aves especialistas em várzea são relacionadas com 3 variáveis ambientais consideradas importantes para aves de várzea: o número de arbustos do gênero *Tessaria*, o número de árvores do gênero *Cecropia* e o número de outras espécies de árvores. Nós também testamos se a ocupação e detectabilidade das espécies muda entre os períodos do pulso de inundação. Nosso estudo foi realizado em 19 sítios amostrais nas várzeas do rio Madeira no estado de Rondônia, Brasil, incluindo sítios impactados pela barragem de Santo Antonio. A amostragem foi feita com gravadores autônomos e posteriormente desenvolvido um modelo de identificação semi-automática para cada espécie.

O melhor modelo de ocupação mostrou que o número de arbustos de *Tessaria* é positivamente relacionado a ocupação de 4 espécies: *Myrmochanes hemileucus*, *Cranioleuca vulpecula*, *Mazaria propinqua e Synallaxis gujanensis.* O número de árvores do gênero *Cecropia foi positivamente relacionado a ocupação de uma única espécie, em Todirostrum maculatum. O número de outras árvores foi positivamente relacionado a ocupação de Myrmoborus leucophrys*, *Hypocnemis peruviana* e *Pipra fasciicauda.* A probabilidade de ocupação é similar entre os períodos de amostragem, o que indica que as espécies permanecem nos locais. *A probabilidade de detecção, porém, teve uma variação significante para 9 das 10 espécies, provavelmente relacionada a variação sazonal na atividade vocal.* Essa variação na detectabilidade deve ser considerada nas amostragens de aves nas várzeas. Adicionalmente, a classificação das espécies de aves de várzea de acordo com o tipo de especialização em habitat pode ajudar a definir quais são as espécies mais vulneráveis a impactos ambientais, como os causados por usinas hidroelétricas.

Palavras-chave: barragens na Amazônia, correspondência de padrões, estrutura da vegetação, modelos de identificação automática, monitoramento acústico passivo, rio Madeira, ripário.

Floodplains are a fundamental component of the high diversity of bird species in the Amazon basin, with more than 400 species recorded in them. It is assumed that at least 15% are restricted to these environments (Remsen and Parker III 1983, Cohn-haft et al. 2007b, Laranjeiras et al. 2019). An important feature that explains the patterns of species richness and distribution in floodplains is the gradient of different habitats formed along rivers, influenced by the strong effect of erosion and sediment deposition resulting from water energy and flood pulses (Remsen and Parker III 1983).

The seasonal and natural amplitude of fluctuation in rivers' water levels can flood areas that vary from a few meters to kilometers, and many species that occur in these habitats have developed unique behavioral and ecological adaptations that allow them to cope with constant environmental changes caused by water fluctuations (Remsen and Parker III 1983, Rowedder et al. 2021). The duration and intensity of rains vary geographically and cause changes in water level among periods of high and low precipitation featuring a flood pulse (Junk et al. 1989). When water levels rise, rivers deposit sediments and nutrients in floodplains, favoring the establishment of vegetation. This intense dynamism caused by the constant destruction and creation of the substrate on which the floodplain develops creates complex landscapes (Junk et al. 2011).

Floodplain landscapes are composed by vegetation formations of different stages of the ecological succession process (Remsen and Parker III 1983, Robinson and Terborgh 1997, Junk et al. 2011). In white-water rivers (Amazonian rivers with a high concentration of sediments from the Andes), the initial stage of succession after the initial deposition of sediments is characterized by rapid colonization of herbaceous vegetation (Wittmann et al.

2010, Junk et al. 2011). After establishing grasses, shrubs and pioneer trees develop, forming monospecific clusters that characterize the second stage of succession. At this point, the establishment of this arboreal vegetation reduces the impact of erosion, stabilizes the substrate, and provides shading, favoring the establishment of secondary plant species (Wittmann et al. 2010, Junk et al. 2011). Finally, the mature floodplain forest is found in the highest places, which have shorter flooding periods. This mature floodplain forest has developed understory and a greater diversity of large tree species and characterizes an advanced stage of succession (Wittmann et al. 2002).

Understanding this dynamic of ecological succession is important, as some floodplain bird species are associated with particular microhabitats, with specific environmental conditions and vegetation structure elements (Rosenberg 1990, North 1996, Petermann 1997, Robinson and Terborgh 1997). For example, Pearly-breasted Conebill (*Conirostrum margaritae*) and Brownish Elaenia (*Elaenia pelzelni*) have a strong relationship with the distribution of the 2 tree species of the genus *Cecropia* that occur in floodplains: *C. membranacea* and *C. latiloba* (Urticaceae; Rosenberg 1990, Melo et al. 2020). White-bellied Spinetails (*Mazaria propinqua*) and Black-and-white Antbird (*Myrmochanes hemileucus*), among others, are considered strongly associated with herbaceous and shrubby vegetation on river islands, especially with the shrub *Tessaria integrifolia* (Asteraceae; Rosenberg 1990). Although ornithologists commonly categorize bird habitats (e.g., tall floodplain forest, upland forest; Remsen and Parker III 1983, Rosenberg 1990, Petermann 1997, Cohn-Haft et al. 2007a), bird species distribution in the floodplains seems to follow continuous and subtle gradients (Laranjeiras et al. 2019, Naka et al. 2020). Furthermore, knowledge about how species occupy these habitats has continually changed. For example, bird species previously recognized as obligate river island specialists (Rosenberg 1990) were recorded in areas of small-scale agriculture on the Amazon River banks (Armacost Jr. and Capparella 2012).

A poorly studied feature of floodplain birds is their response to the flood pulse, especially for species that occupy habitats in the early stages of ecological succession (Schulenberg and Rosenberg 2020a, b, c). One study reported the behavioral responses of 5 specialist birds in floodplain forests between the dry and rainy seasons in Amazonia and observed a vertical movement upwards in the vegetation when water level rose, with permanence in the same sites (Rowedeer et al. 2021). However, there is still a gap in our knowledge of the temporal and spatial variation patterns in habitat occupancy of practically all floodplain species.

Currently, the construction and operation of dams and hydroelectric plants have caused changes in the natural dynamics of rivers in the Amazon and caused the loss and degradation of floodplain habitats. More than 400 dams are either operating or in the planning stages throughout the Amazon basin (Latrubesse et al. 2017). However, we know little about how bird species restricted to floodplains respond to environmental impacts, such as the construction of hydroelectric dams (Latrubesse et al. 2020). River disruption and regulation by dams can cause habitat loss, decrease, or even suppress ecological connectivity among populations of organisms dependent upon seasonally flooded environments (Latrubesse et al. 2020). Increased knowledge about how species occupy the landscape, especially those restricted to floodplains, can help define priorities for conservation in these environments.

To understand bird spatial and temporal occupancy patterns in the floodplains, we selected 10 birds known to have different habitat affinities and degrees of dependence on floodplain vegetation. Our main goals were to determine: (a) the probability of occupancy given 3 environmental variables known for their importance in the occurrence of floodplain species (number of *Tessaria integrifolia* shrubs, number of *Cecropia* trees, and number of 'other' trees [trees different from the previous 2 species]); and (b) if the probability of occupancy and detectability changed over the 4 periods that characterize the flood pulse (dry season, beginning of rains, rainy season, and ebbing).

Methods

Study area

Our study took place in 19 sites in the Madeira River floodplain, in the municipality of Porto Velho (10 sites), and the district of Jaci-Paraná (9 sites; Fig. 1). There, patches of *Tessaria* shrubs are considered early stages of succession, while *Cecropia* sp. forests are found in more advanced stages (Robinson and Terborgh 1997). Because some floodplain birds are specialized in habitats with a high density of *Tessaria* shrubs or *Cecropia* trees (Rosenberg 1990), and some are dependent on floodplain forests (which have a high density of different species of trees; Remsen and Parker III 1983, Petermann 1997), we established plots of 20 × 100 m, using the recorder as a central point. We counted the number *Tessaria* shrubs, *Cecropia* trees, and the number of tree species different from *Cecropia* or *Tessaria* that had a diameter at breast height (DBH) $\geq$ 10 cm (Supplementary Material Table S1; Fig. S1).

Mean rainfall throughout the Madeira River basin ranges from 2000–2500 mm, with a rainy season between December–April, and a peak flood (in Porto Velho) between March–April followed by a decrease in the water levels in June. In this region, the amplitude of the flood pulse in the Madeira River varies from 10.8–12.4 m between the periods of lowest and highest water levels (Goulding et al. 2003).

Acoustic recording

We used autonomous recorders (LG Smartphone wrapped in a water-resistant case and connected to a Monoprice external condenser microphone) at each site, installed in the vegetation at the height of 1.80 m from the ground or water surface depending on the sampling season. The minimum distance between recorders/sites was 400 m. Previous studies using the same recorder model found that the detection distance for most species is 100 m from the recorder (Campos-Cerqueira et al. 2019), so this is the distance we considered as sufficient to avoid pseudo-replication.

We programmed recorders to obtain 1 min-long recordings every 10 min, which corresponds to 144 recordings per recorder/d. We sampled for 20 d during each of the 4 seasons of the flood pulse: starting in September 2017 (dry season, with the lowest water level), December 2017 (beginning of the rainy season), March 2018 (top of the rainy season and the water level), and June–July 2018 (ebb season), totaling 80 d of sampling. Recordings were deposited on the RFCx Arbimon platform in the public project Birds of Madeira

Flooded Habitats (https://arbimon.rfcx.org/project/birds-of-madeira-flooded-habitats/dashboard).

Selection of bird species

We selected species that were restricted or that occur mainly in Amazon floodplain habitats or that have different degrees of dependence on these environments based on information available in Birds of the World (Billerman et al. 2020; Table 1).

Semi-automated identification models

We used semi-automated classification algorithms in the RFCx ARBIMON platform (https://arbimon.rfcx.org) to determine each species' presence and absence in audio recordings. The semi-automatic identification models were used in a set of 100,702 recordings. We had no detections during nighttime, so we only used recordings made between 05:00–18:50 h. Classifications of all recordings were based on a template matching procedure. This procedure searches through audio data for acoustic signals and detects regions highly correlated with a template selected by the user. Regions of interest (ROIs) with values above a correlation threshold are presented as potential detections (LeBien et al., 2020). We selected the threshold of 0.1 to increase the number of presences (although this increases the number of false positives and may capture variations in call types). We also tested the threshold of 0.3, but the number of presences for some species was low (Table S2). We manually inspected all potential detections to eliminate false positives using the score filter on all matches resulting from the automated classification to validate the results, marking only the true positives as a presence. The score filter groups the highest-scoring matches in descending order, optimizing the time to find true positives with manual inspection.

Occupancy models

We use the presence/absence matrix (1 presence or absence per sampling day) generated after the semi-automatic identification model's classification to fit dynamic occupancy models through the *colext* function of the Unmarked package in R (MacKenzie et al. 2003). We organized our presence/absence matrix, including all sites as rows and each day of sampling as a column, for the 4 sampling seasons, with September as the first sampling season. We chose to use days as sampling units as they are suitable for occupancy analysis and reduce the volume of data that would become unfeasible when using recordings/minutes as units.

Dynamic occupancy models allow inferring about the occurrence of a species on all sampling sites considering changes in occurrence due to colonization, migration/extinction processes, and imperfect detection (MacKenzie et al. 2003, Kéry and Chandler 2016). The dynamic occupancy models include a sampling-level parameter describing the probability of detection conditioned to occupancy (p) and 3 biological-level parameters describing the probability of a site being occupied in the first sampling (psi), the colonization (gam), and migration/extinction (eps) probabilities (MacKanzie et al. 2003).

We included models with the first-sampling occupancy as a function of 1 of the 3 environmental variables (number of *Tessaria*, number of *Cecropia*, and number of other trees). We included detection probability as a function of the sampling period because species occurrence in the floodplain can vary according to the flood pulse period (Rosenberg 1990). For each species, we tested 9 models, with parameters and covariates, and a null model with only the intercept, with the probabilities estimated for all sampling sites together (Table 2).

We compared all models according to the Akaike Information Criterion, adjusting for small sampling sizes (ΔAICc), and we estimated occupancy by averaging all models with ΔAICc < 2.0 using the function modavgPred from the AICmodavg package (Mazerolle 2020). To project each species' occupancy probability over the seasons, we used 1000 non-parametric bootstraps iterations using the best model. The best model was also used to project the detection frequency by season. We did all analyses in R version 4.0.3 (R Core Team 2020).

Results

The number of recordings with positive detections resulting from the classification of semi-automatic identification models ranged from 366 in White-browed Antbird to 7,789 in Spotted Tody-Flycatcher. The number of occupied sites varied from 3 in Silvered Antbird and Band-tailed Manakin to 16 in Straight-billed Woodcreeper (Table S2).

The variable number of *Tessaria* shrubs explained the initial occupancy probability in 4 species: Plain-crowned Spinetail, White-bellied Spinetail, Parker’s Spinetail, and Black-and-white Antbird (Fig. 2, Table 3). The model with the number of *Cecropia* explained the initial occupancy probability for Spotted Tody-Flycatcher. The number of other trees explained the initial occupancy probability in 3 species: White-browed Antbird, Peruvian Warbling-Antbird, and Band-tailed Manakin (Fig. 2, Table 3). Two species, Silvered Antbird, and Straight-billed Woodcreeper did not have the initial occupancy probability explained by any of the variables (Fig. 2, Table 3).

Based on the best model, the pattern of occupancy and detection probability among flood pulse seasons varied among species. The probability of occupancy among seasons doesn't vary significantly for any species (Fig. 3). Silvered Antbird had the lowest and Straight-billed Woodcreeper had the highest probability of occupancy (Fig. 3). The detection probability among seasons varied for most species, but not for Straight-billed Woodcreeper. A considerable variation in detection probability among seasons was observed in White-browed Antbird, Silvered Antbird, Peruvian Warbling-Antbird, and Band-tailed Manakin (Fig. 4). Band-tailed Manakin had the lowest detection probability (0.00; 1 presence in March) at the top of the rainy season, but it also had the highest value at the beginning of the rainy season (1.00; 279 presences in June–July; Fig. 4).

Discussion

Our models explained the probability of occupancy for 4 species in *Tessaria* shrub habitat, 1 species in *Cecropia* tree habitat, and 3 species in habitats with other trees. The pattern of occupancy among seasons did not vary for any species; however, detection probability did for most of them.

One of the most notable characteristics of the Amazonian basin floodplains is the heterogeneity of habitats characteristic of different ecological succession stages (Remsen and Parker III 1983). Some species are generalists and occupy diverse environments, but others have become microhabitat specialists (Rosenberg 1990, Robinson and Terborgh 1997). Similar to our study, Robinson and Terborgh (1997) also found more species restricted to habitats dominated by *Tessaria* shrubs than habitats with an abundance of *Cecropia* trees.

Our quantitative occupancy estimates agree with the association of White-bellied Spinetail, Parker's Spinetail, and Black-and-white Antbird with *Tessaria* (Rosenberg 1990, Remsen 2020a, Schulenberg and Rosenberg 2020a, b, c). Shrubs of *Tessaria* occur in early successional stages of floodplain vegetation and are an essential habitat for some lowland species (Remsen and Parker III 1983, Rosenberg 1990, Robinson and Terborgh 1997, Cohn-Haft et al. 2007a).

Species such as Black-and-white Antbird, Parker's Spinetail, and White-bellied Spinetail occasionally occur in other early successional habitats (Billerman et al. 2020, Schulenberg et al. 2007). However, they seem to be more common in areas with an abundance of *Tessaria* (Rosenberg 1990). For example, on river islands in Peru, White-bellied Spinetail practically occurred only in *Tessaria*, and 55% of the foraging behavior occurred associated with this shrub (Rosenberg 1990). The vegetation structure in these early stages of succession is so distinctive from other Amazonian habitats that most of the birds restricted to floodplains in the Amazon occur there (Petermann 1997). Due to the strong association of these species with *Tessaria*, future studies investigating the persistence of this shrub in areas under the impact of hydroelectric plants may have important implications for the conservation of these bird species (Melo et al. 2021).

This strong association between birds and a dominant plant species also occurs is similar to specialization in bamboo by some bird species in the Amazon. Some of these specialists occasionally occur in other habitats but are more common in areas with high bamboo density (Lebbin 2007, 2013). Although our results indicate that the occupancy of Plain-crowned Spinetail is associated with an increased number of *Tessaria, this species* occurs in several early successional stage habitats and prefers areas with dense vegetation, but its occurrence appears to be restricted to seasonally flooded habitats along rivers throughout its range of (Remsen 2020b).

In our study, we found the Spotted Tody-Flycatcher as the only species associated with an increased number of *Cecropia* trees, but the information available in the literature indicates that these species is a broader generalist, occurring in virtually all floodplain habitats and even in degraded habitats within cities (Lees and Moura 2017, Walther 2020). In our study, although Spotted Tody-Flycatcher is predicted to occupy areas impacted by the dam (sites 11–15 in Fig. S1), its occupancy was higher in areas with more *Cecropia* and *Tessaria*.

Another group of highly specialized birds in floodplains is forest-dependent species (Remsen and Parker III 1983). In our study, Peruvian Warbling-Antbird, White-browed Antbir*d*, and Band-tailed Manakin had an occupancy probability related to a higher number of other tree species that characterize the floodplain forest. Studies indicate that some floodplain forest species tend not to occupy upland forest areas (Rowedder et al. 2021). Interspecific aggressiveness and territoriality between congeneric species that occupy different habitats in successional stages may be a hypothesis that explains why some floodplain species do not occur on terra firme (Robinson and Terborgh 1997). Forest species may have ecological and behavioral limitations that prevent them from crossing large areas of open habitats (Less and Peres 2009), making the forest floodplain specialist species a priority for conservation since impacts such as dams can convert floodplain forests into open habitats (Cochrane et al. 2017, Melo et al. 2021).

In our study, 2 species did not have the probability of occupancy associated with any of the 3 variables. The Straight-billed Woodcreeper is a habitat generalist, occurring in various habitat types throughout its range (Marantz et al. 2020). In the case of Silvered Antbird, other essential elements of the landscape, which were not evaluated in our study, maybe more associated with the occupancy patterns of this species, such as the presence of vegetation above water (Zimmer et al. 2020). Likewise, future studies may further advance the understanding of these habitat relationships by testing the occupancy with more variables (e.g., *Gynnerium* spp. cane stands) that were not tested in our study.

The occupancy among the different periods of the flood pulse didn’t vary for any species, indicating that even floodplain understory species maintain their territories as long as there is still vegetation above the water. Recent studies have revealed that forest floodplain species change the foraging height following the rise in the water level in the rainy season (Rowedder et al. 2021). In the case of species that occupy habitats with naturally lower vegetation of the early successional stages of the floodplain, there is a gap in knowledge about the response of these birds to the decrease in available habitat during the rainy season. Our results demonstrate that the species we study remain on the same sites at different stages of the flood pulse seasons. This result is significant for the knowledge of the ecology of species considered specialists in floodplain fluvial islands (White-bellied Spinetail, Parker’s Spinetail, and Black-and-white Antbird in our study), which already occupy a spatially limited environment.

The detection probability among seasons varied considerably for most species. In most birds, the detection probability is strongly related to vocal activity. It can vary throughout the day, throughout the year, and among years (Campos-Cerqueira and Aide 2016, Odom et al. 2016, Jahn et al. 2017, Demko and Mennill 2018, Peréz-Granados et al. 2019) and is influenced by both endogenous factors, such as hormonal changes during the reproductive period (Odom et al. 2016, Demko and Mennil 2018), and exogenous ones, such as moonlight and temperature (Pérez-Granados et al. 2020).

It is possible that the detection probability variation that we found in our study is related to the period of reproductive activity that differs among the species of our study. For example, Spotted Tody-Flycatcher has the highest detection probability in the ebb season, coinciding with the known reproductive period for this species in the floodplains of the Madeira River (Melo and Greeney 2019). In the Band-tailed Manakin, males vocalize in leks (Kirwan and Green 2011). The variation we found indicates that the peak of male vocalization in the Madeira River floodplains occurs during the dry season and decreases at the beginning of the rainy season, possibly due to the presence of active nests. During the rainy season, practically no vocal activity occurs, perhaps indicating the post-reproductive period. The 3 river island specialists closely associated with *Tessaria* had the highest probability of detection during the dry season, which may indicate the breeding season for birds specializing in this habitat type.

Our results provide more information about the habitat preferences of some floodplain species and highlight the importance of *Tessaria integrifolia* for the conservation and maintenance of species diversity in the floodplain. New studies using a larger number of variables and covering a larger region could deepen the patterns found here. Increasing our knowledge on the habitat requirements of species could be fundamental in a scenario of increasing threats to the floodplains, such as the planning for the implementation of several hydroelectric plants in the Amazon (Latrubesse et al. 2017, 2020).

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Table 1. Selected floodplain bird species and whether they are restricted to riverine habitats in the Amazon according to information available in Birds of the World (Billerman et al. 2020).

Family	**Common name**	**Scientific name**	**Habitat**	**Endemic to the Amazonia**
Dendrocolaptidae	Straight-billed Woodcreeper	*Dendroplex picus*	Several different habitat types along with its distribution	No
Furnariidae	Plain-crowned Spinetail	*Synallaxis gujanensis*	Floodplains	Yes
Furnariidae	White-bellied Spinetail	*Mazaria propinqua*	River island specialist	Yes
Furnariidae	Parker's Spinetail	*Cranioleuca vulpecula*	River island specialist	Yes
Thamnophilidae	Black-and-white Antbird	*Myrmochanes hemileucus*	River island specialist	Yes
Thamnophilidae	White-browed Antbird	*Myrmoborus leucophrys*	Mainly floodplain	Yes
Thamnophilidae	Silvered Antbird	*Slateria naevia*	Floodplains, and locally along streams in upland forest	Yes

Thamnophilidae	Peruvian Warbling Antbird	*Hypocnemis peruviana*	Mainly floodplain forest, less frequently in upland forest	Yes
Rhynchocyclidae	Spotted Tody-Flycatcher	*Todirostrum maculatum*	Associated with wet areas, also disturbed sites	Yes
Pipridae	Band-tailed Manakin	*Pipra fasciicauda*	Floodplain and gallery forest	No

Table 2. List of the dynamic occupancy models. Probability of a site being occupied in the first sampling (psi), the colonization (gam), migration/extinction (eps) probabilities, and probability of detection conditioned to occupancy (p). The Y argument means an effect on the model parameter.

Model	Description
psi(.)gam(.)eps(.)p(.)	Null model, without effect in occupancy, colonization, extinction, and detection
psi(.)gam(.)eps(.)p(Y)	No effect in occupancy, colonization, extinction, but season conditioning the detection probability
psi(.)gam(Y)eps(Y)p(.)	Season affecting colonization and extinction, but not occupancy and detection probability

psi(.)gam(Y)eps(Y)p(Y)	Season affecting colonization, extinction, and detection probability
psi(Tree)gam(Y)eps(Y)p(Y)	Number of trees affecting probability a site be occupied in the first sampling, and season affecting colonization, extinction, and detection probability
psi(Cecropia)gam(Y)eps(Y)p(Y)	Number of *Cecropia* affecting probability a site be occupied in the first sampling, and season affecting colonization, extinction, and detection probability
psi(Tessaria)gam(Y)eps(Y)p(Y)	Number of *Tessaria* affecting probability a site be occupied in the first sampling, and season affecting colonization, extinction, and detection probability
psi(Tree)gam(.)eps(.)p(Y)	Number of *Tessaria* affecting probability a site be occupied in the first sampling, and season affecting the detection probability
psi(Cecropia)gam(.)eps(.)p(Y)	Number of *Cecropia* affecting probability a site be occupied in the first sampling, and season affecting the detection probability
psi(Tessaria)gam(.)eps(.)p(Y)	Number of *Tessaria* affecting probability a site be occupied in the first sampling, and season affecting the detection probability

Table 3. All dynamic occupancy model for each bird species. Probability of a site being occupied in the first sampling (psi), the colonization (gam), migration/extinction (eps) probabilities, and probability of detection conditioned to occupancy (p). The Y argument means an effect on the model parameter.

Species	**Best occupancy model**	**Number of parameters**	**AICc**	**ΔAICc**	**Weight**	**Cumulative weight**
Straight-billed Woodcreeper	psi(.)gam(.)eps(.)p(.)	4	1285.07	0	0.84	0.84
	psi(Tree)gam(.)eps(.)p(Y)	8	1289.95	4.88	0.07	0.91
	psi(.)gam(.)eps(.)p(Y)	7	1290.26	5.19	0.06	0.97
	psi(Tessaria)gam(.)eps(.)p(Y)	8	1293.36	8.28	0.01	0.98
	psi(Cecropia)gam(.)eps(.)p(Y)	8	1293.51	8.44	0.01	1
	psi(.)gam(Y)eps(Y)p(.)	8	1296.23	11.16	0	1
	psi(.)gam(Y)eps(Y)p(Y)	11	1317.23	32.16	0	1

	psi(Tree)gam(Y)eps(Y)p(Y)	12	1326.98	41.91	0	1
	psi(Cecropia)gam(Y)eps(Y)p(Y)	12	1330.55	45.47	0	1
	psi(Tessaria)gam(Y)eps(Y)p(Y)	12	1330.85	45.78	0	1
Plain-crowned Spinetail	psi(Tessaria)gam(.)eps(.)p(Y)	8	485.72	0	0.91	0.91
	psi(.)gam(.)eps(.)p(.)	4	490.59	4.87	0.08	0.98
	psi(.)gam(.)eps(.)p(Y)	7	494.81	9.09	0.08	0.99
	psi(Tree)gam(.)eps(.)p(Y)	8	496.11	10.39	0.01	1
	psi(Cecropia)gam(.)eps(.)p(Y)	8	501.02	15.3	0.01	1
	psi(.)gam(Y)eps(Y)p(.)	8	503.52	17.8	0	1
	psi(.)gam(Y)eps(Y)p(Y)	11	523.89	38.17	0	1
	psi(Tessaria)gam(Y)eps(Y)p(Y)	12	524.96	39.24	0	1
	psi(Tree)gam(Y)eps(Y)p(Y)	12	535.28	49.57	0	1

	psi(Cecropia)gam(Y)eps(Y)p(Y)	12	540.17	54.45	0	1
White-bellied Spinetail	psi(Tessaria)gam(.)eps(.)p(Y)	8	388.08	0	0.98	0.98
	psi(.)gam(.)eps(.)p(.)	4	396.97	8.89	0.01	0.98
	psi(Tree)gam(.)eps(.)p(Y)	8	399.99	11.91	0	0.99
	psi(.)gam(.)eps(.)p(Y)	7	400.06	11.98	0	1
	psi(Cecropia)gam(.)eps(.)p(Y)	8	406.26	18.17	0	1
	psi(.)gam(Y)eps(Y)p(.)	8	416.54	28.46	0	1
	psi(Tessaria)gam(Y)eps(Y)p(Y)	12	434.21	46.12	0	1
	psi(.)gam(Y)eps(Y)p(Y)	11	435.61	47.53	0	1
	psi(Tree)gam(Y)eps(Y)p(Y)	12	445.61	57.53	0	1
	psi(Cecropia)gam(Y)eps(Y)p(Y)	12	451.88	63.79	0	1
Parker’s Spinetail	psi(Tessaria)gam(.)eps(.)p(Y)	8	342	0	0.81	0.81
	psi(.)gam(.)eps(.)p(.)	4	344.94	2.94	0.19	1

	psi(Tree)gam(.)eps(.)p(Y)	8	353.96	11.96	0	1
	psi(.)gam(.)eps(.)p(Y)	7	354.02	12.02	0	1
	psi(.)gam(Y)eps(Y)p(.)	8	357.09	15.08	0	1
	psi(Cecropia)gam(.)eps(.)p(Y)	8	360.22	18.22	0	1
	psi(Tessaria)gam(Y)eps(Y)p(Y)	12	380.49	38.49	0	1
	psi(.)gam(Y)eps(Y)p(Y)	11	382.17	40.17	0	1
	psi(Tree)gam(Y)eps(Y)p(Y)	12	392.16	50.16	0	1
	psi(Cecropia)gam(Y)eps(Y)p(Y)	12	398.44	56.44	0	1
Black-and-white Spinetail	psi(Tessaria)gam(.)eps(.)p(Y)	8	311.14	0	0.88	0.88
	psi(.)gam(.)eps(.)p(.)	4	315.2	4.06	0.12	1
	psi(Tree)gam(.)eps(.)p(Y)	8	323.09	11.95	0	1
	psi(.)gam(.)eps(.)p(Y)	7	323.15	12.01	0	1
	psi(Cecropia)gam(.)eps(.)p(Y)	8	329.35	18.21	0	1

	psi(.)gam(Y)eps(Y)p(.)	8	334.77	23.63	0	1
	psi(Tessaria)gam(Y)eps(Y)p(Y)	12	357.26	46.12	0	1
	psi(.)gam(Y)eps(Y)p(Y)	11	358.71	47.56	0	1
	psi(Tree)gam(Y)eps(Y)p(Y)	12	368.7	57.56	0	1
	psi(Cecropia)gam(Y)eps(Y)p(Y)	12	374.97	63.83	0	1
White-browed Antbird	psi(Tree)gam(.)eps(.)p(Y)	8	338.1	0	0.52	0.52
	psi(.)gam(.)eps(.)p(Y)	7	338.66	0.56	039	0.52
	psi(Cecropia)gam(.)eps(.)p(Y)	8	343.12	5.02	0.04	0.91
	psi(Tessaria)gam(.)eps(.)p(Y)	8	343.26	5.16	0.04	0.96
	psi(.)gam(.)eps(.)p(.)	4	347.22	9.12	0.01	0.99
	psi(.)gam(Y)eps(Y)p(.)	8	362.59	24.49	0	1
	psi(.)gam(Y)eps(Y)p(Y)	11	369.98	31.88	0	1
	psi(Tree)gam(Y)eps(Y)p(Y)	12	379.49	41.39	0	1

	psi(Cecropia)gam(Y)eps(Y)p(Y)	12	384.51	46.41	0	1
	psi(Tessaria)gam(Y)eps(Y)p(Y)	12	385.03	46.91	0	1
Silvered Antbird	psi(.)gam(.)eps(.)p(Y)	7	189.11	0	0.87	0.87
	psi(Tessaria)gam(.)eps(.)p(Y)	8	194.68	5.57	0.05	0.92
	psi(Tree)gam(.)eps(.)p(Y)	8	195.24	6.13	0.04	0.96
	psi(Cecropia)gam(.)eps(.)p(Y)	8	195.26	6.15	0.04	1
	psi(.)gam(.)eps(.)p(.)	11	208.45	19.34	0	1
	psi(.)gam(Y)eps(Y)p(.)	12	219.58	30.47	0	1
	psi(.)gam(Y)eps(Y)p(Y)	12	220.05	30.94	0	1
	psi(Tessaria)gam(Y)eps(Y)p(Y)	12	235.67	46.56	0	1
	psi(Tree)gam(Y)eps(Y)p(Y)	8	236.24	47.13	0	1
	psi(Cecropia)gam(Y)eps(Y)p(Y)	4	236.26	47.15	0	1
Peruvian Warbling-Antbird	psi(Tree)gam(.)eps(.)p(Y)	8	495.29	0	0.88	0.88

	psi(.)gam(.)eps(.)p(Y)	7	500	4.71	0.08	0.97
	psi(Tessaria)gam(.)eps(.)p(Y)	8	502.18	6.89	0.03	0.99
	psi(Cecropia)gam(.)eps(.)p(Y)	8	505.04	9.75	0.01	1
	psi(.)gam(.)eps(.)p(.)	4	521.91	26.61	0	1
	psi(.)gam(Y)eps(Y)p(Y)	11	533.67	38.38	0	1
	psi(Tree)gam(Y)eps(Y)p(Y)	12	539.04	43.75	0	1
	psi(.)gam(Y)eps(Y)p(.)	8	539.6	44.31	0	1
	psi(Tessaria)gam(Y)eps(Y)p(Y)	12	546.48	51.19	0	1
	psi(Cecropia)gam(Y)eps(Y)p(Y)	12	548.79	53.5	0	1
Spotted Tody-Flycatcher	psi(Cecropia)gam(.)eps(.)p(Y)	8	457.66	0	0.49	0.49
	psi(Tessaria)gam(.)eps(.)p(Y)	8	459.5	1.84	0.2	0.69
	psi(Tree)gam(.)eps(.)p(Y)	8	459.75	2.09	0.17	0.86
	psi(Cecropia)gam(Y)eps(Y)p(Y)	7	460.19	2.53	0.14	1

	psi(Tessaria)gam(Y)eps(Y)p(Y)	4	487.1	29.44	0	1
	psi(Tree)gam(Y)eps(Y)p(Y)	11	491.34	33.68	0	1
	psi(.)gam(.)eps(.)p(Y)	12	498.88	41.22	0	1
	psi(.)gam(Y)eps(Y)p(Y)	12	500.81	43.15	0	1
	psi(.)gam(.)eps(.)p(.)	12	500.97	43.31	0	1
	psi(.)gam(Y)eps(Y)p(.)	8	502.27	44.61	0	1
Band-tailed Manakin	psi(Tree)gam(.)eps(.)p(Y)	8	176.48	0	0.80	-73.04
	psi(.)gam(.)eps(.)p(Y)	7	180.19	3.71	0.12	-78
	psi(Cecropia)gam(.)eps(.)p(Y)	8	182.44	4.96	0.07	-75.52
	psi(Tessaria)gam(.)eps(.)p(Y)	8	184.79	8.31	0.01	-.77.2
	psi(.)gam(Y)eps(Y)p(Y)	11	203.49	27.01	0	-71.89
	psi(Tree)gam(Y)eps(Y)p(Y)	12	209.85	33.37	0	-66.93
	psi(Cecropia)gam(Y)eps(Y)p(Y)	12	214.8	38.32	0	-69.4

psi(Tessaria)gam(Y)eps(Y)p(Y)	12	218.12	41.64	0	-71.06
psi(.)gam(.)eps(.)p(.)	4	275.66	99.18	0	-132.4
psi(.)gam(Y)eps(Y)p(.)	8	282.23	105.75	0	125.91

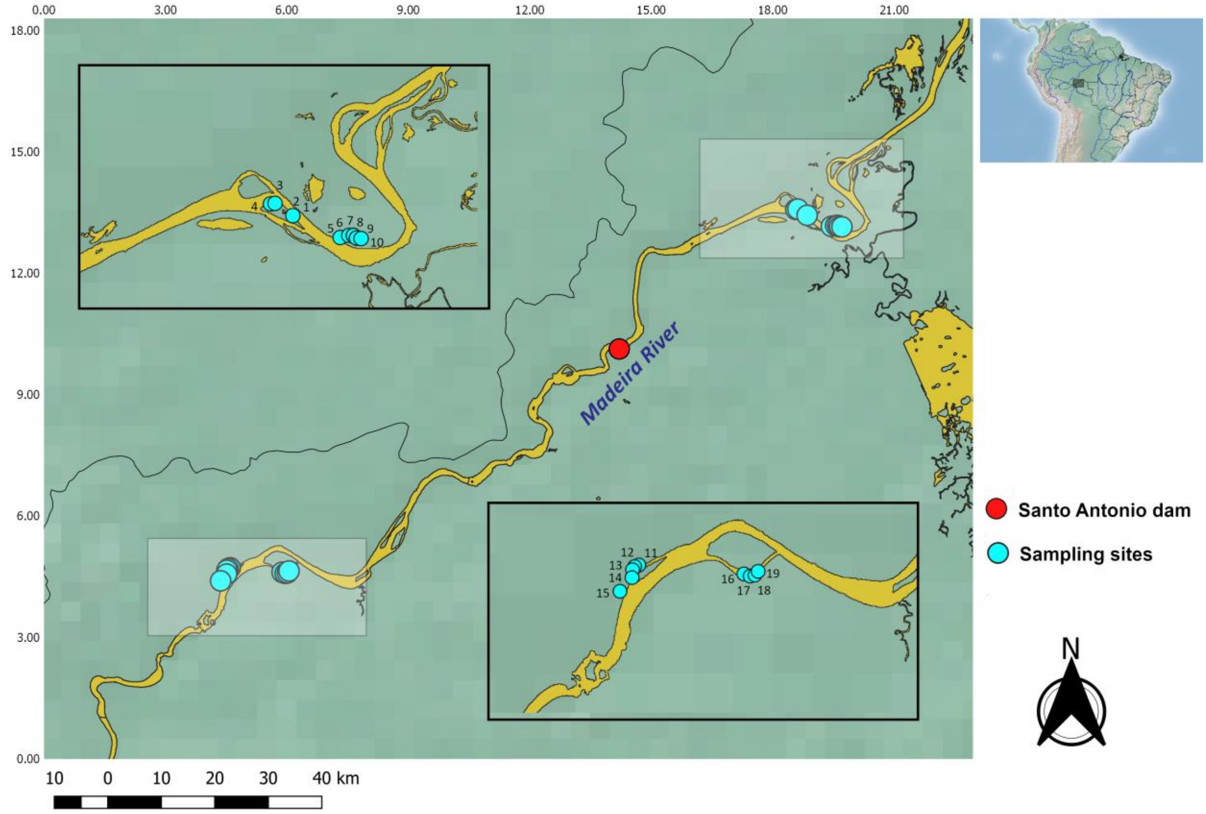

Figure 1. Map of the studied area on the Madeira River and its location in Brazil. The number of sites is the same as in Table S1.

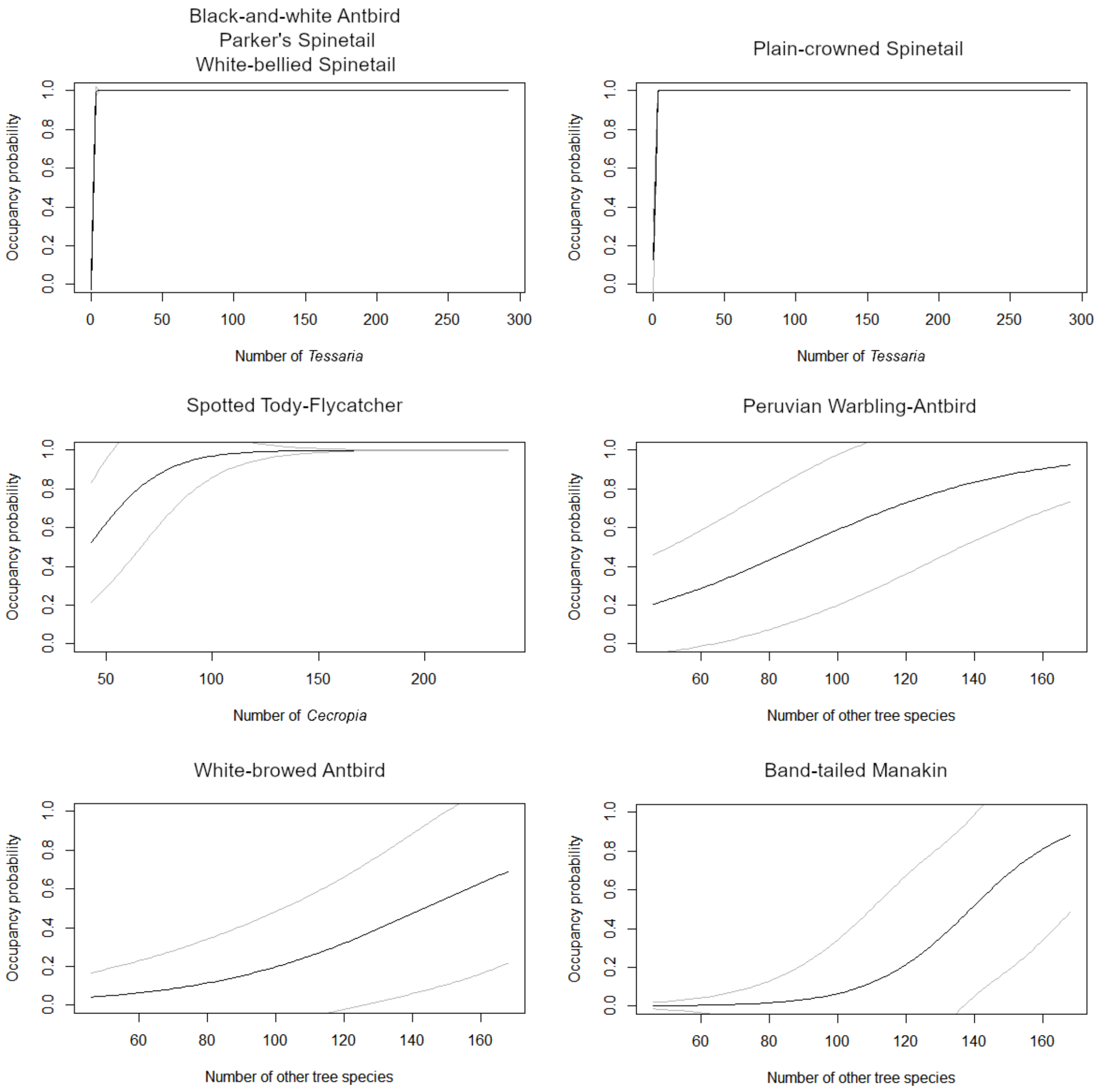

Figure 2. Predicted relationship between occupancy and environmental variables based on the best model. Gray lines represent the 95% confidence interval.

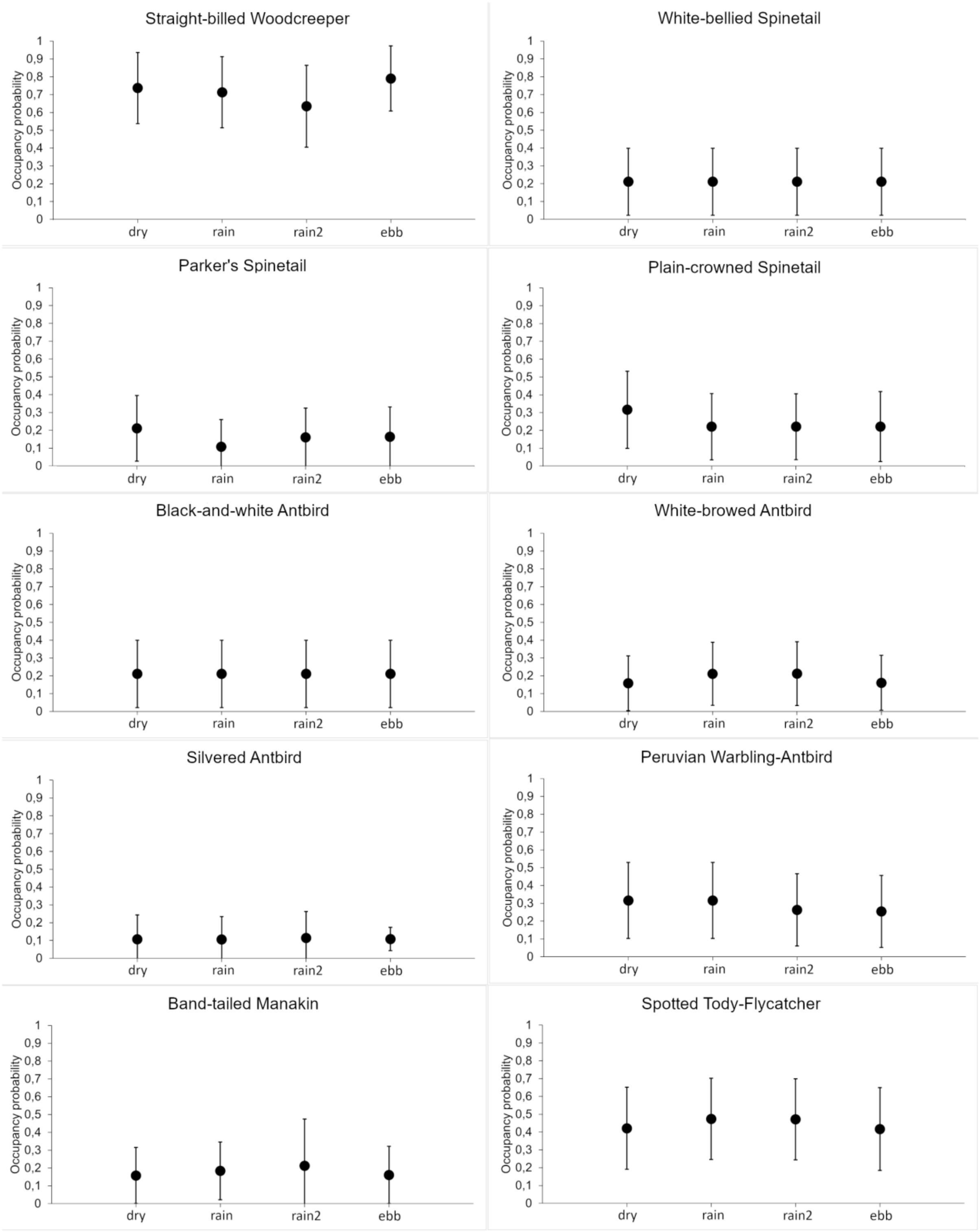

Figure 3. Occupancy probability and 95% confidence interval between the flood pulse seasons for each bird species predicted by the best model. Rain = beginning of the rain season, rain2 = top of the rain season.

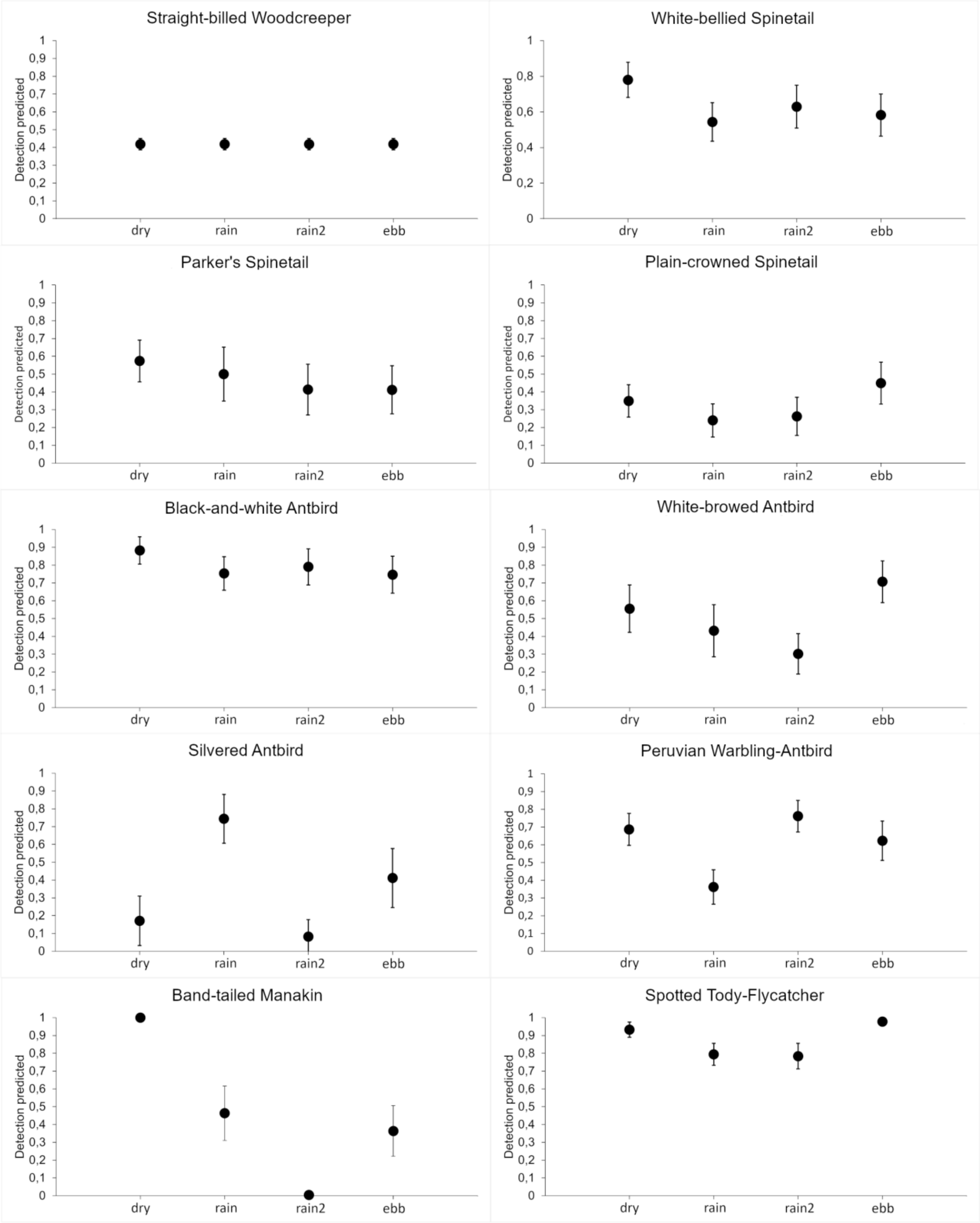

Figure 4. Detection predicted and 95% confidence interval between the flood pulse seasons for each bird species predicted by the best model. Rain = beginning of the rain season, rain2 = top of the rain season.

Understanding the spatial and temporal occupancy patterns of floodplain bird species

Supplemental material

Table S1. The number of *Cecropia* trees., *Tessaria integrifolia*, and other tree species in a 20 x 100 m plot at each sampling site.

Environmental variable	**Sites**																		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Number of *Cecropia* sp.	74	263	45	48	45	0	0	0	54	15	13	26	33	11	0	158	40	89	0
Number of *Tessaria integrifolia*	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	64	256	292
Number of other tree species	2	8	32	46	115	140	154	137	121	168	8	9	14	7	2	11	4	2	0

Table S2. The number of matches resulting from pattern matching with thresholds of 0.1 and 0.2 and the number of true presences after manual validation.

Species	**Threshold 0.1**		**Threshold 0.3**	
	Number of matches	**Number of true presences**	**Number of matches**	**Number of true presences**
Straight-billed Woodcreeper	25,341	589	787	200
Plain-crowned Spinetail	53,728	741	712	242
White-bellied Spinetail	41,818	1,511	690	276
Parker’s Spinetail	79,702	373	5,066	195
Black-and-white Antbird	56,150	1,332	1,349	297
White-browed Antbird	18,768	366	570	197
Silvered Antbird	25,573	378	580	182

Peruvian Warbling Antbird	34,214	874	1,344	420
Spotted Tody-Flycatcher	24,467	7,789	769	745
Band-tailed Manakin	73,907	1,370	2,745	840

Table S3. Number of occupied sites per sampling season and the total number of occupied sites for each species.

Species	**Dry season**	**Beginning of the rain season**	**Top of the rain season**	**Ebb season**	**Total number of occupied sites**
Straight-billed Woodcreeper	14	14	12	13	16
Plain-crowned Spinetail	9	8	4	8	11
White-bellied Spinetail	4	4	4	4	4
Parker’s Spinetail	4	2	3	3	4
Black-and-white Antbird	4	4	4	4	4
White-browed Antbird	4	3	4	3	4
Silvered Antbird	2	2	1	2	3
Peruvian Warbling Antbird	6	5	5	6	6
Spotted Tody-Flycatcher	8	9	8	7	9

Band-tailed Manakin	3	3	1	3	3

Table S4. Presence and absence of each species per sampling site.

	Sites																		
Species	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Straight-billed Woodcreeper	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1
Plain-crowned Spinetail	1	1	1	1	0	0	0	0	0	0	1	0	1	1	0	1	1	1	1
White-bellied Spinetail	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Parker’s Spinetail	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Black-and-white Antbird	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
White-browed Antbird	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
Silvered Antbird	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
Peruvian Warbling Antbird	0	0	0	0	1	0	1	1	1	1	0	0	1	0	0	0	0	0	0
Spotted Tody-Flycatcher	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1

Band-tailed Manakin	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0

Figure S1. Habitats sampled in the Madeira River: (a) site dominated by *Tessaria integrifolia* (site 19); (b) site dominated by *Cecropia* sp. (site 2); (c) lowland forest (site 7); (d) site degraded by the Santo Antônio dam (site 13). The characteristics of the sites are in Table S1.

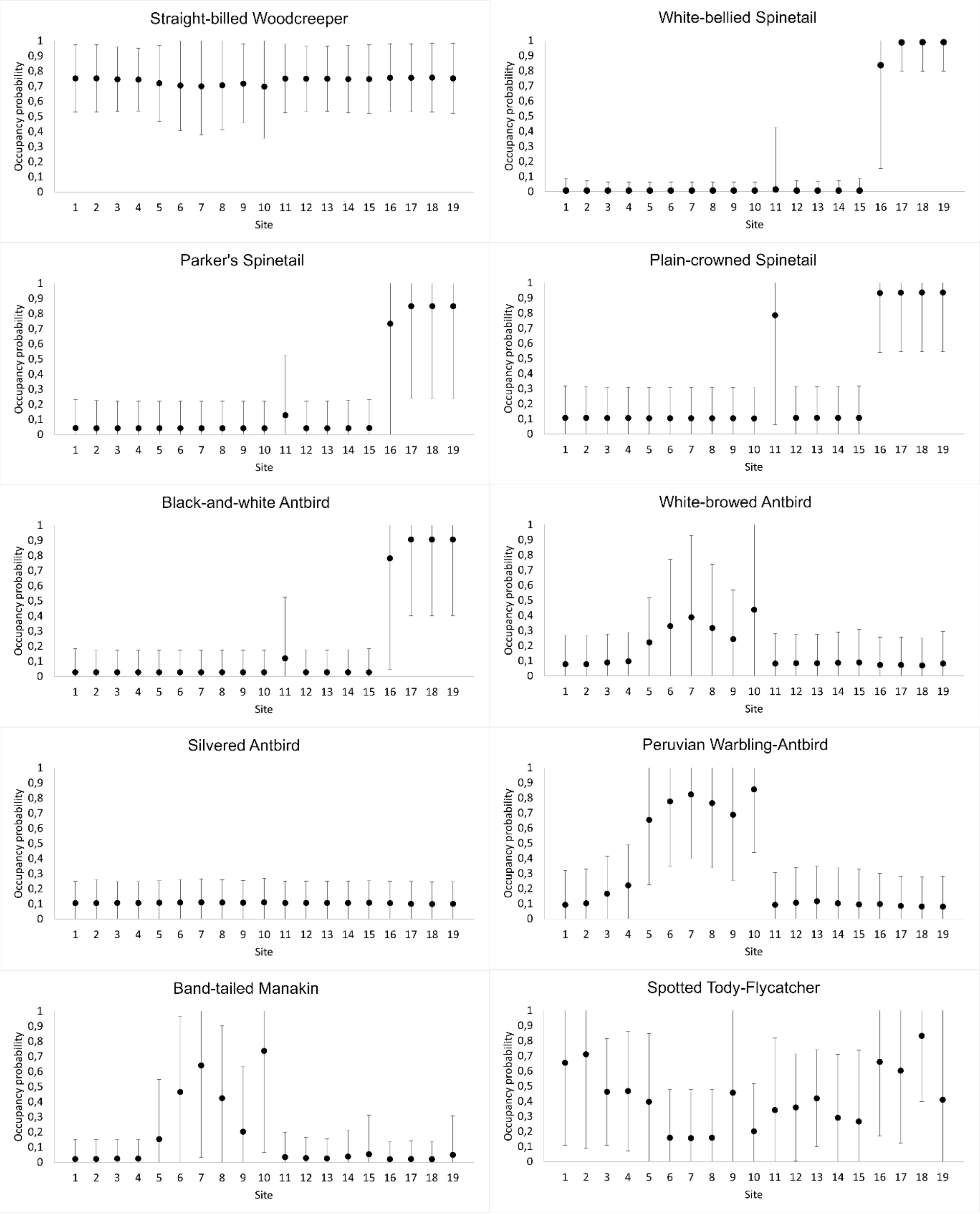

Figure S2. Occupancy probability of each species by sampling site. Error bars represent 95% confidence interval. Sites 11 to 15 correspond to the sites most impacted by the dam.

Considerações finais

Os resultados apresentados nessa tese contribuem para o conhecimento das espécies de aves de várzea, um ambiente historicamente negligenciado em pesquisas ornitológicas na Amazônia, especialmente quando comparado as comunidades de aves de florestas de terra firme.

No **Capítulo 1** investigamos como a comunidade de aves de várzea responde a implantação de uma grande usina hidroelétrica na Amazônia. Nossos resultados revelam que o impacto depende da afinidade ambiental de cada espécie, sendo que as espécies florestais são as mais impactadas, devido à forte alteração do habitat, com a conversão da floresta em um ambiente mais aberto. Essa alteração promove a extinção local de espécies florestais, embora espécies altamente especializadas e restritas as várzeas, como o grupo de espécies típicas dos habitats em estágios iniciais de sucessão ecológica e consideradas especialistas em ilhas fluviais persistem na área impactada pelo reservatório da usina. Esse é um resultado importante da perspectiva da conservação de espécies de várzea, uma vez que espécies exclusivas da várzea estão potencialmente mais ameaçadas por alterações no habitat. Aparentemente, esse é o primeiro estudo que foca no impacto de uma barragem nas espécies de várzea.

Com base em nossos resultados recomendamos que futuros estudos que avaliem o impacto de usinas hidroelétricas na Amazônia priorizem as espécies restritas as várzeas, levando em conta a afinidade de habitat de cada espécie. Também é fundamental que seja feito um monitoramento a médio e longo prazo a jusante das barragens, com um desenho amostral que considere amostragens antes e depois de concluído o empreendimento. A criação de áreas protegidas que incluam áreas de várzea, inclusive ilhas fluviais, deve ser adotada como medida compensatória para a implementação de novos empreendimentos hidroelétricos.

No **Capítulo 2** contribuímos com novas informações sobre os padrões de ocupação e detectabilidade de algumas espécies com diferentes graus de especialização na várzea. Nossos resultados confirmam que espécies de plantas como *Tessaria integrifolia* são elementos importantes para algumas em relação a especialização das espécies de várzea. O aumento do conhecimento de quais elementos da paisagem da várzea são importantes para as espécies especialistas nesse ambiente pode ajudar no planejamento de ações de conservação e definição das espécies prioritárias para a conservação na várzea, além de auxiliar na compreensão da história evolutiva desses táxons e nos padrões biogeográficos observados nesse ambiente. Ao que tudo indica, este foi apenas o segundo estudo que investigou como algumas espécies de várzea respondem ao pulso de inundação e o primeiro que utilizou espécies não florestais para responder essa questão, com isso preenchendo uma importante lacuna no conhecimento da ecologia dessas espécies. Nosso resultado mostrou que a ocupação dos ambientes pelas espécies não muda ao longo das diferentes fases do pulso de inundação, porém a detectabilidade das espécies varia entre os períodos, o que indica que determinadas fases do pulso de inundação, como a estação seca, podem ser os melhores momentos para a realização de inventários ornitológicos nas várzeas.

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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).

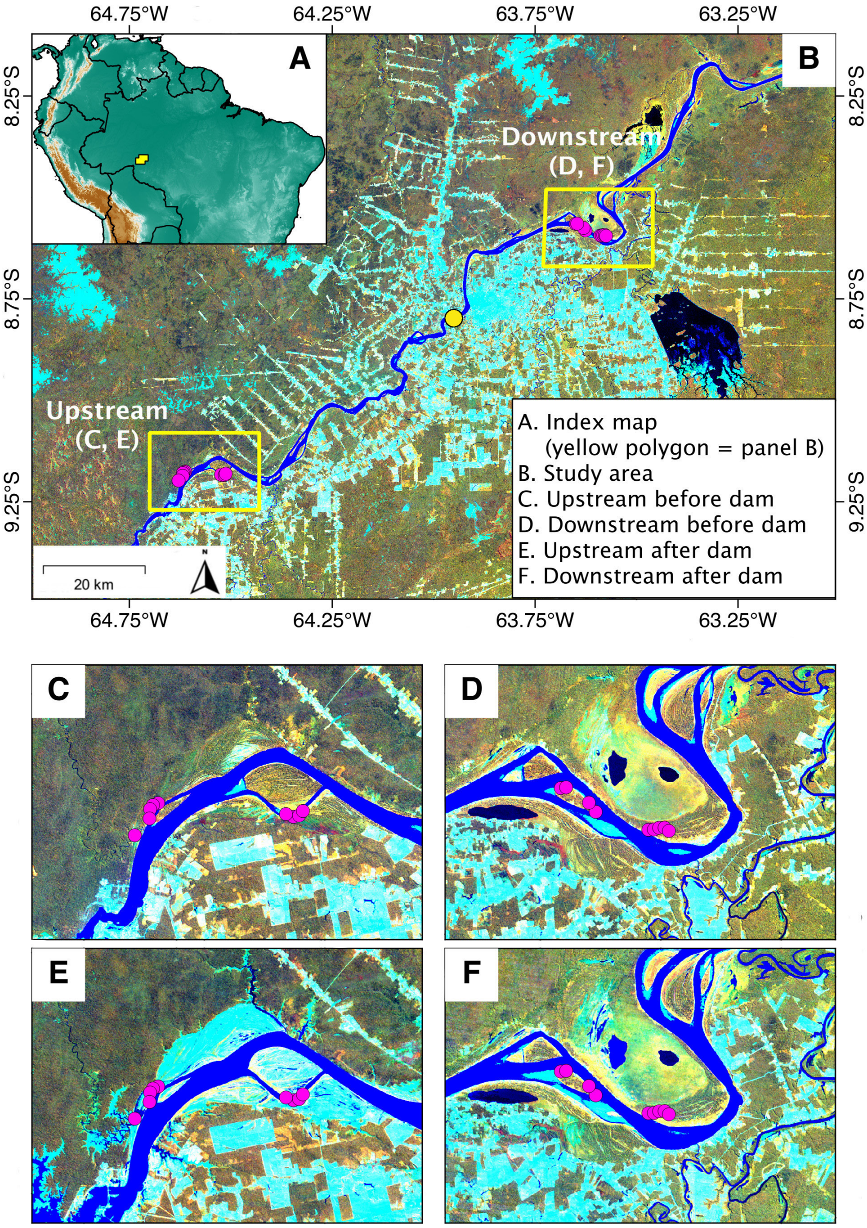

Figure 1. A – Location of the study area (yellow spot); B – Location of the Santo Antônio dam (yellow circle) and upseam and downstream bird sampling sites (pink circles) along the upper Madeira River, Rondônia state, Brazil; B-F – Landsat TM/ETM+ composite images in background false color with bands 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).

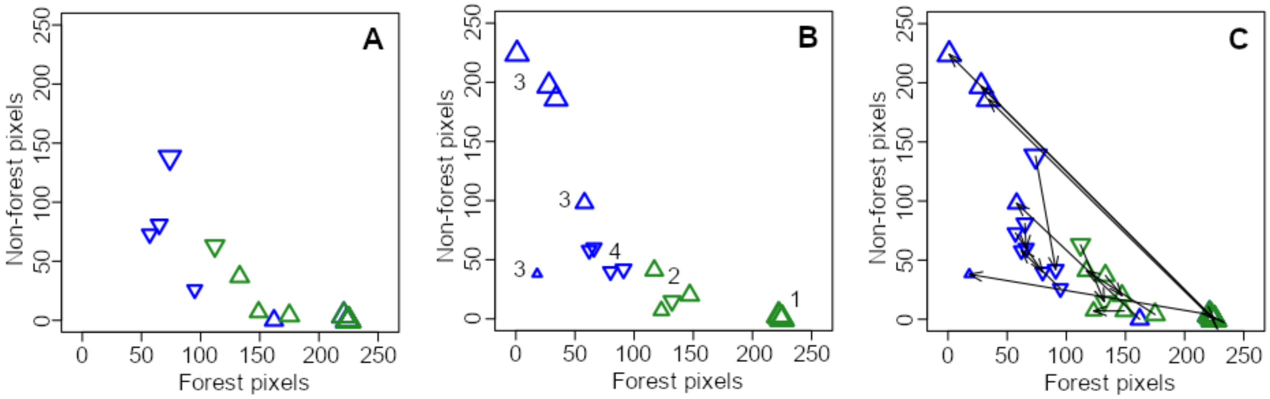

Figure 2. Scatterplots of the sampling sites downstream and upstream from the Santo Antônio dam on the Madeira River resulting from PCA showing how many pixels in a 15 by 15 pixel window centered over the sampling site in a Landsat TM/ETM+ composite image were classified as forest and how many as non-forest 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.

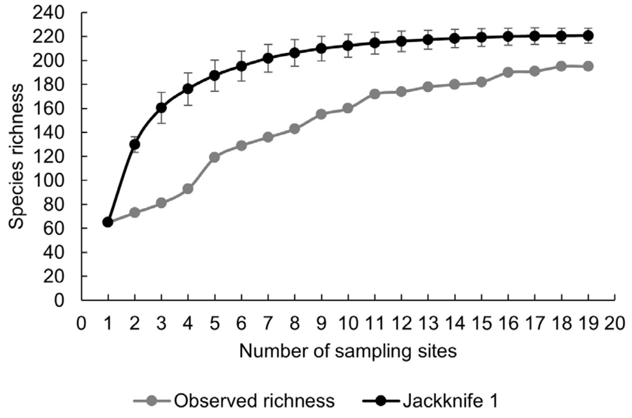

Figure 3. Species accumulation curves of observed and estimated (first order Jackknife estimator) species richness for floodplain avifauna sampled at 19 sites along the upper Madeira River.

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,

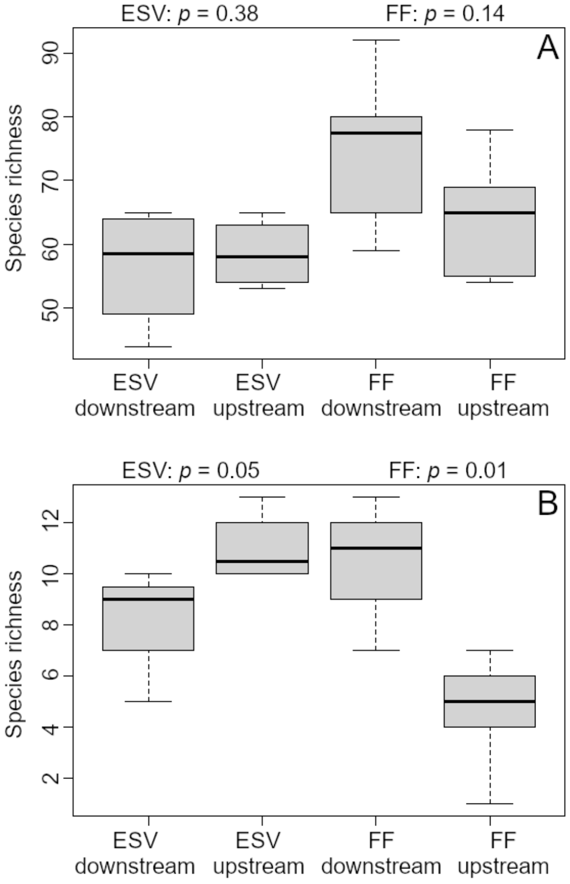

Figure 4. Species richness for all bird species (A), and floodplain specialists (B) in floodplain forest (FF) and early successional vegetation (ESV) sampling sites upstream and downstream from Santo Antônio dam on the Madeira River. The significance level of the Wilcoxon-Mann-Whitney test is shown.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

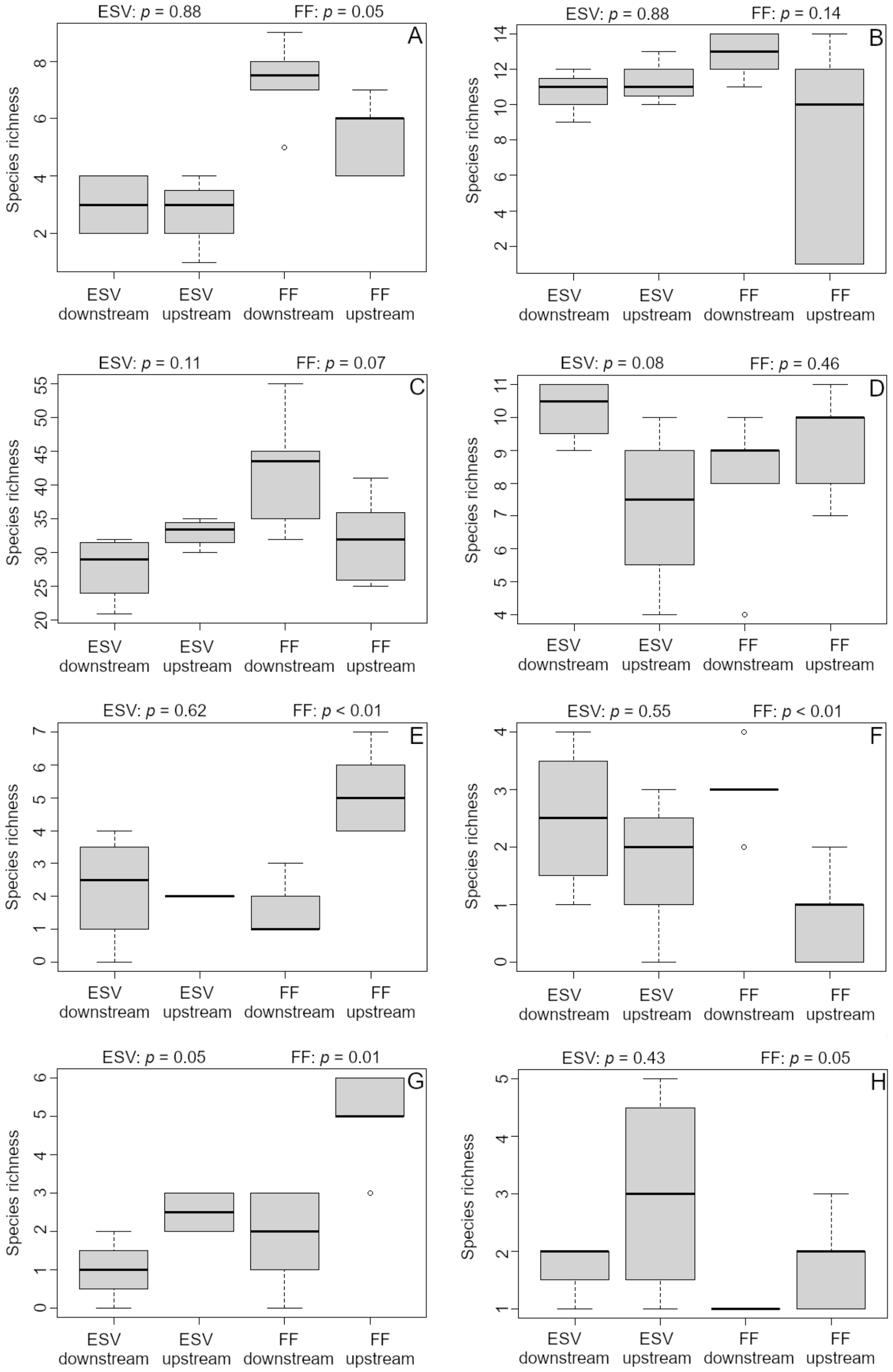

Figure 5. Species richness of different bird trophic guilds in floodplain forest (FF) and early successional vegetation (ESV) sampling sites upstream and downstream from Santo Antônio dam on the Madeira River. A – carnivores; B – frugivores; C – insectivores; D – omnivores; E – piscivores; F – nectarivores; 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, $p < 0.05$).

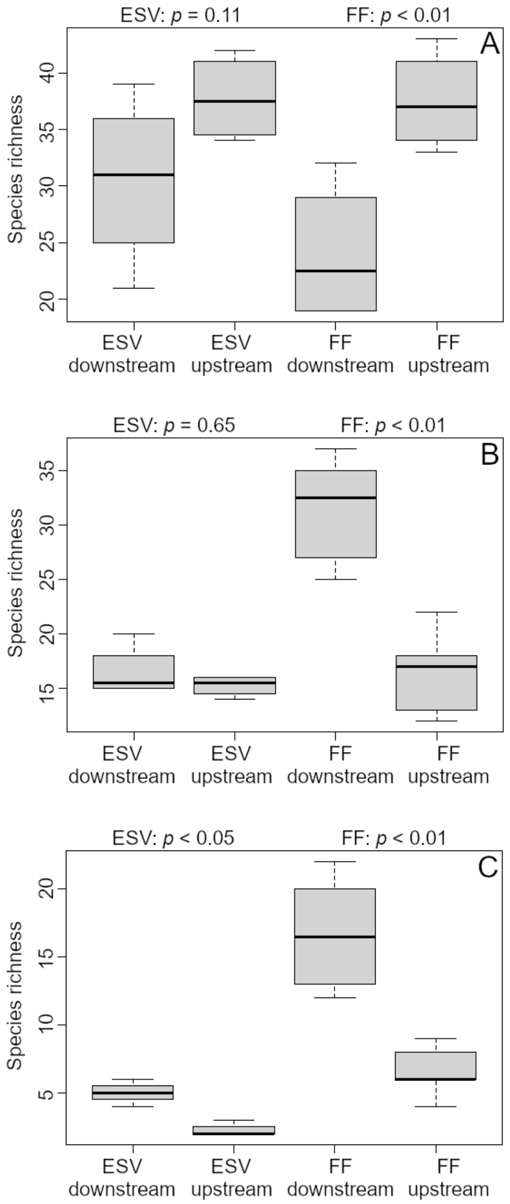

Figure 6. Species richness of birds in different levels of sensitivity to environmental disturbance in floodplain forest (FF) and early successional vegetation (ESV) sampling sites upstream and downstream from Santo Antônio dam on the Madeira River. A – low; B – medium; C – high sensitivity. The significance 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)

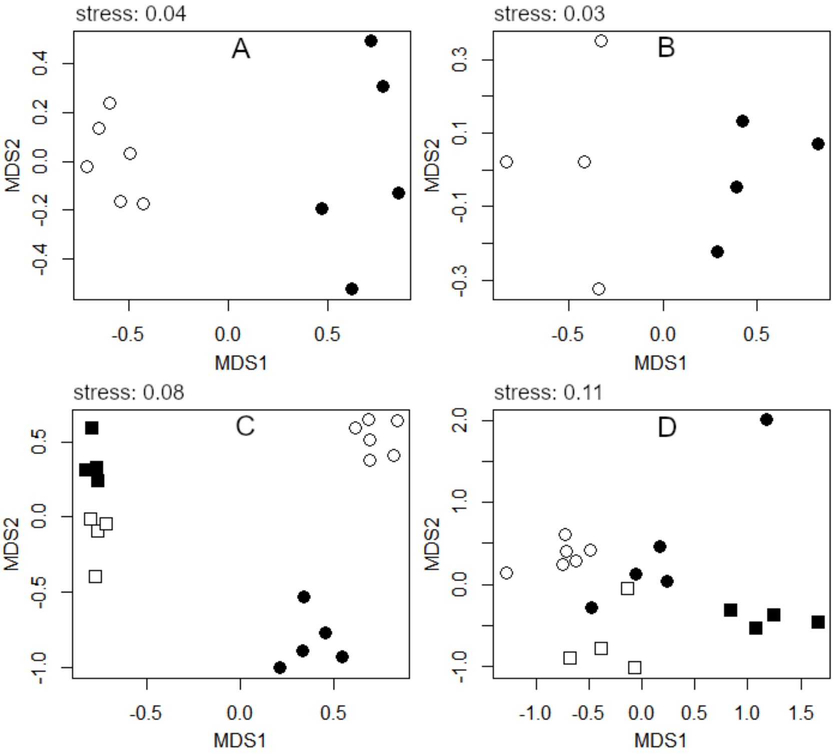

Figure 7. NMDS ordination of bird species composition based on presence/absence data for floodplain forest (A), early successional vegetation (B), all sites combined (C), and only floodplain specialist species (D) upstream and downstream from Santo Antônio dam on the Madeira River. White symbols = downstream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

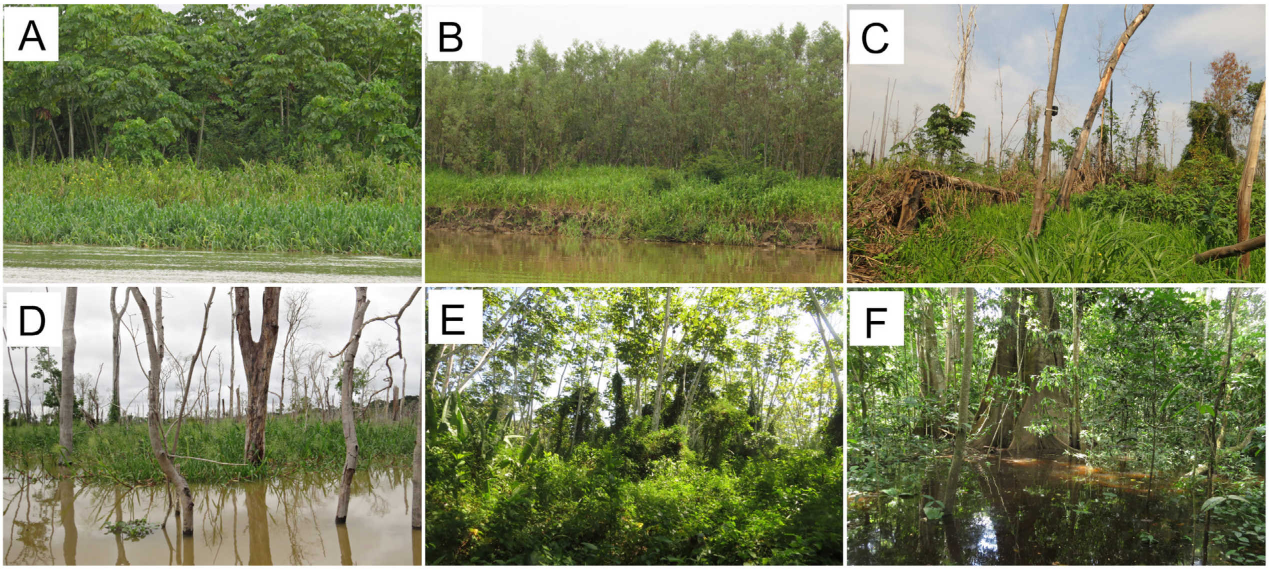

Figure S1. Sampling habitats in the upper Madeira River. Upstream (after the Santo Antônio dam reservoir filling): A – early successional vegetation dominated by *Cecropia* trees; B – early successional vegetation dominated by *Tessaria integrifolia*; C – dead floodplain forest in the dry season (September); 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).

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).

Species	Sensitivity	Guild	Downstream sites		Upstream sites	
			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		Upstream sites	
			Floodplain forest (6)	Early successional vegetation (4)	(Dead) floodplain forest (5)	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