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LUIZA PRESTES DE SOUZA

PESCA DOS GRANDES BAGRES MIGRADORES NA BACIA AMAZÔNICA: UMA TRAJETÓRIA DE SOBREPESCA

BELÉM, PA

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Tese de Doutorado apresentada ao Programa de Pós-graduação em Ecologia Aquática e Pesca, como requisito para obtenção do título de Doutor em Ecologia Aquática e Pesca pela Universidade Federal do Pará.

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DEDICATÓRIA

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".... Navego o rio Solimões/Amazonas, desde os Andes, pelo Amazonas, vindo ao Pará e Amapá, da cabeceira à foz, procurando desvendá-lo, mas com isso, acabo me encontrando..."

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SUMÁRIO

APRESENTAÇÃO DA TESE

A presente tese está estruturada considerando o enfoque de cada capítulo, com uma introdução geral norteadora, objetivos gerais e específicos, materiais e métodos, dois capítulos em formato de artigos e considerações finais. Esse formato segue as normas do regimento da Pós-graduação em Ecologia Aquática e Pesca – PPGEAP, Resolução 4.782/2016 do Conselho Superior de Ensino, Pesquisa e Extensão – CONSEPE da Universidade Federal do Pará – UFPA.

O primeiro capítulo intitulado “Revisão das pescarias dos grandes bagres migradores na bacia Amazônica: uma trajetória de sobrepesca” teve por objetivos: (i) revisar a produção e a história geopolítica da pesca dos grandes bagres migradores na Amazônia, (ii) caracterizar a composição do tamanho dos peixes por região da bacia e suas implicações para a migração e o manejo pesqueiro, iii) revisar o estado das pescarias nas diferentes unidades populacionais, com ênfase na piramutaba *B. vaillantii* explotada pela frota pesqueira de arrasto no estuário do rio Amazonas; (iv) avaliar a eficácia das medidas de manejo e conservação adotadas para a pesca em escala continental dos grandes bagres migradores..

O segundo capítulo intitulado “Histórico de explotação da piramutaba, *Brachyplatystoma vaillantii*, no estuário do rio Amazonas, Brasil” teve por objetivo avaliar seu estoque no estuário do rio Amazonas integrando vários conjuntos de dados, incluindo captura, índice de abundância, composição do comprimento e informações biológicas. Também se discutiu o possível efeito de intervenções de manejo nas séries temporais de mortalidade por pesca e biomassa estimadas a partir da avaliação.

A seção de considerações finais reúne as principais ideias de cada capítulo em um único texto de conclusão da tese.

RESUMO

A explotação intensiva dos grandes bagres migradores tem ocorrido entre o estuário e às encostas dos Andes e tem causado a sobrepesca de algumas unidades populacionais, manifestando a baixa eficiência do manejo pesqueiro. Esta tese revisa o histórico de produção pesqueira dos grandes bagres migradores do gênero *Brachyplatystoma* (*B. rousseauxii; B. vaillantii; B. filamentosum* e *B. capapretum; B. platynemum* e *B. juruense*), considerado a região geopolítica de sua produção e a composição etária por região, e avalia o status de explotação e as medidas de gestão/conservação aplicada para manejar a principal pesca de bagre da bacia amazônica, a pesca de arrasto em parelha na foz Amazônica. A tese é apresentada em dois capítulos, sendo que o primeiro (i) descreve o histórico da pesca dos principais países que capturam esses recursos pesqueiros e (ii) apresenta um padrão espacial entre adultos e sub-adultos em diferentes regiões ao longo do rio Amazonas, (iii) avalia o rendimento máximo sustentável (MSY), a mortalidade por pesca (F) e a mortalidade em MSY (F_{MSY}) para a pesca de arrasto da piramutaba *B. vaillantii* no estuário da Amazônia, e (iv) testa as medidas de gestão através da tendência encontrada nos valores históricos de F usando Mann-Kendall. O segundo capítulo (i) avalia o status do estoque da piramutaba no estuário da amazônico usando diferentes conjuntos de dados (informações de biologia, dados de captura e de comprimento e um índice de abundância) na plataforma integrada Stock Synthesis (SS) versão 3.30.13, e (ii) investiga o possível efeito de intervenções de manejo nas séries temporais de mortalidade por pesca e biomassa. A presente tese elucida questões relacionadas a pesca e conservação dos grandes bagres migradores na bacia amazônica, apresenta novas abordagens na avaliação de estoques da pesca de arrasto da piramutaba *B. vaillantii* e traz à tona a preocupação com a sustentabilidade a longo prazo para essas e outras pescarias em larga escala na Amazônia.

Palavras-chave: *Brachyplatystoma*, pesca de arrasto, rio Amazonas, manejo da pesca, avaliação de estoque

ABSTRACT

The intensive exploitation of goliath catfish occurs between the estuary and piedmont Andes and leads overfishing in some unit populations, showing a low efficiency of the management plans. This thesis review the historic fisheries production of the goliath catfish (*B. rousseauxii; B. vaillantii; B. filamentosum e B. capapretum; B. platynemum* e *B. juruense*), considering the geopolitics production and age composition by region and assesses exploitation status and management/conservation measures applied to manage the central catfish fishing in the Amazon basin, pair trawling in the Amazon mouth. The thesis is presented in two chapters, the first of which (i) describes the fishing history of the leading countries that catch these fishery resources and (ii) presents a spatial pattern between adults and sub-adults in different regions along the Amazon River. (iii) assesses the maximum sustainable yield (MSY), fishing mortality (F), and MSY mortality (F_{MSY}) for piramutaba *B. vaillantii* trawl fishing in the Amazon estuary, and (iv) tests the measures management through the trend found in the historical values of F using Mann-Kendall. The second chapter (i) assesses the status of piramutaba stock in the Amazon estuary using different data sets (biology information, capture and length data, and an abundance index) on the integrated platform Stock Synthesis (SS) version 3.30.13, and (ii) investigates the possible effect of management interventions on fishing mortality and biomass time series. This thesis elucidates questions related to fishing and conservation of goliath catfish in the Amazon basin, presents new approaches in the assessment of piramutaba *B. vaillantii* trawl stocks, and highlights concerns about long-term sustainability for these and other large-scale fisheries in Amazon basin.

Keywords: *Brachyplatystoma*, trawl fishery, Amazon river, fisheries management, stock assessment

1. INTRODUÇÃO GERAL

As pescarias amazônicas são tradicionalmente descritas como artesanais, já que envolvem diferentes barcos pesqueiros, que utilizam várias artes de pesca e explotam diversos estoques de peixes (Welcomme, 2008), especialmente em uma grande área de bacia de drenagem onde a diversidade de peixes e a heterogeneidade ambiental são elevadas (Welcomme, 2008). Uma das grandes exceções é a pesca dos grandes bagres migradores no rio Amazonas, tendo em vista que é uma atividade pesqueira que visa uma única espécie ou um grupo de espécies semelhantes (Barthem et al., 1997; Bartley *et al.*, 2016; Welcomme *et al.*, 2016; Funge-Smith, 2018).

A atividade pesqueira que tem como alvo os grandes bagres migradores é difundida na bacia Amazônica e abastece os mercados de peixes locais e fábricas de processamento de peixes ao longo do rio Amazonas e na costa do estuário Amazônico (Barthem et al., 1997; Barthem e Goulding, 2007). Nos estudos do transporte de sedimentos pela hidrografia amazônica, há que se considerarem três tipos de rios: de água branca, com grande quantidade de sedimento em suspensão, rios de água clara e de água preta, os dois últimos transportam pouquíssima carga sólida em suspensão (Sioli, 1984). A pesca dos grandes bagres migradores ocorre principalmente em águas abertas de canais de rios de água branca e no estuário do rio Amazonas, onde a produção de peixes é baseada principalmente em algumas espécies da família de água doce Pimelodidade, especialmente do gênero *Brachyplatystoma* (Bayley e Petrere, 1989; Agudelo-Córdoba *et al.*, 2000; Barthem e Goulding, 2007).

As sete espécies existentes de *Brachyplatystoma* são conhecidas em inglês como “goliath catfish”, expressão alusiva ao grande tamanho (Lundberg *et al.*, 2011) e, incluem as maiores espécies de bagres da Amazônia (Lundberg e Akama, 2005) e aquelas que realizam as mais longas migrações de peixes de água doce do mundo (Barthem *et al.*, 2017). Os grandes bagres são espécies migratórias representadas por piramutaba - *B. vaillantii*, dourada - *B. rousseauxii*, piraíba - *B. filamentosum* e *B. capapretum*, babão - *B. platynemum*, flamengo - *B. juruense* e zebra - *B. tigrinum*. São os principais predadores do canal fluvial e estuarino e variam em comprimento máximo conhecido de comprimento furcal (CF) de 60 a 280 cm (Barthem *et al.*, 2017). Seis dessas sete são amplamente explotadas pela pesca comercial na Bacia Amazônica, com apenas uma espécie, *B. tigrinum*, restrita principalmente à metade ocidental da bacia e raramente relatada nos registros de desembarque de peixes (Lundberg e Akama, 2005; Barthem e Goulding, 2007; Lundberg *et al.*, 2011). No entanto, *B. tigrinum* é explotado pela pesca ornamental e é uma das espécies mais valorizadas no mercado internacional, com um preço individual de US $ 15,3 dólares (Anjos *et al.*, 2009). Dentre os grandes bagres migradores, quatro (*B. vaillantii*, *B. rousseauxii*, *B. platynemum* e *B. juruense*) realizam migrações de longa distância (> 1.000 km), enquanto evidências indicam que as outras duas espécies de *Brachyplatystoma* (*B. filamentosum* e *B. capapretum*) parecem realizar migrações mais curtas (Petrere *et al.*, 2004; Barthem *et al.*, 2017).

A explotação dos grandes bagres migradores é relativamente recente, com exceção do estuário, devido aos tabus contra o consumo desses peixes nas áreas rurais da Amazônia, de origem social ou cultural, esses tabus restringiam o consumo de espécies de peixes lisos, associando sua ingestão à proliferação de doenças e infecções de feridas (Begossi *et al.*, 2004). A explotação em larga escala de bagres começou após o estabelecimento de instalações de refrigeração ao longo dos grandes rios e estuários na década de 1970 (Rodriguez-Fernandez, 1991; Fabré e Barthem, 2005; Barthem e Goulding, 2007). Essas plantas aproveitaram a abundância de um recurso subexplotado de peixes e estabeleceram os mercados de exportação de bagres no Brasil e na Colômbia (Rodríguez-Fernández, 1991; Agudelo-Córdoba *et al.*, 2000; Begossi *et al.*, 2004; Fabré e Barthem, 2005; Almeida, 2006; Barthem e Goulding, 2007). Atualmente os pescadores do Brasil, Colômbia, Peru, Bolívia e Equador explotam estoques dos grandes bagres usando vários tipos de artes e barcos de pesca, incluindo a frota pesqueira mais industrializada da Bacia Amazônica, a frota de arrasto de fundo que atua no estuário da Amazônia (Fabré e Barthem, 2005; Barthem e Goulding, 2007; Batista *et al.*, 2018).

A pressão de pesca difere de acordo com a área da bacia Amazônica, pois ocorre em diferentes grupos de idades dos grandes bagres. A pressão pesqueira que ocorre mais a oeste da bacia Amazônica, próximo aos Andes, na área de desova dos grandes bagres, é baixa, com a frota de pesca artesanal utilizando principalmente redes de emalhar à deriva e redes de cerco, além de arpões e espinhel, tendo como alvo adultos dos grandes bagres (Prestes *et al.*, in prep.). Vale ressaltar que ao norte da bacia, no rio Japurá/Caquetá, principalmente nas duas cachoeiras de La Pedrera e Córdoba, a captura dos bagres é maximizada com o estreitamento do rio (Rodriguez, 1992; Rodriguez, 1999). Na margem Sul, a região do rio Madeira se destaca na captura dos grandes bagres como fonte de renda (Doria *et al*., 2012). Já a leste da bacia, as redes de arrasto (equipamento pouco seletivo) impõem uma alta pressão pesqueira na área de crescimento dos grandes bagres, a região estuarina no rio Amazonas, juntamente com a alta taxa de "*bycatch*" de peixes pequenos (Barthem e Petrere Jr, 1995; Ibama, 1999; Jimenez *et al.*, 2013; Barthem *et al.*, 2015; Klautau, Cordeiro, Cintra, Silva, Bastos, *et al.*, 2016; Klautau, Cordeiro, Cintra, Silva, Carvalho, *et al.*, 2016).

Nesse sentido, as principais preocupações relativas ao manejo diferem ao longo da bacia Amazônica e apresentam diferentes desafios, desde construção de barragens nas cabeceiras dos rios, área de desova desse grupo (Forsberg *et al.*, 2017; Anderson *et al.*, 2018; Damme *et al.*, 2019), até o manejo pesqueiro dos grandes bagres e a consequente sobrepesca do crescimento (Barthem e Petrere Jr, 1995; Petrere *et al.*, 2004; Alonso e Pirker, 2005; Agudelo-Córdoba *et al.*, 2013), situação que ocorre quando o esforço de pesca é tão alto que as capturas totais diminuem com o aumento do esforço. Um dos estoques de grandes bagres migradores, que apresenta uma série histórica de dados de pesca e medidas de manejo é a piramutaba (*B. vaillantii*), intensamente explotada no Brasil, Colômbia e Peru (Agudelo-Córdoba *et al.*, 2000; Petrere *et al*., 2004; Barthem e Goulding, 2007; Ibama, 2007; García *et al.*, 2012). No Brasil, a maioria das capturas (~ 80%) provém da frota de pesca industrial que utiliza redes de arrasto de fundo na foz do rio Amazonas (Ibama, 1999; Barthem e Goulding, 2007). Há também uma pequena pesca artesanal ao longo do rio e seus afluentes de água branca que representam o restante da captura. A frota industrial da Amazônia opera desde o início da década de 1970 com três ou quatro diferentes medidas de manejo adotadas também a partir da década de 70 (Dias-Neto *et al.*, 1985; Barthem, 1990; Ibama, 1994; Klautau, Cordeiro, Cintra, Silva, Bastos, *et al.*, 2016).

Análises diversificadas já foram adotadas na avaliação do estoque pesqueiros dos grandes bagres ao longo da bacia Amazônica (Barthem e Petrere Jr, 1995; Ibama, 1999; Petrere *et al.*, 2004; Alonso e Pirker, 2005; Agudelo-Córdoba *et al.*, 2013; Matsunaga *et al.*, 2017), utilizando estimativas de mortalidade por pesca, baseadas em dados de frequência de comprimento e modelos de produção excedentes baseados em dados de captura e esforço. No entanto, análises integradas combinando várias fontes de informação em uma única análise (dados de capturas, comprimento e/ou idade, índices de abundância, entre outros) têm sido cada vez mais utilizados (Haddon, 2010; Methot-Jr. e Wetzel, 2013). A plataforma de análises integradas mais usada atualmente nos EUA é a Stock Synthesis (SS) (Methot-Jr. e Wetzel, 2013; Methot-Jr. *et al.*, 2019), e pode ser útil na avaliação de estoques que possuem dados de fontes diferenciadas como os grandes bagres migradores.

Neste sentido, a presente tese visa elucidar questões relacionadas a pesca e conservação dos grandes bagres migradores na bacia amazônica, apresenta novas abordagens na avaliação de estoques da pesca de arrasto da piramutaba *B. vaillantii* e traz à tona a preocupação com a sustentabilidade a longo prazo para essas e outras pescarias em larga escala na Amazônia.

2. OBJETIVOS

2.1 Geral

Descrever a produção pesqueira dos grandes bagres migradores (*B. rousseauxii; B. vaillantii; B. filamentosum* e *B. capapetrum; B. platynemum, B. juruense*) na bacia Amazônica, assim como analisar o estado do estoque da piramutaba (*Brachyplatystoma vaillantii*) discutindo efeitos das medidas de manejo nesta pescaria.

2.2 Específicos

- Analisar o histórico e a distribuição geopolítica da produção pesqueira dos grandes bagres migradores de importância comercial (*B. rousseauxii; B. vaillantii; B. filamentosum* e *B. capapetrum; B. platynemum, B. juruense*) na bacia Amazônica;
- Caracterizar a distribuição de sub-adultos e adultos dos grandes bagres migradores de importância comercial (*B. rousseauxii; B. vaillantii; B. filamentosum* e *B. capapetrum; B. platynemum, B. juruense*) e suas implicações para o manejo desse grupo na bacia Amazônica;
- Avaliar o estoque da piramutaba (*B. vaillantii*) explotada pela frota industrial na foz do rio Amazonas.
- Avaliar à eficácia das medidas de gestão aplicadas às pescarias da piramutaba (*B. vaillantii*) explotada pela frota industrial na foz do rio Amazonas.

3. MATERIAL E MÉTODOS

3.1 Área de estudo

As áreas de pesca dos grandes bagres migradores na Bacia Amazônica estão associadas aos canais fluviais dos grandes rios entre a encosta dos Andes e a foz do rio Amazonas, especialmente as áreas de água doce ao longo da costa Amazônica. Brasil, Peru, Colômbia, Bolívia e Equador compartilham essa vasta área e, para efeito de abordagem geográfica e geopolítica, esta área foi dividida em quatro regiões de pesca de acordo com as características ambientais e as distâncias da foz do rio Amazonas (Figura 1).

A região do estuário é uma zona de água doce próxima à foz do Amazonas, que é separada em duas partes principais pela grande ilha de Marajó. O rio Amazonas deságua principalmente ao norte da ilha de Marajó, e uma parte menor de sua vazão deságua na baía de Marajó ao sul, através do canal de Breves. A região do estuário se estende rio acima até a confluência dos rios Xingu e Amazonas. A zona de maré estuarina e suas extensões variam de 400 a 500 km, dependendo do nível do rio Amazonas (Goulding *et al.*, 2003). Sua vazão e a corrente norte do Brasil controlam a extensão sazonal da porção de água doce do seu estuário. O ciclo sazonal de sua vazão é responsável pela expansão e retração dos habitats de água doce no estuário, e a corrente Norte do Brasil sempre desvia a pluma amazônica na direção norte, criando assim um gradiente de salinidade latitudinal ao longo da costa amazônica (Curtin e Legeckis, 1986; Nikiema *et al.*, 2007). Os portos comerciais de desembarque de bagres na região do estuário estão localizados principalmente nas cidades brasileiras dos estados do Pará e Amapá.

A região Oriental se refere ao trecho inferior do rio Amazonas de aproximadamente 1.000 km, situado a montante do estuário, a foz do rio Xingu, e a jusante das confluências com os rios Negro e Madeira. Os principais afluentes dos escudos do Brasil e da Guiana, os rios Xingu e Tapajós, desembocam no rio Amazonas, na região Oriental. O rio Tocantins descarrega diretamente região do estuário. Esta região está sujeita aos eventos da maré e do pulso de inundação sazonal provenientes de eventos hidrológicos a montante. Os principais portos comerciais para desembarque dos grandes bagres na Região Leste estão nas cidades do Pará (Viseu, Augusto Correa, Quatipuru, São João de Pirabas, Salinópolis, Maracanã, Marapanim, Curuçá, São Caetano, Vigia, Colares, Soure, Salvaterra, Bragança, Vila do Conde, Abaetetuba, Limoeiro do Ajuru, Cametá, Mocajuba, Baião, Tucuruí, Jacundá, Itupiranga, Monte Alegre, Alenquer, Oriximiná).

Embora posicionada mais internamente, a região Central ainda tem uma altitude inferior a 100 m e inclui uma grande parte da região geológica definida como Bacia de antepaís Amazônica (Lima e Ribeiro, 2011). Inclui aproximadamente 2.000 km do rio Solimões-Amazonas e as partes inferiores de seus rios de água branca com cabeceiras nos Andes, como os rios Madeira, Purus, Juruá, Caquetá-Japurá e Putumayo-Içá. Como na região leste, a região central é caracterizada hidrologicamente por um forte pulso sazonal de inundação. As cidades do departamento do Amazonas na Colômbia e do estado do Amazonas no Brasil recebem a maior parte dos grandes bagres capturados na região central.

A região Ocidental fica nos Andes, abaixo de aproximadamente 300 metros de altitude e contíguo à planície Amazônica. Esta região inclui os trechos superiores dos rios Madeira, Ucayali, Marañón, Putumayo e Caquetá, que são caracterizados por serem altamente turvos devido à sua proximidade aos Andes. Embora ocorra um forte pulso de inundação sazonal, a região é influenciada por picos de enchentes periódicas, conhecidas no Brasil como cabeça d'água, que são ocasionadas por enxurradas na costa andina. Os principais portos de pesca nessa região estão nas cidades dos departamentos de Loreto e Ucayali, no Peru, mas outros pequenos portos recebem os desembarques dos grandes bagres nos departamentos de Cochabamba e Beni na Bolívia, no departamento Madre de Dios no Peru e no departamento do Amazonas na Colômbia.

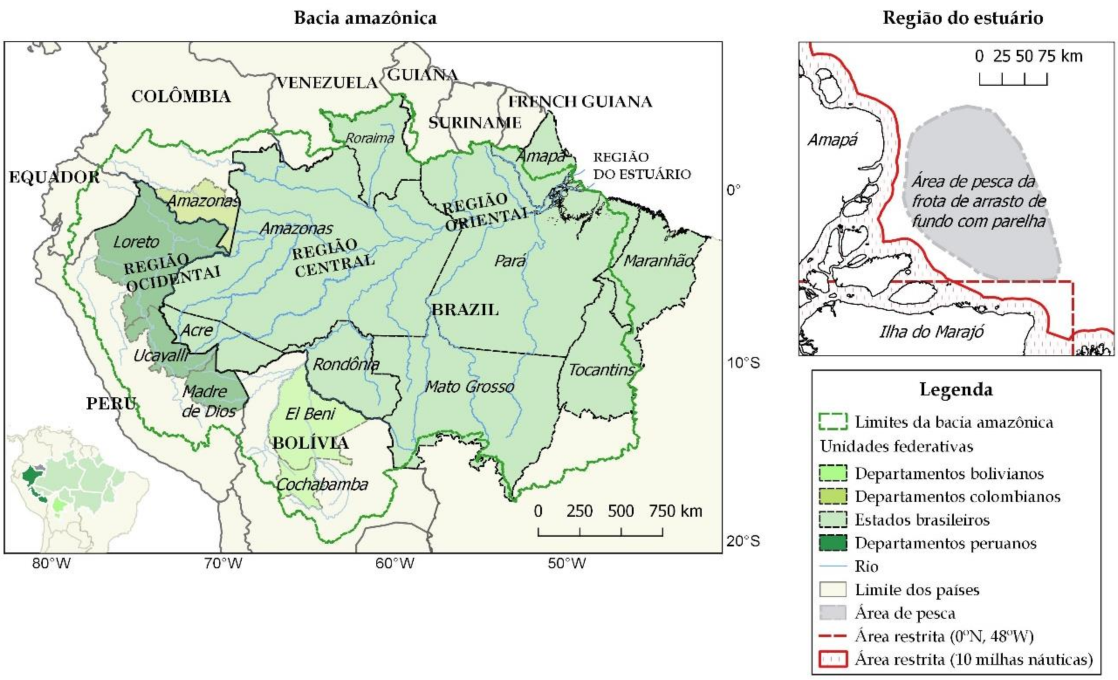


Figura 1. A bacia Amazônica, destacando os países, departamentos ou estados das principais regiões pesqueiras e as regiões de pesca do Estuário, Oriental, Central e Ocidental. A região do estuário inclui a zona de pesca da frota de arrasto de fundo com parelha.

3.2 Coleta de dados

3.2.1 Dados de pesca comercial artesanal para a bacia amazônica

Os desembarques comerciais de peixes ocorrem em portos públicos e privados, sendo que estes últimos pertencem a empresas frigoríficas localizadas ao longo dos grandes rios entre os Andes e o estuário da Amazônia. As estatísticas de desembarque estão disponíveis pelas agências nacionais de pesca do Peru, Colômbia e Brasil (Agência de Pesca Peruana “Dirección Regional de Pesqueria” - DIREPRO; Agência Colombiana de Pesca "Servicio Estadístico Pesquero Colombiano; Instituto Chico Mendes de Conservação da Biodiversidade” - ICMBIO). A atividade pesqueira do Equador é primariamente para subsistência e fornecimento ao mercado local e há dados mínimos registrados (Utreras-Bucheli, 2010; Van Damme *et al.*, 2011).

Brasil, Peru e Colômbia, respectivamente, subsidiam importantes pescarias comerciais com mercados de exportação tradicionais para outras regiões da Bacia Amazônica ou outros países (Barthem e Goulding, 2007). O Peru possui uma longa série de dados sobre pesca na Amazônia, especialmente no Departamento de Loreto, onde a Agência de Pesca Peruana “Dirección Regional de Pesqueria” (DIREPRO) coleta dados desde 1980 continuamente. Já nos departamentos de Madre di Dios e Ucayali estão disponíveis dados de apenas alguns anos em fontes de literatura (Barthem, 1995) e relatórios ou bancos de dados da DIREPRO. A produção pesqueira da Amazônia colombiana, incluindo dados on-line, inclui os portos do Departamento do Amazonas, especialmente nas cidades de Leticia e La Pedrera (disponíveis on-line pela Agência Colombiana de Pesca "Servicio Estadístico Pesquero Colombiano" (Sepec, n.d.) e abrange os períodos entre 1993 e 1999, 2006 e 2007).

No Brasil ocorrem as maiores pescarias da Amazônia, e os dados para as quatro espécies de grandes bagres migradores explotados (*B. rousseauxii*, *B. vaillantii* e as duas espécies de piraíbas agrupadas, *B. filamentosum* e *B. capapretum*) estão disponíveis on-line pelo Instituto Brasileiro de Conservação Ambiental “Instituto Chico Mendes de Conservação da Biodiversidade” (ICMBIO) para nove Estados (Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima e Tocantins) (Icmbio, n.d.). Os relatórios de pesca do site do ICMBIO fornecem informações desde 1944, porém, utilizamos dados a partir de 1980 e 2007. Após 2007, as informações representam estimativas baseadas em projeções estatísticas tendo em vista a interrupção da coleta de dados. Os dados estão disponíveis no site do ICMbio e foram coletados em projetos de estatística pesqueira por agências governamentais (Instituto Brasileiro de Meio Ambiente e dos Recursos Naturais - IBAMA, Ministério da Pesca – MPA) em conjunto com instituições de ensino e pesquisa. Os dados da produção pesqueira de duas outras espécies dos grandes bagres migradores (*B. platynemum* e *B. juruense*) e do período entre 1992 e 2004 foram compilados a partir da literatura de várias fonte de dados (Isaac e Ruffino, 2000; Doria *et al.*, 2012); pela Agência Brasileira de Produção Animal do Ministério da Agricultura, "Ministério da Agricultura, Pecuária e Abastecimento" (MAPA); do banco de dados de desembarque de peixes da Colônia de Pescadores de Porto Velho "Colônia de Pescadores Z-1, Tenente Santana"; e da Eletronorte-Centrais Elétricas do Norte do Brasil, IBAMA-Provárzea e Museu Paraense Emílio Goeldi.

3.2.2 Dados de pesca industrial para a foz do rio Amazonas

Os desembarques em toneladas de piramutaba (*B. vaillantii*) explotada pela frota industrial na foz do rio Amazonas foram obtidos nos anuários estatísticos da agência brasileira responsável pelo gerenciamento das pescas no Brasil (Icmbio, n.d.). Os desembarques da pesca de arrasto industrial direcionada à piramutaba estavam disponíveis de 1971 a 2007. Além dos desembarques, dados de Captura por Unidade de Esforço (CPUE) de 1975 a 1996 foram utilizados. Foi calculado como captura total em toneladas por dia de pesca de 1975 a 1996, período em que o esforço de pesca estava disponível (Ibama, 1999). Os dados estão disponíveis no site do ICMbio e foram coletados em projetos de estatística pesqueira (Superintendência Especial de Aquicultura e Pesca - SUDEPE, IBAMA, MPA, MAPA) por agências governamentais em conjunto com instituições de ensino e pesquisa.

3.2.3 Dados de frequência de comprimento de peixes na bacia Amazônica

Um conjunto de dados de comprimentos dos grandes bagres migradores foi analisado para mapear estatisticamente as classes de tamanho por regiões. Os dados foram obtidos em pescarias comerciais e experimentais entre 1982 e 2011 em pelo menos 187 localizações distribuídas ao longo das quatro principais regiões pesqueiras da Bacia Amazônica, incluindo Brasil, Peru, Colômbia e Bolívia.

As redes de emalhar eram o equipamento usado na maioria das pescarias comerciais, embora algumas amostras incluíssem espinhel. A pesca comercial de *B. vaillantii* foi baseada em redes de cerco no rio Amazonas (Solimões) e redes de arrasto no estuário. As análises de *B. vaillantii* e *B. rousseauxii* incluíram o tipo de equipamento de pesca para eliminar o viés da seletividade. A pesca experimental e comercial utilizou redes de emalhar com tamanho de malhas de 12 a 20 cm entre nós opostos, medidas na diagonal. Os dados de tamanho dos peixes foram agrupados em categorias sub-adultos e adultos, delimitadas pelo tamanho mínimo de maturidade (Minimum Maturity Size - MMS) para cada espécie previamente definida (Barthem *et al.*, 2017). Os dados foram agrupados espacialmente conforme as quatro principais regiões pesqueiras: Estuário, Oriental, Central e Ocidental. Os dados acima relatados são provenientes de banco de dados de projetos coordenados pelo Prof. Michael Goulding (Área oeste bacia Amazônica – 2002-2006; Área central bacia Amazônica – 1977-1980), pelo Prof. Ronaldo B. Barthem (Área central bacia Amazônica – 1993-1995; Área leste bacia Amazônica – 1983-1996; Área estuário bacia Amazônica – 1982-1997), do projeto JICA (Área estuário bacia Amazônica – 1996-1997) e, projeto Aquamazon (Área estuário bacia Amazônica – 2008-2011).

Dados de composição do comprimento (comprimento furcal) de piramutaba (*B. vaillantii*) explotada pela frota industrial na foz do rio Amazonas foram obtidos por diferentes agências e projetos ao longo dos anos. A Superintendência de Desenvolvimento da Pesca (SUDEPE) coletou os dados de composição do comprimento de 1979 a 1980, que variaram de 7 a 122 cm. Diferentes projetos executados pelo Museu Paraense Emílio Goeldi (MPEG) forneceram dados para os períodos de 1982 a 1985 e 1993 a 1997. Esses dados foram compilados em um banco de dados de composição de comprimento usando classes de comprimento de 5 cm de comprimento.

4. REFERÊNCIAS BIBLIOGRÁFICAS

AGUDELO-CÓRDOBA, E. et al. Breeding, growth and exploitation of *Brachyplatystoma rousseauxii* castelnau, 1855 in the caqueta river, colombia. **Neotropical Ichthyology,** v. 11, n. 3, p. 637-647, 2013.

AGUDELO-CÓRDOBA, E. et al. **Bagres de la amazonia colombiana: Un recurso sin fronteras**. Bogotá: SINCHI, 2000. 253.

ALMEIDA, O. T. D. **A indústria pesqueira na Amazônia**. Manaus: Ibama/Provarzea, 2006. 110 p.

ALONSO, J. C.; PIRKER, L. E. M. Dinâmica populacional e estado atual da exploração de piramutaba e de dourada. In: FABRÉ, N. N. e BARTHEM, R. B. (Ed.). **O Manejo da Pesca dos Grandes Bagres Migradores**: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, Brasília, 2005. p.21-28.

ANDERSON, E. P. et al. Fragmentation of Andes-to-Amazon connectivity by hydropower dams. **Science Advances,** v. 4, n. 1, p. eaao1642, 2018.

ANJOS, H. D. B. D. et al. ORNAMENTAL FISH EXPORT OF THE STATE OF AMAZONAS, AMAZON BASIN, BRAZIL. **Boletim Do Instituto De Pesca,** v. 35, p. 259-274, 2009.

BARTHEM, R. B. Descrição da pesca da piramutaba (*Brachyplatystoma vaillantii*. Pimelodidae) no estuário e na calha do rio amazonas. **Boletim do Museu Goeldi, N.S. Antropologia,** v. 6, n. 1, 1990. ISSN 1807-5398.

BARTHEM, R. B. Development of commercial fisheries in the amazon basin and consequences for fish stocks and subsistence fishing. In: CLUSENER-GODT, M.;SACHS, I., *et al* (Ed.). **Brazilian Perspectives on Sustainable Development of the Amazon Region**. Paris: The Parthenon Publishing Group, 1995. p.175-204.

BARTHEM, R. B.; GOULDING, M. **An unexpected ecosystem: the Amazon as revealed by fisheries**. Missouri Botanical Garden Press, 2007. 241.

BARTHEM R.B.; PETRERE Jr M.; ISAAC V.; RIBEIRO M.C.L.B.; Mcgrath D.G.; VIEIRA I.J.A.; BARCO M.V. A pesca na Amazônia: Problemas e perspectivas para o seu manejo. In: **Padua CV, Bodmer RE, Cullen LJ (eds) Manejo e Conservação de Vida Silvestre no Brasil**. Conselho Nacional de Desenvolvimento Científico e Tecnológico, 1997. pp 173-185

BARTHEM, R. B. et al. Goliath catfish spawning in the far western Amazon confirmed by the distribution of mature adults, drifting larvae and migrating juveniles. **Scientific Reports,** v. 7, p. 41784, Feb 06 2017. ISSN 2045-2322 (Electronic)

2045-2322 (Linking). Disponível em: < https://www.ncbi.nlm.nih.gov/pubmed/28165499 >.

BARTHEM, R. B. et al. Estrutura de tamanho e distribuição espacial da piramutaba (*Brachyplatystoma vaillantii*) na foz Amazônica: implicações para o manejo da pesca. **Bol. Inst. Pesca, São Paulo,** v. 41, n. 2, p. 249-260, 2015.

BARTHEM, R. B.; PETRERE JR, M. Fisheries and population dynamics of the freshwater catfish *Brachyplatystoma vaillantii* in the amazon estuary. In: ARMANTROUT, N. B., Condition of the World's Aquatic Habitat. Proceedings of the World Fisheries Congress, Theme 1. , 1995, Athens, Greece. Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi. p.329-350.

BARTLEY, D. M.; GRAAF, G.; VALBO-JORGENSEN, J. Commercial inland capture fisheries. In: CRAIG, J. (Ed.). **Freshwater fisheries ecology**: John Wiley & Sons, 2016. p.438-448.

BATISTA, V. S. et al. Drivers of the upper River Amazon giant catfish fishery **Fisheries Management and Ecology**, 2018.

BAYLEY, P.; PETRERE JR., M. Amazon fisheries: Assessment methods, current status and management options. **Canadian Special Publication of Fisheries and Aquatic Science**. 106, 385-398. 1989.

BEGOSSI, A.; HANAZAKI, N.; RAMOS, R. M. Food chain and the reasons for fish food taboos among Amazonian and Atlantic Forest fishers (Brazil). **Ecological Applications** v. 14, p. 1334-1343, 2004.

CURTIN, T. B.; LEGECKIS, R. V. Physical observations in the plume region of the Amazon river during peak discharge - I. Surface variability. **Continental Shelf Research,** v. 6 n. 1/2, p. 31-51, 1986.

DAMME, P. A. V. et al. Upstream dam impacts on gilded catfish *Brachyplatystoma rousseauxii* (Siluriformes: Pimelodidae) in the Bolivian Amazon. **Neotropical Ichthyology,** v. 17, 2019. ISSN 1679-6225. Disponível em: < http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1679-62252019000500213&nrm=iso >.

DIAS-NETO, J.; DAMASCENO, F. G.; PONTES, A. C. D. P. **Biologia e pesca de piramutaba, *Brachyplatystoma vaillantii*, Valenciennes, na região Norte do Brasil**. SUDEPE-PDP, p.47-112. 1985

DORIA, C. et al. A pesca comercial na bacia do rio Madeira no Estado de Rondônia, Amazônia brasileira. **Acta Amazonica,** v. 42, p. 29-40, 2012.

FABRÉ, N. N.; BARTHEM, R. B. **O manejo da pesca dos grandes bagres migradores: piramutaba e dourada no eixo Solimões-Amazonas**. ProVárzea, IBAMA, MMA, 2005.

FORSBERG, B. et al. The potential impact of new Andean dams on Amazon fluvial ecosystems. **PloS one,** v. 12, n. 8, p. e0182254, 2017. Disponível em: < https://doi.org/10.1371/journal.pone.0182254 >.

FUNGE-SMITH, S. J. **Review of the state of world fishery resources: inland fisheries**. Rome: 2018.

GARCÍA, A. et al. Desembarque de pescado fresco en la ciudad de iquitos, región loreto-amazonía peruana. **Folia Amazonica,** v. 21, n. 1-2, p. 45-52, 2012.

GOULDING, M. et al. **The Smithsonian atlas of the Amazon**. Washington London: Smithsonian Books, 2003. 253.

HADDON, M. **Modelling and quantitative methods in fisheries**. CRC press, 2010.

IBAMA. **Camarão norte e piramutaba**. Brasília: IBAMA, 1994. 148.

______. V Reunião do grupo permanente de estudos sobre a piramutaba. **Coleção Meio Ambiente. Série Estudos Pesca (Brasil),** v. 26, p. 1-92, 1999.

______. Estatística da pesca (planilhas) 2005. 2007.

ICMBIO. Estatística por região. **Retrieved Octuber 15, 2019, from http://www.icmbio.gov.br/cepsul/biblioteca/acervodigital/38download/artigos-cientificos/112-artigos-cientificos.html**, n.d.

ISAAC, V. J.; RUFFINO, M. L. A estatística pesqueira no baixo amazonas: Experiencia do projeto iara. **IBAMA. Coleção Meio Ambiente. Série Estudos Pesca,** v. 22, p. 201-224, 2000.

JIMENEZ, E. A.; ASANO FILHO, M.; FRÉDOU, F. L. Fish bycatch of the laulao catfish *Brachyplatystoma vaillantii* (valenciennes, 1840) trawl fishery in the amazon estuary. **Brazilian Journal of Oceanography,** v. 61, n. 2, p. 129-140, 2013. ISSN 1679-8759.

KLAUTAU, A. G. C. D. M. et al. Analysis of the Industrial Fishing of Piramutaba Catfish, *Brachyplatystoma vaillantii* (Valenciennes 1840), in two Estuarine Areas of the Brazilian Amazon. **Pan-American Journal of Aquatic Sciences,** v. 11, n. 2, p. 143-150, 2016.

KLAUTAU, A. G. C. D. M. et al. Impacted biodiversity by industrial piramutaba fishing in the Amazon River mouth. **Bol. Inst. Pesca, São Paulo,** v. 42, n. 1, p. 102-111, 2016.

LIMA, F. C. T.; RIBEIRO, A. C. Continental-scale tectonic controls of biogeography and ecology. In: ALBERT, J. S. e REIS, R. E. (Ed.). **Historical Biogeography of Neotropical Freshwater Fishes.** : University of California Press, Berkeley, 2011. p.145-164.

LUNDBERG, J. G.; AKAMA, A. *Brachyplatystoma capapretum*: A new species of goliath catfish from the amazon basin, with a reclassification of allied catfishes (siluriformes: Pimelodidae). **Copeia,** v. 2005, n. 3, p. 492-516, 2005.

LUNDBERG, J. G.; SULLIVAN, J. P.; HARDMAN, M. Phylogenetics of the South American catfish family Pimelodidae (Teleostei: Siluriformes) using nuclear and mitochondrial gene sequences. **Proceedings of the Academy of Natural Sciences of Philadelphia,** v. 161, n. 1, p. 153-189, 2011. ISSN 0097-3157.

MATSUNAGA, A. M. F.; JUNIOR, I. F.; ITÓ, L. S. Análise quantitativa da influência de parâmetros ambientais sobre a captura por unidade de esforço (CPUE) da piramutaba *Brachyplatystoma vaillantii* (Valenciennes, 1840) da costa amazônica do Brasil. **Bol. Téc. Cient. Cepnor,** v. 17, n. 1, p. 09-19, 2017.

METHOT-JR., R. D.; WETZEL, C. R. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. **Fisheries Research,** v. 142 p. 86- 99, 2013.

METHOT-JR., R. D.; WETZEL, C. R.; TAYLOR, I. G. **Stock Synthesis User Manual**. NOAA Fisheries. Seattle, WA. 2019

NIKIEMA, O.; DEVENON, J.-L.; BAKLOUTI, M. Numerical modeling of the Amazon River plume. **Continental Shelf Research,** v. 27, n. 7, p. 873-899, 2007. ISSN 02784343.

PETRERE, M. et al. Review of the large catfish fisheries in the upper Amazon and the stock depletion of piraíba (*Brachyplatystoma filamentosum* Lichtenstein). **Reviews in Fish Biology and Fisheries,** v. 14, n. 4, p. 403-414, 2004. ISSN 0960-3166

1573-5184.

PRESTES, L. et al. A review of the goliath catfish fishery in the Amazon Basin: an history of overfishing., in prep.

RODRÍGUEZ-FERNÁNDEZ, C. A. **Bagres, Malleros e Cuerderos en El Bajo Rio Caquetá. Estudios en la Amazonia colombiana**. Tropenbos-Colombia, 1991. 152.

RODRIGUEZ, C.A. Bagres, Malleros y Cuerderos en el Bajo Rio Caqueta. Commercial Fisheries in the Lower Caqueta River. **Estudios en la Amazonia Colombiana II**, 1992. 2nd ed. Tropenbos-Colombia, Santa Fe´ de Bogota, DC, 152 pp.

RODRIGUEZ, C.A. Arponeros de la Trampa del Sol. Sustentabilidad de la Pesca Comercial en el Medio Caqueta´. **Estudios en la Amazonia Colombiana XVII**.1999.

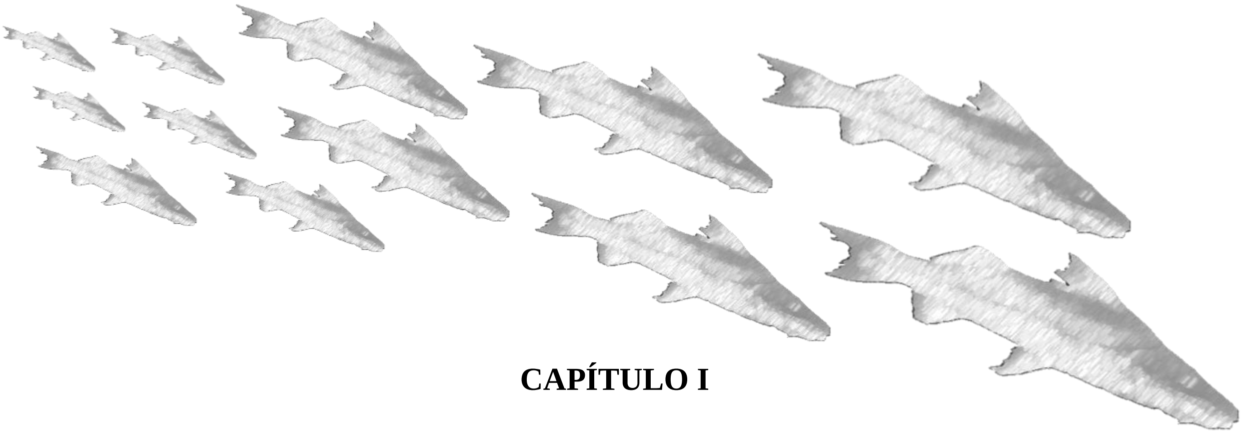
SEPEC. Boletines estadísticos pesqueors y de la acuicultura. http://sepec.aunap.gov.co/Home/BoletinesEstadisticos, n.d. Acesso em: Octuber 15.

UTRERAS-BUCHELI, V. M. **Caracterización de la pesca de grandes bagres en el Alto Río Napo (Ecuador), recomendaciones para su manejo y conservación.** . 2010. (Master's Thesis.). Universidad Internacional de Andulucía (UNIA), Sevilla, Spain.

VAN DAMME, P. A. et al. Pesca comercial en la cuenca amazónica boliviana. In: (Ed.). **Los peces y delfines de la Amazonía boliviana: hábitats, potencialidades y amenazas**. Cochabamba, Bolivia: INIA, 2011. p.247-291.

WELCOMME, R. **Inland fisheries: Ecology and management**. John Wiley & Sons, 2008. ISBN 0470995688.

WELCOMME, R. L. et al. Fisheries of the rivers of Southeast Asia. In: CRAIG, J. F. (Ed.). **Fisheries ecology in South American river basins**: John Wiley & Sons, 2016. p.363-376.



CAPÍTULO I

A REVIEW OF THE GOLIATH CATFISH FISHERY IN THE AMAZON BASIN: A HISTORY OF OVERFISHING

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A review of goliath catfish overfishing in the Amazon Basin

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Abstract

This paper reviews overfishing of goliath catfishes (*B. rousseauxii; B. vaillantii; B. filamentosum and B. capapretum; B. platynemum* and *B. juruense*) in the Amazon Basin within the context of fisheries management. The commercial exploitation of goliath catfishes in the Amazon Basin occurs from the Amazon River estuary to the Andean piedmont and includes Brazil, Colombia, Ecuador, Peru and Bolivia. Fishing pressure in the Amazon Basin increased rapidly after 1970 when refrigerated processing companies in Brazil and Colombia began exporting fish. The states of Pará and Amazonas in Brazil and the department of Amazonas in Colombia became the principal geopolitical stakeholders of goliath catfish production and accounted for most of the commercial catch of these species. With the exception of *B. platynemum*, the differential length distribution of goliath catfishes captured in commercial fisheries of the Amazon indicates fishing pressure is highest in the regions where subadults are dominant. Overfishing of *B. filamentosum, B. capapetrum*, *B. rousseauxii* and *B. vaillantii* occurred in different regions in the Amazon Basin at different times after the 1970 when large-scale goliath catfish exploitation began. The historical analysis of maximum sustainable yield (MSY), fishing mortality (F) and mortality at MSY (FMSY) for *B. vaillantii* trawl fishing in the Amazon estuary point to overfishing a few years after large-scale commercial fisheries began for this species. The increasing trend in fish stock mortality related to estuarine trawl fisheries first appeared in reports as early as 1985, but not in time to implement measures to prevent overfishing. Export markets and the low efficiency of fisheries management have historically characterized goliath catfish fisheries in the Amazon Basin, and this combination led to rapid overfishing of the various species. The management of migratory goliath species will require interstate/department and international cooperation to control both overfishing and environmental impacts.

Keywords

Brachyplatystoma, goliath, catfish, overfishing, fishery, Amazon, management

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All the data used in this article are in tables, graphs and supplementary material

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We do not use any software, for all the calculations the equations are available in the text

Main text

Introduction

Commercial inland fisheries are generally multi-species and multi-gear operations, especially in a large river basin where fish diversity and environmental heterogeneity are elevated (Welcomme 2008). There are few examples where inland fishery catches are dominated by only a single species or few similar species. Examples include the Nile perch (*Lates niloticus*) in Lake Victoria where it is an introduced species, clupeids in Lake Tanganyika, hilsa (*Tenualosa ilisha*) in the Ganges River and goliath catfishes in the Amazon River (Barthem et al. 1997; Bartley et al. 2016; Funge-Smith 2018; Welcomme 2008). Goliath catfish fisheries are widespread in the Amazon Basin and they supply local fish markets and fish processing plants along the Amazon River and its estuary. Migratory catfish fisheries occur mainly in open waters of turbid river channels and in the Amazon River estuary where a few species of the freshwater family Pimelodidade, especially of the genus *Brachyplatystoma*, account for most of the catfish production (Agudelo-Córdoba et al. 2000; Barthem and Goulding 2007).

The seven extant species of *Brachyplatystoma* (Table 1) are known vernacularly in English as goliath catfishes (Lundberg et al. 2011), and include two of the three largest fishes in the Amazon (Lundberg and Akama 2005), *Brachyplatystoma vaillantii*, *B. rousseauxii*, *B. juruense*, *B. platynemum*, *B. filamentosum,* *B. capapretum* and *B. tigrinum*. Two or three (*Brachyplatystoma vaillantii*, *B. rousseauxii*) of the goliath catfishes undertake the longest freshwater fish migrations in the world (Barthem et al. 2017). Goliath catfishes are major river channel and estuarine predators, and range in maximum known adult fork length (FL) from 60 to 280 cm. Six of the seven goliath catfish species are widely exploited by commercial fisheries in the Amazon Basin, with only one species, *B. tigrinum*, restricted mostly to the western half of the basin and rarely reported in fish landing records (Barthem and Goulding 2007; Lundberg and Akama 2005; Lundberg et al. 2011). However, ornamental fisheries exploit *B. tigrinum* and it is one of the most valued Amazonian fish species in the international aquarium market (Anjos et al. 2009). Four goliath catfishes (*B. vaillantii*, *B. rousseauxii*, *B. platynemum*, and *B. juruense*) undertake long-distance migrations (> 1,000 km), whereas existing field evidence indicates that *B. filamentosum, B. capapretum* and *B. tigrinum* appear to undertake shorter migrations (Barthem et al. 2017).

With the exception of the estuary, the large-scale exploitation and local consumption of catfish is relatively recent in the Amazon Basin because of a historical food taboo against smooth-skinned fishes (Begossi et al. 2004). Catfish fisheries are now widespread in the Amazon Basin, including not only the Amazon River but also the lower portions of its turbid rivers with headwaters that arise in the Andes, such as the Madeira, Purus, Juruá, Caquetá-Japurá and Putumayo-Içá. Large-scale exploitation of catfish began after the establishment of refrigeration plants along the large rivers and estuary in the 1970s (Fabré and Barthem 2005; Rodríguez-Fernández 1991; Barthem and Goulding 2007). These plants took advantage of the abundance of an underexploited fish resource and targeted catfish export markets in Brazil and Colombia. Currently, fishers in Brazil, Colombia, Peru, Bolivia and Ecuador exploit goliath catfish stocks using many types of fishing gear and boats, including bottom pair-trawlers in the Amazon estuary (Barthem and Goulding 2007; Batista et al. 2018; Fabré and Barthem 2005).

Uncontrolled fishing effort led to the serious overexploitation of the most important catfish stocks within a decade or two after major fisheries for these species began. Furthermore, the low efficiency of fisheries management plans exacerbated this situation in all Amazonian countries that exploit these species (Agudelo-Córdoba et al. 2013; Alonso and Pirker 2005; Barthem and Petrere Jr 1995; Petrere et al. 2004). The management of goliath catfishes in the Amazon Basin is challenging because of the large area involved and highly complex fisheries. Diverse fleets and gear used from the Amazon River estuary to the Andean piedmont, along with limited and poor quality fisheries data, hamper fish stock assessments (Barthem and Goulding 2007; Batista et al. 2018; Fabré and Barthem 2005; Fitzgerald et al. 2018; Jiao et al. 2011). Furthermore, large-scale environmental modifications in the Amazon, such as dams and watershed deforestation, are an increasing threat to fisheries in general, but especially migratory species that require ecological connectivity at transnational levels (Finer and Jenkins 2012; Forsberg et al. 2017; Goulding et al. 2019; Malhi et al. 2008). The effectiveness of the management and conservation of the continental-scale migratory goliath catfish species depends on the coordinated action of all countries involved because of the enormous life-history areas the species occupy (Goulding et al. 2019). International coordinated actions need to be reached through international agreements and cooperation

(Valbo-Jørgensen et al. 2008), but the present absence of initiatives by Amazonian countries presents an alarming fisheries situation for the region.

This review aims to highlight overfishing of goliath catfishes within a geopolitical, biological and management context in the Amazon Basin, and finally, to call attention to the possible imminent demise of the large-scale fisheries of these species and the urgency of adequate management strategies.

Methods

Study area and fishing regions

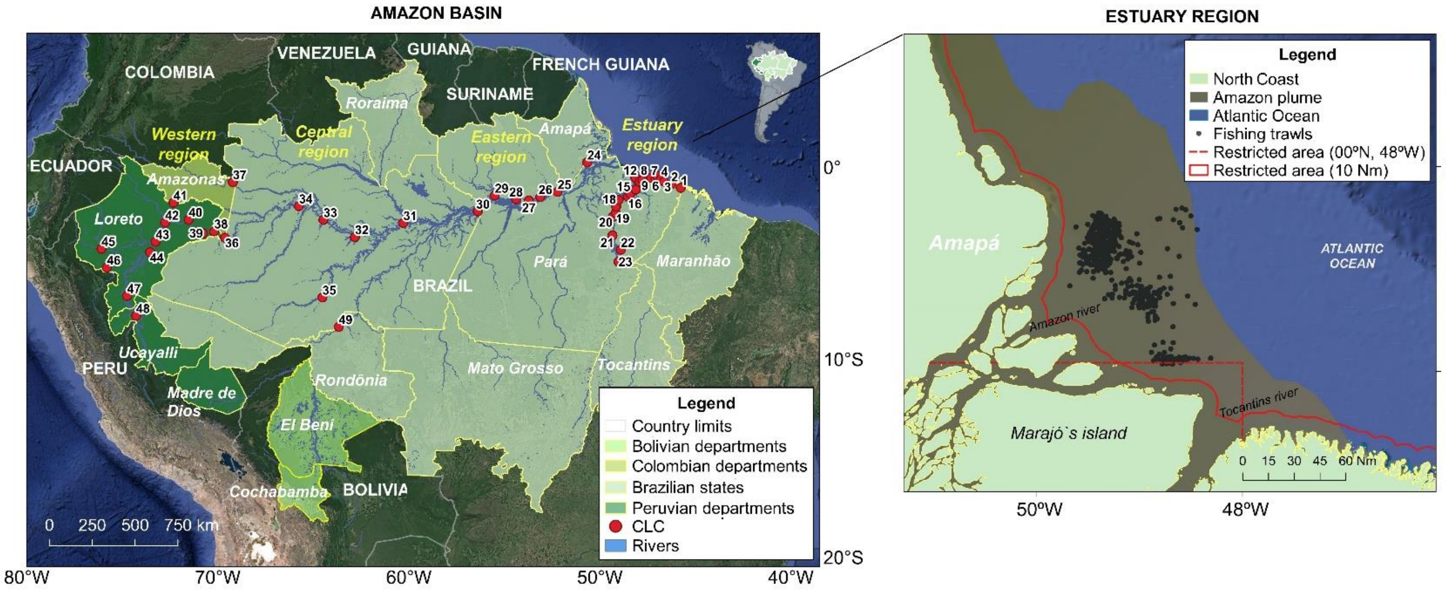
The goliath catfish fishing areas in the Amazon Basin are associated with the channels of the large rivers between the Andean piedmont in the west and the Amazon River estuary in the east, the latter including the freshwater areas off the Amazon coast. Brazil, Peru, Colombia, Bolivia and Ecuador share this vast area and we divide it into four fisheries regions according to their environmental characteristics and distances from the Amazon River mouth (Figure 1).

The Estuary Region encompasses the freshwater zone from just north of the Amazon River mouth to south of Marajó Island that separates the Amazon River from Marajó Bay. The Amazon River channel discharges to the north of Marajó Island, but Amazon River water also reaches Marajó Bay to the south via the Breves Channel. The Estuary Region extends upriver to the confluence of the Xingu and Amazon rivers where tidal influence is pronounced. Depending on the level of the Amazon River, the estuarine tidal zone and its extensions vary 400 to 500 km (Goulding et al. 2003a). Amazon River discharge and the North Brazil Current control the seasonal extension of the freshwater portion of the Amazon estuary. The seasonal cycle of Amazon River discharge is responsible for the expansion and retraction of the freshwater habitats in the estuary, and the North Brazil Current always deflects the Amazon plume in a northward direction, thus creating a latitudinal salinity gradient along the Amazon coast (Curtin and Legeckis 1986; Nikiema et al. 2007). Commercial catfish landing ports in the Estuary Region are in Brazilian cities in the states of Pará and Amapá.

The Eastern Region is the approximately 1,000 km lower portion of the Amazon River, less the Estuary Region, and is delimited upstream at the mouths of the Negro and Madeira rivers and downstream at the mouth of the Xingu River. The main tributaries of the Brazilian and Guiana shields, the Xingu and Tapajós rivers, discharge into the Amazon River in the Eastern region. The Tocantins River discharges directly into the estuary. Tides occur in the lower Eastern Region but, for the most part, there is a strong seasonal flood pulse emanating from upstream hydrological events. The main commercial ports for catfish landing in the Eastern Region are in Brazilian cities of the state of Pará.

Although inland, the Central Region is still largely less than 100 m in elevation and includes a large portion of the Amazonian lowlands. It includes approximately 2,000 km of the Amazon River (Solimões-Amazonas) and the lower portions of its turbid rivers with headwaters in the Andes, such as the Madeira, Purus, Juruá, Caquetá-Japurá and Putumayo-Içá rivers. As with the Eastern Region, a strong seasonal flood pulse characterizes the Central Region hydrologically. Cities in the department of Amazonas in Colombia and the state of Amazonas in Brazil receive most of the catfish caught in the Central Region.

The Western Region includes the Andean Piedmont below approximately 300 m and its contiguous lowlands. It includes the upper portions of the Madeira, Ucayali, Marañón, Putumayo and Caquetá rivers. Andean sediments render these rivers highly turbid and though a strong seasonal flood pulse occurs, it has more peaks than those observed in the Central and Eastern regions. The main fishing ports in this region are in cities in the departments of Loreto and Ucayali in Peru, but other small ports receive catfish in the departments of Cochabamba and Beni in Bolivia, Madre de Dios in Peru and Amazonas in Colombia.



1 Viseu - BR
2 Augusto Correa - BR
3 Quatipuru - BR
4 São João de Pirabas - BR
5 Salinópolis - BR
6 Maracanã - BR
7 Marapanim - BR
8 Curuçá - BR
9 São Caetano - BR
10 Vigia - BR
11 Colares - BR
12 Soure - BR
13 Salvaterra - BR
14 Bragança - BR
15 Vila do Conde - BR
16 Abaetetuba - BR
17 Limoeiro do Ajuru - BR
18 Cametá - BR
19 Mocajuba - BR
20 Baião - BR
21 Tucuruí - BR
22 Jacundá - BR
23 Itupiranga - BR
24 Macapá - BR
25 Almerim - BR
26 Prainha - BR
7 Monte Alegre - BR
28 Alenquer - BR
29 Oriximiná - BR
30 Parintins - BR
31 Manacapuru - BR
32 Coari - BR
33 Alvarães - BR
34 Fonte boa - BR
35 Lábrea - BR
36 Leticia – BR, Santa Rosa - PE, Tabatinga - BR
37 La Pedrera - CO
38 Caballochocha - PE
39 San Pablo - PE
40 Pevas - PE
41 Estrecho - PE
42 Mazan - PE
43 Nauta – PE
44 Requena - PE
45 Datem - PE
46 Yurimáguas - PE
47 Contamana - PE
48 Pucallpa - PE
49 Porto Velho - BR

Fig. 1 The Amazon Region, highlighting the countries, departments (Bolivia-BO, Peru-PE, Colombia-CO) or states (Brazil-BR) and catfish landing cities (CLC) of the main fishing regions. The Estuary region, highlighting the North Coast (Amazon estuary and Atlantic Ocean), the black points showing where fishing trawls operate, the catfish landing cities (CLC) and the restricted trawl fleet areas based on current legislation (IBAMA, 1999)

Commercial fisheries data for the Amazon Basin

Commercial fish landings occur in public and private ports, with the latter belonging to refrigeration plants located along the large rivers between the Andes and Amazon Estuary. Landing statistics are available by national fisheries agencies for Peru, Colombia and Brazil. Ecuador's freshwater fishing activity is primarily for subsistence and local market supply, and minimal recorded data are available (Utreras-Bucheli 2010). Fishery production for the Bolivian Amazon includes commercial fishing activity in the Beni and Cochabamba departments (Figure 1). The available Bolivian data refer to total fish consumed for the years 1986 to 1994 (Van Damme et al. 2011).

Brazil, Peru and Colombia, in that order, support important commercial fisheries with traditional export markets to other regions or countries in the Amazon Basin (Barthem and Goulding 2007). Peru has a long time series of Amazonian fishery data, especially in the department of Loreto where the Peruvian Fishing Agency "Dirección Regional de Pesqueria" (DIREPRO) has collected data since 1980. Fishery data in the Madre de Dios and Ucayali departments of Peru are only available for a few years (Figure 1). Data sources for Peruvian fishery production include literature sources (Barthem et al. 1995) and reports or databases of DIREPRO. Colombian Amazonian fishery production, including online data, includes the ports of the department of Amazonas, especially in the cities of Leticia and La Pedrera (Figure 1) (reports of fishery production data are available online by the Colombian Fishery Agency "Servicio Estadístico Pesquero Colombiano" (SEPEC n.d.) and cover the periods between 1993 and 1999 and 2006 and 2007). Brazil supports the largest fisheries in the Amazon, and data for four of the goliath catfish species exploited (*B. rousseauxii*, *B. vaillantii*, *B. filamentosum* and *B. capapretum*) are available online by the Brazilian environmental conservation agency "Instituto Chico Mendes de Conservação da Biodiversidade" (ICMBIO) for nine states (Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima and Tocantins) (ICMBIO n.d.). The fishing reports of the ICMBIO website provide information since 1944, but the most reliable data is for the period between 1980 and 2007. Before that period, information regarding species names, the origin of fish catches relative to states, and/or the type of fishing fleet was often misleading. Subsequent to 2007, when data collecting ended, information represents estimates based on statistical projections. Fishery production data for *B. platynemum* and *B. juruense* from the period between 1992 and 2004 were compiled from the literature (Doria et al. 2012; Isaac and Ruffino 2000); from refrigeration plant reports produced by the Brazilian Agency of Animal Production of the Agriculture Ministry "Ministério da Agricultura, Pecuária e Abastecimento" (MAPA); from the fish landing database of the Porto Velho Fishing Colony "Colônia de Pescadores Z-1, Tenente Santana"; and from Eletronorte–Centrais Elétricas do Norte do Brasil, IBAMA-Provárzea, and Museu Paraense Emílio Goeldi (Figure 1).

Due to the limitation of the available data and the uncertainty of the data collection methodology used in different countries and states or departments (states in Brazil and departments in Bolivia, Peru and Colombia), we used the average annual catch by species and states or departments as indicative of regional production.

Fish size data in the Amazon Basin

Our dataset of goliath catfish lengths obtained from various sources provided length ranges for the four main fisheries regions: Estuary, Eastern, Central and Western (Figure 1). The data included commercial and experimental fisheries between 1982 and 2011 that represented at least 187 locations over a vast area of the Brazil, Peru, Colombia and Bolivia. Gillnets were the gear used in most commercial fisheries, though some samples included trotlines. Commercial fisheries of *B. vaillantii* included seine net catches in the Central Region and trawl catches in the Estuary Region. Trawls and seine nets used in the estuary and/or river channels captured fish with comparable sizes to those taken with gillnets, although trawls and seines also capture small fish that escape gillnets. Analyses of *B. vaillantii* and *B. rousseauxii* included gear to consider the selectivity bias in analyzes. Experimental and commercial fisheries used gillnets with mesh sizes ranging 12-20 cm measured diagonally. Finally, minimum maturity size (MMS) (Barthem et al. 2017) was used to separate subadult and adult categories for each fishery region.

Trawl fishery data and Analyses in the Amazon estuary

Annual capture data of *B. vaillantii* by the trawl fleet was collected by the Brazilian agencies responsible for fishery management (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA 1999). Most recent data are available on the website of ICMBIO (http://www.icmbio.gov.br/cepsul/biblioteca/acervodigital/38download/artigos-cientificos/112-artigos-cientificos.html). Fish size samples include different periods compiled from a range of sources related to fishing periods. The technical reports of the Superintendência do Desenvolvimento da Pesca - SUDEPE provided the fish size composition for the period 1979-1980. Datasets of different projects sponsored by the Museu Paraense Emílio Goeldi – MPEG provided data for the periods 1982-1985 and 1993-1997, and the data for the years 2008-2011 were provided by "Industrial Fishing Monitoring of the Pará State Project" supported by the Ministerio da Pesca, MPA.

The status of the *B. vaillantii* trawl fishery was determined by the trends of two biological indicators: (i) the relationship between the present catch and the maximum sustainable yield (MSY) level (Gaertner et al. 2001), and (ii) the relationship between the current fishing mortality, F, and the F that produces MSY (F/F_{MSY}) (Pons et al. 2017). We estimated the MSY level by the changes over time in the relative rate of catch increase (RRCI) (Equation 1) by periods of the gradual development of the trawl fishery for *B. vaillantii* (Gaertner et al. 2001; Grainger and Garcia 1996). The limits of each period were determined by the set of years where the smoothed RRCI, or RRCI' (Equation 2), exhibits a declining trend or continuous increase in the exploitation rates, as presupposed by the method (Gaertner et al. 2001). The principle of the RRCI' is that it declines to zero when the fishery reaches the mature phase and the catch reaches the maximum yield, considered by the model as the MSY proxy or MSY_{RRCI}. The model assumes that fishing effort had increased over time, which is consistent with the trawl fishery for *B. vaillantii*, despite a regulation in 2002 prohibiting more than three boats fishing together. We adopted a period of three years (L) as the age groups that are vulnerable to fisheries in the estuary area before they start to migrate, to calculate the averaged previous catches (Cav) (Equation 3) and the second-degree polynomial to fit the regression between RRCI' and Cav.

$$RRCI_t = \frac{\left[C_t - \left[\frac{(C_{t-1}+C_{t-2}+C_{t-3})}{3}\right]\right]}{\left[\frac{(C_{t-1}+C_{t-2}+C_{t-3})}{3}\right]} \qquad \text{Equation 1}$$

$$\mathrm{RRCI}'_t = \left(\frac{\sum_{t-1}^{t+1} RRCI_t}{3}\right) \qquad \text{Equation 2}$$

$$Cav_t = \left(\frac{1}{L}\right)\sum_{i=0}^{L} C_{t-i} \qquad \text{Equation 3}$$

The relationship between current fishing mortality, F, and the F that produces MSY (F/F_{MSY}) was calculated considering F as the difference between the total mortality (Z) of each year and the natural mortality (M), and F_{MSY} as 0.30 year^{-1} (Alonso and Pirker 2005). The total mortality (Z) was estimated by the length-converted catch curve procedure of FiSAT II (Gayanilo et al. 2005), considering the maximum asymptotic length $L\infty$ = 110.5 cm and the growth coefficient K =0.10 (Alonso and Pirker 2005). Natural mortality (M) was estimated by three methods: (i) Pauly´s methods (Pauly 1980): $log_{10}\mathrm{M} = 0.0066 - 0.279\, log_{10}L_\infty + 0.6543\, log_{10}\mathrm{K} + 0.4634\, log_{10}\mathrm{T}$, with the mean environmental temperature T= 27,8°C (Barthem and Petrere Jr 1995); (ii) Taylor's method: $M = \frac{-\ln(1-0{,}95)}{A_{0{,}95}}$, where $A_{0.95}$ is the age at which 99% of the cohort would be dead (Sparre and Venema 1997): and (iii) Cubillos's methods (Cubillos 2003): $M_c = \frac{3*K*(1-0{,}62)}{0{,}62}$, where K is the growth coefficient. Fishing mortality was estimated to be the average of the three different methods. The stock was considered overfished if the catch exceeded the MSY proxies (Gaertner et al. 2001) or if the indices F/F_{MSY} were larger than one (Pons et al. 2017). We analyzed the effect of fisheries management during the study period with the Mann-Kendall test for monotonic temporal trend on the fishing mortality data. The "Kendall" package for the Mann- Kendall test of the program R (RCoreTeam 2013) was used considering α = 0.05 as the error.

Results and Discussion

History and geopolitics of goliath-catfish fishery production

The late 1950s mark the beginning of modern commercial fishing in the Amazon Basin, especially in Brazil with the use of motorized boats, ice plants, and nylon nets and lines (Meschkat 1960). Due to historical taboos against eating catfish, intensive fishing pressure on the Amazon catfish stock began only in the early 1970s after the availability of fish processing plants along the main river channel in Brazil and Colombia to export frozen fish to other regions or countries. The estuary was an exception to the catfish taboo because marine and freshwater catfish exploitation occurred since the indigenous period. In the early 1970s, industrial-scale fishing companies operating in the estuary, and subsidized by the Brazilian government, focused especially on *B. vaillantii* because of its export market. In Colombia, the increased production of coca for the international cocaine market during the years 1978-1982 led to an economic boom that indirectly stimulated the catfish fishery in the Amazonas and Caquetá rivers (Agudelo-Córdoba et al. 2000; Almeida 2006; Barthem and Goulding 2007; Begossi et al. 2004; Fabré and Barthem 2005; Rodríguez-Fernández 1991).

Fishing companies and artisanal fishing fleets exploit goliath catfish in the Amazon Basin. Bottom pair-trawler fishing operations began exploiting the Amazon estuary in 1972 to supply local fish processing industries. The current trawler fleet is composed of 48 vessels with an average boat length of 22 meters, outfitted with navigation instruments such as GPS and sonar, ice capacity of 35 to 60 tons and powered on average by 375 HP engines. The paired bottom otter-trawl was the technique developed to fish on the soft mud originating from Amazon River sediments deposited in the mouth area. The general characteristics of the estuarine trawl fleet make it the most modern and powerful fishing operation that exploits fish species in the Amazon, although it is restricted to a limited area of the Estuary Region (Figure 1) (Barthem and Goulding 2007; Klautau et al. 2016b). The artisanal fishing fleet is made up of diverse types of fishing boats and operates locally across the Amazon using mainly drifting gillnets and seines, and to a limited extent harpoons and longlines (Barthem and Goulding 2007; Batista et al. 2018; Fabré and Barthem 2005).

Total production of goliath catfish fisheries is available for the period between 1980 and 2007, but there are many gaps in the historical datasets. The available data for the Madre de Dios Department in Peru is limited to three years, nine years for Bolivian and Colombian departments, 12 years for the department of Ucayali and 21 years for the department of Loreto in Peru (Table S1 of the supplementary material). The low local presence and/or abundance of some species probably accounts for their poor showing in species records. Fishery statistics for *B. platynemum* and *B. juruense* are limited to a few years, and then only for Brazilian states. The only goliath catfish data in Bolivia are for *B. rousseauxii*. As indicated by historical fisheries data, the natural limit of *B. vaillantii* in the Madeira Basin was near Porto Velho in Brazil, and the lower biogeographic limits of *B. juruense* are in the Eastern Region. Most goliath catfish landing data refers to distinct scientifically recognized species. The one exception includes *B. filamentosum* and *B. capapretum*, two species grouped in fisheries data under the common name piraíba in Brazil and saltón elsewhere in the Amazon, as they are very similar superficially.

The average annual fishery production of goliath catfishes varies widely in relation to the species and the state or department. Total annual production of each species ranges from 18,976 t for *B. vaillantii* and 22 t for *B. juruense* (Table S2). Investment in fish processing plants in Brazil and Colombia, the two most important countries exploiting catfish, largely determines the scale of present goliath catfish fisheries. The Brazilian states of Pará and Amazonas and the Colombian department of Amazonas represent together 92% of total goliath catfish production in the Amazon Basin. Thus, this geopolitical group contains the most important stakeholders for commercial fisheries of goliath catfishes (Figure 2).

Goliath catfish composition varies between countries and departments or states. In general, *B. vaillantii*, *B. rousseauxii* and the two piraíba species (*B. filamentosum* and *B. capapretum*) represent together 99% of total production. The Eastern and Estuary regions (Pará and Amapá, Brazil) dominate the production of *B. vaillantii* (86%) and *B. rousseauxii* (61%), whereas the production of *B. platynemum* (95%) and *B. juruense* (74%) is concentrated in the Central Region (Amazonas Department in Colombia and Amazonas State in Brazil). Ninety percent of the two piraíba species production is dispersed in Pará, Amapá and Amazonas states in Brazil and Amazonas Department in Colombia. The fishery production of *B. filamentosum* and *B. capapretum* species is unknown, but it probably varies regionally (Huergo et al. 2011) (Figure 2).

The trawler fishing fleet is relatively small (currently 48 vessels) and operates in a limited area near the Amazon River mouth in Brazil, compared with the much more widely distributed artisanal fishing fleet. However, the trawler fishing fleet accounts for 46% of total goliath catfish production in Brazil, including

67% of *B. vaillantii* production and 18% of *B. rousseauxii* production. *B. vaillantii* accounts for 89% of total estuary production of goliath catfishes captured by trawlers, followed by *B. rousseauxii* (11%) and *B. filamentosum* and *B. capapretum* (0.2%).

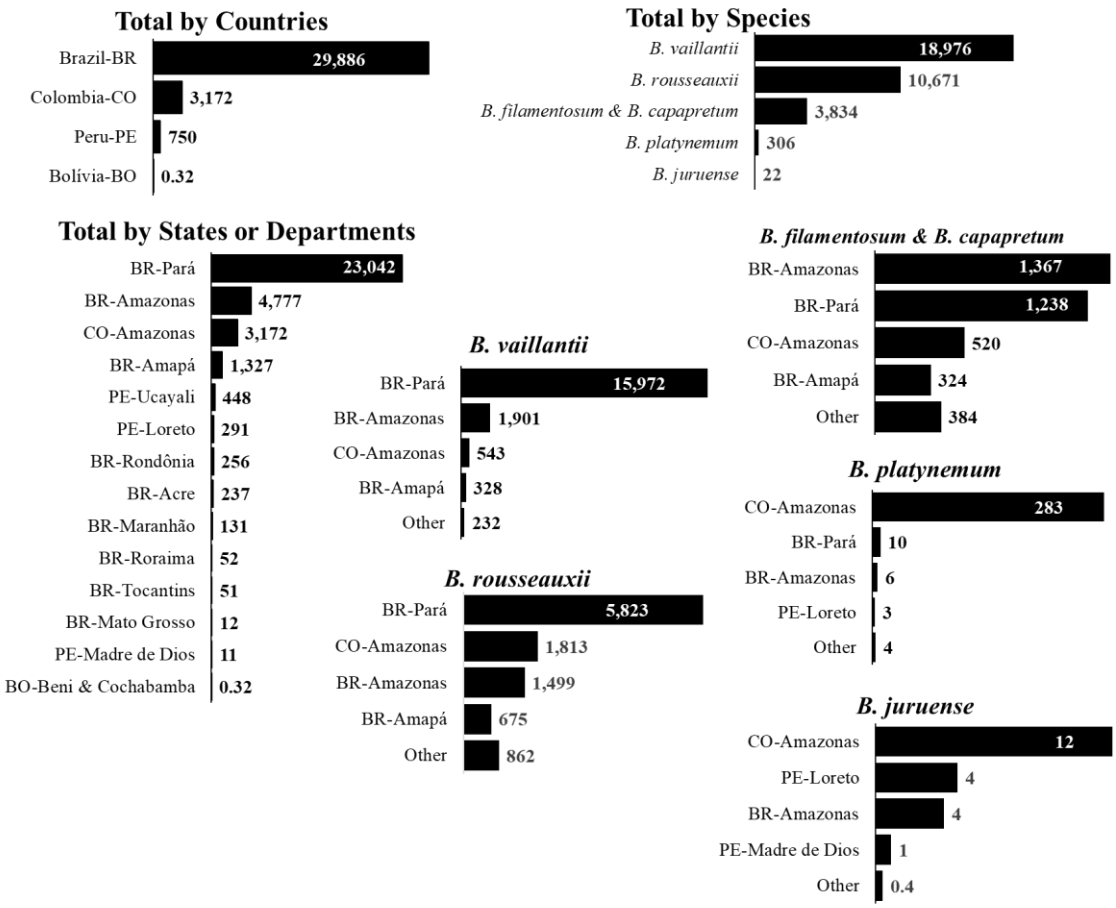


Fig. 1 Average annual production (metric tons) of goliath catfish species in relation to countries and states or departments

Migration behavior and size class distribution of the goliath catfishes

Size-class distribution analyses include the lengths of 325,236 goliath catfishes and the gear used to catch them from the four main fisheries regions between 1982 and 2011 (Table S3). The analyses included all species except *B. filamentosum* and *B. capapretum* because it is impossible to define the MMS with mixed species in fishery data. No measurements were available for *B. vaillantii* in the Western Region, though the species is exploited modestly near Iquitos in Peru and as far upstream as the Manseriche Gorge of the Marañón River at the edge of the Andes. Likewise, catches of *B. juruense* and *B. platynemum* are minimal in the Eastern Region.

The most striking size distribution pattern for most goliath catfishes analyzed is the decreasing presence of subadult fish from east to west. The exception was *B. platynemum*, which did not present such an obvious size-class separation regionally between subadult and adult fish. Only *B. vaillantii* and *B. rousseauxii* appeared in significant numbers in the fisheries of the Eastern and Estuary regions. The *B. vaillantii* catch is composed mainly of subadult fish in all regions, though the abundance of young fish decreases from east to west. Gillnet catches of *B. vaillantii* revealed more adults in the Eastern Region than in the Estuary, though this gear can be highly selective because of mesh size. However, the much less selective seine and trawl net catches, respectively in the Central Region and Estuary, showed the same pattern. Immature *B. rousseauxii* dominated in the Eastern Region. The size composition from trawl catches, which is less selective than gillnets, indicated a strong dominance of subadults of both *B. vaillantii* and *B. rousseauxii* in the Estuary Region. Most specimens of *B. rousseauxii* and *B. platynemum* captured in the Central Region were adult fish, while most specimens of *B. juruense* in the same region were subadults. All *B. rousseauxii* and *B. platynemum* and 99% of the *B. juruense* specimens examined in the Western Region near the Andean Piedmont were adults (Figure 3).

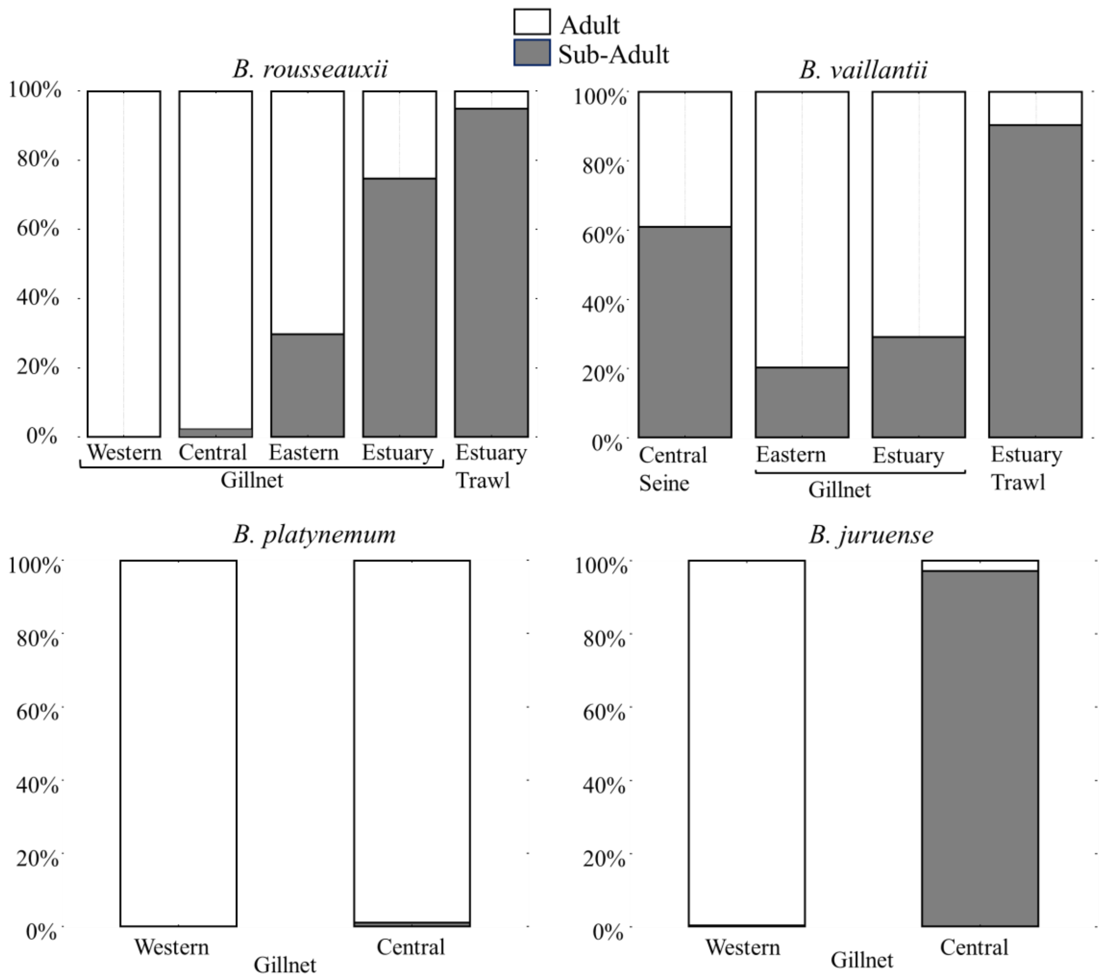


Fig. 3 Fish size composition of goliath catfishes captured by fishing gear and regions

Of the goliath catfish species, the migration patterns of *B. vaillantii* and *B. rousseauxii* are the best understood. Adult and subadult schools leave the estuary and migrate upriver during the low discharge period of the Amazon River (Barthem and Goulding 1997). Other goliath catfish species undertake similar upstream movements and full-time, part-time or occasional fishers capture them during the migration period (Agudelo-Córdoba et al. 2000; Barthem and Goulding 2007; García et al. 2012). Fish migration behavior largely explains the size composition differences of *B. rousseauxii*, *B. vaillantii* and *B. juruense* captured in different regions. As indicated by the presence of adult fish, the Western Region is the spawning area, and the downstream sections are the nursery areas for smaller fish. The Estuary Region is the nursery area for *B. vaillantii* and *B. rousseauxii* and the Eastern Region appears to be the nursery area for *B. juruense* based on limited data (Barthem et al. 2017). Published studies indicate at least two populations of *B. platynemum* in the Amazon Basin, indicating different migration patterns than those of the other goliath catfishes, and perhaps different nursery and spawning areas (Hahn et al. 2019; Hauser et al. 2019; Ochoa et al. 2015). Depending on the area, fishing pressure results in different exploitation consequences. The main concern for fishery management of goliath catfishes in the Estuary Region is growth overfishing. This is due to the non-selectivity of trawl-net catches that also include a high bycatch rate not only of young goliath catfishes but also of small adult fish of other species (Barthem et al. 2015; Barthem and Petrere Jr 1995; IBAMA 1999; Jimenez et al. 2013; Klautau et al. 2016a; Klautau et al. 2016b). Fishing pressure in the goliath catfish-spawning area in the Western Amazon is relatively low and based mainly on drifting gillnets and seines, and much less so on harpoons and longlines. Of more concern, are proposals to construct large Andean dams on several major tributaries used for spawning by goliath catfishes. These dams could have far-reaching downstream impacts on migratory routes and hydrological cycles, thus interfering with fish migrations and damaging fisheries and their associated wetlands (Anderson et al. 2018; Damme et al. 2019; Forsberg et al. 2017)

Overfishing cases

The first step in assessing the effect of overfishing involves identifying fish stocks that represent discrete biological or genetic populations (Cadrin et al. 2013). The absence of spatial genetic segregation in the main fishing areas of *B. rousseauxii* (Batista and Alves-Gomes 2006) and *B. vaillantii* (Batista et al. 2004) suggests that a single stock is involved. Genetic studies indicate two structured populations of *B. platynemum*, one in the Madeira River and the other in the Amazon River (Hahn et al. 2019; Hauser et al. 2019; Ochoa et al. 2015). The distributions of *B. filamentosum* and *B. capapretum* overlap in the Andes-Amazon turbid rivers, although *B. capapretum* is mostly reported from turbid rivers, whereas *B. filamentosum* distribution includes turbid, clearwater and blackwater rivers and indicates three genetic clades related to water chemistry (Huergo et al. 2011; Huergo 2009). The genetic structure of *B. juruense* is unreported. The low interpopulation genetic differentiation of *B. rousseauxii* and *B. vaillantii* in the Amazon Basin appears related to large-scale migratory behavior that acts as a homogenizing agent (Do Prado et al. 2017). In contrast, *B. filamentosum* and *B. capapretum* do not undertake long-distance migrations (>1,000 km) and spawn widely and in various river types (Barthem et al. 2017; Hermann et al. 2016).

Excessive fishing pressure has resulted in the local reduction or overfishing of the most commercially important goliath catfish species. The depletion of *B. filamentosum* and *B. capapretum* for export markets by local fisheries was reported for the upper Amazon in the region exploited for the Colombian port city of Leticia located at the Colombian, Brazilian, and Peruvian border (Petrere et al. 2004). Overfishing of *B. rousseauxii*, the species undertaking the longest migrations in the Amazon Basin, was observed independently in two fishing zones: in the Caquetá River, Colombia (Agudelo-Córdoba et al. 2013) and in the Amazon River, Brazil (Alonso and Pirker 2005). Finally, *B. vaillantii* has been considered overfished in the Estuary Region since the 1990s (Barthem and Petrere Jr 1995; IBAMA 1999). The status of *B. platynemum* and *B. juruense* stocks are still unknown. Although these studies provide a baseline to support fisheries management programs, information is still scarce, low in periodicity, and without a long series of catch data for most species. The trawl fisheries in the Estuary Region, however, are an exception in terms of the longer historical series of catch data available. Thus, a detailed review of estuary fisheries provides a starting-point model for the management of other goliath catfish stocks.

The Brazilian bottom pair-trawl operations for *B. vaillantii* in the Amazon Estuary, accounting for 76% of the region's catch, represent a rare example of a single-species and large-scale inland fishery in the tropics (Klautau et al. 2016b). *B. vaillantii* landings of the trawler fleet reached their highest value (22,486 tons) in 1977 after only five years in operation. During the 1980s, *B. vaillanti* stocks were overfished and annual production decreased until reaching its historically lowest level (6,299 tons) in 1992 (Barthem and Petrere Jr 1995; IBAMA 1999). The trawl fishery was largely responsible for this situation because its fleet exploits the nursery area that historically accounted for 67% of the *B. vaillantii* catch in Brazil (Barthem and Goulding 2007; IBAMA 1999). Goliath catfish had relatively high economic value in Amazonian fisheries due to export markets outside of the Amazon. In 1986 and 1987, *B. vaillantii* was the third most important fish exported from Brazil as a whole (Barthem and Goulding 2007). Since that time, overfishing of *B. vaillantii* has continued and the species no longer appears in export lists.

The historical analysis of the exploitation of trawl fisheries for *B. vaillantii* represent a 40-year dataset between 1972 and 2011 (Table S4). The MSY level estimates represent changes in annual catch data available until 2006. The variation of RRCI' defined four sets of years with a declining trend as presupposed by the method (Gaertner et al. 2001) (Figure 4). The development of goliath catfish fisheries corresponds to four periods. The first period of 1976-1980 corresponded to the first expansion of the trawl fishery for *B. vaillantii* in the estuary. The second period included export markets (1982-1985) that also after 1983 commercialized fish smaller than 28 cm (fork length), the previous usual minimum length. Third, was an increase in the number of fishing boats from 43 to 66 boats in the period 1986-1991. The fourth period (1997-2000) corresponds to the second expansion of the fishery after the historic lowest catch in 1992, when many boats began fishing together despite a total estuary industrial fishing limit of 48 boats (Barthem et al. 2015; IBAMA 1999). Later restrictions implemented in 2002 set a maximum of three fishing boats that could work together.

The MSY estimated through the fit of the second-degree polynomial showed a decreasing trend during the historical data series. The MSY decreased from 1970 to 2000, dropping off from 18,591 t/year in the first period (1976-1980) to 16,109 t/year in the second period (1982-1985) and 14,915 t/year in the third period (1986-1991). The MSY stabilized in the last period (1997-2000) to 12,197t/year (Figure 5 and Table 2). The annual catch exceeds the MSY in all periods, indicating overexploitation six years after the beginning of this fishery. The analyses of the F/FMSY ratio based on 16 years of data showed a similar pattern of overexploitation. The F/F_{MSY} ratio value ranged from 0.7 to 11.04, and only in 1996 was the F lower than the F_{MSY}, while in 75% of the years the F was at least twice the F_{MSY} (Figure 5 and Table S3). Previous estimates of MSY using the conventional Schaeffer-model ranged between 14,732 and 24,700 t/year (IBAMA 1999), but the most recent estimate of MSY using the CLIMPROD software indicated a lower value than that (11.273 t/year) estimated in this paper and points to an even more serious overfishing situation (Matsunaga 2012).

Although overfishing of *B. vaillantii*'s was first observed in 1984 and 1985 (Barthem and Petrere Jr 1995), our analysis indicates that catches have exceeded the sustainable maximum for almost the entire period and this stock has suffered high fishing mortality rates since the 1970s, just a few years after trawling began. Considering that the Brazilian government subsidized the trawler fleet, it is now evident that it was too large compared to the resource available. However, even with excessive fishing pressure, *B. vaillanti* stocks did not collapse as happened with *B. filamentosum* and *B. capapretum* in the upper Amazon. The apparent resilience of the *B. vaillantii* stock appears related to its wide distribution in the Amazon Basin and an opportunistic trophic behavior that allows it to prey on abundant smaller fishes in both the estuary and river channels (Barthem and Goulding 1997). These attributes are associated with stocks less susceptible to collapse, as was observed in some tropical tuna species (Pons et al. 2017). Furthermore, although the *B. vaillantii* nursery area overlaps with the trawler fishing area, exploitation of the species in other areas is modest and it is apparently almost nonexistent in the spawning area, thus largely eliminating the threat of recruitment overfishing (Barthem and Goulding 2007). The pattern for *B rousseauxii* is somewhat similar (Barthem and Goulding 1997), but differs from *B. vaillantii* in that its exploitation is intense in all areas, including its spawning area in the western Amazon, thus making it also susceptible to collapse. Fishing for *B. filamentosum* and *B. capapretum* has characteristics similar to those of *B rousseauxii*, with high fishing pressure at all life history stages. As these two species (*B. filamentosum* and *B. capapretum*) undertake local migrations, they are more susceptible to local collapse. The depletion of *B. filamentosum* and *B. capapretum* observed in the upper Amazon is most likely the result of local overfishing of all size classes large enough to market (Petrere et al. 2004).

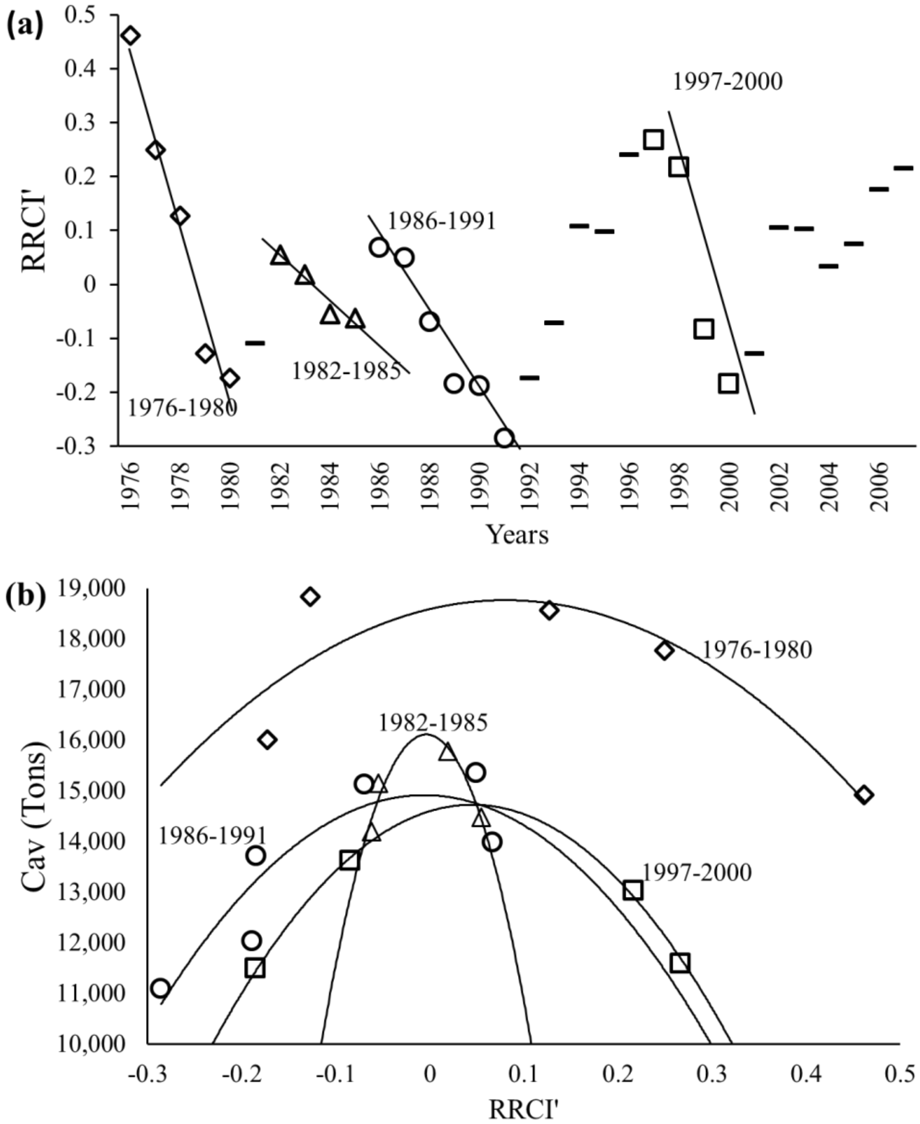


Fig. 4 Analysis of the relative catch rate (RCCI) for *B. vaillantii* bottom pair-trawl fishery from 1972 to 2006. (a) Changes over time in the relative rate of increase of catches (RRCI) for piramutaba in the mouth of the Amazon River during a 34-year period (1972 to 2006). Years corresponding to significant changes in the fishery were not used to estimate the maximum yield and are represented by black dash, and the data with minor changes are used for the regression represented by diamonds, squares, circles, and triangles for each trend of years. (b) Changes in catch trends (Cav) for piramutaba against changes in the relative rate of increase in catches (RCCI) over the historical 34 year period (1972 to 2006)

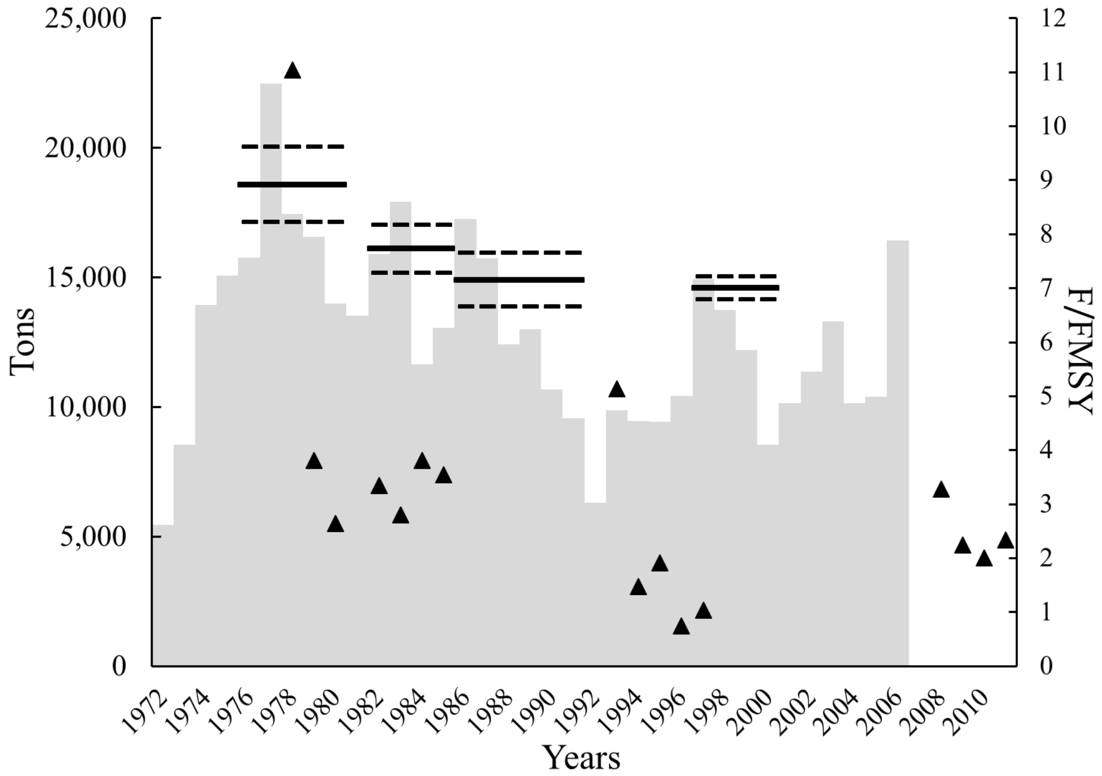


Fig. 5 Annual catches (tons) of the *B. vaillantii* bottom pair-trawler fishing fleet in the Amazon estuary (gray bars) combined with the MSY proxies (tons) with 95% confidence limits (continuous and dotted line) and the F/F_{MSY} ratio (triangle). The data of the annual catches are available for the 1972-2016

Management and conservation scale of goliath catfishes

Compared to other fisheries in the region, the outstanding feature of goliath catfish fisheries in the Amazon was government subsidization that led to excessive fishing for export markets. Furthermore, insufficient knowledge and monitoring of fishery resources exacerbated overfishing of goliath catfishes. Similar circumstances occur in marine fisheries (Pauly 2019; Sumaila et al. 2016). Goliath catfish overfishing in the Amazon may serve as a forewarning of the unintended consequences of subsidized fisheries to supply export markets. At present, fisheries management regulations of goliath catfishes aimed at fishing gear, minimum size limits, time limitations and place restrictions are coordinated only by local regional governments and in general poorly implemented (Ruffino 2004). Considering the large migration areas that involve not only many states/departments, but also perhaps five countries and the wide spatial separation of nursery and spawning areas, present local regulations even if enforced are insufficient to manage these important species. Considering the vast life history areas of the long-distance migratory catfishes, environmental impacts and/or overfishing in either upstream or downstream areas could have far-reaching consequences in the opposite direction. For example, the large catches of small fish in the Eastern and Estuary Regions, and the absence of small fish upriver, render nearly fruitless the adoption of minimum size limits by states or departments of the Central and Western Regions (Figure 2 and Figure 3). Moreover, the effect of fishing effort in different regions may cause different types of overfishing that would affect the fishery across the Amazon Basin, such as growth overfishing in the Eastern and Estuary regions or recruitment overfishing (spawning fish) in the Western Region.

Present measures to prevent or eliminate growth-overfishing focus mostly on trawl fishing in the Estuary Region. This management program began in the 1970s and has three main strategies: (i) closed areas, (ii) fishing effort restrictions and (iii) closed seasons (Table 3). The local managers have economic and technical limitations for applying the legislation, and most enforcement targets the bottom pair-trawler fishery. Consequently, it has not been possible to identify and test the effectiveness of each strategy since first applied. Thus, we tested the effectiveness of fishery management for goliath catfishes based on historical data considering the effect of all strategies to reduce fishing mortality. As a result, we observed a significant descendent trend of fishing mortality during the time period (Mann-Kendall test; tau = -0.393, 2-sided p-value= 0.0382), suggesting that measures applied have had some effect on reducing fishing pressure, but it was not enough to avoid overfishing.

The low effectiveness of the management measures adopted by bottom pair-trawler fisheries in the Amazon Estuary had negative economic and biological consequences on fishery resources, and presents challenges for the long-term sustainability of large-scale fisheries in the Amazon (Almeida 2006). The low position of fishery management policy in the Brazilian economic and political arenas further aggravates the situation (Reis-Filho and Leduc 2017). For example, the implementation and enforcement of total allowable catches (TACs), considered one of the most positive influences on the rebuilding of overfished stocks (Pons et al. 2017), is impaired by the lack of fishery monitoring by Brazilian agencies. In general, there is no general international agreement on what fisheries management targets should be (Hilborn and Ovando 2014), but evaluating status relative to MSY reference points is a common practice (with the knowledge that biomass levels other than BMSY may often be desired). Future stock assessment of *B. vaillantii* caught in Amazon Estuary should include this type of analysis. In addition, supervision of other management strategies, such as minimum mesh size of the cod-end of trawls and the number of boats fishing together, appears unfeasible due to minimal commitment to these measures by the fishers and owners of fishing boats.

Goliath catfish exploitation in the Western Region targets individuals captured during reproductive periods (Barthem et al. 2017). There are no restrictions on this fishery, other than the minimum size limits, which are largely irrelevant since only large size classes are present (Barthem et al. 2019). Fortunately, relatively little commercial fishing occurs in the reproductive region and some headwater spawning areas are in protected areas (Goulding et al. 2003b). Reduced fishing activity in the spawning areas avoids recruitment overfishing for most goliath catfishes, the main exception being *B. filamentosum* and *B. capapretum* that spawn over a much wider area.

There is now considerable discussion and proposals to build large dams in the Andean Piedmont and at higher elevations (Anderson et al. 2018; Damme et al. 2019; Finer and Jenkins 2012; Forsberg et al. 2017; Tollefson 2011). Andean dam impacts on inter-basin migratory fish species would be far greater than those presented by the large dams now constructed or proposed for Brazilian Shield rivers, such as the Tocantins, Xingu and Tapajós. These tributaries are relatively unimportant to long-distance migratory goliath catfishes, though important to other local migratory species. The two recent Madeira River dams are the first to interrupt the connectivity between the Amazon Estuary and the Western Region. The Madeira River is the Amazon's largest tributary and has a vast goliath-catfish headwater spawning area in Bolivia and Peru. An experimental migratory fish bypass is being tested at the Santo Antonio Dam near Porto Velho in the state of Rondônia, Brazil, but initial results indicated the interruption of upstream moving subadult and adult goliath catfishes (Damme et al. 2019; Hahn et al. 2019; Santos et al. 2018). Furthermore, the ability of downstream moving juveniles to pass through this downstream dam is still unclear. Whereas the main challenges of the Madeira dams are as barriers, the impoundments present little if any blockage of sediments and nutrients (Anderson et al. 2018; Forsberg et al. 2017). In contrast, Andean dams would have high structural walls that could radically change sediment, nutrient and river flow cycles, thus disrupting probable physical and biological cues and environmental conditions that migratory fish need for successful spawning. These impacts would probably also be compounded by headwater deforestation and uncontrolled mining activities that exacerbated water pollution. Spawning habitat destruction in the Andean Piedmont and contiguous downstream areas is the single greatest danger that the goliath catfishes face in the longer run, though overfishing is critical to address immediately.

The goliath catfishes are transnational species exploited in five Amazonian countries. The management of their fisheries, if they are to be preserved, will require international cooperation to control overfishing and environmental impacts. This will require compliance with various international agreements already signed, including but not limited to the Food & Agriculture Organization (FAO), the Organization Cooperation Treaty Organization (OTCA), the Ramsar Convention, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the Convention on the Conservation of Migratory Species of Wild Animals (CMS) (Valbo-Jørgensen et al. 2008).

Tables

Table 1– Scientific and common names of the Amazon Goliath catfish species: EN: English name; PN: Portuguese name; SN: Spanish name

<table>
<tr><td>Scientific Name</td><td>Common Names</td><td>Exploited by</td></tr>
<tr><td>Brachyplatystoma juruense (Boulenger, 1898)</td><td>EN: Zebra catfish; PN: Zebra, Flamengo; SN:Zebra, Flamengo, Alianza</td><td rowspan="6">Commercial fishing</td></tr>
<tr><td>Brachyplatystoma platynemum Boulenger, 1898</td><td>EN: Slobbering catfish; PN: Babão; SN: Baboso, Saliboro, Flemosa</td></tr>
<tr><td>Brachyplatystoma rousseauxii (Castelnau, 1855)</td><td>EN: Gilded catfish; PN: Dourada; EN: Dorado, Plateado</td></tr>
<tr><td>Brachyplatystoma vaillantii (Valenciennes, 1840)</td><td>EN: Laulao catfish; PN: Piramutaba; SN: Pirabutón, Manitoa</td></tr>
<tr><td>Brachyplatystoma capapretum Lundberg & Akama, 2005</td><td rowspan="2">EN: Kumakuma; PN: Piraíba, Filhote; SN: Lechero, Pirahiba, Saltón</td></tr>
<tr><td>Brachyplatystoma filamentosum (Lichtenstein, 1819)</td></tr>
<tr><td>Brachyplatystoma tigrinum (Britski, 1981)</td><td>EN: Tigerstriped catfish; PN: Tigre, Dourada-zebra; SN: Zúngaro-tigrinus</td><td>Ornamental fishing</td></tr>
</table>

Table 2- Maximum Sustainable Yield estimates from a relative catch rate (RCCI´) analysis for the industrial *B. vaillantii* fishery at the mouth of the Amazon River from 1972 to 2006.

RCCI´ time period	Year of MSY estimate	MSY estimate (tons/year)	95% confident interval (tons)
1987-1980	1978	17,446	17,142-20,041
1982-1985	1982	15,915	15,181-17,038
1986-1991	1987	15,728	13,879-15,951
1997-2000	1999	12,197	14,165-15,039

Table 3- The set of control rules employed for the fishing management of the *B. vaillantii* bottom pair-trawl fishing in the Amazon estuary (Barthem et al. 2015; IBAMA 1999).

<table>
<tr><td colspan="2">Management tools</td><td>Year</td><td>Description</td></tr>
<tr><td colspan="2">Closed area</td><td>1976-1987</td><td>In 1976 was established a restricted area by the quadrant 0º5´N and 48ºW and in 1987 the closed area was extended along the 10 miles of the coast</td></tr>
<tr><td rowspan="4">Fishing effort restrictions</td><td>Number of a fishing boat</td><td>1983</td><td>Maximum of 48 fishing boats</td></tr>
<tr><td>Mesh size of the cod-end</td><td>1983</td><td>Minimum of 100 mm</td></tr>
<tr><td>Total catch allowed</td><td>1983</td><td>Maximum of 21,500 tons</td></tr>
<tr><td>Boats fishing together</td><td>2002</td><td>Maximum of three</td></tr>
<tr><td colspan="2">Closed season</td><td>2002</td><td>Three months (September to November)</td></tr>
</table>

Supplementary material

Table S1: Annual capture records of goliath catfishes by country between 1980 and 2007.

Year	Bolivia	Brazil (all States)	Colombia	Peru		
				Loreto	Ucayali	Madre de Dios
1980		34,193		2	456	
1981		21,256		174	458	
1982		27,966		48	600	
1983		32,903		267	649	
1984		22,599		249	419	
1985		24,649		198	518	
1986	0.04	28,552		293	320	
1987	0.60	27,842		229	190	
1988	0	21,501		607	718	
1989	0	26,052		430	771	
1990	1.16	18,766		235	97	
1991	0.22	17,661		528	176	
1992	0.88	14,388		427		
1993	0	10,001	5,773			
1994	0	17,644	3,131			
1995		17,499	3,407			
1996		30,864	2,530			
1997		36,966	2,245			
1998		33,646	3,614			
1999		40,419	3,743			
2000		37,543		306		
2001		38,100		219		
2002		43,644		255		
2003		38,719		214		
2004		45,449		214		18
2005		43,397		305		6
2006		46,154	2,111	545		
2007		38,432	1,997	372		9
Annual Average	0.32	29,886	3,172	291	448	11

Table S2- Average annual production of goliath catfish species by states or departments.

States or Department	*B. vaillantii*	*B. rousseauxii*	*B. filamentosum & B. capapretum*	*B. platynemum*	*B. juruense*	Total
Acre (Brazil)	0	129	108	0	0	237
Amapá (Brazil)	328	675	324	0	0	1,327
Amazonas (Brazil)	1,901	1,499	1,367	6	4	4,777
Amazonas (Colombia)	543	1,813	520	283	12	3,172
Beni & Cochabamba (Bolivia)	0	0.3	0	0	0	0.3
Loreto (Peru)	49	190	45	3	4	291
Madre de Dios (Peru)	0	5	2	3	1	11
Maranhão (Brazil)	115	2	14	0	0	131
Mato Grosso (Brazil)	0	0	12	0	0	12
Pará (Brazil)	15,972	5,823	1,238	10	0.4	23,042
Rondônia (Brazil)	44	167	45	1	0	256
Roraima (Brazil)	0	20	32	0	0	52
Tocantins (Brazil)	0	4	47	0	0	51
Ucayali (Peru)	24	345	79	0	0	448
Total	18,976	10,671	3,834	306	22	33,809

Table S3- Number of goliath catfishes sampled by regions, fishing gear and subadult and adult categories.

Species	Region	Gear	SubAdult	Adult	Total	
B. juruense	Western	Gillnet	3	574	577	613
	Central	Gillnet	35	1	36	
B. platynemum	Western	Gillnet	5	3,022	3,027	3,635
	Central	Gillnet	7	601	608	
B. rousseauxii	Western	Gillnet	0	5,496	5,496	55,171
	Central	Gillnet	224	8,794	9,018	
	Eastern	Gillnet	595	1,395	1,990	
	Estuary	Gillnet	12,058	4,019	16,077	
	Estuary	Trawl	21,446	1,144	22,590	
B. vaillantii	Central	Seine	257	164	421	265,817
	Eastern	Gillnet	498	1,718	2,216	
	Estuary	Gillnet	12,220	28,303	40,523	
	Estuary	Trawl	201,316	21,341	222,657	
Total			248,664	76,572	325,236	

Table S4- The annual catch of *B. vaillantii* (tons) by the trawler fishing fleet and the corresponding relative rate of catch increase (RRCI), catch increase smoothed RRCI (RRCI') and the averaged previous catches (Cav). The F/F_{MSY} indices were estimated considering the average of the three estimates of natural mortality: F_P (Pauly method), F_T (Taylor method) and F_C (Cubillos method).

Year	Catch	RRCI	RRCI´	Cav	F_P/F_{MSY}	F_T/F_{MSY}	F_C/F_{MSY}	F/F_{MSY}
1972	5,440							
1973	8,559							
1974	13,930	0.990	0.804	9,310				
1975	15,070	0.619	0.623	12,520				
1976	15,767	0.259	0.462	14,922				
1977	22,486	0.507	0.249	17,774				
1978	17,446	-0.018	0.127	18,566	10.790	11.246	11.087	11.041
1979	16,576	-0.107	-0.127	18,836	3.557	4.013	3.854	3.808
1980	14,004	-0.257	-0.173	16,009	2.390	2.846	2.687	2.641
1981	13,525	-0.155	-0.110	14,702				
1982	15,915	0.083	0.055	14,482	3.090	3.546	3.387	3.341
1983	17,908	0.237	0.019	15,783	2.557	3.013	2.854	2.808
1984	11,637	-0.263	-0.055	15,153	3.557	4.013	3.854	3.808
1985	13,066	-0.138	-0.062	14,204	3.290	3.746	3.587	3.541
1986	17,254	0.215	0.067	13,986				
1987	15,728	0.125	0.049	15,349				
1988	12,404	-0.192	-0.069	15,129				
1989	12,998	-0.141	-0.184	13,710				
1990	10,685	-0.221	-0.189	12,029				
1991	9,574	-0.204	-0.286	11,086				
1992	6,299	-0.432	-0.173	8,853				
1993	9,875	0.115	-0.071	8,583	4.890	5.346	5.187	5.141
1994	9,458	0.102	0.107	8,544	1.223	1.679	1.520	1.474
1995	9,432	0.104	0.098	9,588	1.657	2.113	1.954	1.908
1996	10,419	0.087	0.240	9,770	0.490	0.946	0.787	0.741
1997	14,935	0.529	0.267	11,595	0.790	1.246	1.087	1.041
1998	13,740	0.185	0.217	13,031				
1999	12,197	-0.064	-0.084	13,624				
2000	8,537	-0.373	-0.185	11,491				
2001	10,142	-0.117	-0.128	10,292				
2002	11,378	0.105	0.105	10,019				
2003	13,304	0.328	0.102	11,608				
2004	10,142	-0.126	0.033	11,608				
2005	10,413	-0.103	0.075	11,286				
2006	16,420	0.455	0.176	12,325				
2007								
2008					3.023	3.479	3.320	3.274
2009					1.990	2.446	2.287	2.241
2010					1.757	2.213	2.054	2.008
2011					2.090	2.546	2.387	2.341

References

Agudelo-Córdoba E, Petrere Jr M, Joven-León ÁV, Peláez M, Bonilla-Castillo CA, Duponchelle F (2013) Breeding, growth and exploitation of *Brachyplatystoma rousseauxii* Castelnau, 1855 in the Caquetá River, Colombia. Neotropical Ichthyology 11:637-647

Agudelo-Córdoba E et al. (2000) Bagres de la Amazonia Colombiana: Un recurso sin fronteras. Estudios Regionales de la Amazonia Colombiana. SINCHI, Bogotá

Almeida OTd (2006) A indústria pesqueira na Amazônia. Ibama/Provarzea, Manaus

Alonso JC, Pirker LEM (2005) Dinâmica populacional e estado atual da exploração de piramutaba e de dourada. In: Fabré NN, Barthem RB (eds) O Manejo da Pesca dos Grandes Bagres Migradores. Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, Brasília, pp 21-28

Anderson EP et al. (2018) Fragmentation of Andes-to-Amazon connectivity by hydropower dams. Science Advances 4:eaao1642 doi: 10.1126/sciadv.aao1642

Anjos HDBd, Amorim RMD, Siqueira JA, Anjos CRd (2009) Ornamental fish exporto of the State of Amazonas, Amazon Basin, Brazil. Boletim Do Instituto De Pesca 35:259-274

Barthem RB, Goulding M (1997) The catfish connection: Ecology, migration, and conservation of amazon predators. Biology and resource management series. Columbia University Press, New York

Barthem RB, Petrere Jr M, Isaac V, Ribeiro MCLdB, McGrath DG, Vieira IJA, Barco MV (1997) A pesca na Amazônia: Problemas e perspectivas para o seu manejo. In: Padua CV, Bodmer RE, Cullen LJ (eds) Manejo e Conservação de Vida Silvestre no Brasil. Conselho Nacional de Desenvolvimento Científico e Tecnológico, pp 173-185

Barthem RB, Goulding M (2007) An unexpected ecosystem: the Amazon as revealed by fisheries. Missouri Botanical Garden Press,

Barthem RB et al. (2017) Goliath catfish spawning in the far western Amazon confirmed by the distribution of mature adults, drifting larvae and migrating juveniles Scientific reports 7:41784 doi:10.1038/srep41784

Barthem RB, Guerra H, Valderrama M (1995) Diagnóstico de los recursos hidrobiológicos de la Amazonía. Tratado de Cooperación Amazonica, Lima, Peru

Barthem RB, Mello-Filho A, Assunção W, Gomes PFF (2015) Estrutura de tamanho e distribuição espacial da piramutaba (*Brachyplatystoma vaillantii*) na foz Amazônica: implicações para o manejo da pesca. Bol Inst Pesca, São Paulo 41:249-260

Barthem RB, Petrere Jr M Fisheries and population dynamics of the freshwater catfish *Brachyplatystoma vaillantii* in the amazon estuary. In: Armantrout NB (ed) Condition of the World's Aquatic Habitat. Proceedings of the World Fisheries Congress, Theme 1. , Athens, Greece, 1995. Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, 1237, pp 329-350

Barthem RB, Silva-Júnior ULd, Raseira MB, Goulding M, Venticinque E (2019) Bases para a conservação e o manejo dos estoques pesqueiros da Amazônia. In: Galucio AV, Prudente ALdC (eds) Museu Goeldi: 150 anos de ciência na Amazônia. Editora MPEG, Belém, Brasil, pp 147-190

Bartley DM, de Graaf G, Valbo-Jørgensen J (2016) Commercial inland capture fisheries. In: Craig JF (ed) Freshwater fisheries ecology. John Wiley & Sons, pp 438-448. doi:10.1002/9781118394380.ch35

Batista JdS, Formiga-Aquino K, Farias IP, Alves-Gomes JA (2004) Genetic variability studies of piramutaba (*Brachyplatystoma vaillantii*) and dourada (*B. rousseauxii*) (Pimelodidae: Siluriformes) in the Amazon: Basis for management and conservation. Paper presented at the International Congress on the Biology of Fish, Manaus, AM, Brazil,

Batista JS, Alves-Gomes JA (2006) Phylogeography of *Brachyplatystoma rousseauxii* (Siluriformes—Pimelodidae) in the Amazon Basin offers preliminary evidence of the first case of “homing” for an Amazonian migratory catfish. Genetics and Molecular Research 5:723-740

Batista VS, Alonso JC, Ladle RJ, Fabré NN (2018) Drivers of the upper River Amazon giant catfish fishery Fisheries Management and Ecology doi:10.1111/fme.12270

Begossi A, Hanazaki N, Ramos RM (2004) Food chain and the reasons for fish food taboos among Amazonian and Atlantic Forest fishers (Brazil). Ecological Applications 14:1334-1343

Cadrin SX, Kerr LA, Mariani S (eds) (2013) Stock identification methods: applications in fishery science. Academic Press,

Cubillos LA (2003) An approach to estimate the natural mortality rate in fish stocks. Naga, WorldFish Center Quarterly 26:17-19

Curtin TB, Legeckis RV (1986) Physical observations in the plume region of the Amazon river during peak discharge - I. Surface variability. Continental Shelf Research 6 31-51

Damme PAV, Córdova-Clavijo L, Baigún C, Hauser M, Doria CRdC, Duponchelle F (2019) Upstream dam impacts on gilded catfish *Brachyplatystoma rousseauxii* (Siluriformes: Pimelodidae) in the Bolivian Amazon. Neotropical Ichthyology 17

Do Prado FD, Fernandez-Cebrian R, Foresti F, Oliveira C, Martinez P, Porto-Foresti F (2017) Genetic structure and evidence of anthropogenic effects on wild populations of two Neotropical catfishes: baselines for conservation. Journal of Fish Biology doi:10.1111/jfb.13486

Doria CRdC, Ruffino ML, Hijazi NC, Cruz RLd (2012) A pesca comercial na bacia do rio Madeira no Estado de Rondônia, Amazônia brasileira. Acta Amazonica 42:29-40

Fabré NN, Barthem RB (2005) O manejo da pesca dos grandes bagres migradores: piramutaba e dourada no eixo Solimões-Amazonas. ProVárzea, IBAMA, MMA,

Finer M, Jenkins CN (2012) Proliferation of hydroelectric dams in the Andean Amazon and implications for Andes-Amazon connectivity. PLoS One 7:e35126 doi:10.1371/journal.pone.0035126

Fitzgerald CJ, Delanty K, Shephard S (2018) Inland fish stock assessment: Applying data-poor methods from marine systems. Fisheries Management and Ecology 25:240-252 doi:10.1111/fme.12284

Forsberg B et al. (2017) The potential impact of new Andean dams on Amazon fluvial ecosystems. PloS one 12:e0182254 doi:10.1371/journal.pone.0182254

Funge-Smith SJ (2018) Review of the state of world fishery resources: inland fisheries. FAO, Rome

Gaertner D, Fonteneaub A, Laloëa F (2001) Approximate estimate of the maximum sustainable yield from catch data without detailed effort information: Application to tuna fisheries. Aquat Living Resour 14 1−9

García A, Vargas G, Tello S, Duponchelle F (2012) Desembarque de pescado fresco en la ciudad de Iquitos, región Loreto- Amazonía Peruana. Folia Amazonica 21:45-52

Gayanilo FC, Sparre P, Pauly D (2005) FAO-ICLARM stock assessment tools II—Revised version. FAO, Rome,

Goulding M, Barthem R, Ferreira EJG, Duenas R (2003a) The Smithsonian atlas of the Amazon. Washington London: Smithsonian Books,

Goulding M, Cañas CM, Barthem RB, Forsberg B, Ortega H (2003b) Amazon Headwaters. Rivers, Wildlife and Conservation in Southeastern Peru. ACA & ACCA. Grafica Biblos. Lima, Peru,

Goulding M et al. (2019) Ecosystem-based management of Amazon fisheries and wetlands. Fish and Fisheries 20:138-158 doi:10.1111/faf.12328

Grainger RJR, Garcia S (1996) Chronicles of marine fishery landings (1950–1994). Trend analysis and fisheries potential. Vol 359. Fisheries Technical Paper. FAO,

Hahn L et al. (2019) Genetics and telemetry indicate unexpected movements among structured populations for *Brachyplatystoma platynemum* in the Amazon Journal of Fish Biology doi:10.1111/jfb.13978

Hauser M et al. (2019) Shedding light on the migratory patterns of the Amazonian goliath catfish, *Brachyplatystoma platynemum*, using otolith 87 Sr/86Sr analyses. Aquatic Conservation: Marine and Freshwater Ecosystems doi:10.1002/aqc.3046

Hermann TW, Stewart DJ, Limburg KE, Castello L (2016) Unravelling the life history of Amazonian fishes through otolith microchemistry Royal Society Open Science 3:160206 doi:10.1098/rsos.160206

Hilborn R, Ovando D (2014) Reflections on the success of traditional fisheries management. ICES Journal of Marine Science 71:1040-1046doi:10.1093/icesjms/fsu034

Huergo GM, Filgueiras-Souza RJ, Batista JDS, Formiga-Aquino K, Alves-Gomes JA (2011) Molecular genetics as a tool for fisheries management in the Brazilian Amazon: Piraíba (*Brachyplatystoma filamentosum* and *Brachyplatystoma capapretum*)(Siluriformes: Pimelodidae) in white-water rivers. Pan-American Journal of Aquatic Sciences 6:280-289

Huergo GPCM (2009) Estimativa da diversidade genética da piraíba (*Brachyplatystoma filamentosum* Lichtenstein, 1819) e da piraíba negra (*Brachyplatystoma capapretum* Lundberg e Akama, 2005), na Amazônia Brasileira, inferidas por meio do DNA mitocondrial: subsídios para manejo e conservação. Dissertation, INPA

IBAMA (1999) V Reunião do grupo permanente de estudos sobre a piramutaba. Coleção Meio Ambiente Série Estudos Pesca (Brasil) 26:1-92

ICMBIO (n.d.) Estatística por região. http://www.icmbio.gov.br/cepsul/biblioteca/acervodigital/38download/artigos-cientificos/112-artigos-cientificos.html. Accessed Octuber 15, 2019

Isaac VJ, Ruffino ML (2000) A estatística pesqueira no baixo amazonas: Experiencia do projeto IARA. IBAMA Coleção Meio Ambiente Série Estudos Pesca 22:201-224

Jiao Y, Cortés E, Andrews K, Guo F (2011) Poor-data and data-poor species stock assessment using a Bayesian hierarchical approach Ecological Applications 21:2691-2708 doi:10.1890/10-0526.1

Jimenez EA, Asano Filho M, Frédou FL (2013) Fish bycatch of the laulao catfish *Brachyplatystoma vaillantii* (valenciennes, 1840) trawl fishery in the amazon estuary. Brazilian Journal of Oceanography 61:129-140

Klautau AGCdM, Cordeiro APB, Cintra IHA, Silva LEOd, Bastos CEMC, Carvalho HRLd, Itó LS (2016a) Analysis of the Industrial Fishing of Piramutaba Catfish, *Brachyplatystoma vaillantii* (Valenciennes 1840), in two Estuarine Areas of the Brazilian Amazon Pan-American Journal of Aquatic Sciences 11:143-150

Klautau AGCdM, Cordeiro APB, Cintra IHA, Silva LEOd, Carvalho HRLd, Itó LS (2016b) Impacted biodiversity by industrial piramutaba fishing in the Amazon River mouth. Bol Inst Pesca, São Paulo 42:102-111

Lundberg JG, Akama A (2005) *Brachyplatystoma capapretum*: A new species of goliath catfish from the Amazon Basin, with a reclassification of allied catfishes (Siluriformes: Pimelodidae) Copeia 2005:492-516

Lundberg JG, Sullivan JP, Hardman M (2011) Phylogenetics of the South American catfish family Pimelodidae (Teleostei: Siluriformes) using nuclear and mitochondrial gene sequences. Proceedings of the Academy of Natural Sciences of Philadelphia 161:153-189

Malhi Y, Roberts JT, Betts RA, Killeen TJ, Li W, Nobre CA (2008) Climate change, deforestation, and the fate of the Amazon. Science 319:169-172 doi:10.1126/science.1146961

Matsunaga AMF (2012) Influência da vazão e da precipitação na avaliação do estoque de piramutaba *Brachyplatystoma vaillantii* da costa norte do Brasil. MSc Thesis, Universidade Federal Rural da Amazônia, UFRA

Meschkat A (1960) Report to the government of Brazil on the fisheries of the amazon region. Food and Agriculture Organization (FAO), Rome, Italy

Nikiema O, Devenon JL, Baklouti M (2007) Numerical modeling of the Amazon River plume. Continental Shelf Research 27:873-899 doi:10.1016/j.csr.2006.12.004

Ochoa LE et al. (2015) Genetic structure and historical diversification of catfish *Brachyplatystoma platynemum* (Siluriformes: Pimelodidae) in the Amazon Basin with implications for its conservation. Ecology and Evolution 5:2005-2020 doi:10.1002/ece3.1486

Pauly D (1980) On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks

Pauly D (2019) Vanishing Fish: Shifting Baselines and the Future of Global Fisheries. Greystone Books, Vancouver

Petrere M, Barthem RB, Córdoba EA, Gómez BC (2004) Review of the large catfish fisheries in the upper Amazon and the stock depletion of piraíba (*Brachyplatystoma filamentosum* Lichtenstein). Reviews in Fish Biology and Fisheries 14:403-414 doi:10.1007/s11160-004-8362-7

Pons M et al. (2017) Effects of biological, economic and management factors on tuna and billfish stock status. Fish and Fisheries 18:1-21 doi:10.1111/faf.12163

RCoreTeam (2013) R: A language and environment for statistical computing. Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

Reis-Filho JA, Leduc AOHC (2017) Management-Challenged Brazilian Governance and the Low Relevance of National Fishery Management Policy: Recommendations to Promoteviable Small-Scale Fisheries Fisheries and Oceanography Open Access Journal 2:555583 doi:10.19080/OFOAJ.2017.02.555583

Rodríguez-Fernández CA (1991) Bagres, Malleros e Cuerderos en El Bajo Rio Caquetá. Estudios en la Amazonia colombiana. vol 2. Tropenbos-Colombia,

Ruffino ML (ed) (2004) A pesca e os recursos pesqueiros na Amazônia brasileira. IBAMA MMA

Santos RE, Pinto-Coelho RM, Fonseca R, Simões NR, Zanchi FB (2018) The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin Fisheries. Management and Ecology 25:380-391 doi:10.1111/fme.12305

SEPEC (n.d.) Boletines estadísticos pesqueors y de la acuicultura. http://sepec.aunap.gov.co/Home/BoletinesEstadisticos. Accessed Octuber 15, 2019

Sparre P, Venema SC (1997) Introdução a avaliação de mananciais de peixes tropicais. Parte 1: Manual FAO

Sumaila UR, Lam V, Le Manach F, Swartz W, Pauly D (2016) Global fisheries subsidies: An updated estimate. Marine Policy 69:189-193 doi:10.1016/j.marpol.2015.12.026

Tollefson J (2011) A struggle for power. Nature 479:160-161

Utreras-Bucheli VM (2010) Caracterización de la pesca de grandes bagres en el Alto Río Napo (Ecuador), recomendaciones para su manejo y conservación. MSc Thesis. Universidad Internacional de Andulucía (UNIA).

Valbo-Jørgensen J, Marmulla G, Welcomme R (2008) Migratory Fish Stocks in Transboundary Basins — Implications for Governance, Management and Research. In: Lagutov V (ed) Rescue of Sturgeon Species in the Ural River Basin. NATO Science for Peace and Security Series C: Environmental Security. Springer Netherlands, pp 61-86. doi:10.1007/978-1-4020-8924-4_5

Van Damme PA, Carvajal-Vallejos FM, Rua A, Córdova L, Becerra P (2011) Pesca comercial en la cuenca amazónica boliviana. In: Los peces y delfines de la Amazonía boliviana: hábitats, potencialidades y amenazas. INIA, Cochabamba, Bolivia, pp 247-291

Welcomme R (2008) Inland fisheries: Ecology and management. John Wiley & Sons,

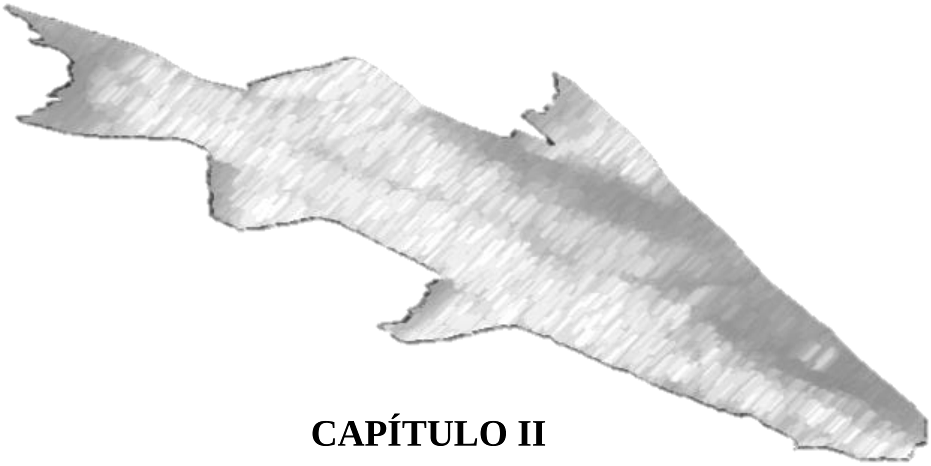
Welcomme RL, Baird IG, Dudgeon D, Halls A, Lamberts D, Mustafa MG (2016) Fisheries of the rivers of Southeast Asia. In: Craig JF (ed.) Fisheries ecology in South American river basins. John Wiley & Sons, pp 363-376. doi:10.1002/9781118394380.ch29

Bartley DM, Graaf G, Valbo-Jorgensen J (2016) Commercial inland capture fisheries. In: Craig J (ed) Freshwater fisheries ecology. John Wiley & Sons, pp 438-448. doi:10.1002/9781118394380.ch35

Funge-Smith SJ (2018) Review of the state of world fishery resources: inland fisheries. Rome

Meschkat A (1960) Report to the government of Brazil on the fisheries of the amazon region. Food and Agriculture Organization (FAO), Rome, Italy

Welcomme R (2008) Inland fisheries: Ecology and management. John Wiley & Sons.



CAPÍTULO II

EXPLOITATION HISTORY OF THE INLAND GOLIATH CATFISH, *BRACHYPLATYSTOMA VAILLANTII*, POPULATION IN THE AMAZON ESTUARY, NORTH BRAZIL.

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Title Page

Exploitation history of the inland goliath catfish, *Brachyplatystoma vaillantii*, population in the Amazon estuary, North Brazil.

Keywords

Piramutaba, trawl fishery, Amazon river, fisheries management, stock assessment

Short running title

Goliath catfish stock assessment

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Conflict of interest

The authors declare no conflict of interests.

Abstract

In this study, we integrated multiple sets of data including catch, an index of abundance, length composition and biological information to assess the status of piramutaba in the Amazon estuary. The data was from landings (1971 to 2007), CPUE (1975 to 1996), and length composition (1982-1985 and 1993-1997). Most of the parameters were fixed except virgin recruits (R_0), the extra standard deviation for Q, and the six parameters of a double-normal selectivity function. The current stock status was forecasted until 2019, and we tested the sensitivity of the model to steepness (h) and Sigma-R (σ_R). The CPUE shows a clear decrease during 1977 to 1992, but increasing in the last five years of the time series. Most of the individuals (selectivity at 50%) was estimated to be around 40 cm and the fit to the length-composition data was good overall. Total Biomass in 2007 was at the lowest historical level (179,445 metric tons) and Spawning Biomass too, however there are a high uncertainty in the assessment results. Even with F/F_{MSY} showing that fishing mortality was above F_{MSY} in some years but it did not cause Biomass (B) and Spawning Biomass (SSB) to drop below $B_{MSY.}$ The Kobe plot trajectories shows that fishery in 2007 was near of an overfished status. It was not until a couple of years later of the implementation of the protected area in 1976 that the fishing mortality of piramutaba was slightly reduced and it was a reduce a little bit more after the implementation of mesh size limits in 1983. After 1985, F/F_{MSY} showed and gradually increase and any apparently effect on F can be seen after the implementation of the closed season in 2002. Monitoring and data collection programs are crucial in order to reduce the uncertainty an improve the assessment for this species.

Key Words

Piramutaba, trawl fishery, Amazon river, fisheries management

Introduction

Brachyplatystoma vaillantii, commonly known in Brazil as piramutaba, belongs to the goliath catfish group. It is a long-distance migratory species widely distributed in the Amazon and Orinoco basins and in coastal rivers of the Guianas (1-3). Piramutaba is a relatively long-lived fish (maximum longevity = 22 years) (4) and forms a large regional panmictic population in the Amazon Basin (5, 6). Piramutaba migrates from the estuary where nurseries are located to the western Amazon where spawning occurs at river channels (7, 8).

Piramutaba is intensively exploited in Brazil, Colombia and Peru (9-12). In Brazil, most of the catches (~80%) come from the industrial fishing fleet that uses bottom pair-trawls at the mouth if the Amazon river (11, 13). There is also a small-scale artisanal fishery along the river and its muddy tributaries that account for the rest of the catch. The Amazon industrial fleet has been operating since the early 1970s where piramutaba is the main target specie (14-17). The catch of the bottom pair-trawler fishing fleet reached its maximum (22,486 tons) in 1977, only five years after it started. In 1992, the catch decreased to its historically lowest level (6,299 tons) (13, 18). *B. vaillantii* represented the third most important fish exported from Brazil in 1986 and 1987 (11), but due to the decreased in catches, exportations critically dropped. The industrial bottom trawl fishery was considered the main responsible for this overexploitation since it operates at the nursery area of the stock (11, 13). The piramutaba industrial fishery in the Amazon estuary faced different management stages since the 70s. It started with the implementation of a protected area in 1974 (19, 20), restriction on the number of boats and a minimum mesh size at the cod-end in 1983, a fishing seasonal closure in 2002 (21), and a vessel monitoring system (VMS) in 2006 to avoid illegal fishing in protected areas

(22). All these management measures are still in place in Brazil however, their effect or performance have been not evaluated.

Fishing mortality estimates, based on length-frequency data, and surplus production models based on catch and effort data, have been previously used to assess the piramutaba stock in the same region (4, 13, 18, 23). All studies suggested that, at the time, the stock was undergoing overfishing. However, all these data have never been combined into one integrated stock assessment model.

Integrated fishery analysis combines several sources of information into a single analysis (i.e. catch, length and/or age data, indices of abundance, among others). The integrate assessment platform most commonly use today in the US is Stock Synthesis - SS (24). SS is a statistical age-structured population-modeling framework highly scalable from data-weak situations (24) and it can flexibly incorporate multiple data sources accounting for different biological and environmental processes. In this study, we integrated multiple sets of data including catch, an index of abundance, length composition and biological information to assess the status of piramutaba in the Amazon estuary. We also discussed the possible effect of management interventions on the time series of fishing mortality and biomass estimated from the assessment.

Methods

Study Area

The industrial trawl fishery targeting piramutaba operates on the shallow freshwater areas over the fluvial mud deposit on the Amazon River mouth, at the Northern Coast of Brazil (14, 23, 25-27) (Fig. 1). This region is considered one of the most productivity areas of the Brazilian continental shelf, due to the important input of sediments and nutrients from the Amazon River, and one of the largest fisheries productions in Brazil (28, 29).

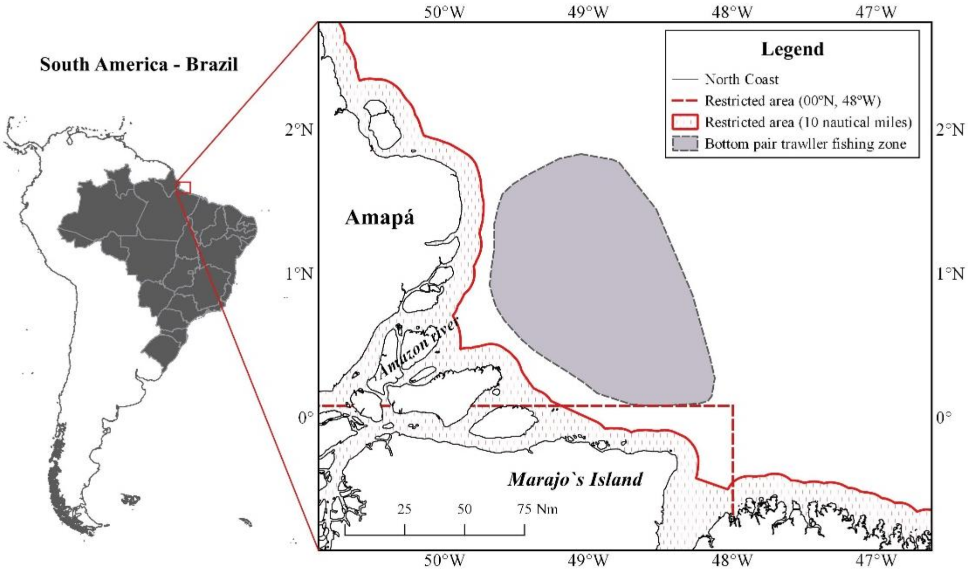


Figure 1. Mouth of the Amazon river where the industrial piramutaba fishery operates, including the two restricted areas for fisheries management.

Data

Piramutaba landings from the industrial trawl fishery targeting piramutaba and multispecies artisanal fleet in the Amazon region from 1971 to 2007 were obtained from the statistical yearbooks from the Brazilian agency responsible for fisheries management in Brazil (13, 30) (Fig. 2). After 2007, the data collection responsibilities were transferred to SEAP/PR (Special Secretariat for Aquaculture and Fisheries from the Presidency of the Republic) created in 2003. This institution evolved into the Fisheries and Aquaculture Ministry (MPA) in 2009, when methodological changes were discussed to improve the older system. This led to a break in the data collection process and catch statistics have not yet become standardized nor implemented nation-wide.

The period of 1976 to 1980 corresponded to the first expansion of the piramutaba trawl fishery in the estuary. From 1982 to 1985 the export market started consuming smaller size and there was an increase in the number of fishing boats (13). The last period from 1997 to 2007, corresponded to the expansion of the fishery after the historic lowest catch in 1992 (Prestes et al, in prep.) (Fig. 2). The catch per unit of effort (CPUE, tons by fishing day) by year and from 1975 to 1996 (13), presents a similar trend as the catch for the period they overlapped (Fig. 2).

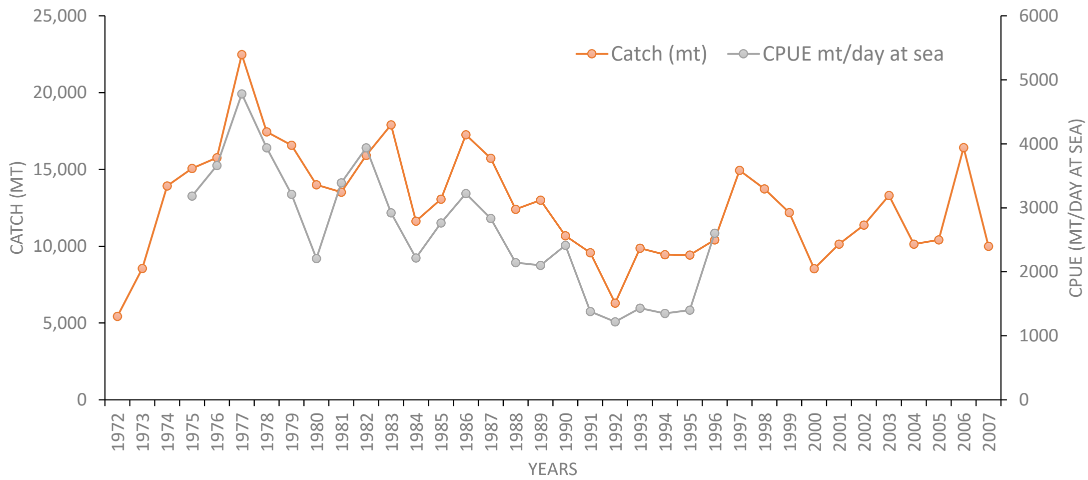


Figure 2. Total landings and CPUE of the industrial piramutaba trawl fishery by year at the Amazon river mouth.

Length composition (fork length) data from the catch were taken from the trawl and artisanal fishery by different agencies along the exploitation period: 1979 to 1980 by the Superintendência do Desenvolvimento da Pesca (SUDEPE); 1982 to 1985 and 1993 to 1997 by the Museum Paraense Emílio Goeldi (MPEG). These data were compiled into one length composition database using 5 cm length bins with a range from 7 to 122 cm (Fig. 3).

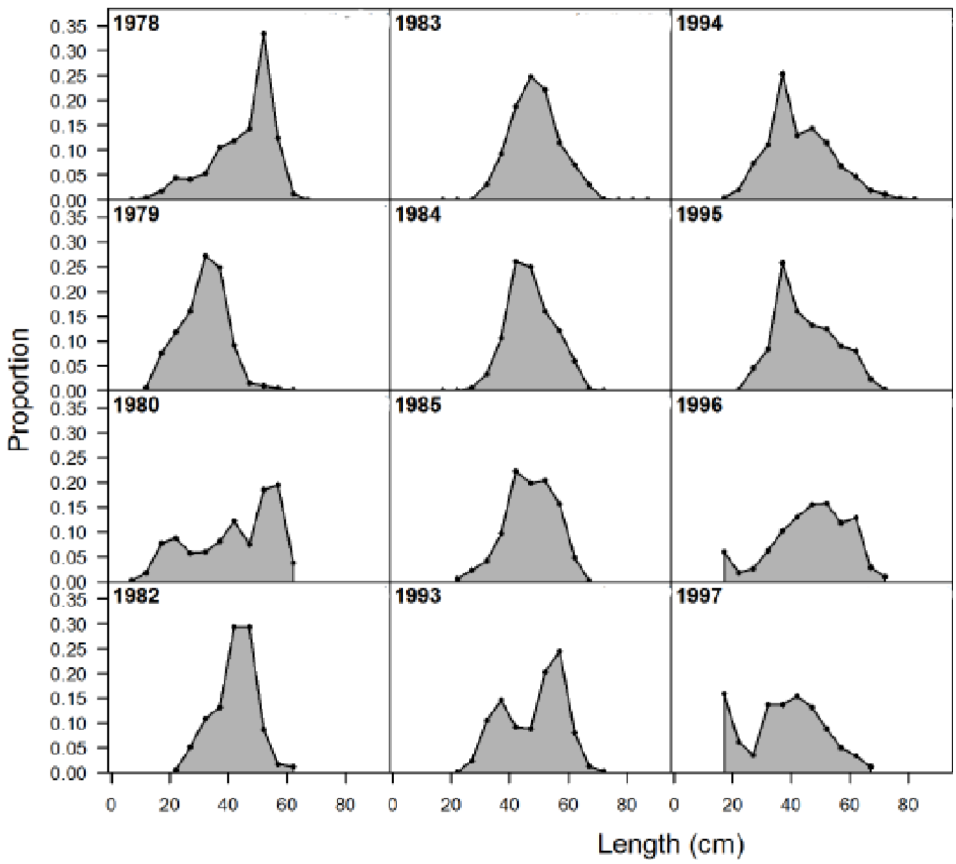


Figure 3. Length composition data for the years when data was available from the industrial trawl fishery of piramutaba at the mouth of the Amazon estuary. The length bin was 5 cm.

Assessment model specifications

Piramutaba was assessed using Stock Synthesis (SS) program version 3.30.13 (24), an integrated age-structured population dynamics model that can incorporate a diversity of fishery and survey data. We included landings from 1971 to 2007, CPUE from 1975 to 1996, and length composition data from the periods 1982-1985 and 1993-1997. The population in 1971 was assumed to be in the unfished state since the fishery started that year.

Only one area was considered in the assessment with no time-block variability in any parameter. In addition, one sex model was implemented since no information by sex exists for this fishery. All biological and fishery parameters considered are specified in Table 1. *Q* was calculated analytically with a low standard deviation (SD=0.1), and an extra parameter for deviations of *Q* was included and estimated. Since there is no information around variability in the CPUE index a standard deviation of 0.1 was arbitrary selected. The recruitment deviations started in 1975, this year was adjusted by checking the recruitment deviations variance, finishing in 1992, and was fixed in 0.5 to be slightly greater than the root-mean-squared error (RMSE) of the main era recruitment deviations. The bias adjustment ramp was used. According to (31), this bias adjustment method corrects the recruitment estimates to be mean unbiased penalizing the likelihood method including a time varying correction.

Sample sizes for the length-frequency data were equally weighted by year. Also, we assigned a final weight to the overall length composition data using the weighting method described by (32). The variance adjustment on length-composition was set to 0.005 as suggested by this method.

Most of the parameters were fixed except virgin recruits (R_0), the extra standard deviation for *Q*, and the six parameters of a double-normal selectivity function (33). A total of three phases were used for sequential optimization, R_0 was estimated in phase 1, three parameters from the double-normal selectivity and the extra standard deviation for *Q* were estimated in phase 2, and the other three parameters from the selectivity curve in phase 3.

Since the assessment model goes up to 2007, to estimate the current stock status as in 2019, we projected the population up to this year assuming an annual catch equal to the average from the last five years of the catch data available (10.055 t).

Sensitivity analysis

We tested the sensitivity of our model to different parameters misspecifications, in particular to steepness (*h*) and recruitment deviations, (SigmaR - Φ_R). These parameters were fixed in the model ranging from 0.5 to 1 for steepness (*h*) and from 0.4 to 0.8 for SigmaR. High value of steepness indicates maximum recruitment possible is reached at relatively small spawning stock sizes and small value attributed to Sigma-R reduces the fitness of the catch rate time series (34). We also performed a different model run assuming time-varying selectivity with blocks from 1971-1983 and 1983-2007 since there was an implementation of a minimum mesh size in 1983 (see S1 Fig.). Table 1 presents the SS model input parameters for the piramutaba bottom trawl available in the literature. However, the value of h, Catch coefficient of variation (CV) and SigmaR were not previously estimated, considering is the first time of estimative those metrics for that species or group. Based on the supposed high fecundity and multiple annual spawning behavior of the specie (1, 8) we considered the steepness (*h)* value relatively high (0.7). For the other side, we considered a middle value for the Sigma-R (0.5) based on the great unpredictability of the piramutaba spawning due to piramutaba spawners are spatially scattered in different headwaters of the Western Amazon, under low fishing pression and different hydrological conditions that determines the spawning event (8, 11, 35, 36). Catch coefficient of variation (CV) was considered 0.01, the uncertainty of the outputs do not change with the range of the CV, so, we adopted this value. We assume these parameters fixed and constant over time considering the lack of data about reproductive of these species in the Amazon region. Model outputs, in particular relative spawning stock biomass estimations (SSB), were sensitive to different Sigma-R (σ_R) values (S1 Fig.).

Results

Predicted CPUE values are under the range of the specified confidence intervals and follows similar trends as the observed values (Fig. 4A). The CPUE shows a clear decrease through time from around 8.5 mt per day at sea in 1977 to 7.0 mt per day at sea in 1992, but increasing in the last five years of the time series.

The estimated dome shape selectivity curve shows that large individuals, above 75 cm, are not present in the catch (Fig. 4B). Most of the individuals (selectivity at 50%) was estimated to be around 40 cm. The fit to the length-composition data was good overall (Fig. 4C), except for 1979, where the model predicted larger fish in the catch than the observed (Fig. 4D).

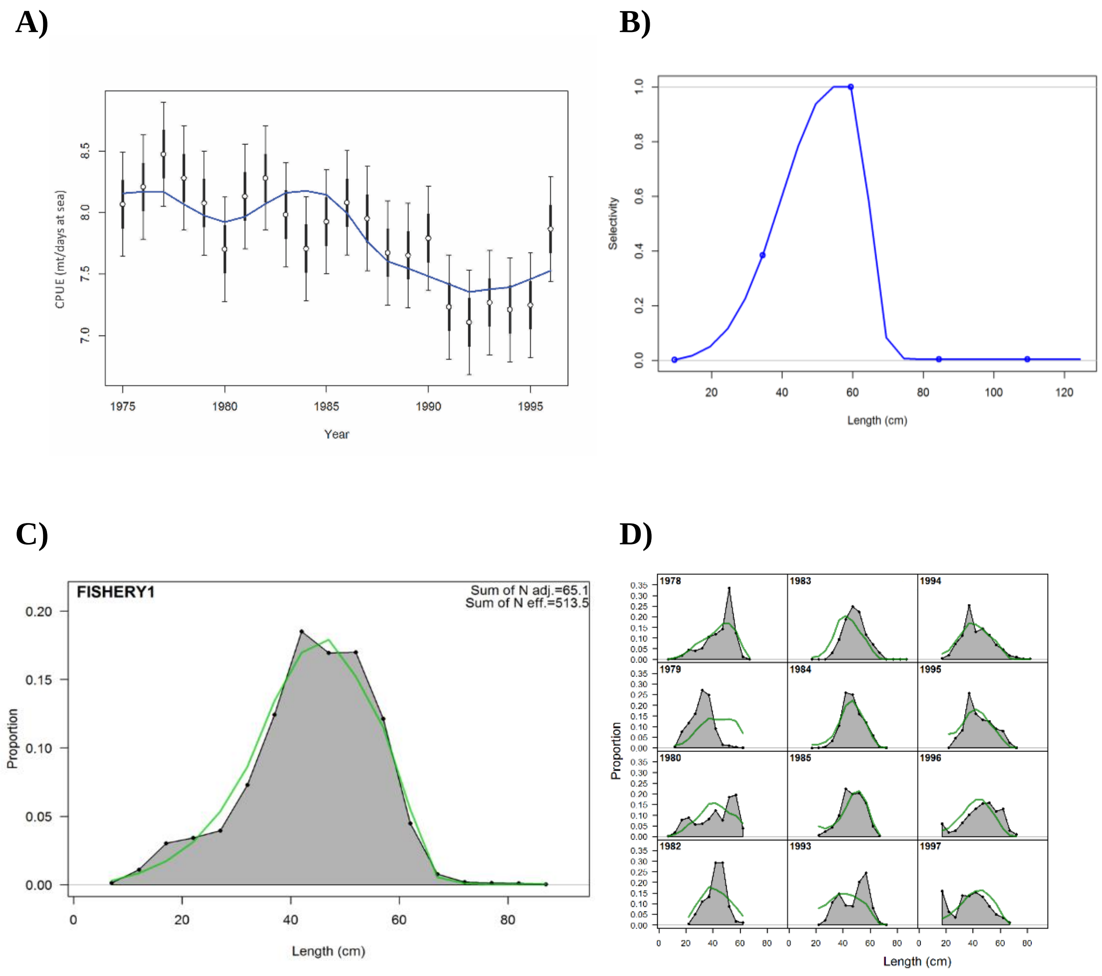


Figure 4. Stock Synthesis model fits to the observed data for the piramutaba bottom trawl fishery at the mouth of the Amazon estuary. **A)** log observed CPUE index (white circles) and model fit (blue line), dark thin lines indicate 95% uncertainty interval around the CPUE value. Thicker lines indicate input uncertainty before addition of estimated additional uncertainty parameter. **B)** Estimated selectivity curve. **C)** Overall observed length distribution and model fit (green line) aggregated across time. **D)** Observed length composition and model feet (green line) by year.

The estimated virgin biomass (B_0) in 1970 was 417,419 metric tons and total biomass (B) showed a constant decline over time until the 2000s where it stabilized with a slightly increasing in the last few years (Fig. 5A). Notice the extremely large confidence intervals around spawning biomass estimates, which is associated to the high uncertainty in the assessment results (Fig. 5B). Total Biomass in 2007 was at the lowest historical level (417,419 metric tons in 1971 and 179,445 metric tons in 2007, around 57% of depletion) and Spawning Biomass has the same trend (197,446 metric tons in 1970 and 63,497.6 metric tons in 2007, around 70% of depletion). The recruitment deviations ranged from - 0.6 to 0.8 presenting mostly positive deviations before 1981, and negative deviations after this year (Fig. 5B). Fishing mortality (F), estimated as the sum of all the apical Fs, increased through time reaching the estimated F_{MSY} value of 0.23 in 1973. After 2007, it started to decrease and stay around F_{MSY} in the last years (Fig. 5C). This is reflected in the trends of biomass in Fig. 5A.

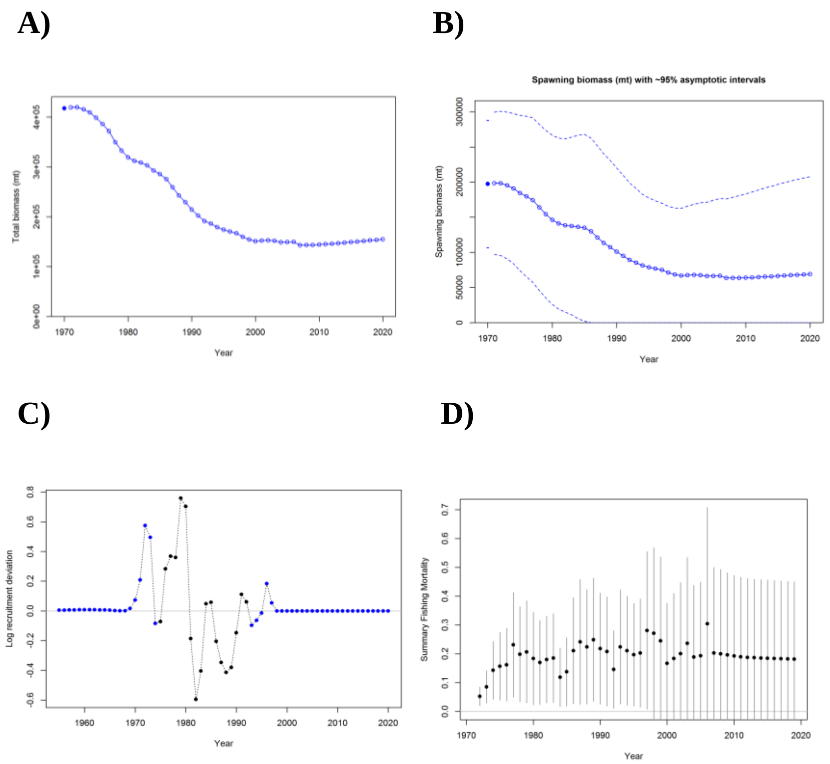
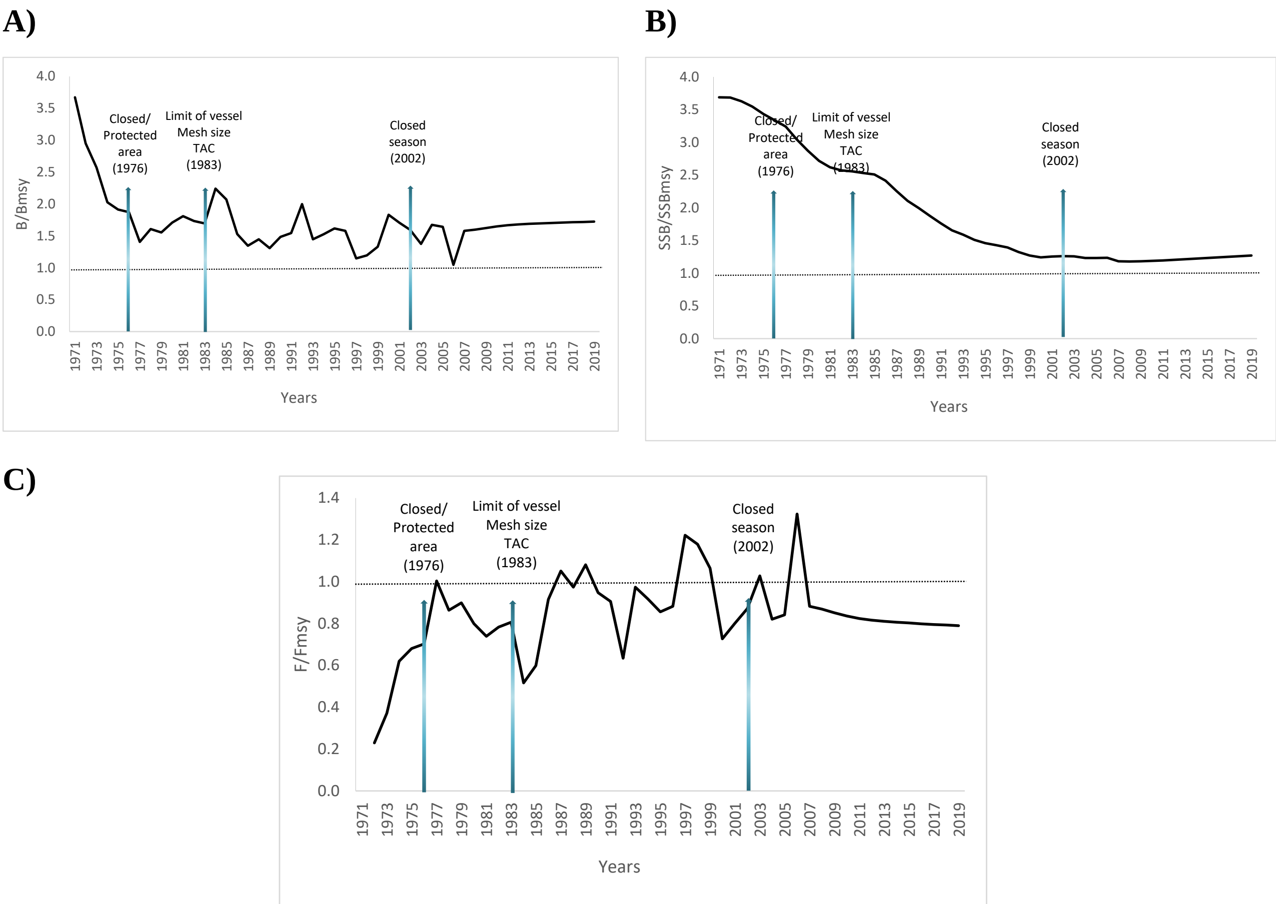


Figure 5. Stock Synthesis model output for the piramutaba bottom trawl fishery at the mouth of the Amazon estuary. **A:** Estimated stock biomass (B). **B:** Estimated Spawning biomass (SSB) with ~95% of asymptotic intervals. **C:** Estimated recruitment deviations (black points are the years utilized in recruitment deviations estimation and blue points are forecast years). **D:** Fishing mortality (F) sum along years of Frates with ~95% of asymptotic intervals.

A summary of the Piramutaba stock assessment model outputs is presented in Table 2. The time series of B/B_{MSY} and SSB/SSB_{MSY} show that the Biomass and Spawning biomass was above the B_{MSY} and SSB_{MSY}, even F/F_{MSY} (Fig. 6A) show that fishing mortality was above F_{MSY} in some years but it did not cause B and SSB to drop below B_{MSY} (Fig. 6B). The *B. vaillantii* stock have clearly experienced a large decline in biomass and spawning biomass, however, if catch assumptions are correct (i.e. catch from 2008 up to today is constant and average around the last 5 years of catch available) the stock is showing a slightly increase in biomass and spawning biomass. The current B/B_{MSY} and SSB/SSB_{MSY} forecasted in 2019 is 1.72 and 1.27 respectively, and the F/F_{MSY} is 0.79 indicating that this stock is not overfished, and it is fished at sustainable levels (Fig. 6C). The Kobe plot trajectories (Fig. 6C and 6D) shows that fishery had some years in overfishing status during these almost 40 years and in 2007 was near of a overfished status, attention for the the B/Bmsy (Fig. 6C) in 2006 was inside of overfished status.

It was not until a couple of years later of the implementation of the protected area in 1976 that the fishing mortality of piramutaba was slightly reduced and it was a reduce a little bit more after the implementation of mesh size limits in 1983. After 1985, F/F_{MSY} showed and gradually increase and any apparently effect on F can be seen after the implementation of the closed season in 2002 (Fig. 6B).



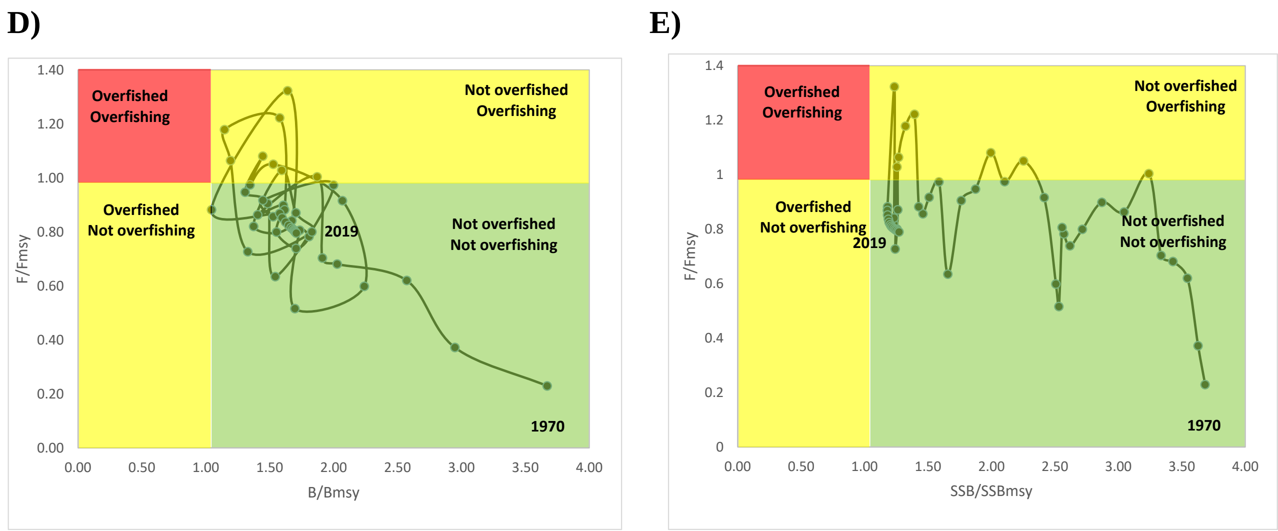


Figure 6. Current fishery status of piramutaba at the Amazon Mouth River. **A:** biomass (*B*) over the biomass that produces MSY (B/B_{MSY}). **B:** Spawning biomass (*SSB*) over the spawning biomass that produces MSY (SSB/SSB_{MSY}). **C:** Fishing mortality (*F*) over the fishing mortality that produces the maximum sustainable yield MSY (F/F_{MSY}) **D:** The kobe plot F/Fmsy versus B/Bmsy from 1970 to 2019 **E:** The kobe plot F/Fmsy versus SSB/SSBmsy from 1970 to 2019. The arrows represent management measures implemented in their respective years (Barthem et al., 2015; IBAMA, 1999). **1)** Closed area in 1976; **2)** limit in the number of fishing boats in 1983/ minimum mesh size implementation in 1983 and total allowable catch in 1983; **3)** restriction of a maximum of three boats fishing together in 2002 and a fishing closed season also in 2002. **C:** Kobe plot showing the trajectory of piramutaba stock status from 1970 to current 2019.

Table 1. Life history, fishery and modelling parameters available in literature used for the piramutaba *B. vaillantii* on Stock Synthesis bottom trawl fishery at the mouth of the Amazon estuary. The lower and upper bounds reported as actual bounds.

Parameter (units)	Symbol	Value	Estimation		Bounds	
		piramutaba	Estimated	External source	Lower	Upper
Natural mortality (year^{-1})	M	0.3	fixed	Alonso & Pirker (2005)	-	-
Minimum age (year)	A_0	0	fixed	Alonso & Pirker (2005)	-	-
Maximum age (year)	A_{max}	22	fixed	Alonso & Pirker (2005)	-	-
Length at A_0 used for the Von-Bertalanffy equation(cm)	L_0	17	fixed	Alonso & Pirker (2005)	-	-
Length at A_{max} used for the Von-Bertalanffy equation (cm)	L_∞	110	fixed	Alonso & Pirker (2005)	-	-
Growth rate (year^{-1})	K	0.13	fixed	Alonso & Pirker (2005)	-	-
Length-weight scaling (kg - cm)	α	6.10E-05	fixed	Pirker (2001)	-	-
Allometric factor	β	3.11	fixed	Pirker (2001)	-	-
Maturity slope (cm^{-1})	Ω_1	-0.25	fixed	Barthem & Goulding (1997)	-	-
Length at 50% maturity (cm)	Ω_2	38.5	fixed	Barthem & Goulding (1997)	-	-
Virgin recruitmentment	$ln\ R_0$	10.86	yes		10.62	11.09
Steepness (-)	h	0.7	fixed		-	-
Recruitment variability (-)	Φ_R	0.5	fixed		-	-
length-at-50% Double normal peak selectivity (cm)	S_1	54.7	yes	Barthem & Goulding (2007)	53.88	55.64
length Double normal top logit selectivity (-)	S_2	-4.99	yes		-5.26	-4.71
length Double normal ascend se selectivity (-)	S_3	6.07	yes		5.92	6.21
length Double normal descend se selectivity (-)	S_4	3.53	yes		3.14	3.91
length Double normal start logit selectivity (-)	S_5	-6.23	yes		-7.16	-5.29
length Double normal end logit selectivity (-)	S_6	-5.43	yes		-6.32	-4.53
Catchability	$ln\ q$	-3.31	yes		-7	5
Extra Standard Deviation	q'	0.11	yes		0.071	0.149
CV of catch and CPUE index	CV_s	0.01/0.1	fixed		-	-

Table 2. Estimated benchmark for the piramutaba *B. vaillantii* on Stock Synthesis bottom trawl fishery at the mouth of the Amazon estuary. The lower and upper bounds reported as actual bounds.

Parameter (units)	Symbol	Value estimated piramutaba	Bounds	
			Lower	Upper
Biomass initial (mt)	B_0	417,419	-	-
Current Biomass (mt)	B_{2007}	179,445	-	-
Forecasted biomass (mt)	B_{2019}	195,979	-	-
Spawning Biomass initial (mt)	SSB_0	198,262	146,588	249,935
Current Spawning Biomass (mt)	SSB_{2007}	63,498	6,132	120,862
Forecasted Spawning biomass (mt)	SSB_{2019}	67,840	0	138,556
Catch at MSY (mt)	C_{msy}	10,921.0	8,657.0	13,185.0
Current Fishing mortality (year-1)	F_{2007}	0.20	0.5	0.35
Forecasted Fishing mortality (year-1)	F_{2019}	0.18	0.5	0.31
Fishing mortality at MSY (year-1)	F_{MSY}	0.23	-	-
Biomass at MSY (mt)	B_{MSY}	113,697	-	-
Spawning biomass (mt)	SSB_{MSY}	53,780	-	-
Current Biomass Stock/Biomass Stock in MSY (-)	B_{2007}/B_{msy}	1.58	-	-
Forecasted Biomass Stock/Biomass Stock in MSY (-)	B_{2019}/B_{msy}	1.72	-	-
Current Spawning Biomass/Spawning Biomass in MSY (-)	SSB_{2007}/SSB_{msy}	1.18	-	-
Forecasted Spawning Biomass/Spawning Biomass in MSY (-)	SSB_{2019}/SSB_{msy}	1.27	-	-
Current Fishing mortality/Fishing mortality at MSY (-)	F_{2007}/F_{msy}	3.44	-	-
Forecasted Fishing mortality/Fishing mortality at MSY (-)	F_{2019}/F_{msy}	3.20	-	-

Discussion

This is the first time that *B. vaillantii* has been evaluated using an integrated assessment model in the Amazon estuary. The stock seems to be currently fished at sustainable levels. Our results are consistent with previous studies using less data that suggested that Piramutaba was undergoing overfishing in Brazil in the past (4, 18, 23). Integrated assessments, i.e. SS, allowed us to combine multiple data sets and explore which one was more informative. Identifying which types of data are most informative and needed for a particular assessment method is a critical first step in managing stocks with data limitations (37). Even though SS is typically applied in data-rich circumstances, it was suitable to explore and used it in data limited situations (38) like piramutaba fisheries in Brazil.

CPUE and catch data in the Piramutaba assessment model were more informative than the length composition data. This could be the result of inconsistencies in size data collection among programs or biases in the sizes sampled. Most of the large individuals of this population are not selected in the fishery since they mainly live upstream (8). However, this is why we down weighted these data using the Francis method. The length-composition data for the performance of an age-structured assessment model is important, mostly in assessment of data-limited stocks, in most of the time (37).

During the development of the final assessment model, different approximations were tested such as time-varying selectivity and catchability (S1 Fig.), mostly because there have been changes in selectivity and catchability through time (see S1 Fig.), (11, 14). However, the data was not informative and the results were not realistic.

The is large uncertainty in the model estimations. R_0 profiles presented in the S1 Fig. showed that most of the data was not informative and except for the index of abundance most of the other parameters presented a flat likelihood profile (S1 Fig.). A Bayesian approach could improve the uncertainty around the model estimations (39), however we tried to use this approach and the data was insufficient to reduce this uncertainty.

The fisheries information available for many stocks in Brazil is currently scarce. This is aggravated by the new Brazilian economy and political situation (40). The trawl fisheries in the Amazon Estuary, were an exception in terms of availability of historical catch time series. However, in 2007, these data stopped to be collected due to political reason explained in the introduction. Starting a new data collection program again is crucial to reduce the uncertainty in stock status estimations as it was show here and in order to measure the effect of management measures that are currently in place.

In S1 Fig. we showed that the assessment model was sensitive to Sigma-R. Recruitment deviations and its magnitude can be a product of environmental influences. Changes in production of this fishery was associated to environmental factors such as precipitation, river discharge and oceanic salinity (23). We need to understand more how environmental covariates influence recruitment in this population. Unfortunately, the environmental data for this area is also scares. If available, this could also be included as a covariate in the assessment model to explain changes in production associated to changes in the environment.

That specie has been suffering an excessive fishing pressure since 70's decade. In general in a Kobe plot (Fig. 6D and 6E), typically you should see that a stock starts in the lower right as the fishery develops, then moves into the upper left as the population becomes overexploited, and finally, as appropriate management is applied, it cycles around the center of the plot (41). Piramutaba has been considered overfished in the Estuary Region since the 1990s (13, 18), however, total biomass never dropped below sustainable levels. She apparent resilience of the *B. vaillantii* stock could be related to the fact that it is widely distributed in the Amazon basin and presents an opportunistic behavior predating on the most abundant resources in the estuary and river habitats (1, 35).

No clear effects have been seen in the time series of biomass and fishing mortality after the implementation of different management measures. However, the combination of all of them might be the reason of why piramutaba in the Amazon river is fished at sustainable levels and is not undergoing overfishing. The priority for this stock today is to have a better monitoring and data collection program in order to reduce the uncertainty (42) an improve the assessment for this species.

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References

1. Barthem RB, Goulding M. The catfish connection: Ecology, migration, and conservation of amazon predators. New York: Columbia University Press; 1997. 144 p. p.
2. Lundberg JG, Akama A. *Brachyplatystoma capapretum*: A new species of goliath catfish from the amazon basin, with a reclassification of allied catfishes (siluriformes: Pimelodidae). Copeia. 2005(3):492-516.
3. Lundberg JG, Sullivan JP, Hardman M. Phylogenetics of the South American catfish family Pimelodidae (Teleostei: Siluriformes) using nuclear and mitochondrial gene sequences. Proceedings of the Academy of Natural Sciences of Philadelphia. 2011;161(1):153-89.
4. Alonso JC, Pirker LEM. Dinâmica populacional e estado atual da exploração de piramutaba e de dourada. In: Fabré NN, Barthem RB, editors. O Manejo da Pesca

dos Grandes Bagres Migradores: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, Brasília; 2005. p. 21-8.

5. Rodrigues FC, Farias IP, Batista JS, Alves-Gomes J. Isolation and characterization of microsatellites loci for “piramutaba” (*Brachyplatystoma vaillantii*, Siluriformes: Pimelodidae), one of the commercially most important migratory catfishes in the Amazon Basin. Conservation Genetics Resources. 2009;1(1):365-8.
6. Formiga-Aquino K, Batista JS, Huergo GCMP, Briglia-Ferreira SR, Rodrigues FC, Alves-Gomes JA. Variabilidade genética do gênero *Brachyplatystoma* na Amazônia. In: Núñez J, Chu-Koo F, Porto J, García-Dávila CR, editors. Biología de las Poblaciones de Peces Amazónicos y Piscicultura. Comunicaciones del Segundo Coloquio Internacional de la Red de Investigación sobre la Ictiofauna Amazónica: IRD; 2011. p. 37-46.
7. Goulding M, Venticinque E, Ribeiro M, Barthem R, Leite RG, Forsberg B, et al. Ecosystem- based management of Amazon fisheries and wetlands. Fish and Fisheries. 2019;20:138-58.
8. Barthem RB, Goulding M, Leite RG, Canas C, Forsberg B, Venticinque E, et al. Goliath catfish spawning in the far western Amazon confirmed by the distribution of mature adults, drifting larvae and migrating juveniles. Scientific reports. 2017;7:41784.
9. García A, Vargas G, Tello S, Duponchelle F. Desembarque de pescado fresco en la ciudad de iquitos, región loreto-amazonía peruana. Folia Amazonica. 2012;21(1-2):45-52.
10. IBAMA. Estatística da pesca 2007: Brasil, grandes regiões e unidades da federação. Brasília: IBAMA, DIFAP, CGREP -Brasília; 2007. p. 113.

11. Barthem RB, Goulding M. An unexpected ecosystem: the Amazon as revealed by fisheries: Missouri Botanical Garden Press; 2007. 241 p.
12. Agudelo-Córdoba E, Salinas-Coy Y, Sánchez-Páez CL, Muñoz-Sosa DL, Arteaga-Díaz ME, Rodríguez-Prieto OJ, et al. Bagres de la amazonia colombiana: Un recurso sin fronteras. Bogotá: SINCHI; 2000. 253 p.
13. IBAMA. V Reunião do grupo permanente de estudos sobre a piramutaba. Coleção Meio Ambiente Série Estudos Pesca (Brasil). 1999;26:1-92.
14. Klautau AGCdM, Cordeiro APB, Cintra IHA, Silva LEOd, Bastos CEMC, Carvalho HRLd, et al. Analysis of the Industrial Fishing of Piramutaba Catfish, *Brachyplatystoma vaillantii* (Valenciennes 1840), in two Estuarine Areas of the Brazilian Amazon. Pan-American Journal of Aquatic Sciences. 2016;11(2):143-50.
15. IBAMA. Camarão norte e piramutaba: Brasília: IBAMA; 1994. 148 p.
16. Barthem RB. Ecologia e pesca da piramutaba (*Brachyplatystoma vaillantii*): UNICAMP; 1990.
17. Dias-Neto J, Damasceno FG, Pontes ACdP. Biologia e pesca de piramutaba, *Brachyplatystoma vaillantii*, Valenciennes, na região Norte do Brasil. pt. SUDEPE-PDP; 1985.
18. Barthem RB, Petrere Jr M, editors. Fisheries and population dynamics of the freshwater catfish *Brachyplatystoma vaillantii* in the amazon estuary. Condition of the World's Aquatic Habitat Proceedings of the World Fisheries Congress, Theme 1 1995; Athens, Greece. 1237: Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi.
19. Dias-Neto J. A pesca da piramutaba (*Brachyplatystoma vallanti*i) na região norte do Brasil. Atlantica. 1991;13(1):11-9.

20. Loureiro VR. Os parceiros do mar. Natureza e conflito social na pesca em Amazônia. Belém, Brazil: Conselho Nacional de Pesquisas Científicas e Tecnológicos (CNPq)/Museu Paraense Emilio Goeldi (MPEG); 1985.
21. IBAMA. Instrução Normativa nº 05 , de 18 de julho de 2002, (2002).
22. Sousa GCd, Souza Filho PWM, Costa FRd, Cintra IHA, Silva KCdA, Souza RFC, editors. Análise espaço-temporal da pesca da piramutaba *Brachyplatystoma vaillantii* (Valenciennes, 1840) na plataforma continental do Amazonas através do uso de sistema de informação geográfica (SIG). Anais XIII Simpósio Brasileiro de Sensoriamento Remoto, 21-26 abril 2007, INPE; 2007; Florianópolis, Brasil. 3537.
23. Matsunaga AMF, Junior IF, Itó LS. Análise quantitativa da influência de parâmetros ambientais sobre a captura por unidade de esforço (CPUE) da piramutaba *Brachyplatystoma vaillantii* (Valenciennes, 1840) da costa amazônica do Brasil. Bol Téc Cient Cepnor. 2017;17(1):09-19.
24. Methot-Jr. RD, Wetzel CR. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research. 2013;142 86-99.
25. Curtin TB. Physical observations in the plume region of the Amazon River during peak discharge-III. Currents. Continental Shelf Research. 1986;6(1/2):73-86.
26. Ayres Neto A, Falcão LC, Amaral PJT. Caracterização de ecofácies na margem continental norte brasileira - estado do conhecimento. Revista Brasileira de Geofísica. 2009;27(1):97-106.
27. Barthem RB, Mello-Filho A, Assunção W, Gomes PFF. Estrutura de tamanho e distribuição espacial da piramutaba (*Brachyplatystoma vaillantii*) na foz Amazônica: implicações para o manejo da pesca. Bol Inst Pesca, São Paulo. 2015;41(2):249-60.

28. Curtin TB, Legeckis RV. Physical observations in the plume region of the Amazon river during peak discharge - I. Surface variability. Continental Shelf Research. 1986;6 (1/2):31-51.
29. Muehe D, Garcez DS. A plataforma continental brasileira e sua relação com a zona costeira ea pesca (the brazilian continental shelf and its relation with the coastal zone and fishing). Revista Mercator. 2008;4(8).
30. ICMBIO. Estatística por região. Retrieved Octuber 15, 2019, from http://wwwicmbiogovbr/cepsul/biblioteca/acervodigital/38download/artigos-cientificos/112-artigos-cientificoshtml. n.d.
31. Methot-Jr. RD, Taylor IG. Adjusting for bias due to variability of estimated recruitments in fishery assessment models. Can J Fish Aquat Sci. 2011;68:1744-60.
32. Francis RIC. Data weighting in statistical fisheries stock assessment models. CANADIAN JOURNAL FISHERIES AQUATIC SCIENCE. 2011(68):1124-38.
33. Methot-Jr. RD, Wetzel CR, Taylor IG. Stock Synthesis User Manual. Seattle, WA: NOAA Fisheries; 2019.
34. Haddon M. Modelling and quantitative methods in fisheries: CRC press; 2010.
35. Prestes L, Goulding M, Melo-Filho A, Bentes B, Barthem R. A review of the goliath catfish fishery in the Amazon Basin: an history of overfishing. in prep.
36. Goulding M, Barthem R, Smith N, O'Connell T. Natural Resource Use and Habitat Conservation in the Amazon Estuary 2003.
37. Wetzel CR, Punt AE. Performance of a fisheries catch-at-age model (Stock Synthesis) in data-limited situations. Marine and Freshwater Research. 2011;62(8):927-36.

38. Cope JM. Implementing a statistical catch-at-age model (Stock Synthesis) as a tool for deriving overfishing limits in data-limited situations. Fisheries Research. 2013;142:3-14.

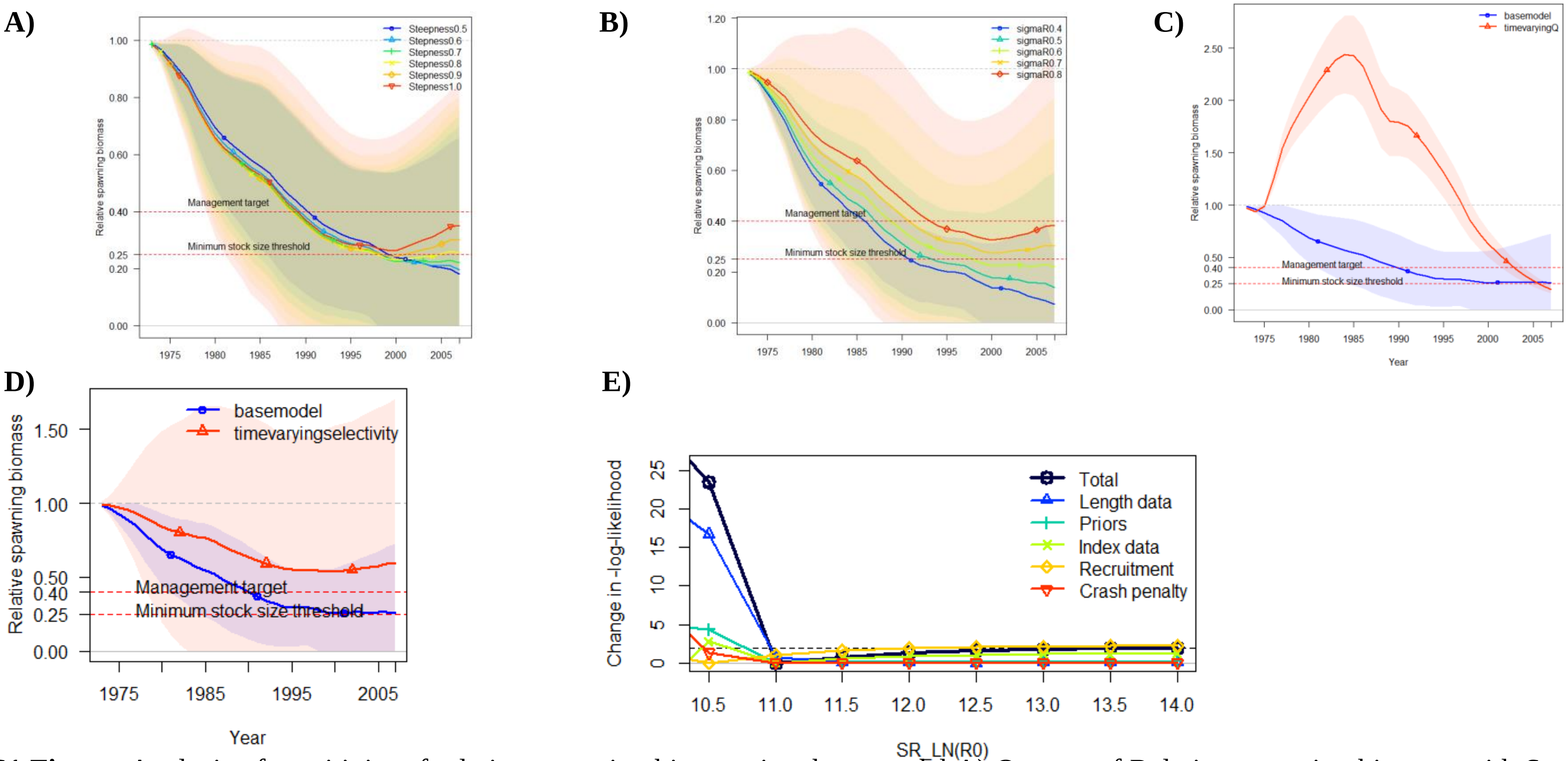
39. Monnahan CC, Branch TA, Thorson JT, Stewart IJ, Szuwalski C. Overcoming long Bayesian run times in integrated fisheries stock assessments. ICES Journal of Marine Science. 2019;76(6):1477-88.

40. Reis-Filho J, Leduc A. Management-Challenged Brazilian Governance and the Low Relevance of National Fishery Management Policy: Recommendations to Promoteviable SmallScale Fisheries. Oceanography & Fisheries Open Access Journal. 2017;2:1-4.

41. Maunder M, Aires-da-Silva A. Evaluation of the Kobe plot and strategy matrix and their application to tuna in the EPO. 2011.

42. Punt, André E., Tuck, Geoffrey N., Day, Jemery, Canales, Cristian M., Cope, Jason M., de Moor, Carryn L., De Oliveira, José A. A., Dickey-Collas, Mark, Elvarsson, Bjarki Þ, Haltuch, Melissa A., Hamel, Owen S., Hicks, Allan C., Legault, Christopher M., Lynch, Patrick D., Wilberg, Michael J. When are model-based stock assessments rejected for use in management and what happens then? Fisheries Research. 2020; 224:105465.

Supporting information



S1 Figure. Analysis of sensitivity of relative spawning biomass in a base model A) Outputs of Relative spawning biomass with Steepness range from 0.5-1 B) Outputs of Relative spawning biomass with Sigma R ranging from 0.4-0.8 C) Outputs of Relative spawning biomass with time varying selectivity D) Outputs of Relative spawning biomass with time varying catchability D) R_0 profile of a base model.

CONSIDERAÇÕES FINAIS

A presente tese aborda as questões relacionadas a pesca e conservação dos grandes bagres migradores na bacia amazônica, principalmente quanto a distribuição de tamanhos de acordo com aspectos migratórios desse grupo, como isso reflete a produção pesqueira por área geopolítica da bacia Amazônica e como cada espécie do grupo dos grandes bagres responde à diferentes intensidades de pressão pesqueira. Esses fatores, aliados a ameaça recente de construção de barragens na área oeste, próximo aos andes, área de desova de grande parte dos grandes bagres migradores, amplia o desafio quanto a conservação e manejo desse grupo na bacia Amazônica.

Na parte leste, a maior preocupação é o ordenamento pesqueiro e medidas de manejo aplicadas a pesca de arrasto da piramutaba que atua na foz do rio Amazonas, uma das atividades pesqueiras mais impactantes que ocorre dentre o grupo dos grandes bagres. Medidas de manejo vêm sendo implementadas por mais de quarenta anos e, como ferramenta norteadora na tomada de decisão de manejo da pesca de arrasto no estuário da bacia Amazônica, novas abordagens na avaliação de estoques da pesca foram realizadas e traz à tona a preocupação com a sustentabilidade a longo prazo para essas e outras pescarias em larga escala na Amazônia.

A presente tese deixou claro que a escassez de informações com baixa periodicidade e, sem uma longa série de dados de captura para a maioria das espécies dos grandes bagres migradores dificulta a utilização de técnicas mais elaboradas, aumentando a imprecisão nos valores de referência para a tomada de decisão no manejo. Nesse sentido, é fundamental que a coleta de dados seja retomada, visto que a situação da pesca no Brasil de forma geral não é boa e, é agravada pela baixa importância da política de gestão da pesca nos novos contextos econômicos e políticos brasileiros.

A pesca de arrasto na região do estuário, no entanto, é uma exceção em termos de disponibilidade de série histórica mais longa de dados de capturas para o grupo dos grandes bagres migradores, porém, mesmo dispondo de dados de diferentes fontes de dados, ainda assim é necessário dar continuidade a coleta, visto que, ao longo de quase 40 anos de pescarias o estoque esteve várias vezes em sobrepesca de crescimento "*overfishing*" considerando os valores de MSY e mortalidade por pesca. Porém no segundo artigo, analises com foco em Biomassa e Biomassa desovante confirmaram que a pesca esteve várias vezes em sobrepesca de crescimento, porém em 2007, quando os dados deixaram de ser coletados, o estoque estava muito próximo da sobrepesca de recrutamento "*overfished*", tipo de sobrepesca que leva a atividade pesqueira ao colapso. Considerando o manejo aplicado à pesca de arrasto da piramutaba, *B. vaillantii*, não foi detectada nenhuma mudança na trajetória de mortalidade por pesca ou biomassa total e do estoque desovante. E, frente a fortes indícios de falta de fiscalização nas normas estabelecidas, não podemos afirmar se as medidas não funcionam ou, se não foram de fato implementadas.

Nesse sentido, a discussão na implementação e a aplicação de medidas de manejo na pesca dos grandes bagres migradores deve refletir sobre todas as ações que já foram tomadas no passado, sua eficiência e eficácia, a fiscalização e, principalmente o monitoramento dessas medidas. E, a partir daí, começar a discutir novas medidas de manejo como capturas totais permitidas (TAC´s), uma das influências mais positivas na reconstrução de estoques sobrepesca no mundo. Os modelos utilizados nesta tese, desde o mais simples como no primeiro artigo até o mais complexo mostraram um valor de MSY em torno de 10.000 ±1 t/ano e, F_{msy} = 0.23 similar ao de Alonso e Pirker, 2005 – F_{msy} = 0.30. Com esses valores disponíveis é possível propor ações mais concretas de manejo além de período de defeso e áreas proibidas para pesca, mas, que ainda tem um longo caminho de discussão e implementação no Brasil, visto que são prejudicadas pela falta de monitoramento e fiscalização da produção pesqueira pelas Agências brasileiras.