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A tomada de decisões conservacionistas baseadas em informações sobre a biodiversidade em empreendimentos hidrelétricos na Bacia Amazônica brasileira

Rodrigo Vasconcelos Koblitz

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Orientador: William Ernest Magnusson, Dr.
Coorientadora: Helena de Godoy Bergallo. Dra.

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Prof. Dr. Fernando Mendonça D'Horta	Inpa	Aprovado
Profa. Dra. Flávia Costa	Inpa	Aprovado com correções
Prof. Dr. Jansen Zuanon.	Inpa	Aprovado com correções
Prof. Dr. Efrem Gondim	Inpa	Aprovado
Prof. Dr. Phillip Martin Fearnside	Inpa	Aprovado com correções

Sinopse:

Este estudo examinou a tomada de decisões sobre a instalação de aproveitamentos hidrelétricos na Amazônia brasileira. Foi feita uma análise das metodologias utilizadas através de curvas de rarefação e dos efeitos que as conclusões baseadas nessa ferramenta podem provocar. Os alvos de biodiversidade foram avaliados através da sobreposição desses com as hidrelétricas construídas e planejadas para a bacia, considerando diferentes tipos de impacto que podem ser ocasionados por barragens. Os alvos considerados relevantes foram usados para analisar os efeitos sobre a biodiversidade do atual plano do setor elétrico para a bacia do rio Tapajós. Foi feita uma simulação das barragens propostas sobre essa bacia e os pontos mais eficientes de produção de hidroeletricidade com menor degradação na biodiversidade foram analisados através da fronteira de Pareto.

Palavras-chave: alvos de biodiversidade, bacia do Tapajós, curva do coletor, Estudos de Impacto Ambiental, hidrelétricas, Planejamento Sistemático da Conservação, região hidrográfica da Amazônia brasileira

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O que é a verdade? Inércia. Uma hipótese que satisfaz,
que exige o consumo mínimo de força intelectual.
Friedrich Wilhelm Nietzsche

Resumo

O Estudo de Impacto Ambiental - EIA é utilizado para entender os impactos de uma intervenção humana no meio ambiente e sugerir se o empreendimento é ou não viável sob o ponto de vista ambiental. No entanto, atualmente, são usadas poucas ferramentas ecológicas de análise para embasar essa conclusão. Uma delas é a exigência legal da estabilização da curva do coletor, que tem um forte aceite pelas empresas de consultoria e pelos órgãos licenciadores porque é bem conhecida e utilizada por alguns pesquisadores no mundo para analisar EIAs. Entretanto, as premissas da análise raramente são encontradas em situações reais de tomada de decisão sobre hidrelétricas. No capítulo 1 analisamos se o estimador de número de espécies dado pela Curva do Coletor é robusta a essa ausência de premissas. Utilizamos anuros como o elemento da fauna porque eram os dados disponíveis nos 4 sítios de amostragem. O principal fator que impede o uso da curva do coletor é a impossibilidade de se realizar amostragens aleatórias em grandes áreas de difícil acesso. Em algumas escalas espaciais, a ausência de aleatorização não é relevante, mas esse não é o caso de empreendimentos hidrelétricos na bacia amazônica. Na impossibilidade de atender a esse pressuposto, a tomada de decisão baseada em curva do coletor é pouco elucidativa sobre a validade da amostragem. A riqueza de espécies estimada pela curva do coletor tem tido pouca aplicabilidade pela biologia da conservação. O conhecimento dos elementos da biodiversidade presentes é considerado mais relevante atualmente e, portanto, a realização de amostragens em toda área de inferência é uma recomendação mais útil, pois o conhecimento das espécies menos raras pode ajudar mais na tomada de decisão. A complementaridade é o atual paradigma da biologia da conservação, que conta com alguns algoritmos e ferramentas largamente usadas no mundo. Os mais comuns desses algoritmos podem ser nomeados de Planejamento Sistemático da Conservação (PSC), que é uma lógica que estabelece algumas etapas fundamentais que o processo de decisão deve seguir até chegar a se discutir o que deve ou não ser preservado. Escolher os alvos que devem ser considerados como relevantes é parte crítica desse processo. No capítulo 2 realizamos essa etapa do PSC e procuramos estabelecer os alvos para a região hidrográfica da Amazônia brasileira que estão ameaçadas pelas hidrelétricas a serem instaladas. Para isso, inicialmente consideramos a lista de alvos apresentadas nos EIAs, aqueles exigidos pela legislação, e em um encontro de pesquisadores sobre hidrelétricas. Foram elencados 335 alvos entre espécies e feições geográficas que potencialmente seriam afetados pelas barragens. A seleção de alvos prioritários foi feita através da sobreposição

espacial desses alvos iniciais com todas as barragens construídas e planejadas na região hidrográfica da Amazônia. As análises indicaram que apenas alvos aquáticos foram ameaçados pelas represas e também ficou evidente que a bacia do Tapajós será a mais afetada pela instalação das novas barragens.. Na bacia do Tapajós será feito o maior investimento em construção de novas barragens pela proposta do setor elétrico. No capítulo 3, foi feita uma simulação das combinações de barragens mensurando o potencial hidrelétrico e nos impactos previstos sobre a biodiversidade que cada potencial combinação de empreendimentos poderia causar. Os elementos de biodiversidade usados foram as espécies (p.e *Trichechus inunguis* e *Brachyplatystoma rousseauxii*) e ambientes (p.e. pedrais e rios conectados) selecionados no capítulo 2. Como custo da preservação desses elementos foram considerados a quantidade de energia perdida em Mega Watts(que são as barragens que não poderia ser construída) para que a área não fosse degradada e o alvo pudesse persistir. A análise foi feita através da Fronteira de Pareto, que é uma ferramenta apropriada para comparar dois recursos competitivos. A investigação dessa curva pode mostrar alguns níveis ótimos de utilização de um recurso prejudicando o mínimo possível do uso do outro recurso. Através da fronteira de Pareto alguns pontos encontraram a situação de ganha-ganha, mostrando que pode ser compatível a produção de energia com a preservação ambiental, mas essas melhores combinações não são a proposta atual do governo. A fronteira de Pareto revela que um dos pontos de maior eficiência mostrou que é possível produzir 78% da energia elétrica potencial planejada com uma perda estimada de 21% da biodiversidade em relação à proposta atual do governo. Todos os resultados foram fortemente influenciados pela escolha dos alvos analisados e esses devem ser investigados mais a fundo antes da tomada de decisões sobre hidrelétricas na bacia.

Conservation decision-making based on information on biodiversity in environmental impacts assessments of hydroelectric dams in the Brazilian Amazon

Abstract

Environmental impact studies (EIAs) are used to understand the potential impacts of a construction and to suggest whether the project is viable under the environmental point of view. However, few ecological tools of analysis are currently used for this conclusion. One of them is the legal requirement for the stabilization of the collector curve, which has been strongly accepted by the consultants and employees of Ibama (Brazilian Institute of Environment and Renewable Natural Resources) because it is well known and used by some researchers in the world to analyze EIAs. However, the assumptions of the analysis are rarely found in real decision-making situations about hydroelectric dams. The main factor that prevents its use is the impossibility of performing random sampling in large areas of difficult access. In some spatial scales, the absence of randomization is not relevant, but this is not the case with hydroelectric projects in the Amazon basin. If this assumption can not be met, decision-making based on the collector curve is not informative about the validity of the sampling. The species richness measured by the collector curve has had little applicability by conservation biology. Knowledge of the elements of biodiversity present is considered more relevant today and, therefore, sampling in all area of inference is a more useful recommendation, since knowledge of less rare species can give more support in decision making. Complementarity is the current paradigm of conservation biology that relies on some widely used algorithms and analytical tools in the world. Choosing conservation targets that should be considered relevant is a critical part of this process. Initially, we considered the list of targets presented in the EIAs, those required by the legislation, and also those listed at a workshop of researchers on hydroelectric dams in the Tapajós River basin. The selection of priority targets was made in this study through the spatial overlap of these initial targets with all the dams built and planned in the Amazon basin. The analyzes indicated that only aquatic targets were threatened by dams, and the use of a high number of targets may lead to the erroneous conclusion that there is little impact on the targets analyzed. The Tapajós basin is planned to receive the greatest investment in construction of new dams by the current proposal of the Brazilian Ministry of Mines and Energy. Using only the targets that were selected in Chapter 2, a simulation of dam combinations was made by contrasting the

hydroelectric potential and the degradation in biodiversity that each potential combination could cause. By means of the Pareto frontier analysis, some arrangements of dams have resulted in “win-win” situations, showing that energy production can be compatible with environmental preservation, but these best combinations are not the current government's proposal. One of the most efficient points showed that it is possible to produce 78% of the potential electricity with a loss of 21% of biodiversity compared to the current government proposal. All the results were strongly influenced by the choice of the analyzed targets and these should be investigated more thoroughly before hydroelectric decisions are made in the basin.

Sumário

Introdução geral	17
Capítulo 1 - Effect of species-counting protocols and the spatial distribution of effort on rarefaction curves in relation to decision making in environmental impact assessments	22
ABSTRACT.....	24
INTRODUCTION.....	25
MATERIAL AND METHODS.....	28
Study Area and Experimental Design.....	28
Statistical Analysis.....	29
Individual-based protocol vs. Sample-based protocol.....	29
Bias in conservation decisions due to not meeting the assumptions of rarefaction curves	30
Effect of clumped sampling on complementarity.....	31
Effect of clumped sampling on overestimation of sampling adequacy for identification of vulnerable species.....	31
RESULTS.....	32
Individual-based protocol vs. Sample-based protocol.....	32
Effect of clumped sampling on complementarity.....	32
Effect of clumped sampling on estimation of sampling adequacy for identification of vulnerable species.....	33
DISCUSSION.....	33
Individual-based protocol vs. Sample-based protocol.....	33
Effect of clumped sampling on complementarity.....	34
Effect of clumped sampling on estimation of sampling adequacy for identification of vulnerable species.....	34
ACKNOWLEDGMENTS:.....	37
REFERENCES:.....	38
SUPPORTING INFORMATION DATA:.....	40

Capítulo 2 - The selection of targets for environmental decision-making on hydroelectric projects in Brazilian Amazon.....	43
Abstract.....	45
1. Introduction.....	45
2. Methods.....	48
2.1. Study area.....	48
2.2. Targets.....	48
2.3. Impact zones.....	49
2.3.1. Definition of Impact Zones.....	50
2.3.1.1. Existing and planned reservoirs.....	50
2.3.1.2. Areas of uncertainty in rivers under inventory.....	50
2.4. Overlap and the list of selected targets.....	51
3. Results.....	51
3.1 Targets selected.....	52
3.1.1. Commercial fish species (regional and Amazon).....	52
3.1.2. Endangered species.....	52
3.1.3. Migratory fish.....	52
3.1.4. Regional commercial fish species.....	52
3.1.5. Geographic features.....	52
3.1.6. Charismatic species.....	53
4. Discussion.....	53
Acknowledgments.....	56
Appendix.....	56
References.....	57

Capítulo 3 – Planejamento de barragens na Bacia do Rio Tapajós: incluindo a biodiversidade na tomada de decisão	61
Resumo.....	62
Introdução.....	62
Métodos.....	65
Área de Estudo.....	65
Alvos de biodiversidade.....	66
Zonas de impacto.....	66
Iterações.....	68

Resultados.....	69
Discussão.....	71
Referências.....	73
Apêndice.....	73
Síntese.....	74
Referências bibliográficas:.....	77
Apêndices.....	82
Parecer da Aula de Qualificação.....	82
Ata de defesa da Tese.....	83

Lista de Tabelas

Capítulo 2 - The selection of targets for environmental decision-making on hydroelectric projects in Brazilian Amazon

Table 1. The number of targets impacted, arranged by the proximity of the impact (dam existing or planned) and by hydrographic basin (39 = North Atlantic, 42 = Xingú sub-basin, 44 = Tapajós sub-basin, 46 = Madeira sub-basin, 48 = Negro sub-basin, ALL = Amazon basin as a whole). The targets found in the “existing” column are also present in the “planned” column, albeit with a shift in the intensity of the impact. This is because a target that is low risk (30–50% of its area of occurrence affected) in an existing reservoir may be medium risk (50–70% impact) in the case of a dam that has yet to be built.....60

Lista de Figuras

Capítulo 1 - Effect of species-counting protocols and the spatial distribution of effort on rarefaction curves in relation to decision making in environmental impact assessments.

Fig 1. Schematic layout of four modules used in analyses of effects of clumped sampling on identification of vulnerable species. The general approach in EIA, was to determine whether species found in the impacted area occurred in other areas. We used the reduced-set (one module with 10 plots along 2 transects) to represent clumped sub sampling. The four modules together (complete set) sampled the whole area of interest. The details this analysis are presented in the main text.....41

Figure 2. Rarefaction Curves for anurans based on individuals (dotted line) had greater curvature, indicating that at all localities the asymptote is approached with less effort compared to samples based on plots (solid-line). In axis x the downside indicated the number of sampling plots in upper side, the number of individuals, which are the average of individuals per plot. Santo Antonio (a), Ducke (b), Uatumã (c) and UFAM (d).....41

Figure 3. In a) Relationship between the number of exclusive species in pairs of transects and distance between those pairs of transects in a) the Manaus region (Uatumã, Ducke and UFAM localities), where only two transects were used in each locality, and b) the same relationship from the Santo Antônio locality for three modules with two transects each.....42

Capítulo 2 - The selection of targets for environmental decision-making on hydroelectric projects in Brazilian Amazon

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Figure 1. The division of the Amazonian hydrographic region (CNRH 2013) in Brazil, showing the five sub-basins analyzed in the present study: Madeira (558,653 km²), Xingú (506,880 km²), Tapajós (492,255 km²), North Atlantic (82,722 km²) and Negro (579,076 km²).....59

Figure 2. The layers that is overlapping with biodiversity features. In A) Spatial representation of dams under operation or in construction and planned dams and in B) of river under inventory.....60

Capítulo 3 - Produção de hidroeletricidade e preservação da biodiversidade na bacia do Tapajós são compatíveis?

Figura 1 a) a Bacia do rio Tapajós na região hidrográfica da Amazônia. Parte b) mostra os principais rios da bacia com as barragens já construídas. Parte c) mostra a proposta de ocupação da Bacia com todas as barragens planejadas até 2030 e a zona cinza engloba todas as UHES, PCHS, e CGHs que juntas formaram o grupo das menores barragens e foram usadas como grupo nas modelagens feitas aqui.....65

Figura 2. Exemplo de uma combinação de barragens a) na bacia do Tapajós que criou uma região de rio livre menor que 100 km. Parte b) mostra um arranjo de hidrelétricas com a presença das hidrelétricas Cachoeira dos Patos e Cachoeira do Cai e sem a presença da hidrelétrica de Jamanxim, as ilhas ficavam restritas a um ambiente com menos de 100 quilômetros e aos arranjos que tinham essa combinação foram atribuídas uma zona de impacto de poucos trechos livres. Entretanto, se o arranjo tivesse a hidrelétrica de Jamanxim c), não era atribuído a zona de impacto rio-livre na mesma zona. Mesmo sem ser computado esse impacto na zona de impacto rio-livre, as ilhas suprimidas pela presença da UHE Jamanxim foram computadas na zona de impacto do reservatório.....68

Figure 3. Os gráficos mostrados na parte superior mostra os arranjos de barragens que tiveram pelo menos dois pontos mais eficientes. As setas indicam os limites que identificamos como sendo os pontos mais eficientes dos gráficos. As letras que estão ao lado da seta indica que há uma figura na parte inferior com as barragens selecionadas nessa opção. Na parte inferior, acima de cada arranjo mostrado tem a zona de impacto, a quantidade de MW que o arranjo produz, entre parênteses a percentagem do total de MW previstos pra bacia, o número de alvos afetados pelo arranjo e, entre parênteses, a quantidade relativa de targets que estarão preservados com esse arranjo.....70

Introdução geral

O licenciamento ambiental brasileiro carece de normas específicas definindo o que deve ser feito ou como deve ser analisado um Estudo de Impacto Ambiental (EIA). Procurando minimizar essa lacuna, em 2007 o Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) publicou sua primeira legislação definindo uma ferramenta e um parâmetro ecológico a serem usados nesses estudos. Uma das exigências foi a estabilização da curva do coletor (RC) nas amostragens de fauna. Desde o início do processo de licenciamento em 1986 no Brasil (Resolução Conama, 1986), os trabalhos de campo dos EIA- RIMAs (Estudo de Impacto Ambiental e Relatório de Impacto Ambiental) foram severamente criticados pela literatura científica e um dos aspectos mais criticado é o subdimensionamento das amostragens da biodiversidade (Trajano, 2010). Uma tentativa de regulamentar a organização de um EIA, quanto a parte da biodiversidade, foi a publicação da Instrução Normativa 146/2007 . Essa norma institui que as coletas de fauna dos EIAs devem apresentar a Curva do Coletor estabilizada em todos os pontos de amostragem para que o estudo esteja apto a ser analisado pelo Instituto. Como não havia outras definições explícitas de como deveria ser construída a curva do coletor, a unidade de esforço amostral variou entre estudos, como dias de coleta (Ecology Brasil, 2009 Volume 8, p 23) ou indivíduos coletados (Eletrobras et al., 2009 – vol 14, p. 500). Além disso, em alguns EIAs, a amostragem ficou concentrada em algumas poucas regiões da área do empreendimento, para alcançar a exigência do Ibama com baixo investimento em amostragens de campo (<http://licenciamento.ibama.gov.br/Hidreletricas/UHE%20Riacho%20Seco/TEXTOS/Volume%201/Capitulo%20V/881000-60RL-1000-1-Cap%20V-Areas%20de%20Influencia.pdf>).

A presente tese tem como objetivo analisar como o conhecimento científico tem sido usado no licenciamento e planejamento ambiental de barragens na Amazônia brasileira. Para isso, no capítulo 1 investigamos se a estabilização da curva do coletor pode ajudar na tomada de decisões sobre a viabilidade ambiental de uma obra. Inicialmente, mensuramos o efeito do uso de diferentes unidades de esforço para o mesmo conjunto de dados. Grande parte da literatura científica estabelece que as unidades amostrais devem ser distribuídas aleatoriamente na paisagem para que a RC possa estimar a riqueza de espécies (Gotelli & Colwell, 2001), que é usada ou para comparação entre sítios ou como estimador do esforço amostral necessário a ser cumprido. Uma das sugestões na literatura é de exigir que as espécies coletadas

cheguem a 80% do total de espécies previstas para o local pelo RC antes de interromper as amostragens (Thompson et al., 2007). A RC pode ou não ser robusta à não aleatoriedade na distribuição dos sítios de amostragem (Réjou-Méchain et al. 2011), mas essa propriedade depende fortemente da escala espacial utilizada. A amostragem aleatória em grandes áreas de ambientes florestados é impraticável. Testamos então se, na escala espacial de empreendimentos na Amazônia, na ausência de uma amostragem aleatória, é possível usar a RC para a tomada de decisões.

Em 2007, o Grupo de Trabalho (GT) de Monitoramento de Fauna foi criado no IBAMA. O GT realizou em 2009 uma oficina sobre Licenciamento Ambiental com diversos pesquisadores, empreendedores e empresas de consultoria do País. Nesse encontro, o GT propôs que a principal decisão do IBAMA em um processo de licenciamento, qual seja, se o empreendimento pode ou não ser construído, seja respondida através do estudo da complementariedade. Uma região é mais complementar do que outra se ela possui mais características da biodiversidade que só ocorrem nela (Margules & Pressey, 2000). Esse método de decisão é fortemente utilizado pela biologia da conservação atualmente, que prioriza a conservação de regiões mais complementares (Possingham & Ball, 2000). Assim, a utilização apenas da riqueza de espécies para a tomada de decisão tem sido desencorajada (Fleishman et al., 2006). Atualmente, existem alguns instrumentos e algoritmos que dão suporte a esse tipo de decisão, como o *Marxan* (Watts et al., 2009) ou *Zonation* (Moilanen et al., 2005), que são conhecidos genericamente como parte da metodologia de Planejamento Sistemático da Conservação (PSC). O PSC procura sistematizar as etapas necessárias para a tomada de decisão e sua lógica pode ser usada em qualquer escala de interesse (Margules & Pressey, 2000).

A bacia Amazônica tem sido foco de investimento do setor elétrico (empreiteiras, Ministério de Minas e Energia e Agencia Nacional de Energia Elétrica) e do governo brasileiro. O objetivo oficial do governo brasileiro é aumentar a produção de 22,757 MW por ano para 75,000 MW por ano até 2030. Apesar dos esforços do governo em planejar a instalação de barragens nacionalmente, pouco tem sido feito sobre planejamento ambiental em escala similar. No capítulo 2, procuramos minimizar essa lacuna realizando a primeira etapa de um PSC, que é a escolha dos alvos de biodiversidade que devem ser considerados como relevantes para orientarem a tomada de decisão sobre conservação. A retomada da construção de grandes barragens na Amazônia é recente, com o funcionamento das hidrelétricas Santo Antônio e Jirau iniciado em 2011 e 2013, respectivamente. Os EIAs desses e de outros empreendimentos similares na bacia apresentam um número muito grande de alvos e quase todos são considerados

inicialmente como não impactados. A definição das áreas mais relevantes para conservação é fortemente influenciada pela escolha do alvo que se pretende preservar (Warman et al., 2004). Uma das consequências da análise obrigatória de alvos que sabidamente não serão influenciados por uma obra, é a conclusão de que o empreendimento impactará pouco a biodiversidade. Outra consequência é que o investimento de recursos em estudos de elementos da biodiversidade que potencialmente não precisariam ser investigados diminui os recursos daqueles prioritários e que deveriam ser usados para a tomada de decisão. Então, para definir os alvos da bacia Amazônica úteis para o planejamento de barragens, comparamos os alvos que são tradicionalmente usados em EIAs da região de empreendimentos similares e que constam na legislação. Em 2011 houve uma tentativa de planejamento conjunto entre Ministério do Meio Ambiente e Ministério de Minas e Energia sobre o conjunto de barragens atualmente propostas para a bacia do rio Tapajós, e foi promovido um encontro de especialistas do bioma amazônico para apresentar quais seriam os alvos prioritários para a conservação naquela bacia (MMA & MME, 2011). Além dos alvos usados tradicionalmente e aqueles listados na legislação, usamos também o resultado desse encontro para montar a lista inicial de alvos a serem investigados no capítulo 2.

Uma mesma barragem impacta alvos de formas diferentes. Por exemplo, espécies de peixes migradores são afetadas por barragens situadas a milhares de quilômetros de suas áreas de reprodução, como é o caso da dourada *Brachyplatystoma rousseauxii* (Siluriformes: Pimelodidae), um grande bagre que migra do estuário amazônico até os Andes e será impactado em toda a extensão de sua área de vida por barragens situadas no Rio Madeira a 2600 quilômetros do oceano (Val et al., 2016). Por outro lado, peixes de corredeiras (ao menos aqueles sedentários) podem não ser impactados por barragens situadas a apenas algumas dezenas de quilômetros a jusante. Isso porque pouca ou quase nada de sua área está sobreposta com a área que será afetada. A classificação da escala espacial e onde o alvo será impactado por causa de uma barragem tem sido feita por alguns autores (Lee et al., 2016). A mera sobreposição entre a área de alagamento das barragens com a área de ocupação dos alvos não seria útil para quantificar os impactos de um aproveitamento hidrelétrico. Associar o alvo ao tipo de impacto provocado pelas barragens é crucial para mensurar o efeito de uma barragem. Um outro fator relevante para a definição da prioridade de conservação é a escala geográfica em que se toma a decisão (Sarkar et al., 2006). Como, legalmente, uma espécie não pode ser deliberadamente extinta no Brasil (Brasil, CF. art 225, inciso IV), um empreendimento não pode ser autorizado se essa for a consequência. Entretanto, essa

não é a única decisão a ser tomada. Outras escalas de interesse, mesmo que não legalmente, podem ser usadas como delimitação espacial para a persistência da biodiversidade. A preservação de alguns alvos de valor cultural ou carismático, como golfinhos (*Sotalia fluviatilis*) ou o peixe-boi (*Trichechus inunguis*), pode ser considerada como relevante em uma escala menor, como a de uma sub-bacia. No capítulo 2, nós identificamos as motivações pelos quais determinados alvos estavam sendo propostos, a escala geográfica de interesse de sua conservação e a qual impacto de uma barragem ele estaria suscetível. Nós avaliamos as ameaças à biodiversidade nas cinco sub-bacias previstas para receber a maioria das hidroelétricas na Amazônia brasileira. Dentre estas sub-bacias da Amazônia, a sub-bacia do rio Tapajós receberá maior investimento do governo brasileiro, maior que todas as outras juntas, o que justifica sua escolha para um estudo de caso da presente tese.

No capítulo 3, usando os alvos de conservação identificados no capítulo anterior, procuramos classificar os arranjos de barragens (quais grupos de aproveitamentos hidrelétricos construídos e planejados) que causariam um menor impacto na biodiversidade em relação à quantidade de energia produzida. O efeito de barragens não é aditivo e a perda da biodiversidade devido a um conjunto de barragens pode ser muito maior que a soma de seus efeitos individualmente. Hidrelétricas distantes entre si, mas que afetam o mesmo elemento de biodiversidade, podem ser incompatíveis com a preservação desse alvo. Esse é um problema em que a intensidade do impacto de uma barragem pode ser maior ou menor dependendo das outras barragens sendo consideradas. Esse tipo de problema de codependência da escolha de sítios tem sido largamente tratado através do Planejamento Sistemático da Conservação (Margules e Pressey, 2000). Os algoritmos do PSC comumente usados são o *simulated annealing* (MARXAN, Possingham & Ball 2000) e processos mais heurísticos, como Zonation (Moilanen, 2005). Ambos utilizam o conceito de complementaridade e a relevância de um determinado sítio para a conservação depende dos outros sítios escolhidos para fazer parte do sistema de área protegidas (ou não degradadas). Pela lógica da complementaridade, se o conjunto de sítios já selecionados possui as características de biodiversidade presentes no sítio sob consideração, a importância desse sítio para inclusão no sistema de conservação é diminuída. De outro modo, se o grupo escolhido não possui a biodiversidade contida no sítio, esse se torna essencial para inclusão no sistema se o objetivo é proteger todos os alvos.

Outra opção de fazer as escolhas dos melhores arranjos tem sido a análise combinatória de todos os potenciais aproveitamentos hidrelétricos (Ziv et al., 2011), tendo

como objetivo encontrar quais deles são os mais eficientes por gerar uma produção de energia com menor impacto na biodiversidade. Essa é a melhor forma de resolver esse problema de escolhas quando o número de opções é limitado, porque garante que a melhor solução é encontrada, uma vez que avalia de fato todas as possibilidades. Uma limitação, porém, é que o número de opções deve ser pequeno, sob pena da quantidade de iterações necessárias se tornar impraticável computacionalmente. Esse inclusive é o motivo para que sejam usados algoritmos de otimização como aqueles previamente citados. No capítulo 3, nós fizemos a análise combinatória das opções de barragens construídas e planejadas para a bacia do rio Tapajós e procuramos identificar quais arranjos poderiam ser mais eficientes naquela bacia.

Objetivos:

O presente estudo teve como objetivo geral:

Avaliar como o conhecimento ecológico científico tem sido usado no processo de tomada de decisões de conservação da biodiversidade em processos de licenciamento ambiental de empreendimentos hidrelétricos na Amazônia Brasileira

E como objetivos específicos:

1) Investigar se estimativas de números de espécies baseadas em curvas de rarefação na escala espacial de um empreendimento hidrelétrico de grande porte na Bacia Amazônica são robustas à ausência de aleatoriedade na amostragem;

2) Definir quais elementos de biodiversidade devem ser usados na avaliação de impactos ambientais e tomada de decisão sobre a viabilidade ambiental de barragens hidrelétricas na Bacia Amazônica;

3) Considerando os empreendimentos hidrelétricos planejados pelo governo brasileiro para a bacia do rio Tapajós, identificar se existem opções de arranjo espacial de barragens que combinem eficiência em termos da produção de energia com o menor dano possível à biodiversidade.

Capítulo 1

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Title Page

Title:

Effect of species-counting protocols and the spatial distribution of sampling effort on rarefaction curves in relation to decision making in environmental-impact assessments.

Authors:

Rodrigo Vasconcelos Koblitz ^{1,2}

Albertina Pimentel Lima ¹

Marcelo Menin ³

Diana Rojas ¹

Luiz Henrique Condrati ¹

William Ernest Magnusson ¹

¹ Instituto Nacional de Pesquisas da Amazônia – INPA.

Av. André Araújo, 2936. Petrópolis, Manaus/AM, Brasil- CEP 69067-375.

Phone: +559236431834.

² Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – IBAMA

SCEN Trecho 2, Ed. Sede, Bl A. Brasília/DF, Brasil - CEP 70818-900.

Phone: +556133161212

³ Universidade Federal do Amazonas – UFAM

Av. General Rodrigo Octávio, 6200, Coroado I. Manaus/AM, Brasil - CEP 69077-000

Phone: +559233051480 +559284261963

ABSTRACT

Rarefaction Curves are frequently used in Environmental Impact Assessments (EIAs) to evaluate sampling sufficiency, but without clear guidelines of how to ensure that the assumptions of the methods are met. Infrastructure projects in the Brazilian Amazon and elsewhere often affect extensive areas in remote locations with difficult access, and random sampling under such conditions may be impractical. We tested the influence of sampling unit (sample or individual) and geographic distance between samples on rarefaction curves, and evaluated the magnitude of errors resulting from the misuse of rarefaction curves in biological conservation decision making, using frogs as a focal group and analyzing four Amazonian sampling sites. Individual-based rarefaction curves were steeper than those generated by sample-based rarefaction curves. Geographic distance influenced the number of exclusive species in a predictable fashion only in one area, and not in the Environmental Impact Assessment site. Misuse of rarefaction curves in EIAs generated large errors in the identification of vulnerable taxa. Because the rarefaction curve model is sensitive to the assumption of randomness and geographic distance can influence it unpredictably, we suggest that rarefaction curves should not be used as the only (or the most important) factor to estimate sample completeness when making management decisions for environmental licensing purposes.

Keywords: Decision making; Environmental Impact Assessment; Environmental legislation; Species rarefaction curve; Species richness

INTRODUCTION

A rarefaction curve is a model for estimating the number of species in any assembly defined in time and space. Rarefaction curves are used to predict the relationship between sampling effort and species to be found, and it has been suggested that they should be used as criteria to determine sampling sufficiency in Environmental Impact Assessments involving diverse taxonomic groups, such as lizards in Australia (Thompson 2007, Thompson *et al.* 2007), troglobitic species in Europe (Trajano 2010) and fish in Amazon streams (Hamblen & Canney 2007). Samples are considered sufficient when a predetermined proportion of the species estimated to be present is reached (Thompson *et al.* 2007), and the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), the Brazilian environmental agency responsible for licensing large civil-construction projects, began requiring rarefaction curves in Environmental Impact Assessments from 2007 (IBAMA 2007). However, there are assumptions for the valid use of rarefaction curves to estimate sampling adequacy that are unlikely to be met in Environmental Impact Assessments. As the legal requirements do not define the spatial arrangement of sampling, they do not guarantee that estimates of sampling sufficiency are realistic, and we show in this paper that their use can strongly bias management decisions.

The species accumulation curve describes the relationship between the number of species detected and their sequential accumulation via some unit of effort. This can be defined in terms of the number of individuals, or sample units, that can refer to spatial (e.g. number of plots) or temporal (e.g. number of hours of observation, collection days) factors (Colwell & Coddington 1994). The shape of the species-accumulation curve changes depending on how the accumulated effort is ordered, and potentially the same group of samples can have several species-accumulation curves. A single descriptor of the relationship between the number of species and the accumulation of effort for a group of samples or individuals can be obtained with rarefaction curves (Magurran 2004).

Thompson (2007) suggested that the Australian Environmental Protection Authority adopt a rarefaction curve-based criterion of sample sufficiency using the number of individuals as the unit of effort. Similarly, Environmental Impact Assessments in Brazil have estimated the number of species with individual-based protocols (Eletrobras et al., 2009 – vol 14, p. 500). However, a key premise for the use of rarefaction curves is that the sampling effort is distributed consistently within the area of interest and that data values are independent of each other. In general, data independence can only be assured by random sampling, but if the starting position of a regular sampling grid is chosen randomly, the resulting sampling array can effectively be considered random in most cases (Williams *et al.* 2002). In general, during fieldwork for environmental assessments, individuals are sampled collectively and are not encountered randomly or individually in systematic sampling. Because it is often more effective to collect multiple individuals in sampling units (hereafter referred to as sample-based collecting), many authors recommend the adoption of collective samples as the unit of effort (Gotelli & Colwell 2001). When a rarefaction curve for taxa collectively sampled is based on individuals, the asymptote, and therefore the number of species in the area is underestimated (Gotelli & Colwell 2001). In Environmental Impact Assessments, this results in samplings being terminated prematurely, or generates an overconfidence in the estimates of biotic complementarity.

Using sample-based rarefaction curves is only valid if the samples are distributed randomly in the area of interest. Sampling plots in only a subset of the area results in a smaller number of species estimated to be present than when plots are distributed across the whole area (Chiarucci *et al.* 2009). The degree of bias in estimates of the number of species present, and therefore in sampling sufficiency, depends on the difference between the area sampled and the area in which inferences will be made, and on the biological group being investigated. Taxa that have clumped distributions (high beta diversity) will be subject to greater bias in estimates than taxa in which the species occupy the whole area relatively homogeneously. When the areas to be surveyed are large, remote and difficult to access, such as those in the Amazon basin, and many other regions

where large infrastructure projects have been proposed, the placement of samples in truly random arrays is frequently unfeasible. The choice of individuals as the unit of effort can further confuse the interpretation of rarefaction curves, as the bias of rarefaction-curve methods is influenced by two types of clumping – that between individuals and that between sampling units. Another difficulty with extracting relevant information from large areas is that the sampled area is often much smaller than the area of interest. In general, studies for hydroelectric-dam Environmental Impact Assessments in Brazil survey only a small portion of the area that would be affected (e.g. CHESF *et al.* 2009 Vol. 2 Sect. 2 p. 6-36).

Most conservation decisions are based on the concept of complementarity (Margules & Pressey 2000), which evaluates the number of species that are not in common between potential management units. Differences among sampling units are expected as a simple effect of distance (Hubbell 2001). If differences depend only on distance, it may be possible to correct estimates for clumped sampling. Use of rarefaction curves assumes that sampling is done only within relatively homogeneous habitats, in which case distance should have little effect, and any such effects should be logarithmically related to the distance between samples (Hubbell 2001). When species are clumped, the distance-decay relationships for assemblage similarity can be much more complicated (Morlon *et al.* 2008). Therefore, the effect of clumped sampling on the number of species unique to one or other management unit in comparisons between management units should also be evaluated.

Despite the known biases, the effects of species clustering are strongly influenced by spatial scale (Réjou-Méchain *et al.* 2011) and may not always represent a serious problem in the calculation of rarefaction curves or evaluation of complementarity. In this paper, we evaluate the magnitude of the bias caused by these common practices in the construction of rarefaction curves in environmental assessments, using as a case study large-scale surveys of frogs in the Santo Antônio hydroelectric dam in Brazilian Amazon, and studies at three other localities in the region but covering smaller areas and using similar sampling methods.

MATERIAL AND METHODS

Study Area and Experimental Design

Similar sampling protocols were used at the four localities for which we obtained data. Three sampling grids, all in Amazonas State, were created mainly for academic studies (Uatumã Biological Reserve [Uatumã - 59W 15' 07", 1S 48' 25"] and Fazenda Experimental of the Universidade Federal do Amazonas [UFAM - 60W 05' 48", 2S 38' 38"], both occupying approximately 25 km², and Reserva Florestal Adolpho Ducke [Ducke - 59W 55' 48", 2S 57' 40"] with 64 km²). The fourth site, the Santo Antônio hydroelectric dam, with sample plots spread over an area of 2,529 km², was located around the Madeira River, Rondônia State, Brazil (64W 30, 9S 09' 54"). Sampling followed the RAPELD (a combination of techniques of Rapid Assessment Protocol - RAP and *Protocolo de Estudos de Longa Duração* - PELD, a portuguese acronym for Long-Term Ecological Research - LTER) system at all four sites. This system uses parallel straight transects of 5 km, separated from one another by 1 km, with 250m-long plots that follow a single local contour positioned every 1 km on each transect (for further details, see Magnusson *et al.* 2005 and Magnusson *et al.* 2013). The number of transects, and hence plots varies between localities, and a single set of transects and plots is called a sampling module. To compare individual-based rarefaction curves and sample-based rarefaction curves we used all data available with plots as sampling units. For comparisons based on complementarity we used standard modules as the sampling unit so that effort was equal in all samples. A standard module was defined as a set of two transects of 5 km with their corresponding plots. The Santo Antônio dam sampling site has seven standard modules spaced 15 to 49 km from each other along the river that runs through the study area. At the other localities, the standard modules were close to and parallel to each other so that they covered the whole area of interest. Uatumã has a grid with six transects separated from one another by 1 km (three modules). Ducke has a grid with nine transects, each with eight plots and Ufam has four transects with eight plots each. We standardized the sampling intensity by using standard modules based on two 5 km transects, each with five plots in each locality. To evaluate the

effect of clumping on complementarity, we used small modules consisting of five plots distributed along a single 5 km transect, hereafter referred to as transects. In the last simulation, we used four standard modules at Santo Antônio to calculate the bias caused by clumping of plots on identification of vulnerable species. Tables containing the analyzed data and geographic position of the sampling units are provide as Supporting Information files (Appendix S1).

At each locality, frogs were sampled in three nocturnal surveys using two standardized sampling methods: visual sampling and auditory survey. Each plot was walked by two observers who recorded the number of individuals of each calling species, and searched visually on the leaf litter and vegetation to a height of about 2 m. All frog sightings and/or all calls heard to a distance of approximately 10 m on either side of the transect's centre line were counted. Sampling began at the end of twilight and was terminated around 23:00. Sampling was carried out during the rainy season (November to June) when frogs are easier to detect. Plots were surveyed from November 2002 to May 2004 at Ducke with 72 plots, November 2007 to May 2008 at Uatumã with 30 plots, November 2008 to May 2009 at UFAM with 32 plots, and February 2010 to June 2011 at Santo Antônio, with 70 plots.

The Uatumã, Ducke and UFAM localities are separated from each other by up to 140 km, and are covered by relatively homogeneous old-growth tropical forest and therefore meet the assumption of a single community type being sampled. The Santo Antônio sampling modules are separated from each other by up to 90 km, and one of the objectives of the surveys was to determine whether the area was covered by relatively homogeneous forest or had distinct habitats that might merit specific conservation actions related to the potential impacts of the Santo Antônio hydroelectric dam.

Statistical Analysis

Individual-based protocol vs. Sample-based protocol

We generated individual-based rarefaction curves and selected the exact method for sample-based rarefaction curve using the R package ‘vegan’ (Oksanen *et al.* 2013). We used the ‘specaccum’ package, which implements Gotelli & Colwell’s algorithm (Colwell *et al.* 2004). The method for samples is compatible with the rarefaction method by individuals because both estimate the average number of species not found previously by sampling effort. The rarefaction curve result is the average number of species not previously found in a sample with one less effort unit, which in this case is a sampled area. Here, abundance is not used, but only presence / absence data (Colwell *et al.* 2004). To plot a rarefaction curve when the effort is measured by individuals, ‘specaccum’ uses the rarefaction method, which calculates the average number of species not previously found for a given number of individuals. The integration of the two rarefaction curves (individual-based and sample-based) occurs because the rarefaction method calculates the average number of individuals per sample and plots this number with number of samples. We show the number of individuals and number of samples together on graphs as in Gotelli and Colwell (2001). The relative difference between individual- and sample-based rarefaction curves was calculated as the difference between individual-based rarefaction curve and sample-based rarefaction curve for a given effort divided by the estimated sample-based rarefaction curve value. This provided the relative difference between the rarefaction curves for a given effort, which is a measure of the bias introduced by the use of individual-based rarefaction curves when the individuals were collectively sampled. The average difference for all possible numbers of samples was used to represent the differences between the curves.

Bias in conservation decisions due to not meeting the assumptions of rarefaction curves

Decisions about biological conservation in areas subjected to the effects of environmental impacts are sometimes made on the basis of comparisons of numbers of species, prioritizing conservation of species-rich areas, and sometimes on the basis of complementarity between areas to be impacted and areas to be conserved. The latter type of decision has been widely used in recent decades with the objective of protecting areas that have more exclusive species (those not found in

other areas within the protected-area system). Although we do not agree with the practice of making decisions based only on the number of species, we investigated the effects of bias induced by the inappropriate use of rarefaction curves for both decision criteria.

Effect of clumped sampling on complementarity

The effect of clumped sampling on the complementarity of sampling modules was investigated by comparing the number of exclusive species between transects (number of species that occurred in one but not in the others) and their geographic distance. As rivers are known geographic barriers, at the Santo Antonio locality we used only transects on the left side of the river.

Most transects were close together in the academic localities. To avoid giving undue weight to localities with more transects, within these sites, we chose one transect randomly and its nearest neighbour to be used in analyses. As the same transect was involved in more than one distance calculation, observations are not independent and probabilities were obtained by comparing the observed statistic to the statistics calculated for 1,000 random permutations of the distances.

Effect of clumped sampling on overestimation of sampling adequacy for identification of vulnerable species

To illustrate the effect of inappropriate sampling, we compared the results based on only one standard module from the Santo Antônio site with those based on the use of all four modules. We refer to the use of one module with two transects as the reduced set. As this reduces the geographic coverage and all individuals are collected within a radius < 5 km, we considered this as clumped sampling. We refer to the four modules, each with two transects at the Santo Antonio locality as the complete set because the area they covered was similar to that of the whole area of interest. In each module there were five transects and a total of 10 plots. Within the reduced set, four plots closer to water were within the area to be impacted and six were in areas that would not

be directly impacted by the dam. In the complete set, 16 plots, four in each module, were within the area to be inundated and 24 were outside the impact area (Fig. 1).

Fig. 1.

We used rarefaction curves based on plots combined with jackknife estimates of the total number of species present to determine adequacy of sampling and the magnitude of possible errors in ascribing species to the list found only in the area to be affected. Thompson *et al.* (2007) suggested that collection of more than 80% of the species estimated to be present in a locality indicated adequate sampling in both uniform and heterogeneous environments.

RESULTS

Individual-based protocol vs. Sample-based protocol

Sample-based rarefaction curves had shallower slopes and underestimated the number of species encountered for a given sampling effort (Fig. 1). The mean difference between individual-based and sample-based rarefaction curves was highest at Santo Antônio (25.7%). At the UFAM and Uatumã localities, the differences were similar to each other (10.0% and 9.6%, respectively). The smallest difference was found in Ducke (3.1%) (Fig. 2).

Fig 2.

Effect of clumped sampling on complementarity

For Ducke, Uatumã and UFAM, the number of species found in only one transect (exclusive species - excl) in comparisons among transects (Fig. 2) had an asymptotic (power function) relation with distance (dist) ($\text{excl} = 6.23 * \text{dist}^{0.356}$; permutation test with 9999 repetitions: $p = 0.001$). However, at the Santo Antônio locality, the relationship was not asymptotic and could be represented by a parabola ($20.38 + 0.321 * \text{dist} - 0.0032 * \text{dist}^2$; permutation test with 9999 repetitions: $p = 0.041$). The dissimilarity among sampling units (transects) increased monotonically up to

distances of about 40 km, but sampling units separated by larger distances had less exclusive species than sampling units separated by intermediate distances (Fig. 3).

Fig. 3.

Effect of clumped sampling on estimation of sampling adequacy for identification of vulnerable species

A total of 22 species were found in the area to be directly impacted within the reduced set (partial coverage of the area of interest), and the jackknife estimate based on samples indicated that this represented about 85 % of the species in the impacted area. Of these, ten were not found in the adjacent area and would be considered species of conservation concern to maintain local biodiversity.

The same analyses using the complete set indicated that there were about 49 species in the area to be impacted; and 16 of these were not found outside the impacted area. The 16 species exclusive to the impacted area and therefore relevant to conservation, in the complete set included only three of the species identified in the reduced set as of conservation concern, and included another 13. These results are not concordant with the rarefaction curve analysis of data from the impacted area, which indicated that only six species had not been detected. Therefore, besides giving biased estimates for the number of unique species, the rarefaction curve analysis of sampling adequacy gave erroneous confidence in those estimates.

DISCUSSION

Individual-based protocol vs. Sample-based protocol

The difference between sample-based and individual-based rarefaction curve was evident at all sites, but the maximum difference was higher at the Santo Antônio site (33.4%), which covered a larger area. The degree of clumping of species influences the difference between slopes of individual- and sample-based rarefaction curves. The difference between individual- and sample-based rarefaction curves can be used as an index of clumping, but it does not indicate at what scale

the clumping occurs (Gotelli & Colwell 2001). The magnitude of the difference can only be used to evaluate the degree of clumping in the whole area if the collective sampling units were distributed randomly within the area. In some cases, inadequate local sampling might cause a sharp increase in number of species with the number of individuals just because only the common and widespread species were found and this increases evenness (Peterson 1975). As evenness depends on the number of individuals within sample units and the distribution of the sample units, there is no simple way of relating evenness to degree of clumping. Therefore, use of individual-based rarefaction curves for sample-based collection leads to erroneous conclusions about sampling completeness in terms of the proportion of species estimated to be in the area that was encountered for a given level of effort, and the bias is inherently unpredictable.

Effect of clumped sampling on complementarity

The positive relationship found between the number of exclusive species and geographic distance among the sites in relatively homogeneous forest near Manaus corroborates the results of other studies (Chiarucci *et al.* 2009; Arrhenius 1921). However, at Santo Antônio, the number of exclusive species had a more complex relationship with geographic distance. Sites further apart had fewer exclusive species than sites at intermediate distances. This probably reflects patchily distributed habitats, with the most distant sites being more similar in terms of environment. This is a useful result for conservation planning, but means that the assumption that only one community type was sampled was not met and the proportions of different habitats sampled will affect the rarefaction curves. If sampling had been random and intensive, the resulting species-accumulation curve could still be representative of the area, if not of a particular community. However, as the sampling was clumped, and the distribution of different communities within the area is unknown, the rarefaction curves are not interpretable.

Effect of clumped sampling on estimation of sampling adequacy for identification of vulnerable species

In Brazil, the proposed Environmental Impact Assessment for the Riacho Seco hydroelectric dam on the São Francisco River included clumped surveys covering only about 7.1% for the total area of potential impacts (<http://licenciamento.ibama.gov.br/Hidreletricas/UHE%20Riacho%20Seco/TEXTOS/Volume%201/Capitulo%20V/881000-60RL-1000-1-Cap%20V-Areas%20de%20Influencia.pdf>). The Environmental Impact Assessment for the Santo Antônio do Jari hydroelectric dam (Jari River, Amapá state, Brazil) used more plots, but presented an rarefaction curve only for individuals (http://licenciamento.ibama.gov.br/Hidreletricas/Santo%20Antonio%20%28Rio%20Jari%29/EIA_RIMA%20Agosto%202009/2324-00-EIA-RL-0001-01_08.2.2_Fauna.pdf, pages 46 and 52. Accessed 5 July 2016). In the case of Santo Antônio do Jari, the consultants used a rarefaction curve to imply that there were more species in areas outside the area to be impacted by the dam, and concluded that no species were endangered in the impacted area. In fact, estimates from rarefaction curves cannot be used to determine whether any or all species in the area to be impacted are in the surrounding areas. If there were more species in the impacted area, it would be a reasonable assumption that some must not occur in the surrounding areas, but this would be a very weak and indirect assessment.

The overall extent to which the misuse of rarefaction curves is affecting decisions in environmental-impact studies is hard to estimate because most results are presented in unpublished reports , and very often the spatial distribution of sampling is not sufficiently documented to allow critical evaluation of the results. However, the frequent recommendation to use rarefaction curves to evaluate sampling adequacy in Environmental Impact Assessments in places as diverse as Australia (Thompson 2007; Thompson *et al.* 2007), Europe (Trajano 2010) and Brazil (IBAMA 2007) indicates that the problem is widespread.

Whereas the limitations of using species richness as a criterion for conservation decisions are well known (Margules & Pressey 2000), the problems with using algorithms based on complementarity in hyper-diverse regions where sampling is likely to be inadequate are less well understood (Magnusson *et al.* 2013:70-72). If rarefaction curves indicate that sampling was

adequate when it was not, complementarity analyses may indicate the wrong set of species for analyses. In the case of our simulation of reduced sampling in the impact area of the Santo Antônio hydroelectric dam, inadequate spatial coverage combined with the results of rarefaction curves would indicate 10 species as being potentially extirpated from the area impacted by the dam. However, the more complete analysis indicated that seven of those species did not merit special attention, and a further 13 species not identified in the first analysis were in fact potentially endangered by the dam. The magnitude of this error (20 species misclassified) could not be predicted from the first rarefaction curve analysis, which indicated that only about six species had been overlooked in the impacted area. Obviously, being found only in the impacted area is not the only criterion for listing species as being of concern, but it is the first step in selecting species that are priorities for further research. For example, Carneiro *et al.* (2015) used complementarity of species in impacted and adjacent areas to identify species of conservation concern that merited subsequent analyses using species-distribution models.

The effort (area sampled and researcher hours) of fieldwork at Santo Antônio site was the greatest ever made for Environmental Impact Assessment-based biodiversity sampling in the Amazon rainforest (at least up to the year of its completion in 2010). Nevertheless, the rarefaction curves for anurans did not stabilize. Major infrastructure programs in other biologically diverse regions and biomes also cover enormous areas. For instance, the Three Gorges Dam on the Yangtze River in China flooded 1,084 km² (Xie 2003) and the Altai gas pipeline from Russia to China will run 2800 km through some of the remotest areas in the world (Söderbergh *et al.* 2010).

The fact that the rarefaction curve could not estimate the number of species in the impact area of the Santo Antônio dam may not be a great problem for evaluation of the Environmental Impact Assessment, as use of species richness for decision making is questionable (Margules & Pressey 2000). Finding species that are restricted to the area to be impacted, or which are more abundant there, is a more appropriate criterion for decision making in Environmental Impact Assessments (Koblitz *et al.* 2011). Adequate coverage of the area of interest, with sampling

distributed throughout the study area should be a recommendation for Environmental Impact Assessments in any future large infrastructure-construction projects. However, because of logistical and financial restrictions, random sampling may not be feasible and decisions should be made on estimates of complementarity that take into account the possibility of false absences rather than on biased and uninformative estimates of the number of species in the area.

If it is decided that it is necessary to use rarefaction curves in environmental-impact studies, and they remain as a legal requirement, the findings reported in the academic literature should be incorporated into operational practice. It is common in Environmental Impact Assessments for rarefaction curves to be estimated from samples from only a portion of the area of interest, or using rarefaction curves based on individuals as sample units. While such methods are attractive because they require less effort, they are not short-cuts to rarefaction curves that provide an accurate estimate of the number of species present. As truly randomized sampling over large areas and achieving rarefaction curve stability for megadiverse groups appears impractical (e.g. Longino et al., 2002), we suggest that stabilization of rarefaction curves should not be used routinely to evaluate the adequacy of sampling in environmental impact studies.

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SUPPORTING INFORMATION DATA:

Appendix S1 – Tables with species data collection and geographic coordinates of plots.

‘table_1_SuppInfo.xls’ - The geographic coordinates of all plot in this work.

‘ table_2_SuppInfo.xls’ - Table with species data collection of Reserva Ducke, Rebio Uatumã and Reserva Ufam localities

‘table_3_SuppInfo.xls’ - Table with species data collection of Santo Antonio locality.

TABLES AND FIGURES:

FIGURE LEGENDS:

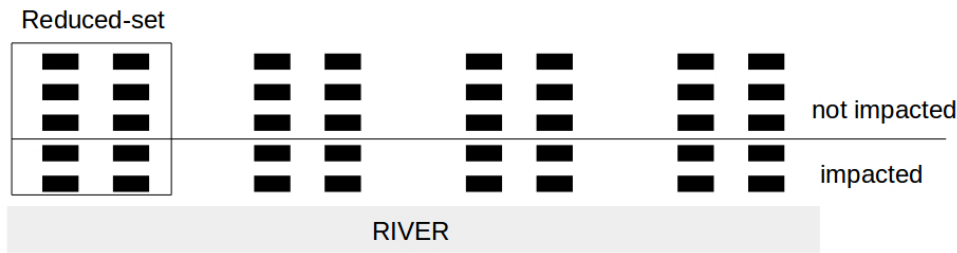


Fig 1. Schematic layout of four modules used in analyses of effects of clumped sampling on identification of vulnerable species. The general approach in EIA, was to determine whether species found in the impacted area occurred in other areas. We used the reduced-set (one module with 10 plots along 2 transects) to represent clumped subsampling. The four modules together (complete set) sampled the whole area of interest. The details of this analysis are presented in the main text.

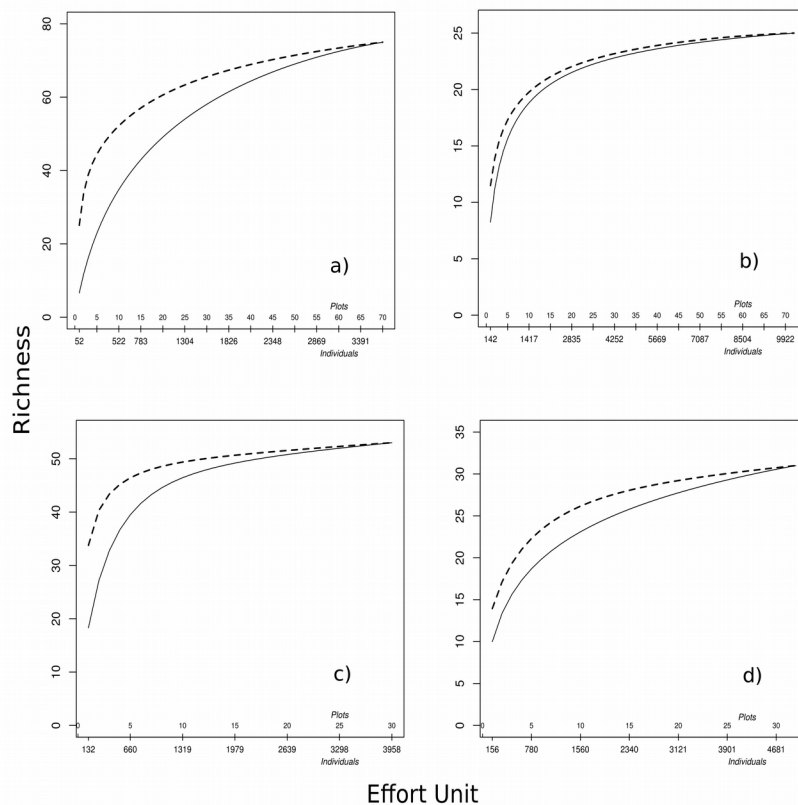


Fig 2. Rarefaction curves for anurans based on individuals (dotted line) had greater curvature, indicating that at all localities the asymptote is approached with less effort compared to samples based on plots (solid-line). In axis x the downside indicated the number of sampling plots, in upper side the number of individuals, which are the average of individuals per plot. Santo Antonio (a), Ducke (b), Uatumã (c) and UFAM (d).

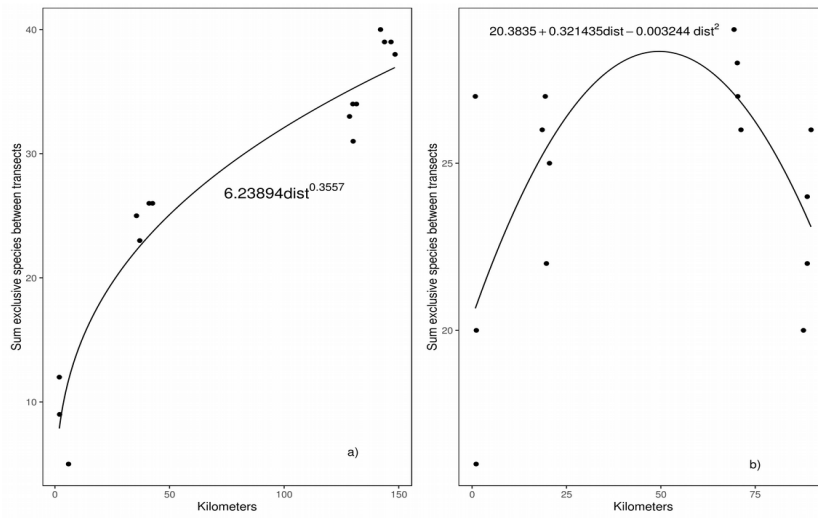


Fig 3. |In a) Relationship between the number of exclusive species and distance between pairs of transects in a) the Manaus region (Uatumã, Ducke and UFAM localities), where only two transects were used in each locality, and b) the same relationship from the Santo Antônio locality for three modules with two transects each.

Capítulo 2

Koblitz, R.V., Bergallo, H. G. & Magnusson, W. E., *submitted*. The selection of targets for environmental decision-making on hydroelectric projects in Brazilian Amazonia. *Biological Conservation*.

Title Page**Title:**

The selection of targets for environmental decision-making on hydroelectric projects in Brazilian Amazonia

Authors:

Rodrigo Vasconcelos Koblitz ^{1,2}

Helena de Godoy Bergallo ³

William Ernest Magnusson ¹

1 Instituto Nacional de Pesquisas da Amazônia – INPA.

Av. André Araújo, 2.936. Petrópolis, Manaus-AM, Brasil- CEP 69067-375.

Phone: +559236433377.

2 Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – IBAMA

SCEN Trecho 2, Ed. Sede, Bl A. Brasília/DF, Brasil - CEP 70818-900.

Phone: +556133161212

3 Universidade Estadual do Rio de Janeiro – UERJ

Rua São Francisco Xavier 524, PHLC 220, Rio de Janeiro, RJ, - CEP 20550-013

Phone: +552123340943

Corresponding author: Rodrigo Koblitz. rodrigokoblitz@yahoo.com.br

The selection of targets for part of process of environmental decision making on hydroelectric projects in Brazilian Amazonia

Abstract

Studies of the environmental impact of hydroelectric power plants in Brazilian Amazonia have identified a large number of targets with the aim of understanding the effects of these projects on the region's biodiversity. The inclusion of targets that have a low potential for disturbance may result in underestimated conclusions about the impact of reservoirs. Toward of understand which targets would be affected by dams, is necessary estimate their geographic location or their area of occupancy. We provide a comprehensive list of the environmental targets typically proposed for hydroelectric projects in the Brazilian Amazonia, define their total area, and compare this area with the hydroelectric dams already in place, the projects planned until 2030, and the rivers currently being inventoried for the evaluation of their hydroelectric potential. None of the terrestrial targets we identified have high potential to be degraded by the construction of hydroelectric dams, but some aquatic targets are threatened seriously throughout the whole region. The Tapajós sub-basin has the largest number of threatened targets, and the loss of connectivity by the secondary tributaries of the Amazon River is currently a greater problem than the loss of the area flooded by the reservoirs. For future research in this field, we recommend the inclusion of aquatic targets and the use of river basin as a main planning unit. This approach should be more effective than the analysis of a large number of targets that are unlikely to be severely impacted by the dam.

Keywords: Amazon Basin, geographical scale, Planning of dams, selection of biodiversity targets, Biological conservation

1. Introduction

The Brazilian electrical energy sector aims to expand its installed capacity in the Amazon region from the current 22,757 MW to 75,000 MW by 2030, an increase of 340% (Table A1 in Appendix A). Over the past few decades, there has been an enormous improvement in the planning capacity of the sector, with legislation and research being applied to specific river basins, although this process has not been accompanied by any relevant increase in the standards of environmental protection, scientific investigation or the processing of the information available on the Biome's biodiversity. The lack of reliable data hampers adequate decision-making and results in the inefficient investment of resources in the environmental licensing process, given that the resources are not applied to the analysis of the features of the local biodiversity that should be prioritized. In the present study, we investigated these shortcomings, and identified which elements of the region's biodiversity currently used for the environmental licensing of hydroelectric projects

are suitable for the decision-making process on the new dams proposed for construction by 2030 for the hydrographic region of Brazilian Amazonia.

The potential effects of hydroelectric dams on the biodiversity of the Amazon region are enormous, although the data on the species potentially affected by these projects are scarce and dispersed within a vast scientific (Lees et al., 2016) and gray literature. The analysis of some components of the local biodiversity is required by the specific Brazilian environmental legislation. Normative instruction 146/2007 of the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA, 2007), the organ responsible for the emission of environmental licenses in Brazil, determines which features should be used in all environmental impact studies (EIS). However, many of these targets may not provide useful parameters for planning of hydroelectric projects in the Amazon region. For example, the jaguar, *Panthera onca*, is identified as an endangered species (Machado et al., 2010) and for this reason, is contemplated by the legal criteria for an environmental target. However, this species is essentially terrestrial, and occurs throughout practically the whole of the Amazon basin. As it is widely distributed, its use as a target in hydroelectric projects may lead to the erroneous conclusion that the dam will have no environmental consequences, given that the species will be protected in other areas.

A new group of targets for the Amazon region was identified recently during a meeting between IBAMA, representatives of the energy sector (Empresa de Pesquisa Energética – EPE; www.epe.gov.br), and a number of scientific specialists with a profound knowledge of the biome's biodiversity (MMA and MME, 2011). The aim of this meeting (referred to henceforth as the Research Meeting) was to propose a list of more effective conservation targets for the Tapajós River basin which is earmarked to supply 77% of the hydroelectric energy generated in the Brazilian Amazon (Cap 2 desta tese. Apêndice Table A1.). The targets identified in the Research Meeting are intended to be more specifically designed for the environmental planning of hydroelectric projects than those include in the current legislation. While some aquatic species included in the original list are included, new targets were also proposed. However, the applicability of these new targets has yet to be evaluated systematically.

The current concepts of environmental planning associate the selection of targets with conservation goals. The aim of this strategy is not only to guarantee the presence of the targets, but also to ensure their survival in large enough quantities to persist in the environment over the long term. These goals are not yet defined in the specific literature on Amazonian hydroelectric projects, nor the legislation. In the present study, by investigating the pertinence of environmental targets, we point out which species would be affected by hydroelectric projects that impact more than 30%, 50% or 70% of the area occupied by the target. The elements of the local biodiversity encountered in this situation can be classified as low, medium or high conservation risk, respectively, and those defined as high risk should be considered targets. We considered species with less than 30% of their distribution affected as no risk. Here we consider the decline in area of occupancy as direct indicator of population decline like in another studies (IUCN, 2016). Then, values of 50 and 70% of lost area is the same that were used in IUCN to set categories of threatened vulnerable and endangered, respectively. We add the values o 30% of lost area to indicate because it is a limit indicate in IUCN for vulnerable species, since this 30% of area may not be reversible,

Brazilian Amazonia has nine major hydrographic sub-basins threatened with the construction of at least one large hydroelectric plant. The planning of the Brazilian federal energy sector considers all sources of electrical energy, but requires studies on a sub-basin scale to define the location of the hydroelectric dams in a given hydrographic basin. This level of classification (sub-basin) may be inadequate for some targets, especially for aquatic species. Migratory species or species with ample geographic distribution that are affected by the loss of connectivity may be indirectly impacted in hydrographic basins

distinct from that in which the dam is installed. This means that the spatial scale on which the environmental planning is conducted may need to vary according to the species or group being analyzed. For example, the Santo Antônio and Jirau dams on the Madeira River are located between the spawning grounds and other areas used in the life cycle of the migratory golden goliath catfish (*Brachyplatystoma rousseauxii*), which covers a distance of 3000 km between these two areas (Barthem et al., 2017). If the populations of this species, which is an economically-important fishery resource throughout the Amazon basin, between Bolivia and the Amazon estuary, decline significantly, the impacts of the Santo Antônio and Jirau hydroelectric dams will extend far beyond the limits of the sub-basins defined by the Brazilian government. Even if the loss of the target is tolerable within the sub-basin itself, its degradation must be quantified throughout the scale of the Amazon basin, given that the conservation status of the whole basin may influence the decisions taken with regard to a specific project. In the present study, we separate these two different scales and consider an important goal for the preservation of a given element of the biodiversity to be its persistence throughout its original distribution, as well as in each of the sub-basins analyzed.

While some migratory species have been relatively well studied, the distribution of most elements of the biodiversity of the Amazon region is still poorly understood. Even so, understanding the targets found throughout the focal region is crucial to adequate decision-making. The concept of complementarity has been used widely in conservation planning, and the decision to degrade an area or not is taken primarily on the basis of the distribution of the local biological resources and whether they are found exclusively in the area to be degraded or not (Pressey et al., 1994). One way to obtain information on a component of the biodiversity throughout a large area is to use surrogates, such as features identified using satellite images (Caro 2010). Some surrogates, such as rapids, are linked directly to the conservation of the species that inhabit the area, either exclusively or preferentially. Others, such as stretches of free river, may potentially conserve the species that require connectivity to persist in the environment, but whose requirements are still poorly known. Where specific information on the occurrence of the species throughout the rivers of the Amazon basin is unavailable, we used surrogates as conservation targets. In the present study, we use the term “target” to refer to both species and their direct or indirect surrogates.

We listed the potential targets found in the legislation, the Research Meeting, and the gray literature, dividing them into four groups: (1) high-risk species listed as endangered by the IUCN or the Brazilian government, and charismatic species with significant public appeal. The charismatic species is an explicit requirement from Brazilian legislation (IN 146/2007); (2) species of commercial value; (3) geographic features (e.g., rock-bottomed river stretches) associated with one or more groups of species; and (4) geographic features assumed to be associated with the conservation of biodiversity (e.g., stretches of free river).

Biodiversity targets may be affected in different ways by the same hydroelectric dams. Sedentary species may be impacted by the loss of habitat flooded by the reservoir. However, migratory and widely-distributed species may be little affected by the loss of the area of the reservoir itself, but rather by the loss of connectivity between the areas up- and downstream of the dam. Similarly, medium-range migratory species that are not affected by the area of the reservoir may not be able to persist in the environment created between two dams if the remaining stretch of river is not large enough for the completion of the species' life cycle, (Santos et al., 2013). In this case, the area impacted by a dam may depend on the component of the region's biodiversity being analyzed.

We also classified the impacts of the hydroelectric dams on potential targets in relation to the proximity of the effect. The planning of a hydroelectric project involves more than just the decision-making and construction stages. While some dams are in operation,

others are still at the planning stage, and in many cases, while construction has yet to begin, the site, design, and generation capacity have already been defined. This group includes rivers that have favorable characteristics for the establishment of hydroelectric dams, but are still being inventoried. In these cases, the lack of a specific site for the dam impairs the definition of the area that will be degraded in the future, and also prevents us from defining areas that should be protected. In this case, the biodiversity found in the rivers still being inventoried was used as a measure of the uncertainties of the preservation of its different elements.

In the present study, we include all the targets commonly used in the legislation, the ones pointed out by the Research Meeting, and the EIAs of the region's hydroelectric projects (Table B1 in Appendix B). We mapped all dams (small and large hydroelectric reservoirs) in the Amazonian hydrographic region and defined the different impact zones for each scheme, associating them with the targets they affect. We also defined the development stage of each dam; that is, whether it was in operation, under construction, planned, or still being inventoried. To investigate which targets should or should not be used for the planning of hydroelectric projects, we superimposed these layers (impact zones and targets) and identified the original area of distribution of each target that was (or would be) lost. We identified the targets that would not be adequate as those which would not lose more than 30% of their area; considered targets that would lose more than 50% but less than 70% of their area as medium risk (of impact); and those that would lose more than 70%, as high risk.

2. Methods

2.1. Study area

The study area encompassed the whole hydrographic region of Brazilian Amazonia, which covers a total area of 3.8 million square kilometers, and is formed by the Brazilian portion of the Amazon River basin and the North Atlantic basin (Fig 1). This division is used for planning by the Brazilian energy sector (CNRH, 2003). We assessed the level of threat to biodiversity of the five river basins earmarked for the implantation of most of the hydroelectric dams in the Brazilian Amazon region, focusing on the sub-basin level (Fig. 1). Pfafstetter's system (Verdin & Verdin, 1999) was used to define the order of the rivers. This is the system adopted by the Agência Nacional de Águas (National Waters Agency - ANA), which regulates the use of hydrological resources in Brazil. In this system, a first-order river is in contact with the estuary (in this case, the Amazon River), while second-order rivers discharge into first-order rivers, and so on.

2.2. Targets

Based on the Research Meeting, normative instruction 146/2007, and the gray literature, the potential targets were classified as (i) endangered species, (ii) migratory species, (iii) geographic features (i.e., beaches, islands, rocky environments, tropical forest, seasonal deciduous forests, Amazonian stone fields, and campinarana grasslands), (iv) charismatic species, (v) commercial fish of regional relevance (regional commercial species), and (vi) commercial fish relevant throughout the Amazon basin, "Amazon commercial species" (Table B1 in Appendix B).

The targets used were those for which data are available for the creation of a spatial representation. The geographic features were obtained directly from the layers available in a number of different sources (Table B1 in Appendix B). The available data only allowed for the definition of the extent of occurrence of the species analyzed in the present study that are the polygons available in IUCN (IUCN, 2014; IUCN, 2016) or in red list of threatened

fauna of Brazil (Machado et al., 2010). This extent is invariably an overestimate of the total area in which the species is found. The use of the extent of occurrence may result in some targets not being considered threatened simply because their presence is overestimated (Almeida-Gomes et al., 2013). To define the area occupied by the species, we identified the environments favorable to its occupancy based on the available published data. We identified these environments within the extent of occurrence of each species and defined this as the area occupied by the species. The criteria used for the identification of the environments appropriate for each target are described in the supplementary material (Table B1 in Appendix B).

In a few cases, the extent of occurrence attributed to a target was underrepresented in its surrogate, especially in the case of species associated with humid zones, wetlands. The limits of these humid zones, to the north and east, are arbitrary (Hess et al., 1995). Given this, we only assessed the targets for which at least 70% of the surrogate was mapped within its extent of occurrence.

Targets that have more than one ecological requirement were assessed in relation to each requirement. For example, the redbtail catfish, *Phractocephalus hemioliopterus*, is found in both the channels of the major rivers and seasonally-flooded forests (Barbarino Duque and Winemiller, 2003). In this case, we defined the area of occurrence of this species in terms of both the courses of rivers (lines) and the areas flooded seasonally. When defining impacts, we superimposed the impact zones separately in the two environments. In this case, the species may be classified as impacted due to the loss of either fluvial or flooded environments. The criteria used for this classification are provided in the supplementary material (Table B1 in Appendix B).

The classification of the species endangered with extinction was based on the Brazilian red list (Machado et al., 2010) and the publications of the International Union for Conservation of Nature (IUCN, 2014, 2016). When the species was cited in both lists, we opted for the latter classification, which is more up to date. We included species that were classified at least as Near Threatened (NT) and, except when suggested specifically in the Research Meeting, we did not include Data Deficient (DD) species.

2.3. Impact zones

The type of impact that a dam may cause to a species will depend on its ecological characteristics. In the present study, we considered three distinct impact zones for each reservoir: (1) the complete isolation of all the stretches of river upstream from the dam (relevant to migratory species and species with an ample distribution), (2) free-flow impact zone (medium-range migratory species not affected directly by the dam, but when the stretch of free river is less than 100 km long). In previous work (Barthem & Gouldind, 2007) set as 100 km the minimum os stretches as requirement of species to define them as migratory and (3) the impact zone of the reservoir itself, which is relevant to non-migratory species (e.g., fish that inhabit areas of rapids).. The area of the reservoir itself was denominated “reservoir impact zone”, and we determined the overlap of these zones with almost all the targets on the list because the area of the reservoir converts the terrestrial environment into an aquatic one, as well as converting lotic habitats into lentic ones. The exceptions were targets, such as migratory species, that are not impacted by the reservoir itself, but rather, by the interruption of the connectivity of the aquatic environment. For the widely-distributed migratory species and some geographic features, such as connection to important downstream resources, the category “upstream impact zone” was created. In this zone, all the stretches of river upstream from the dam were considered to have been impacted. The impact associated with this zone was the loss of connectivity for the targets that depend on this link between the river upstream from the dam and other sub-basins or the ocean. This lost connectivity is minimized in locals where some mechanism of fish transposition (p.e. ladder, elevator) is placed, but the mechanism far from be efficient in

Amazon rivers for fishes. Beyond this, many targets analyzed here are mammal (p.e. dolphins) or reptiles (e.g. turtles) that even have some mechanism idealized. One another type of impact occur on many aquatic species of medium-range migrants and do not range outside the sub-basin or as far as the ocean, but may be affected if the stretch of free river between dams is restrictively short (Agostinho et al., 2004; Barthem and Goulding, 2007). A third zone – free-flow impact zone – was created to include those cases in which the construction of dams has left stretches of free river of less than 100 km.

Impact zones were also defined according to the stage of construction of the project. Each of the three impact zones were divided between existing dams or dams under construction, those that are still at the planning stage, and rivers that are still being inventoried. The latter rivers were not considered to be impacted because the location of the dam has yet to be defined. On the other hand, it is also impossible to guarantee that these areas will be preserved. This zone was considered as an area of uncertainty. The components of the biodiversity impacted by the existing or planned dams by more than 30% were considered to be at risk. In this case, understanding their distribution throughout the basin is an important factor for their conservation. In the case of these components only, we measured the amount of the occupied area present in the rivers under inventory. Threatened biodiversity (more than 30% of the area occupied impacted by existing or planned dams) may suffer a greater amount of degradation if it is present in rivers being inventoried. The evaluation of this uncertainty allows us to determine whether this degradation is complete or may increase in the future. Maps of all the impact zones plotted in this study are available in the supplementary material (maps A1–A12 in Appendix A). Below, we describe the steps followed in the development of the three impact zones for each dam. These steps are detailed in Appendix C.

2.3.1. Definition of Impact Zones

2.3.1.1. Existing and planned reservoirs

Vectorial maps of some of the dams are available on the site of the Brazilian National Agency for Electrical Energy, ANEEL (<http://sigel.aneel.gov.br/sigel.html>). In some cases, the only information available is the location of the site, the size of the area flooded by the reservoir, and the upstream and downstream heights of the dam. In the few cases where even these data were lacking, we plotted the reservoir based on images obtained from Google Earth and other internet sources. Based on these data, the reservoir was plotted following the sequence: (i) the geographic location of the dam was projected to the nearest point of the river (<http://www.ana.gov.br/bibliotecavirtual/solicitacaoBaseDados.asp>), (ii) based on this projection, the maximum upstream length of the reservoir was defined and a polygon was created defining the maximum area of the reservoir, (iii) this polygon was used as a filter to define the area of the topological data to be used in the polygon formats used to profile the topographic data (<http://srtm.usgs.gov/index.php>), (iv) in this layer of topology raster, we selected all the pixels with a height equal to that of the downstream point of the dam (the lowest possible value for the dam), (v) this process was repeated progressively in steps of 1 m until the area was equal to or greater than that of the reservoir.

2.3.1.2. Areas of uncertainty in rivers under inventory

In the case of the rivers still being inventoried, the exact location of the dams has yet to be defined. In this case, we defined the whole area within which the dam may potentially be constructed as a zone of uncertainty. For higher order (2) rivers, a 1-km buffer was established on each margin, with a 500-m buffer being established in the case of third order rivers, 200 m for fourth order rivers, 100 m for fifth order rivers, and 50 m for sixth order rivers.

The upstream impact zone was defined as all the stretches of river upstream from the dam, including the area of the reservoir itself, were defined as being affected by the dam, and were considered to be the upstream impact zone of each reservoir. The free-flow impact zone was created to include the free (without dams) stretches of river that extend for less than 100 km, although the exact distance depends on the order of the river under consideration. If the component of the biodiversity is found only in second-order rivers, it would be affected by dams located at a distance of less than 100 km from one another. However, within this same stretch of second-order river, of less than 100 km, species that inhabit tributaries of lower orders may be able to access these areas (Fig. C.1, in Appendix C). In this case, different areas of habitat may be found between dams, depending on the order of the river being considered, so impact zones of less than 100 km were created for second-, third-, and fifth-order rivers. No biodiversity elements were specific to fourth-order rivers.

2.4. Overlap of targets with impact zones and the list of selected targets

To define the impacts suffered by the potential targets, layers representing appropriate zones of impact (fig. 2) were superimposed over those of the targets (Table B1 in Appendix B). When the impact zones overlapped more than 30%, but less than 50% with the area occupied by a target, the target was considered to be of low risk. When the impact zones overlapped more than 50%, but less than 70% with the area occupied by a target, the target was considered to be of medium risk. Targets for which more than 70% of their area of occurrence overlapped with impact zones were considered to be high risk, while an overlap of less than 30% was considered to be no risk. All the targets with an overlap of over 30% were considered to be selected targets, that is, targets that should be considered in the planning of hydroelectric projects in the Amazon.

The potential targets were not exclusive to a given category or division of the sub-basin. For example, *B. rousseauxii* was included in the migratory-species and commercial-species categories. In addition, the affected area was calculated for the Amazon hydrographic region as a whole and for each of the sub-basins. In the specific case of *B. rousseauxii*, in addition to being included in two potential targets (commercial and migratory), each category was considered to be a target in each sub-basin and also in the Amazon basin as a whole (Table A.3 in Appendix A).

3. Results

Initially, we compiled a list of 335 geographic features and species as potential targets. We excluded 48 of these potential targets because their extent of occurrence did not overlap with any of the impact zones. One was excluded because we couldn't set geographic representation for it, that was the concept of native species. It is a too board concept and was presumed to be satisfy by using all another concepts. The rest of 286 targets were 134 aquatics, 108 terrestrials and 44 need both (e. g. *Blastocerus dichotomus*). The distribution considered for calculation of remains area of thesetargets were their area of occupancy. However it was divided by subbasin and by type of impact zones, when were needed. For example, the turtle *Podocnemis expansa* were identified in 4 sub-basin plus the whole area (Amazon scale) and were overlap with two type of impact zone (reservoir and upstream zone). Then, this specie were analyzed as 10 targets. This combination between target and sub-basin and type of impact resulted in the identification of 1398 potential targets, with 758 endangered species, 210 Amazon commercial species, 267 regional commercial species, 41 migratory species, 98 geographic features, and 24 charismatic species (Table B2 in Appendix B). However, not all the potential targets have sufficient data for analysis, and we eliminated 34 that had less than 70% of their

surrogates mapped within their area of occurrence. The 1364 remaining candidates were superimposed on the impact zones that may affect them and classified as low, medium or high risk if they should lose >30 and ≤50, >50 and ≤70, or >70% of their original area of occurrence, respectively. Considering these criteria, we analyzed 341 targets for the Amazon Basin as a whole, 265 in the Tapajós sub-basin, 217 in the Xingu, 265 in the Madeira, 126 in the North Atlantic sub-basin, and 192 in the Negro River (Table B2 in Appendix B). The existing or planned dams affected 100 targets. The predominant impact was the loss of area upstream (61 targets), followed by the targets impacted by the reservoirs themselves (26 targets) and then the free-flow zone, with 13 targets (Table B2). The other notable results is that all targets are aquatic associated and 8 of them are mix that were classified as aquatic and terrestrial (p.e. Islands) and the remains 92 were exclusive of aquatic system.

Figure 1.

Table 1.

3.1 Targets selected

3.1.1. Commercial fish species (Amazon)

Two species (*Brachyplatystoma rouseauxii* - dourada and *Brachyplatystoma vailantii* - piramutaba) in this group have suffered medium impact (50–70% of its area of occurrence affected), and one (*Goslinia platynema* - babão), low levels of impact (30–50%). All three are found in the Madeira River basin, and their areas of occurrence were affected by more than 30%. The complete list of the area lost by each target is presented in the supplementary material (Table A3 in Appendix A).

3.1.2. Endangered species

We identified 12 endangered species allocated to 20 targets in the basin, sub-basins, and impact zones. Thirteen of these targets are found in the Tapajós sub-basin. Some of the species in this sub-basin, even those with an ample distribution, such as *Podocnemis expansa*, *Podocnemis unifilis*, *Trichechus inunguis* and some bivalves (mollusks) were affected by both the upstream impact zone and the area of the reservoir itself.

3.1.3. Migratory fish

The species in this group overlapped only with the upstream impact zone, and nine species distributed in 22 targets may lose more than 50%, but less than 70%, of their area of occurrence (medium risk).

3.1.4. Regional commercial fish species

The areas in which regional commercial fish species are found will be impacted primarily by the area flooded by the planned dams. Eight species (20 targets) should suffer some degree of threat. Fourteen of the targets were found in the Tapajós sub-basin, and all the others in the Madeira sub-basin. A number of the targets in this group overlap with the free-flow impact zones, with 11 targets being associated with this type of impact, and a further nine being associated with the impact in the area of the reservoir.

3.1.5. Geographic features

This group has three targets that are threatened throughout the Brazilian Amazon basin As Rocky environments, free rivers. The third was fish eggs and larvae drifting, that couldn't measured directly, then we use as surrogate rivers of first to third order. All these three targets will suffer impact of over 30% throughout the basin when superimposed on the upstream impact zones. The Amazon region has a total of 728,600 km of river, of which, 171,300 km have been interrupted by existing dams or those under construction. A further

153,200 km would be disconnected from the hydrographic network by 2030 if all the planned dams are built. This means that 44.5% of Amazonian rivers would be isolated from the rest of the basin and the ocean. The zone of uncertainty (rivers still under inventory) accounts for a further 123,600 km of rivers. The impact of these new dams will be greatest in the Tapajós sub-basin. At the present time, 73,500 km (73.3%) of the 100,300 km of river found in this basin are free, although only 5.23% will remain in this condition if all the dams planned for this basin are built (Table S2). This potential conservation scenario can already be observed in the Xingu basin. Following the construction of the Belo Monte dam, 94.6% of the rivers of the Xingu basin have been isolated. In the specific case of the rocky environments, 24% of the total area has already been isolated by hydroelectric dams, and this proportion will increase to 55% if all the planned projects are built. A further 37% of these features are found in zones of uncertainty in rivers still being inventoried, which could result in a final total loss of 92%.

3.1.6. Charismatic species

The river dolphin, *Sotalia fluviatilis*, was the principal charismatic species affected primarily by the hydroelectric projects of the Tapajós sub-basin. This charismatic species overlapped the upstream impact zones and the reservoirs. On the Tapajós, *S. fluviatilis* loses 30% of its area of occurrence solely through overlap with the reservoirs. The upstream impact zone will provoke a discontinuity of 46% in the area of occurrence of the species.

4. Discussion

A number of different types of targets have been used to study environmental impacts and plan hydroelectric projects in the Amazon region. The culture of the institution, the academic training of the assessors, and legal considerations may all influence the selection of targets. In many cases, the results of these studies have been widely criticized in the scientific literature. One of the reasons for this criticism is the use of an inadequate number of targets for the reliable assessment of impacts. All the targets used in the three sources of investigation (Research Meeting, Legislation and EIAs of dams in a region) are contemplated by the pertinent legislation, although only a few are affected strongly by hydroelectric dams.

The only legislation that exists in relation to mandatory targets (Ibama, 2007) is vague with regard to which targets should be considered, and how they should be used in the decision-making process. As the legislation refers to projects of all types, including airports, highways, and hydroelectric dams, the targets that should be monitored vary considerably. Even so, our assessment of the impacts of dams on the distribution of the targets indicates that all those affected by hydroelectric dams are aquatic (but see caveats below), which would not be the most appropriate targets for other types of project, such as wind farms or airports. The lack of reliable criteria for the selection of appropriate targets tends to obscure relevant aspects of the impact.

The focus on endangered species (IUCN and Brazilian Red List) may indicate that a project will have little impact on biodiversity, but this is because most of these species are terrestrial, and as the Amazon basin is a vast region with relatively well-conserved terrestrial environments, the loss of habitat for these targets will be relatively limited. The rare species category could not be assessed here because it is difficult to classify distributions of most rare species reliably, especially in poorly-known regions, such as the Amazon basin. The concept of endemism also requires a reliable understanding of the distribution of the species involved, which is, once again, problematic in the case of the Amazon region. Some species were classified as endemics in the Research Meeting, however, and only these species were considered to be endemic in the present study.

Our findings are partly corroborated by the Research Meeting (Lees et al., 2016). Rocky environments, beaches, floodplain lakes, islands, and migratory and regional commercial fishes were all listed in this meeting due to their relevance for the environmental decision-making process. The only reptiles considered by our analysis were the river turtles *Podocnemis expansa* and *Podocnemis unifilis*, and the only mammals the Amazonian manatee *Trichechus ininguis* and the river dolphin *Sotalia fluviatilis*. Since no terrestrial targets were identified in our assessment, no birds or terrestrial geographic features, except islands, were considered to be at risk. One other target identified in the Research Meeting, which was also assessed here, was the drift of fish eggs and larvae (evaluated by first to third order rivers as surrogates for pathways). As for connectivity, this target was the most impacted throughout the whole of the Amazon basin, and for all the sub-basins with the exception of the Negro River.

The discontinuity of environments was the greatest threat identified in the present study. Overall, 44.8% of the geographic features, and the migratory and widely-distributed species that overlapped with the upstream impact zone were affected. The widely-distributed species that will be isolated may suffer local extirpation, where the local population is too small to be viable over the long term. However, aquatic migratory species may suffer irreversible impacts. By disconnecting the spawning grounds from other areas visited by the organism during its life cycle, the population will decline rapidly in subsequent years like in case of salmon in North America (Kuby et al., 2005). Despite the investments in attempts to recuperate salmon populations, including the removing of dams, many river basins have yet to recover their original population levels. This problem is exacerbated in tropical environments by the fact that fish ladders, the principal strategy used to mitigate the impact caused by dams on migratory species, have yet to be proven effective (Agostinho et al., 2002). For example,

In recent years, the increase in the production of hydroelectric energy has provoked a growing preoccupation with regard to the cumulative impact caused by dams (Chen et al., 2011). One of the principal impacts on biodiversity is habitat loss. When the species is distributed over a wide area, dams separated by thousands of kilometers may have cumulative impacts on a species, especially in the case of migratory fish. For example, the construction of the Santo Antônio and Jirau dams on the Madeira River led to the loss of the local spawning grounds of the species *Goslinia platynema* (babão), which may lose a second spawning ground through the installation of the Bem Querer dam, earmarked for construction on the Branco River, 2000 km from the Madeira (maps a2 in Appendix A and maps b1 in Appendix B). The impacts suffered by these species may not only surpass the limits of the sub-basins, but may extend as far as neighboring countries, so research and protection measures should be implemented on a continental scale, in order to avoid the extinction of species caused by the building of dams.

The existing hydroelectric dams in the Amazon region have reduced the connectivity of its aquatic habitats considerably, and the free-river target analyzed here would decrease progressively with the installation of every new dam. In the 1970s and 1980s, the dams constructed in the Amazon basin inundated vast areas of forest, such as the Balbina dam, which has a reservoir of 3,129 km² (Benchimol and Peres, 2015). This approach was criticized widely by environmentalists and ecologists (Palmerim et al., 2014) due to its impacts on the local biodiversity. The run-of-river model of hydroelectric scheme widely proposed currently, which uses the river current to generate electricity, does not demand the accumulation of large quantities of water, and requires smaller reservoirs, although it does require a large flow of water. This means that the middle and lower reaches of a river are more appropriate for this type of hydroelectric scheme. While this approach results in a reduction in the size of the reservoirs – the Belo Monte reservoir has an area of only 516 km², for example, and Santo Antônio is only 214 km² – locating the dam in the lower and middle reaches of the basin results in an increase in the discontinuity of the river. In the

Xingu sub-basin, 94% of the rivers will become isolated from the rest of the Amazon river system by the recently-built Belo Monte hydroelectric scheme, and the same trend can be observed in the Tapajós sub-basin, where up to 94% of the rivers will be disconnected from the rest of the Amazon basin if all the planned dams are built.

We measured connectivity by the target “stretches of free river”. This is a reasonably precise measure that can be derived accurately from satellite images. However, it is not clear exactly which biological species it represents. We used this indicator because it is not possible to define the spatial distribution of the species that require this connection with other basins. In this case, while this parameter may contribute to decision-making, it is hampered by the lack of a direct association with particular biological species. Except for the stretches of free river themselves and some geographic features (rocky environments, forests, islands), the greatest challenge for the planning of dams is the lack of knowledge on the distribution of species. Decisions on the configuration of a project must be based on complementarity, and reliable information on the area occupied by the species is critical here. Where this information is lacking, the use of surrogates must be validated so that they can be applied over a wider area. The lack of information on the area occupied by species and their relationship with the surrogates is a source of uncertainty that can only be resolved by the compilation and collection of more data throughout the whole Amazon region.

If, on the one hand, the lack of accurate data on biological targets may hamper planning in the basin, the lack of information on where future hydroelectric projects may be installed also impairs adequate planning. The rivers under inventory are vast areas of uncertainty that hamper decision-making in the same basin, as well as those of other basins. We identified a number of environments that would be affected in the different basins (e. g. stretches of free river, beaches or rocky environments). When a hydroelectric dam is proposed in a basin, it would be advisable to define other basins or stretches of river that should also be preserved, although this is impossible in the case of rivers that are still being inventoried, because it is not possible to designate areas for protection.

According to the known plans of the energy sector, the Tapajós River basin, which currently produces only 10.2% hydroelectricity provided by the whole Amazon basin, will eventually produce 77% of the total. We identified 15 targets that will be affected by the 100 km impact zone, most of which are from the Tapajós basin. This type of habitat restriction, with little free river being left between dams, is common in river basins with a high degree of anthropogenic impact, such as the Paraná basin in southern Brazil (Agostinho et al., 2007). The large number of hydroelectric dams located on the major rivers not only affects their connectivity with the rest of the system, but also the local biodiversity, such as the regional commercial fish species. Migratory species, even medium-range ones, tend to have a higher commercial value, and the impact projected for the whole of the Tapajós sub-basin will have major repercussions for the human communities found in this region. Rocky areas are another sensitive environment, which is a direct surrogate of the fish species restricted to this type of habitat. These species tend to have restricted distributions (e.g., *Ossobutus xinguensis*, which is found only in the Xingu basin), and the degradation of these environments may easily result in the extinction of associated species. In the Tapajós sub-basin, 49% of these environments will be submerged in reservoirs, and a detailed study of the distribution of the rock-associated fish species of the basin would be necessary to understand what would be complementary areas to be preserved.

In the present study, we investigated the targets that are typically used in Environmental Impact Studies and determined that many of these parameters are inappropriate for this evaluation process. We suggest the development of specific legislation for hydroelectric projects, given that many targets, in particular terrestrial ones, are generally inappropriate in these cases. In fact, this approach should adopt specific criteria appropriate to each

region, given that the pattern of degradation is likely to vary considerably among basins. Based on our studies so far, we recommend that, in the case of hydroelectric dams, studies of environmental impact should focus on aquatic targets, and that connectivity, based on a measure of free river, be used as the principal environmental indicator for planning. However, we only considered the targets that have been proposed so far, which were identified in relation to the direct effects of dams. Recent studies have shown that road building is one of the greatest threats to biodiversity (Ibisch et al. 2016). Future studies should also take into account collateral effects, such as roads associated with dam building and access to presently isolated areas by boat travel. These may affect biodiversity, including terrestrial species, independent of the direct affects of the dams.

This study indicated o potential of to use targets to planning dams in a Amazon scale and its sub-basin. The result were completely dependent, like any other PSC work (refs), of targets used. In this point, we present two potential problems with the data used here. First, up to now didn't happen any workshop with the aim to indicate targets for whole amazon and for each one of sub-basin. Second, the model used to set area of occupancy (or the area used for make the calculations of area lost) was simple and potential more elaborated model for each target would change the area and consequently, the results. On example of this area the migratory fishes or sedentary fishes associated with rocky environments in river. We use just one target as rock environments. However, potentially, this target need be divided in many smaller one because they are different. We didn't have this information and so, here, we model as species of migration as most important one, what wouldn't be truth if was used more fishes associated to rock environments in each sub-basin.

Under the current Brazilian system, even when no dams are planned for a given river basin, there is no legal impediment to the proposal of new inventories for dams, even in the near future. This is, in fact, standard procedure, where the authorization of a major hydroelectric project is typically followed immediately by proposals of other, smaller projects. The unpredictability of these operations and the potential for the protection of environments greatly weakens effectiveness decision making on the installation of hydroelectric dams. In this context, one important step would be the creation of a free-river category of conservation unit as propose in other works (Jager et al., 2015) .

In the present study, we superimposed the targets typically used in the licensing of hydroelectric projects in the Amazon Hydrographic Region, and discovered that many of these targets, such as terrestrial species, should generally not be used to evaluate the impacts of these projects. However, some targets that are extremely relevant for decision-making, such as stream-dwelling fish and migratory species, have been insufficiently studied. Given this, we suggest the elaboration of specific legislation for the definition of targets for the environmental planning of hydroelectric projects in the Amazon Hydrographic Region. . Basin-wide studies of population dynamics in the Amazon region should provide important insights into the areas that would be most impacted by the construction of dams. In particular, we conclude that hydroelectric projects should be planned through the principle of complementarity, and that future inventories of areas with the potential for the installation of projects by the energy sector and government agencies should contemplate not only the specific dam sites, but also the definition of areas in which it will not be possible to establish hydroelectric dams in the future.

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Appendix

Appendix A Table A1 - List of dams. Metadata Maps - All the impact zones of the dams represented in the vector files.

Appendix B Table B1 - List of all features of biodiversity identified as potential targets. Table B1 - accessory - Full details for the field `surrogates_and_area_of_occupancy` in Table B1. Table B2 - List of all features of biodiversity identified as potential targets classified in their sub-basin and impact zone. Maps B1 - All the areas of occurrence of biodiversity features (`maps_b1.kml`)

Appendix C Methodological description of creation of impacts zones.

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Figures and Tables

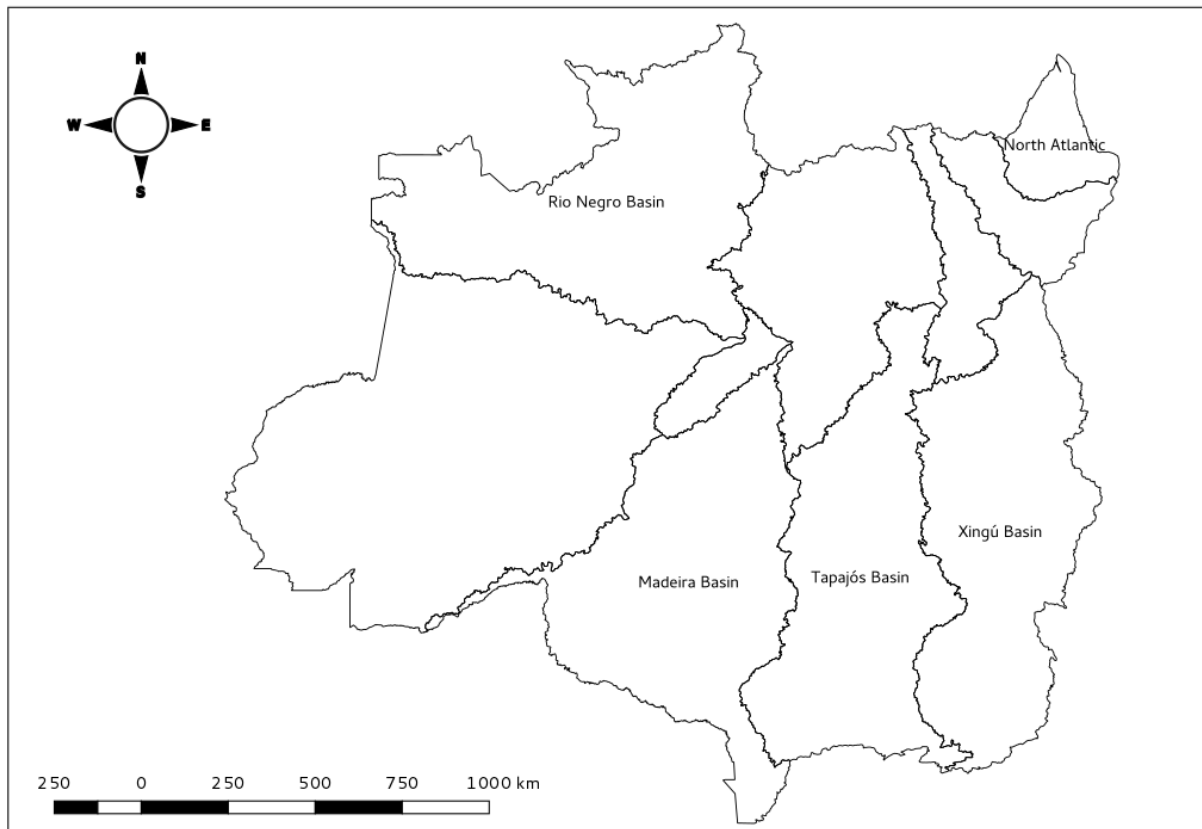


Figure 1. The division of the Amazon hydrographic region (CNRH 2013) in Brazil, showing the five sub-basins analyzed in the present study: Madeira (558,653 km²), Xingu (506,880 km²), Tapajós (492,255 km²), North Atlantic (82,722 km²) and Negro (579,076 km²).

Table 1. The number of targets impacted, arranged by the proximity of the impact (dam existing or planned) and by hydrographic basin (39 = North Atlantic, 42 = Xingu sub-basin, 44 = Tapajós sub-basin, 46 = Madeira sub-basin, 48 = Negro sub-basin, ALL = Amazon basin as a whole). The targets found in the “existing” column are also present in the “planned” column, albeit with a shift in the intensity of the impact. This is because a target that is low risk (30–50% of its area of occurrence affected) in an existing reservoir may be medium risk (50–70% impact) in the case of a dam that has yet to be built.

	basin	Built	Planned
LOW	39	4	2
	42	0	0
	44	0	20
	46	4	7
	48	1	2
	ALL	0	4
MEDIUM	39	0	3
	42	2	2
	44	0	10
	46	10	14
	48	0	0
	ALL	2	3
HIGH	39	0	2
	42	11	14
	44	0	16
	46	0	1
	48	0	0
	ALL	0	0

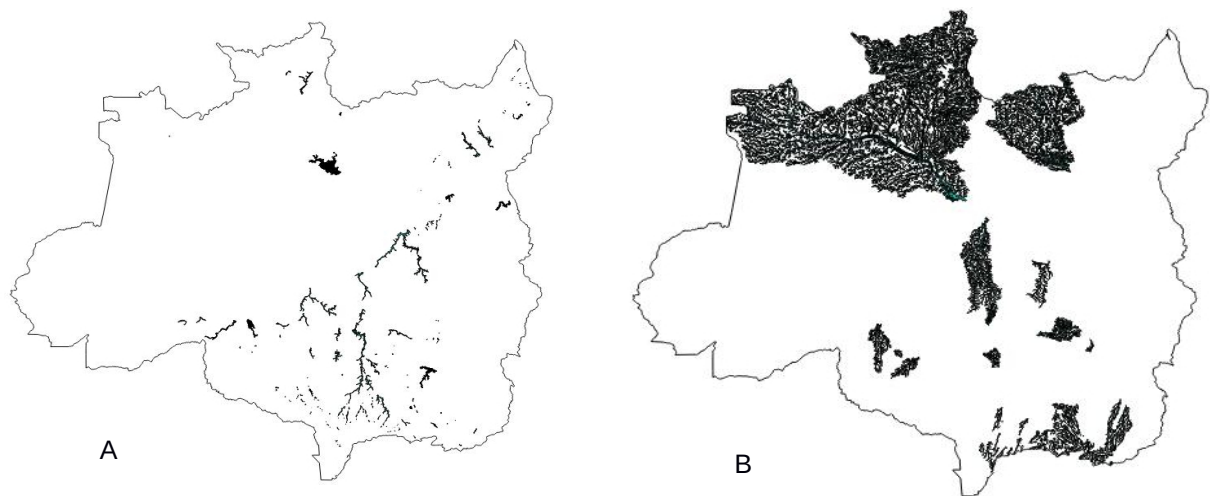


Figure 2. The layers that is overlapping with biodiversity features. In A) Spatial representation of dams under operation or in construction and planned dams and in B) of river under inventory.

Capítulo 3

Koblitz, R.V., Bergallo, H. G. & Magnusson, W. E. Produção de hidroeletricidade e preservação da biodiversidade na bacia do Tapajós são compatíveis? Ainda não submetida. Primeira submissão deverá ser para Plos One. **A Produção de hidroeletricidade e preservação da biodiversidade na bacia do Tapajós são compatíveis?**

Resumo

Boa parte do investimento do governo brasileiro na produção de energia hidroelétrica está direcionada para a Amazônia, mais especificamente na Bacia do rio Tapajós. A intervenção na bacia impactará principalmente a biodiversidade aquática, como decorrência da perda de área tanto pelo alagamento dos reservatórios, como pela pequena área restante entre os reservatórios e pela desconexão das regiões a montante com o restante da bacia e o estuário. No presente trabalho, procuramos identificar quais barragens (construídas e propostas) poderiam produzir energia com um menor impacto na biodiversidade. Encontramos que existe uma forte contradição entre a produção hidroelétrica e a preservação. Além disso, a seleção do tipo de alvo de conservação, se afetado pelo alagamento da área ou pela desconexão, influencia os resultados da análise de eficiência das barragens. Entretanto, independentemente dessa classificação, considerando somente a fauna aquática e não outros impactos como o efeito indireto da construção de uma barragem, p. e. o de aumento na malha viária, conjuntos de barragens menores foram mais eficientes em termos da relação entre a quantidade de energia produzida e a perda da biodiversidade, em todas os arranjos considerados como eficientes esse grupo apareceu.. Sugerimos que esse tipo de empreendimento possa ser foco de maiores investigações do setor elétrico e ambiental.

Introdução

Está previsto um forte investimento do governo brasileiro (Ministério de Minas e Energia - MME, Agência Nacional de Energia Elétrica - ANEEL) e empreiteiras do setor elétrico na bacia do Tapajós. O conjunto proposto de barragens em cascata começa a 330 quilômetros da foz no Rio Amazonas e se estende a montante pelo restante dos 1478 quilômetros dos rios Tapajós e Juruena, e pelos rios Teles Pires e Jamaxim, sendo previstos poucos trechos de rios livres nesses rios principais. O objetivo até 2030 é adicionar 41 hidrelétricas (UHES) e 72 pequenas centrais hidrelétricas (PCHs), e 48 CGHs (centrais de geração hidrelétrica), totalizando 161 empreendimentos entre e com capacidade instalada de 29,331 MW. A decisão do arranjo (qual barragem construir e aonde) é tomada sem uma consulta a área da conservação da biodiversidade. No processo regular de licenciamento, apenas as barragens, individualmente, é que são submetidas a apreciação dos órgãos ambientais para que eles corroborem ou não aquele

empreendimento. Até a presente data, as tentativas de planejamento de bacias não tem tido muito sucesso. Por exemplo, Na sub-bacia do Tapajós foi feita uma tentativa de planejamento integrado e conseguiu-se definir os alvos relevantes(MMA & MME, 2011) , porém não alcançou o resultado esperado de fazer o planejamento de barragens na bacia. Na ausência de algum plano que incorpore a opinião de pesquisadores e especialistas em biodiversidade, constata-se uma lacuna entre o conhecimento científico sobre biodiversidade e a tomada de decisão sobre a construção de barragens. Nesse trabalho, avaliamos o plano do governo e do setor elétrico, com o objetivo de identificar se, adicionando o objetivo da preservação da biodiversidade, o atual plano pode ser considerado eficiente. Além disso investigamos se existem arranjos de barragens (quais grupos de barragens devem ser colocadas) que possam proporcionar as maiores quantidades de capacidade instalada de energia com a mínima perda de biodiversidade quando comparados a outros arranjos na mesma sub-bacia.

A exploração prevista na sub-bacia do Tapajós será veloz e com consequências difíceis de prever. O aprendizado com exploração de barragens na Amazônia tem sido lento. Ainda sobre a barragem de Balbina (1988), apenas em 2013 foi possível concluir sobre uma mudança significativa no comportamento de uma espécie na região. A sub bacia do Tapajós não é diferente do resto da bacia Amazônica e também pouco se conhece sobre a biodiversidade da região. A falta de conhecimento sobre a biodiversidade dificulta o planejamento da bacia.

Como a construção de uma barragem e a proteção da biodiversidade dependem do mesmo recurso, (área), elas são atividades competitivas. O aumento da produção de energia tende a gerar um aumento na perda de biodiversidade e de outro modo o aumento da proteção da biodiversidade tende a diminuir a quantidade de energia instalada na bacia. Uma ferramenta útil para a ajuda entre recursos competitivos é a fronteira de Pareto (Ziv et al., 2012), que delimita os melhores pontos entre dois recursos. Todos os pontos situados na fronteira de Pareto podem ser considerados como eficientes para o sistema (mais detalhes na seção Métodos). Eventualmente, encontra-se em alguns arranjos um aumento da produção de energia maior do que a perda proporcional de biodiversidade (em relação aos outros arranjos testados) e então considera-se tais pontos como mais eficientes do sistema.

O impacto que um arranjo de barragens provoca no meio ambiente pode ser mais complexo do que a simples soma dos impactos de cada uma separadamente, porque a interação entre elas influencia fortemente no impacto. Por exemplo, se uma barragem é instalada na parte baixa da bacia, uma espécie migratória que perde o acesso à área a

montante (como área de reprodução, por exemplo) será pouco influenciada por outras barragens situadas a montante dessa. Nesse exemplo onde é considerado apenas um elemento de biodiversidade, o impacto das duas juntas é igual a o impacto de apenas uma delas. Portanto, a medida de impacto de uma barragem é relativa às escolhas de quais outras barragens serão construídas.

Para fazer a comparação entre a perda da biodiversidade e a produção de hidroeletricidade, neste trabalho usamos os alvos de biodiversidade que foram escolhidos para toda a Bacia Amazônica no capítulo 2 desta tese, incluindo a bacia do Tapajós. Todos os alvos selecionados foram espécies ou ambientes aquáticos, que podem ser afetados de formas diferentes por uma mesma hidrelétrica. Por exemplo, espécies migradoras são afetadas por barragens situadas a milhares de quilômetros de distância, isso porque se tal barragem impedir o acesso ao local de reprodução, a espécie perde esse ambiente para toda a população. Uma espécie deste tipo que ocorre na bacia do Tapajós é *Brachyplatystoma rousseauxii* (Cella-Ribeiro et al., 2015). Para esses elementos da biodiversidade, nós definimos uma zona de impacto de desconexão a montante como aquela que impacta toda a região acima de uma barragem. Outros elementos da biodiversidade são basicamente afetados pela área do reservatório em si, como é o caso de peixes de pedrais, que podem sofrer pouca influência direta de um outro reservatório situado a poucos quilômetros de distância. Para elementos da biodiversidade com esta característica, foi criada uma zona de impacto delimitada espacialmente pela área do próprio reservatório. O terceiro grupo de alvos que estabelecemos foram aqueles que são afetados pela pequena extensão de trechos de rios livres (que restam sem barragens). Presumimos que essas espécies não poderiam permanecer se a extensão de trechos de rio livre entre barragens for menor do que 100 (cem) quilômetros. Alguns dos principais elementos da biodiversidade impactados por esse tipo de arranjo são peixes migradores de média distância e a medida de 100 quilômetros foi usada por indicar um limite para migração de algumas dessas espécies (Barthem & Goulding, 2007), denominada zona de impacto rio-livre.

Uma barragem pode causar diversos impactos sociais e ambientais. Mesmo com impactos profundos na sociedade e na biodiversidade, a demanda de energia continua aumentando no Brasil e aqui tentamos encontrar uma solução melhor de instalação potencial hidroelétrica a partir da proposição do governo. Entretanto, não iremos avaliar as questões sociais que potencialmente são os maiores, mas nos restringiremos apenas a biodiversidade. Nesse trabalho, simulamos os possíveis arranjos de barragens na bacia do Tapajós e identificamos seu potencial de energia elétrica instalada. Para cada arranjo,

mensuramos seu impacto sobre a biodiversidade a partir da quantidade de área perdida (a representação geográfica da biodiversidade é apresentada no Apêndice, nos mapas S1). A partir desses critérios, produção elétrica e intensidade de impacto na biodiversidade classificamos os melhores arranjos identificando as barragens que estavam presentes.

Métodos

Área de estudo

A bacia do Tapajós possui quatro grandes rios. Os rios Juruena e Teles Pires começam a se formar ao sul na parte alta da bacia e em sua porção média se juntam na porção oeste da bacia. Essa geografia da região faz com que a água de toda a parte alta e média da bacia (70% do total) seja drenada para um único grande rio, o Tapajós (Fig. 1B), que mais ao norte conflui com o outro grande rio da bacia, o Jamanxim. O início da instalação das grandes hidrelétricas começou recentemente com a construção das barragens de Teles Pires e São Manuel (Fig. 1A e 1B).

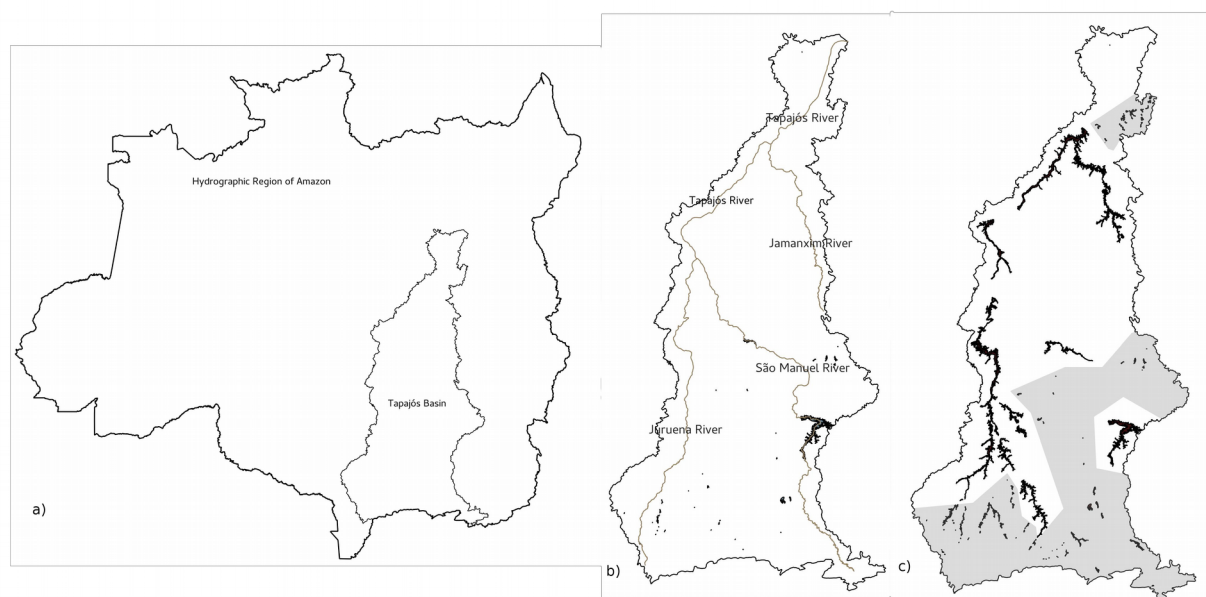


Fig 1 a) A sub-bacia do rio Tapajós na região hidrográfica da Amazônia brasileira. b) Principais rios da sub-bacia do Tapajós, mostrando as barragens já construídas. c) Proposta do governo brasileiro para o uso da sub-bacia para fins de produção de hidroeletricidade, com todas as barragens planejadas até 2030. A zona cinza engloba

todas as UHES, PCHS e CGHs, que juntas formaram o grupo das menores barragens e foram usadas como grupo nas modelagens feitas aqui.

Alvos de biodiversidade

Os alvos de biodiversidade utilizados foram previamente selecionados porque perderiam pelo menos 30% de toda a sua área de ocupação, caso todas as hidrelétricas da bacia fossem construídas. Esse grupo de alvos é composto por 24 espécies e 5 ambientes que foram escolhidos no capítulo 2 dessa tese estão espacializados nos maps_S1, maps_S2 e maps_S3 do material suplementar. . Um mesmo alvo poderia ser utilizado em mais de uma zona de impacto, como foi o caso do peixe-boi *Trichechus inunguis*, que foi considerado tanto afetado pela área do reservatório quanto pela desconexão a montante. Foram utilizados 17 alvos que poderiam ser afetados pela zona de impacto de desconexão a montante, 22 afetados diretamente pela área do reservatório, e 7 pela perda de trechos de rio livre menores que 100 km (n= 46 alvos).

Foi atribuído um critério espacial para a definir se um alvo foi afetado ou não por determinado arranjo. Se o alvo perdia mais que 30 % de sua área por causa das hidrelétricas ele era considerado como atingido. Utilizamos também os critérios de maior risco para a biodiversidade de 50 e 70% da área perdida para se indicar que o alvo teria sido afetado.

Zonas de impacto

Os alvos de biodiversidade podem ser impactados de forma diferente por uma mesma hidrelétrica. Identificamos então três zonas de impacto que uma hidrelétrica pode provocar. A zona de impacto a montante se refere a toda área a montante de uma barragem que ficará desconectada do restante da bacia, ou sem acesso ao estuário. A essa zona de impacto foram atribuídos alvos como espécies migratórias ou de ampla distribuição, que perderiam uma proporção pequena da sua distribuição pela área de um reservatório, mas que precisariam de acesso aos ambientes a montante ou jusante das barragens.

A bacia do Tapajós é dividida em sub-bacias de menores dimensões (de ordens superiores) denominadas de ottobacias. Neste trabalho, usamos sub-bacias de sexta ordem definidas na classificação de Otto Pfafstetter, no qual o rio que deságua no oceano (p.e. Rio Amazonas) é definido como bacia de menor nível (1), aos seus tributários diretos como nível 2, e assim sucessivamente (Verdun & Verdun, 1990)). Para atribuir a zona de impacto a montante de uma barragem, foram incluídas todas as ottobacias que estavam

as barragens e a montante delas . Em cada ottobacia, foi mensurada a quantidade de área dos alvos de biodiversidade que estavam presentes. Para calcular a zona de impacto a montante de um arranjo de barragens, todas as ottobacias presentes nas barragens e a montante dela foram somadas, sendo permitido que uma ottobacia pudesse ser contada apenas uma vez.

A quantidade de área de cada alvo de biodiversidade foi calculada para cada um dos reservatórios. A zona de impacto do reservatório de cada arranjo foi mensurada como a soma das áreas dos alvos presentes nos reservatórios do arranjo. Informações sobre algumas dessas barragens estavam disponibilizadas diretamente pela Aneel (Sigel, 2014). Entretanto, o formato do reservatório das demais barragens foi estimado a partir das informações da sua área disponíveis no site da Aneel (Detalhes no capítulo 2 desta tese)

Para calcular a zona de impacto rio-livre nós inicialmente selecionamos todas as barragens que interceptavam a área de ocupação do alvo. Apenas para essas barragens, nós identificamos quais configurações que geravam trechos de rio menores que 100 km para aquele alvo. Por exemplo, na fig 2 apresentamos um alvo, ilhas, que está ficando em um trecho menor que 100 km caso a configuração das barragens seja a presença das Uhes Cachoeira dos Patos e Cachoeira do Cai, mas com a ausência da Uhe de Jamanxim. Com essa configuração de barragens (as duas presentes e necessariamente a última ausente), haveria a quantificação da perda dessas áreas para as ilhas, mas a mesma configuração não afeta outros alvos de biodiversidade por exemplo, como o surubim (*Pseudoplatystoma* spp.) ou praias. Foram identificados quais as configurações de barragens impactavam cada um dos sete alvos considerados susceptíveis a esse impacto (Fig. 2).

Quando um arranjo era testado, significa dizer que um grupo de barragens foram selecionadas para compor esse arranjo, era medido a quantidade de energia instalada daquele arranjo e o quanto de biodiversidade ele perdia. A quantidade de energia que seria instalada para aquele grupo de barragens, era apenas a soma do potencial hidrelétrico de cada uma delas. A quantidade de biodiversidade perdida era o número de alvos que, se esse grupo de hidrelétricas fossem instalados, perderia mais do que 30% (ou 50 e 70% nos outros dois cenários) de sua área de ocupação

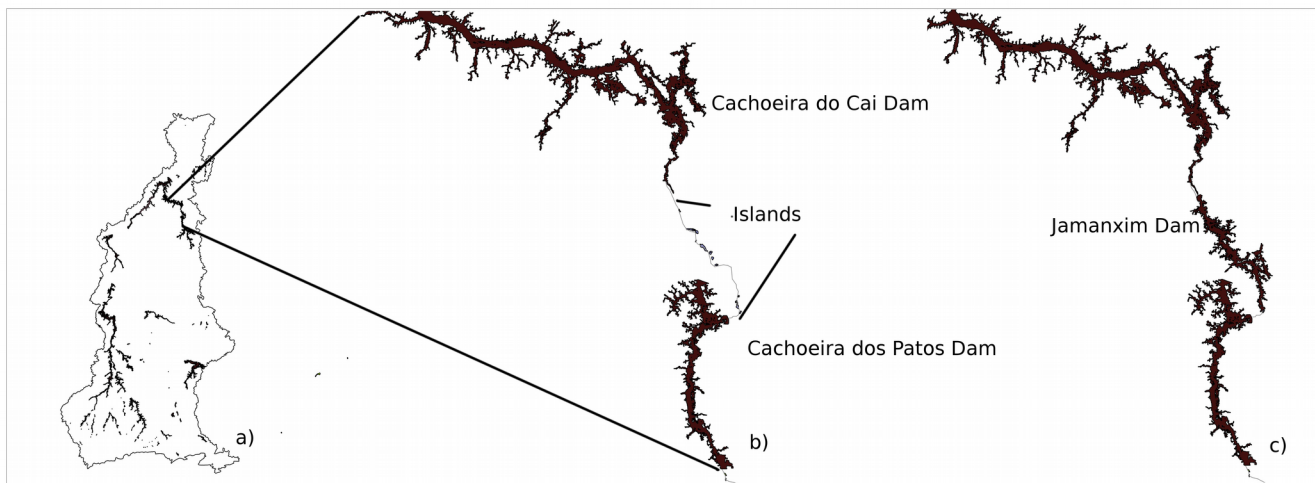


Figura 2. Exemplo de uma combinação de barragens a) na sub-bacia do Tapajós, que criou uma região de rio livre menor que 100 km na sub-bacia do rio Jamanxim. A parte b) mostra uma configuração de hidrelétricas com a presença das UHEs Cachoeira dos Patos e Cachoeira do Caí e sem a presença da UHE Jamanxim. Nos arranjos que tivessem essa configuração essas ilhas ficariam restritas a um ambiente com menos de 100 quilômetros e portanto estariam impactadas pela zona de impacto de trechos livres menores que 100 km . Entretanto, se o arranjo incluísse a UHE Jamanxim c), a mesma região não seria afetada pelo fato de ficar com menos de 100 km, porque toda a extensão estaria impactada. Portanto, o impacto dessas mesmas ilhas, não seria atribuído a zona de impacto de rios-livre menores que 100km, mas sim a zona de impacto do reservatório que é simplesmente a área de reservatório.

Iterações

Foram testados 33.554.431 potenciais arranjos de barragens, a partir da iteração entre as 24 maiores barragens mais um grupo de diversas barragens de menor porte juntas. Esse último grupo com as menores barragens foi criado para que o número de iterações pudesse ser feito. Fazer a combinação de 161 barragens seria impraticável computacionalmente, portanto, juntamos todas as barragens com as menores quantidades de energia potencial (23 hidrelétricas de pequeno porte, 100 pequenas centrais hidrelétricas, e 14 centrais de geração hidrelétricas) e foi definido apenas um grupo com essas reunidas ($n= 25$; Tabela S2, Maps S2 e Fig. 1C). Para cada potencial arranjo foi calculada a quantidade de megawatts que seria instalada (soma dos potenciais hidrelétricos de cada barragem) e a perda de biodiversidade que o arranjo pode provocar. A medida de biodiversidade foi calculada através da área perdida para cada um dos alvos. Para atribuir o valor de perda de biodiversidade para um arranjo somamos a quantidade de área dos alvos de biodiversidade presentes na zona de impacto do arranjo e, caso ela ultrapassasse a tolerância (30, 50 ou 70%) de perda de área, o arranjo impediria que o

alvo alcançasse sua meta. O número de alvos que não alcançavam a meta era o valor de perda de biodiversidade que atribuímos ao arranjo.

Todos os pontos dos potenciais arranjos de barragens foram plotados em um gráfico de produção de hidroeletricidade no eixo das abscissas (X) e impacto na biodiversidade no eixo das ordenadas (Y). Para cada quantidade de biodiversidade impactada eram encontrados diversos arranjos. A fronteira de Pareto foi definida como os pontos que estavam na extremidade direita, mas desde que a quantidade de energia produzida pelo arranjo com aquela quantidade de perda de biodiversidade fosse maior do que os arranjos que impactavam menos a biodiversidade. Por exemplo, na zona de impacto do reservatório com 30% nenhum arranjo que provocava a perda de 8 elementos da biodiversidade produzia mais energia do que o mais produtivo dos arranjos que provocavam a perda de 7 elementos, portanto nenhum arranjo que perdia 8 elementos foi considerado como eficiente (Fig. 3, Zona de impacto do Reservatório com 30% de tolerância). A partir dos pontos presentes na curva de Pareto, visualmente foram identificados os mais eficientes (Fig. 3). Esses eram aqueles que tiveram a maior produção de hidroeletricidade com uma menor perda de biodiversidade em relação aos outros pontos do gráfico.

Apenas para esses pontos relativamente mais eficientes, foram listadas as barragens que estavam presentes no potencial arranjo (Tabela S2) e, quando existia mais de um ponto eficiente para um determinado limite de tolerância (30,50 ou 70%) calculamos a frequência das barragens nesses pontos mais eficientes (Figura S1).

Resultados

O tipo de zona de impacto e o nível de tolerância da degradação da biodiversidade tiveram forte influência na escolha dos arranjos mais eficientes. Utilizando apenas os alvos ameaçados pela desconexão a montante e tolerando uma degradação de até 30% da área do alvo (cenário mais conservacionista), foi possível produzir 9,419 MW, ou 18,383 MW considerando apenas a zona de impacto do reservatório. Com todas as zonas de impactos e, portanto, alvos, esse valor de produção de energia sem impactar significativamente nenhum dos alvos aqui definidos é de 8,733 MW. (Fig. 3). Na Tabela S2 em anexo são apresentadas as hidrelétricas selecionadas em cada um dos potenciais arranjos considerados como eficientes pela análise da fronteira de Pareto. No cenário de alto risco para a conservação, que tolerava uma perda de 70% da área de um alvo, era possível produzir 27,002 MW, 26,049 MW e 22,630 MW para as zonas de impacto a

montante, do reservatório ou de todos os três tipos de alvos juntos, respectivamente (Tabela S2)

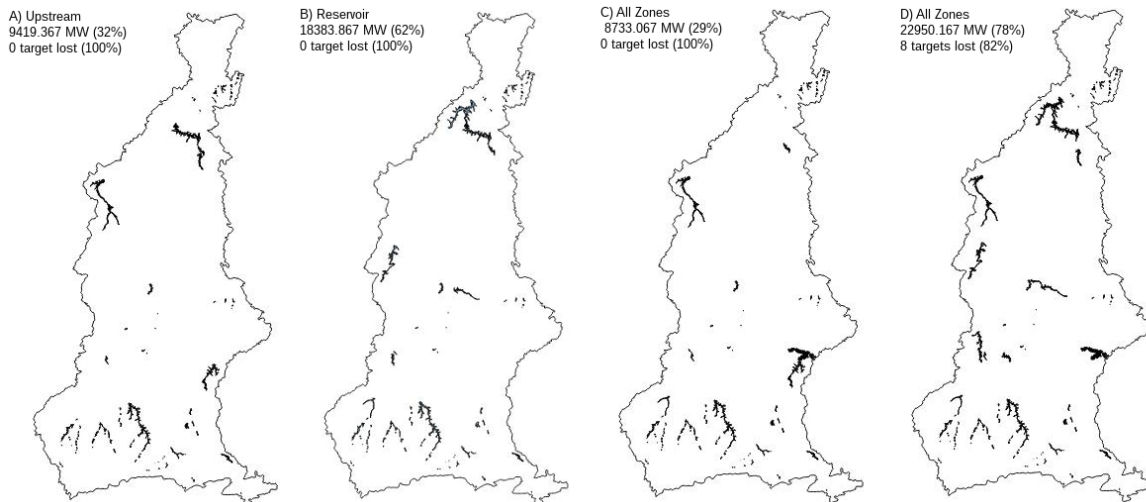
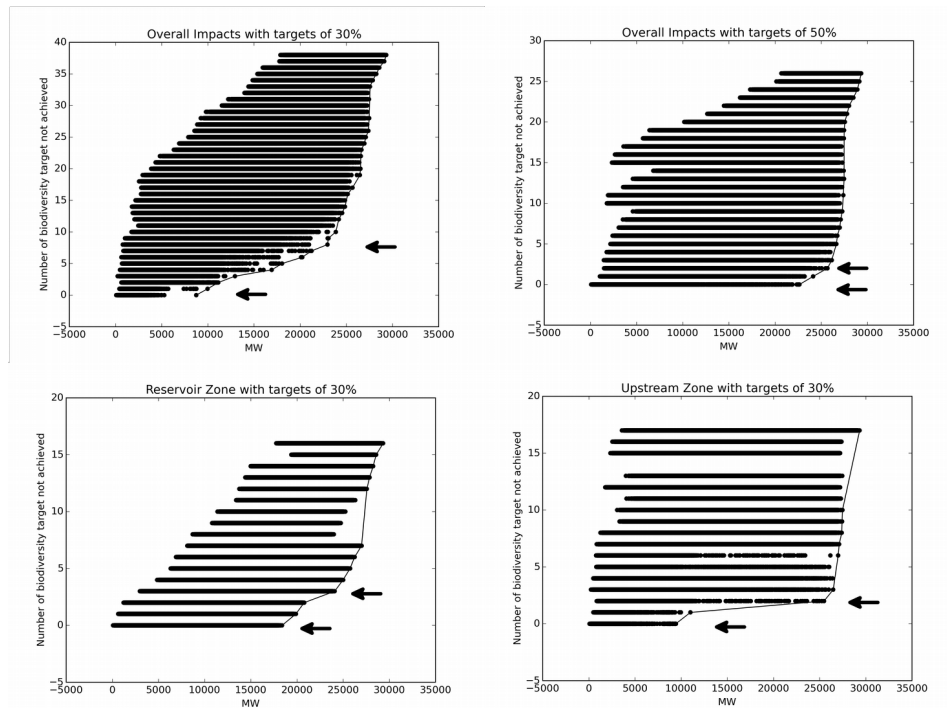


Figure 3. Os gráficos mostrados na parte superior mostra os arranjos de barragens que tiveram pelo menos dois pontos mais eficientes. As setas indicam os limites que identificamos como sendo os pontos mais eficientes dos gráficos. As letras que estão ao lado da seta indica que há uma figura na parte inferior com as barragens selecionadas nessa opção. Na parte inferior, acima de cada arranjo mostrado tem a zona de impacto, a quantidade de MW que o arranjo produz, entre parênteses a percentagem do total de MW previstos pra bacia, o número de alvos afetados pelo arranjo e, entre parênteses, a quantidade relativa de alvos que estarão preservados com esse arranjo.

As barragens agrupadas (menores e localizadas mais a montante nas sub-bacias) foram as únicas presentes em todos os 31 pontos eficientes em todos os cenários. Quando são utilizados apenas os alvos impactados pela desconexão, e considerando o cenário mais preservacionista, três arranjos foram considerados como eficientes, e a maior hidrelétrica proposta para a bacia, e também a mais a jusante, UHE São Luiz do Tapajós, surge uma vez dentre eles. Em um outro cenário, usando apenas os alvos afetados pela zona de impacto do reservatório, essa mesma barragem aparecem nas soluções frequentemente (Fig. S1). De modo similar, o aumento da aceitação da quantidade de área que poderia ser degradada para 50 e 70% faz com que essas mesmas hidrelétricas sejam incluídas nos arranjos selecionados.

Discussão

Nosso estudo demonstra que é possível produzir energia em com um pequeno impacto na biodiversidade. No cenário mais preservacionista, encontramos arranjos que podem produzir 23 GW com uma perda de oito alvos, que corresponde a uma geração de 78% da produção total com uma perda de 21% da biodiversidade em relação à proposta de uso pleno do potencial de geração hidroelétrica da bacia (Fig. 3 D Todas as zonas de impacto com uma tolerância de 30% de perda de área). Os arranjos mais eficientes foram dependentes da escolha do tipo de alvo, se afetado pela área de alagamento do reservatório, ou se afetado pela desconectividade provocada por ele. A tolerância da quantidade de área perdida do alvo também influenciou fortemente os resultados. Tal resultado corrobora estudos similares sobre melhores arranjos de barragens (Jager et al., 2015), que sugerem como opção não instalar barragens nos rios principais das (sub-) bacias. Nesse mesmo arranjo preservacionista, foi possível produzir 8733 MW, que representaria mais que o triplo da energia que é produzida atualmente. Essa contradição de produção e preservação pode ser mediada pelo nível de degradação que toleramos na biodiversidade. Ao considerar a opção menos preservacionista (70% de perda de área dos alvos) os arranjos ótimos incluíram as opções do governo de construir as grandes barragens (p.e. São Luiz do Tapajós). Entretanto, o limite de 70% de perda de área é de alto risco para a preservação desses alvos. Nesse mesmo cenário, não há opções de otimização, porque o aumento de produção de energia é muito pequeno em relação ao aumento da perda de biodiversidade (Fig. S2).

Os alvos selecionados no Capítulo 2 desta tese e que foram usados neste estudo, influenciaram fortemente os resultados. Os arranjos selecionados pelos alvos impactados

pela desconexão (zona de impacto a montante) privilegiaram hidrelétricas longe da região central e topograficamente mais baixa da bacia. Por outro lado, os alvos das zonas de impacto do reservatório privilegiaram as grandes usinas localizadas no rio principal. As maiores hidrelétricas, a fio d'água, propostas pelo governo atualmente, precisam de grande quantidade de água e por isso se posicionam nessas regiões baixas e nos rios principais. Sem considerar a conectividade, pela zona de impacto do reservatório, algumas das grandes barragens (p.e. São Luiz do Tapajós e Jatobá) apareceram mais frequentemente nos potenciais arranjos (Fig. S1 C)). A quantidade de energia que tais usinas produziram parece compensar a área que elas alagam localmente, entretanto isso não acontece quando é considerada a área de desconexão (a UHE São Luiz do Tapajós desconecta 93,9 % da sub-bacia do Tapajós). Quando foram consideradas as três zonas de impacto, essas tendências opostas se amenizaram, mas as grandes hidrelétricas continuaram menos frequentes que as menores e periféricas na sub-bacia (Fig 3 A e Fig. S1 A). No entanto, os alvos utilizados aqui tiveram pesos iguais, o que pode ser contestado. Converter a sub-bacia do Tapajós, que é relativamente bem preservada, em uma bacia com alto grau de degradação da biodiversidade não é uma boa opção. Ainda mais em um ambiente desconhecido como é a Amazônia, que abriga diversas espécies e processos ecológicos a serem descobertos.

Um grupo de barragens que surgiu em todos os arranjos mais eficientes foram as menores barragens, com baixo impacto na biodiversidade aquática. Seu potencial de impacto nos grandes processos ecológicos da bacia (p.e. grandes migradores, espécies de ampla distribuição ou a conectividade em si) parece ser pequeno. Esse grupo é composto de menores barragens situados nas partes periféricas da bacia, e mesmo que individualmente cada uma das barragens tenha uma pequena produção de hidroeletricidade, coletivamente têm um potencial de uma grande hidrelétrica (2,747 MW). Entretanto, não utilizamos nesse estudo o efeito indireto da construção de uma represa. Se associarmos o processo construtivo, como estradas, desmatamento para canteiro de obras e outras interferências, como aparecem em outros estudos (é possível que o resultado seja outro).

No presente trabalho encontramos diversos arranjos de duplo ganho (*win-win situations*) ao analisar suas posições nas fronteiras de Pareto, demonstrando que mesmo sendo recursos competitivos, a produção de energia hidrelétrica e a preservação do meio ambiente podem ser otimizadas. Tais situações podem ser compatíveis com o aumento da produção de energia, desde que tolerados alguns níveis de perda de biodiversidade. Entretanto, é possível que existam outras soluções para um aumento de produção de

hidroeletricidade na sub-bacia do Tapajós. Pelo menos cerca de 30 % do potencial hidráulico da região não foi levantado ainda (EPE, 2007), portanto nós sugerimos que a região em que está localizado o grupo das menores barragens seja investigada em mais detalhe.

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Apêndice

Table S1 – Lista de barragens construídas ou planejadas na bacia do Tapajós encontrados nos pontos mais eficientes na fronteira de Pareto.

Table S2 – Lista de alvos impactados por barragens na bacia do Tapajós.

Figure S1. Frequência da ocorrência das barragens nas soluções que tiveram pelo menos dois pontos considerados como mais eficientes na fronteira de Pareto.

Figure S2. Todos os arranjos das zonas de impacto e de determinado nível de tolerância (subtítulos) que apresentaram apenas uma solução como mais eficiente na fronteira de Pareto.

Síntese

A decisão sobre onde e quais barragens construir é um planejamento feito com décadas de antecedência e com regular reanálise por parte do setor elétrico (MME – Ministério de Minas e Energia, ANEEL – Agência Nacional de Energia Elétrica e empreiteiras de energia). O resultado de tal esforço é uma projeção de quanto de energia hidrelétrica será explorada em cada bacia do País e ainda quais os empreendimentos que devem ser construídos para alcançar a meta de quantidade de energia. Então, decisões sobre quais barragens devem ser construídas na Amazônia são dependentes do preço de uma barragem na região sudeste. De modo similar, a decisão da área ambiental também precisa ser tomada de forma comparativa. O atual paradigma da biologia da conservação é a complementaridade. Para usar essa lógica, é preciso conhecer onde os elementos de biodiversidade estão e sugerir que alguns locais devem ser protegidos, se determinados outros serão degradados. Porém, apesar de serem duas estratégias de planejamento com características similares, o planejamento elétrico tem mínima ou nenhuma influência da área ambiental. As principais decisões sobre ocupação são as de planejamento, mas apenas após essa fase é se consulta os órgãos ambientais sobre se a obra pode ou não ser construída. Nesse momento do processo decisório, os órgãos ambientais não podem influir ou negociar uma obra em detrimento da outra, pois sua decisão está limitada a aprovar ou negar uma obra.

Aqui vimos que essa tomada de decisão sobre um empreendimento possui poucas ferramentas ecológicas legalmente. Uma delas, potencialmente a única sobre biodiversidade com parâmetros definidos, é a estabilização da Curva do Coletor. Tal instrumento tem severas limitações de ser usado porque, para uma área de usina hidrelétrica na Amazônia comum, não é possível aleatorizar as amostras e nessa escala, as estimativas de riqueza de espécies não são robustas a não aleatoriedade. Esse não parece ser uma dificuldade real porque a curva do coletor pouco informaria sobre o critério mais relevante, a complementaridade. Para se decidir pela complementaridade é preciso escolher os alvos, que seriam considerados como relevantes a serem conservados. Essa etapa é crítica no planejamento e no setor elétrico ela é óbvia, quantidade de energia instalada. Por outro lado, os alvos da área ambiental não são tão claros. Por isso, no capítulo dois espacializamos em toda a região Amazônica os alvos comumente usados

para a região e encontramos que muitos deles não eram influenciados pela presença de uma ou mesmo qualquer hidrelétrica. Uma outra significativa conclusão é de que os alvos considerados relevantes estão essencialmente associados ao ambiente aquático,

Outros trabalhos têm sido feitos na Amazônia com o intuito de elaborar um planejamento sistemático dos empreendimentos hidrelétricos. Um desses esforços foi sobre a sub-bacia do Tapajós (onde está previsto a instalação do maior número de barragens e potência instalada de toda a bacia Amazônica) e reuniu os Ministérios do Meio Ambiente e o Ministério de Minas e Energia. Apesar de não ter tido o efeito desejado e nenhum planejamento conjunto ter sido produzido, através dele elaborou-se uma lista de alvos (MMA & MME, 2011) que avaliamos junto com outros no capítulo 2. Usamos o resultado dessas análises para indicar situações de otimização apenas na sub-bacia do Tapajós no capítulo 3. A simulação que fizemos nessa sub-bacia utilizando os alvos selecionados previamente demonstrou que a produção de energia com a preservação de muitos elementos da biodiversidade pode ser compatível, mas não no planejamento apresentado pelo governo. Encontramos que é possível gerar 77% da energia pretendida com uma perda de 21% da biodiversidade em relação a proposta governamental. Um grupo de barragens na região intermediária entre as cabeceiras e os rios principais, foram selecionados em todos os pontos mais eficientes. Como o levantamento do potencial da bacia ainda não está feito por completo, sugerimos que essas regiões possam ser estudadas mais pormenorizadamente pelo setor elétrico antes da instalação do atual plano. Ainda, os alvos usados influenciam fortemente os melhores arranjos e no presente trabalho utilizamos o mesmo peso para todos eles. Sugerimos então que esses alvos sejam analisados através de encontros de pesquisadores antes para que sejam feitas as proposições dos arranjos de barragens mais eficientes para a sub-bacia do Tapajós.

As preocupações com a preservação ambiental deveria ser um dos critérios no momento da tomada de decisão do planejamento das barragens do estado brasileiro. Atualmente, decidindo se sim ou não sobre um empreendimento, os órgãos ambientais contribuem pouco com a tentativa de produzir energia e preservar o meio ambiente. Esse momento do planejamento é adequado para que todas as áreas sugiram os critérios para se definir onde é possível ou não colocar uma barragem. Se a escala espacial e temporal usada pelo setor elétrico se mantiver, todo o País, grandes decisões podem ser feitas nesse momento. Se é melhor investir na Amazônia, se vale a pena restringir a exploração de barragens a bacias já exploradas, são alguns exemplos. Isso só é possível se o setor da conservação puder indicar que é preciso conservar uma região no Estado de Rondônia

para concordar com uma hidrelétrica em Roraima. Vimos que ao menos para a sub-bacia do Tapajós foi possível otimizar a relação entre produção de energia. A extensão desse trabalho para todo o País pode trazer decisões muito mais eficientes do que a proposta atual.

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AULA DE QUALIFICAÇÃO

PARECER

Aluno(a): RODRIGO VASCONCELOS KOBLITZ
Curso: ECOLOGIA
Nível: DOUTORADO
Orientador(a): WILLIAM ERNEST MAGNUSSON

Título:

"Tomada de decisões conservacionistas baseadas em informações sobre biodiversidade em empreendimentos na Bacia Amazônica"








BANCA JULGADORA:

TITULARES:

Jansen Alfredo Sampaio Zuanon (INPA)
Karl Didier (WCS)
Renato Cintra (INPA)
Susan Aragon (INPA)
Jean-Louis Bernard Guillaumet (IRD MNHN-França)

SUPLENTES:

Efrem Jorge Gondim Ferreira (INPA)
Rita de Cássia Guimarães Mesquita (INPA)

	PARECER	ASSINATURA
Jansen Alfredo Sampaio Zuanon (INPA)	() Aprovado (X) Reprovado	
Karl Didier (WCS)	(X) Aprovado () Reprovado	
Renato Cintra (INPA)	(X) Aprovado () Reprovado	
Susan Aragon (INPA)	(X) Aprovado () Reprovado	
Jean-Louis B. Guillaumet (IRD MNHN-França)	(X) Aprovado () Reprovado	
Efrem Jorge Gondim Ferreira (INPA)	() Aprovado () Reprovado	
Rita de Cássia Guimarães Mesquita (INPA)	() Aprovado () Reprovado	

Manaus (AM), 16 de maio de 2013

OBS: O aluno deverá investir no embasamento teórico subjacente à proposta de tese, de modo a explicitar a contribuição científica decorrente do estudo. A banca recomenda também que o aluno e seu orientador reavaliam a escala geográfica pretendida para o estudo.

PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA

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

Aos 02 dias do mês de março do ano de 2017, às 09:00 horas, no Auditório dos PPG's ATU/CFT/ECO, Campus III, INPA/V8, reuniu-se a Comissão Examinadora de Defesa Pública, composta pelos seguintes membros: o(a) Prof(a). Dr(a). **Philip Martin Fearnside**, do Instituto Nacional de Pesquisas da Amazônia - INPA, o(a) Prof(a). Dr(a). **Fernando Mendonça D'Horta**, da Universidade de São Paulo - USP, o(a) Prof(a). Dr(a). **Flávia Regina Capellotto Costa**, do Instituto Nacional de Pesquisas da Amazônia - INPA, o(a) Prof(a). Dr(a). **Jansen Alfredo Sampaio Zuanon**, do Instituto Nacional de Pesquisas da Amazônia - INPA, o (a) Prof(a). Dr(a). **Efrem Jorge Gondim Ferreira**, do Instituto Nacional de Pesquisas da Amazônia - INPA, tendo como suplentes o(a) Prof(a). Dr(a). André Pinassi Antunes, da Wildlife Conservation Society - WCS, e o(a) Prof(a). Dr(a). Mário Eric Cohn-Haft, do Instituto Nacional de Pesquisas da Amazônia - INPA, sob a presidência do(a) primeiro(a), a fim de proceder a arguição pública do trabalho de **TESE DE DOUTORADO** de **RODRIGO VASCONCELOS KOBLITZ**, intitulado "**A TOMADA DE DECISÕES CONSERVACIONISTAS BASEADAS EM INFORMAÇÕES SOBRE A BIODIVERSIDADE EM EMPREENDIMENTOS HIDRELÉTRICOS NA BACIA AMAZÔNICA**", orientado(a) pelo(a) Prof(a). Dr(a) William Ernest Magnusson, do Instituto Nacional de Pesquisas da Amazônia - INPA e coorientado(a) pelo(a) Prof(a). Dr(a). Helena de Godoy Bergallo, do (a) Universidade do Estado do Rio de Janeiro - UERJ. Após a exposição, o(a) discente foi arguido(a) oralmente pelos membros da Comissão Examinadora, tendo recebido o conceito final:

APROVADO(A)

REPROVADO(A)

POR UNANIMIDADE

POR MAIORIA

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

Prof(a).Dr(a). PHILIP MARTIN FEARNSIDE

Prof(a).Dr(a). FERNANDO MENDONÇA D'HORTA

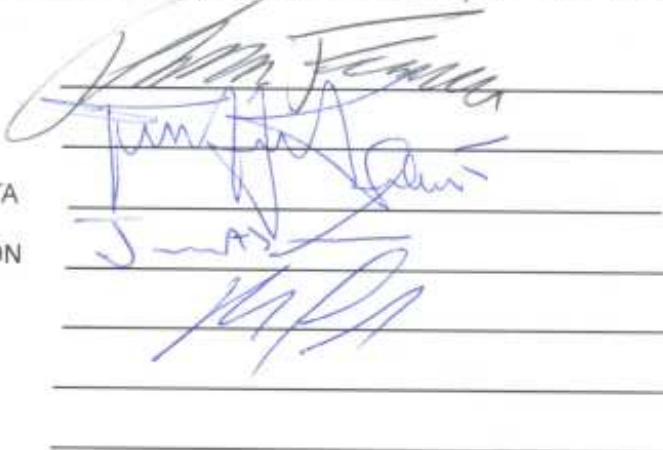
Prof(a).Dr(a). FLÁVIA REGINA CAPELOTTO COSTA

Prof(a).Dr(a). JANSEN ALFREDO SAMPAIO ZUANON

Prof(a).Dr(a). EFREM JORGE GONDIM FERREIRA

Prof(a).Dr(a). ANDRÉ PINASSI ANTUNES

Prof(a).Dr(a). MÁRIO ERIC COHN-HAFT




Coordenação PPG-ECO/INPA