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Planejamento de linhas de energia e a mitigação de impactos sobre a biodiversidade

Tese de Doutorado

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PLANEJAMENTO DE LINHAS DE ENERGIA E A MITIGAÇÃO DE IMPACTOS SOBRE A BIODIVERSIDADE

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Tese de Doutorado apresentada ao Programa de Pós-Graduação em Ecologia, do Instituto de Biociências da Universidade Federal do Rio Grande do Sul, como parte dos requisitos para obtenção do título de Doutor em Ciências com ênfase em Ecologia.

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RESUMO

Linhas de energia são infraestruturas necessárias para suprir a crescente demanda energética, sendo inúmeros os benefícios socioeconômicos gerados pela expansão desse sistema. Contudo, em decorrência da extensão e da heterogeneidade ambiental por onde passam, são responsáveis por gerar diferentes impactos no ambiente, representando uma ameaça à biodiversidade sobretudo quando os aspectos ambientais são negligenciados nas fases iniciais de planejamento. Considerando que grande parte dos impactos ambientais persiste ao longo da operação das linhas, é preciso dar atenção à malha energética em operação, promovendo ações adequadas de mitigação de seus impactos. Esta tese de doutorado foi elaborada com a intenção de qualificar o conhecimento e a pesquisa sobre a forma como as linhas de energia impactam o ambiente no qual estão inseridas, contribuindo para a melhor integração dos aspectos ambientais no seu planejamento e visando a mitigação de diferentes impactos. No capítulo 1 proponho uma abordagem para traçar rotas de linhas de transmissão que garantam o evitamento de impactos através da melhor incorporação de variáveis ambientais relacionadas à integridade da vegetação ainda na fase de planejamento de projeto. Também identifico segmentos de rota com consenso entre as perspectivas de engenharia e ambiental. A identificação dessas áreas de coincidência indica locais de menor conflito entre as duas perspectivas e tem potencial de otimizar a tomada de decisão de projetos individuais. No capítulo 2 proponho um modelo conceitual que permite uma avaliação preliminar do risco de eletrocussão de aves no Brasil, resultado da combinação da exposição (densidade de infraestruturas elétricas dentro da área de distribuição das espécies) e da suscetibilidade da avifauna (características morfológicas e comportamentais associadas a um maior risco de eletrocussão). Essa abordagem permite identificar áreas de alto risco de eletrocussão bem como espécies mais vulneráveis. No capítulo 3 apresento evidências de morte por eletrocussão em redes de média tensão da arara-azul-de-lear (*Anodorhynchus leari*), espécie indicada como prioritária em relação ao risco de eletrocussão no capítulo anterior. Ao descrever possíveis causas e padrões dos registros de fatalidades, promovo o reconhecimento das eletrocussões como uma nova ameaça à espécie e recomendo possíveis alternativas de mitigação. No capítulo 4, descrevo os principais aspectos estruturais e funcionais de estradas e linhas de energia, revisando brevemente as semelhanças e dissimilaridades nos tipos e magnitude de impactos dessas duas malhas sobre a biodiversidade. Adicionalmente, destaco algumas lacunas de conhecimento que, quando preenchidas, poderão fortalecer nossa capacidade de predizer, prevenir ou remediar os impactos dessas duas infraestruturas lineares que co-ocorrem regularmente. Essa tese explora abordagens que podem ser adaptadas e

utilizadas em um contexto de tomada de decisão, referente tanto ao planejamento e expansão da malha quanto ao licenciamento ambiental dos projetos individuais. Essa tese também tem importantes contribuições sob a perspectiva da Hierarquia de Mitigação de impactos, com algumas de suas diferentes etapas contempladas nos capítulos aqui apresentados.

Palavras-chave: eletrocussões de aves, hierarquia de mitigação, infraestruturas lineares, linhas de transmissão, linhas de distribuição.

ABSTRACT

Power line planning and impact mitigation measures on biodiversity. Power lines are infrastructures continuously expanding worldwide to supply the human population's demands for electricity. Poorly planned power line networks may represent a risk for biodiversity by crossing sensitive areas, resulting in different impacts such as habitat loss and degradation, and by promoting wildlife fatalities. Considering that part of the impacts persists throughout the operation phase, it is also necessary to pay attention to the installed energy grid, promoting efficient impact mitigation measures. This doctoral thesis was elaborated to improve the knowledge and the research on how power lines impact the environment in which they are installed, contributing to a better integration of environmental aspects in its planning and aiming at the mitigation of different impacts. In **Chapter 1** I present a systematic approach to compare alternative routes of power lines and indicate the route with the lowest environmental impact, focusing on the avoidance of forest loss. Additionally, I identify route segments where a consensus between engineering and environmental considerations exists. This procedure identifies geographic-divergent segments, enabling the early identification of areas with potential conflicts where impact minimization needs to be negotiated. In **Chapter 2** I develop a framework to model the risk of bird electrocution in Brazil as an interaction between the species-specific exposure to power lines (pole density within a species distribution range) and susceptibility (morphological and behavioral traits associated with electrocution hazards). This study identifies spatial patterns of bird electrocution, highlighting priority areas of electrocution susceptibility, electrocution risk, and the more vulnerable species to this impact. In **Chapter 3** I report electrocution deaths of the endangered Lear's Macaw, a species indicated as priority in relation to the risk of electrocution in the previous chapter. I describe possible causes and patterns of fatality records, highlight the importance of considering electrocution risks as an overlooked threat, and I suggest some effective and efficient mitigation measures aimed at reducing the impact of power lines along the species distribution area. In **Chapter 4** I briefly remark the main structural aspects of roads and power lines considering their attributes, global extension, effect zone, and I shortly review the similarities and differences in the top-five impact categories common to both. In addition, I identify some knowledge gaps that should be further explored in power line and road research agenda. This thesis explores approaches that can be adapted and used in a decision-making context, regarding planning and network expansion and environmental licensing of individual projects. This thesis also has important contributions from the Mitigation Hierarchy perspective, with some of its different steps covered in the chapters presented here.

Keywords: bird electrocution, distribution lines, linear infrastructures, mitigation hierarchy, high-voltage lines.

Sumário

INTRODUÇÃO GERAL

Impactos de linhas de energia sobre a biodiversidade

O crescimento do setor energético e a garantia do acesso universal a esse serviço demandam modificações nas paisagens que incluem a instalação de novas linhas de transmissão (LTs) e de distribuição de energia (LDs). Segundo a International Energy Agency (2018), há um crescimento de mais de um quarto no consumo mundial de energia previsto para ocorrer até 2040. Mesmo que o investimento em fontes de energia ditas como renováveis e limpas seja uma prioridade para alcançar metas mais sustentáveis, a única forma de escoar a energia gerada até os centros consumidores é através da instalação de LTs e LDs (Kishore and Singal 2014; Jones et al. 2015). No entanto, o planejamento e a expansão desse sistema de transporte de energia ainda são desafiadores quanto à incorporação de melhores práticas ambientais.

Obviamente, há inúmeros benefícios socioeconômicos gerados pela expansão energética. Contudo, em decorrência da sua extensão e da heterogeneidade ambiental por onde passam, as linhas de energia são responsáveis por gerar diferentes impactos no ambiente, representando uma ameaça à biodiversidade (Bagli et al. 2011), sobretudo quando os aspectos ambientais são subestimados na fase de planejamento.

Tanto para o contexto de expansão quanto de regularização da malha energética existente, é fundamental avaliar os impactos na biodiversidade e planejar medidas sob a perspectiva da hierarquia da mitigação (Kiesecker et al. 2010) (Figura 1). De acordo com essa abordagem, após ter a predição das consequências ambientais reconhecida, evitar impactos é a primeira medida que deveria ser considerada no planejamento de qualquer empreendimento (delimitação espacial cuidadosa das infraestruturas, priorizando locais distantes de áreas importantes para a conservação da biodiversidade), seguida da minimização (redução da duração, intensidade e/ou extensão dos impactos que não podem ser completamente evitados), restauração (reabilitação de áreas degradadas durante a instalação e ao longo da operação) e por fim, a compensação dos danos ambientais residuais adversos que não podem ser evitados, minimizados e/ou restaurados (Villarroya et al. 2014) (Figura 1). Contudo, na tradição do licenciamento ambiental das linhas de energia, o reconhecimento do evitamento de impactos já na fase de planejamento locacional das infraestruturas raramente vem sendo praticado ou as abordagens utilizadas são limitadas em termos de contexto, métricas e ações propostas.

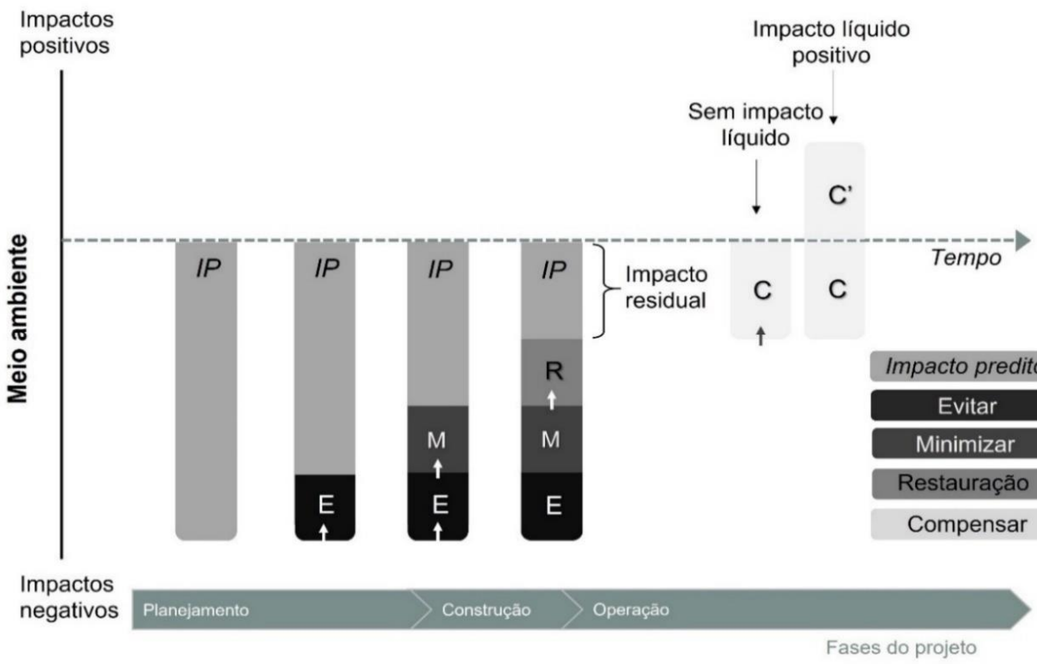

Figura 1. Etapas da hierarquia de mitigação de impactos no tempo relacionadas às fases de planejamento, instalação e operação dos empreendimentos. Figura adaptada de Kiesecker et al. (2010).

A necessidade de considerar os impactos à biodiversidade no planejamento e tomada de decisões sobre empreendimentos de infraestrutura tem sido enfatizada em diversos marcos legais. Com início a partir da elaboração da Lei da Política Nacional do Meio Ambiente nos Estados Unidos em 1965 – a qual influenciou a implementação e regulamentação do licenciamento ambiental em muitos países; com a Diretiva da União Europeia 85/337/CEE; com a instituição da Convenção para Diversidade Biológica, a qual estabeleceu procedimentos que devem exigir a Avaliação de Impacto e Minimização de Impactos Negativos para projetos propostos que possam ter sensíveis efeitos na diversidade biológica (CDB, Artigo 14); e, mais recentemente, com o Plano Estratégico de Biodiversidade. Esse último estabeleceu as Metas de Aichi voltadas à redução da perda de biodiversidade, as quais têm como foco a integração dos valores da biodiversidade em estratégias de desenvolvimento e nos procedimentos de planejamento nacionais (Meta 2) e a redução da taxa de perda, degradação e fragmentação de habitats nativos (Meta 5).

Embora as consequências ambientais em resposta à presença das linhas de energia estejam sendo investigadas, principalmente em países do hemisfério norte (Biasotto 2017), a definição de rotas mais adequadas sob uma perspectiva ambiental para a implantação de LTs tem sido uma dificuldade enfrentada por conservacionistas e tomadores de decisão (Bagli et al. 2011). No Brasil, um país com enorme extensão territorial e grande complexidade socioambiental, o delineamento locacional das LTs é um desafio e, apesar de alguns esforços na regulamentação do processo de licenciamento ambiental das LTs (e.x., Portaria nº 421, de 26 de outubro de 2011), ainda há uma série de barreiras que só poderão ser superadas quando houver uma melhor incorporação das variáveis ambientais no planejamento dessas infraestruturas.

No Brasil, a elaboração dos projetos de LTs se inicia com a formulação de corredores principais (10 a 20km de largura) realizado pela Empresa de Pesquisa Energética (EPE) previamente aos procedimentos licitatórios conduzidos pela Agência Nacional de Energia Elétrica (ANEEL), que concede às concessionárias de energia o serviço de construção e operação da infraestrutura antes do início do procedimento de licenciamento ambiental (de Araújo 2016) (Figura 2). Em resumo, os projetos de LTs são concedidos às empresas antes de terem sua viabilidade ambiental analisada e aprovada pelos órgãos ambientais competentes, portanto, a concessão dos empreendimentos acontece anteriormente à caracterização dos impactos ambientais que poderão ser causados (Campos 2011; Cardoso Jr. 2014; de Araújo 2016; Jahnel 2016). Esse processo vai totalmente contra a lógica de menor impacto e praticamente inviabiliza que o evitamento de impactos possa ser devidamente priorizado, além de gerar pressões políticas e jurídicas, uma vez que as empresas precisam da confirmação de que o projeto seja executado, dado que esse já foi concedido via leilão. Em outras palavras, se até o momento da concessão ainda não há possibilidade de avaliar com precisão os custos ambientais decorrentes da instalação do projeto, então não poderá haver garantias de que as estimativas de custos serão suficientes para a aplicação de medidas que irão garantir que a implantação do empreendimento seja correta e de qualidade (Campos 2011).

Somado ao contexto acima, ainda que erroneamente atribuída a questões ambientais, a morosidade e parte dos conflitos referentes ao licenciamento dessas estruturas se dá também por outras fragilidades no procedimento de definição do trajeto das linhas (Lima and Magrini 2010; Cardoso and Hoffmann 2019). Por exemplo, pela falta de critérios ambientais explícitos na triagem das alternativas, o que inviabiliza a compreensão de como cada variável foi considerada, e pela rasa consideração de atributos ambientais vinculados aos seus principais impactos ainda na fase de planejamento (de Araújo 2016; Malvestio et al. 2018). No que tange às linhas de distribuição de energia, essas não passam pelas usuais etapas de licenciamento ambiental uma vez que são consideradas como geradoras de baixo impacto devido sua extensão e voltagem (kV) e, geralmente, têm sua instalação efetivada sem uma análise criteriosa de impactos ambientais, a depender da discricionaridade de cada estado (e.x. FEPAM 2018a).

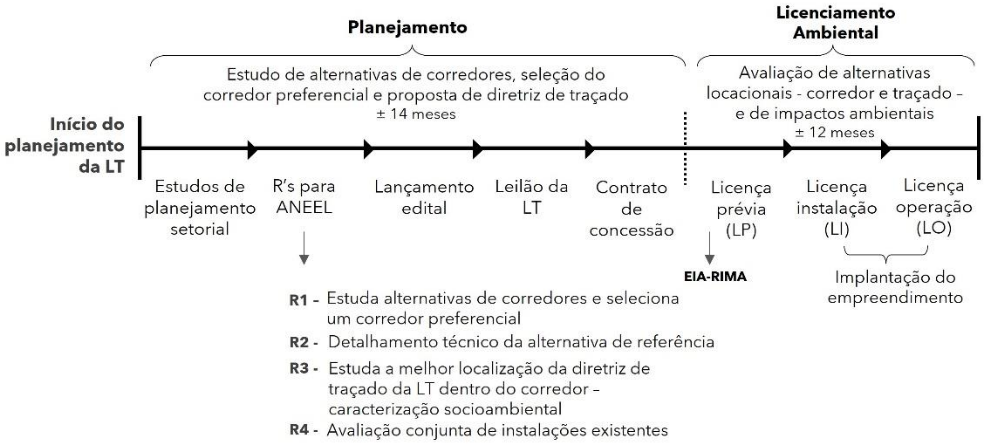

Figura 2. Condução do processo de planejamento e licenciamento ambiental de linhas de transmissão de energia no Brasil. Contrato de concessão da LT é cedido anteriormente à caracterização e avaliação dos impactos ambientais pelos órgãos ambientais competentes.

Linhas de energia impactam a biodiversidade através de alterações e efeitos diversos no ambiente, sendo causadoras de pelo menos 28 diferentes impactos (Figura 3) (Biasotto and Kindel 2018, 2021). Como consequência do manejo do solo e da vegetação no corredor exigido para implantação de LTs (área desobstruída abaixo dos cabos e parcialmente nas servidões) e da abertura de acessos para instalação das infraestruturas, a perda e a degradação de habitat podem ser pontuadas como um dos principais efeitos diretos na paisagem (Biasotto 2017). Associados a essas modificações na paisagem, são também reconhecidos outros efeitos, como por exemplo, a fragmentação, efeito de borda, efeito de barreira ou filtro, efeito de corredor, criação de novos habitats, entre outros (Biasotto and Kindel 2018).

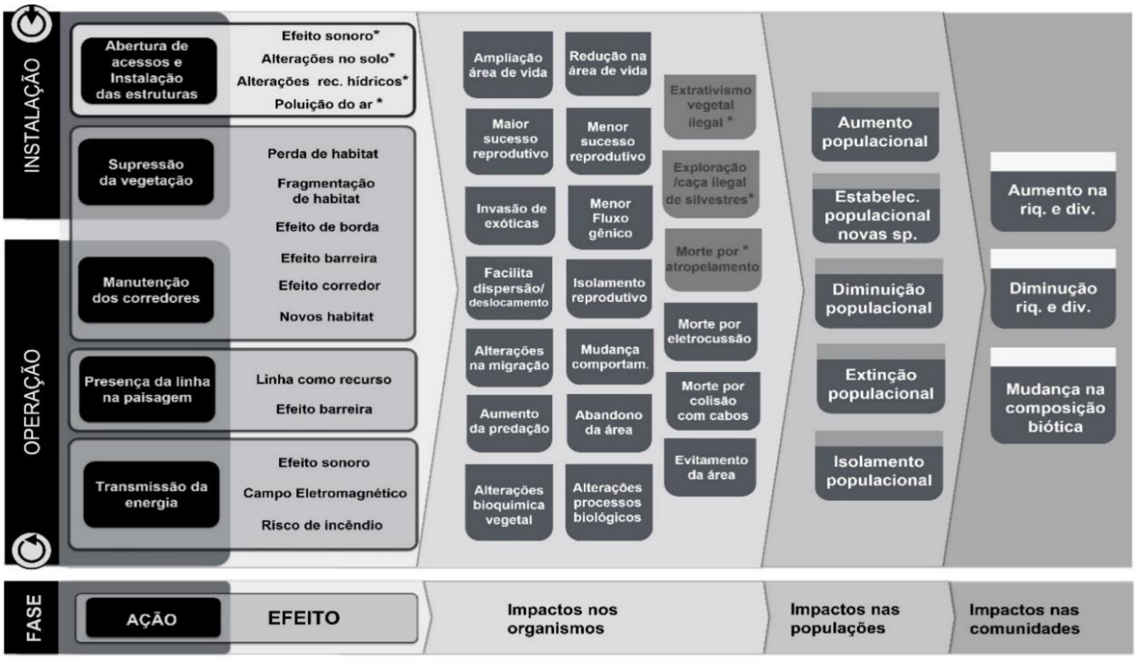

Figura 3. Modelo conceitual dos efeitos ambientais e impactos na biota causados pela instalação e operação de linhas de energia. 'Ação' significa a atividade ou atributo do empreendimento que induz as mudanças no ambiente. 'Efeito' representa uma mudança ligada ao ambiente abiótico, uma alteração química ou física. 'Impacto' descreve as consequências bióticas resultantes de tais alterações, categorizadas em respostas em nível de indivíduo, população e comunidade. Figura traduzida e adaptada de (Biasotto and Kindel 2018).

De todos os grupos faunísticos afetados pela implantação de linhas de energia, as aves são as que sofrem a maior diversidade de impactos (Biasotto and Kindel 2018). Um estudo que avaliou as taxas de mortalidade de aves causadas por diferentes infraestruturas antrópicas estimou que as linhas de energia estão entre as cinco principais causas de morte de aves no mundo (Loss et al. 2015). O aspecto mais amplamente estudado dessa interação é a mortalidade direta de aves, ocasionada pelas colisões com os cabos (Bernardino et al. 2018; D'Amico et al. 2019) e através das eletrocussões nos postes de energia (Lehman et al. 2007; Eccleston and Harness 2018).

Referente às eletrocussões, o choque elétrico nas aves acontece devido à diferença de potencial energético entre estruturas, ou seja, especificamente nas ocasiões em que uma ave encosta simultaneamente em dois cabos condutores de energia ou em um cabo e em uma estrutura aterrada dos postes (Bevanger 1994, 1998), muito provavelmente culminando com a morte do animal. Diferindo de outros mecanismos de fatalidade, as eletrocussões não representam apenas uma ameaça à conservação das espécies afetadas, como também são responsáveis por quedas de energia que resultam em um impacto financeiro sobre os usuários de eletricidade em todos os segmentos do setor energético (Burgio et al. 2014).

Embora as eletrocussões sejam consideradas um problema global, elas não têm sido adequadamente documentadas, permanecendo mal dimensionadas e sendo estudadas em poucos países (Demeter et al. 2018) (Figura 4). No Brasil, por exemplo, as eletrocussões são registradas principalmente na literatura cinza (Bach et al., 2017), havendo apenas registros ocasionais e oportunísticos publicados (e. g., Gusmão et al. 2020) e raros estudos que abordam o uso das estruturas e potencial dano causado a elas (e. g., Efe and Filippini 2006; Carneiro de Oliveira 2008). Contudo, não existem razões ambientais, técnicas e nem econômicas para acreditar que o cenário das eletrocussões no Brasil possa ser diferente do que é observado em outras partes do mundo.

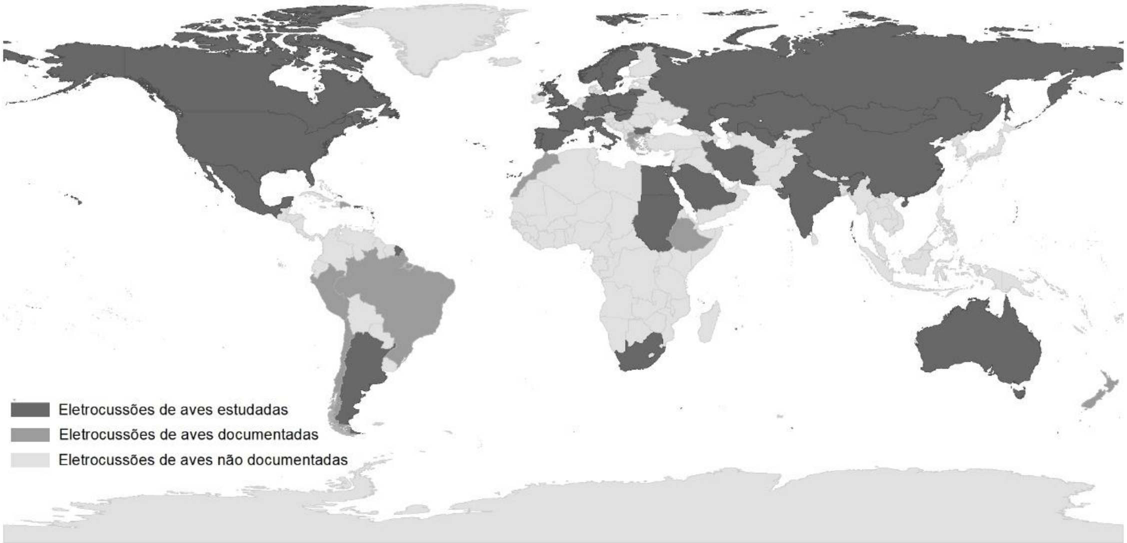

Figura 4. Estudo das eletrocussões de aves no mundo. Cinza escuro - países com pelo menos um artigo científico estudando eletrocussões de aves; Cinza intermediário - países com pelo menos um artigo reportando documentações ocasionais sobre eletrocussões de aves; Cinza claro – países sem documentação sobre eletrocussões de aves em artigos. Compilação de referências bibliográficas conduzida por L.D.B. a partir de outros trabalhos de revisão sobre a temática (Lehman et al. 2007; Eccleston and Harness 2018; Biasotto and Kindel 2018) em agosto de 2021.

Por fim, muito do que sabemos sobre os impactos ambientais causados pelas linhas de energia é análogo para rodovias, por ambas serem estruturas lineares densamente distribuídas ao longo das mais distintas paisagens. Apesar de rodovias e linhas compartilharem determinadas características, elas também diferem em muitos aspectos estruturais, o que influencia fortemente seus respectivos impactos, tornando possível traçar um paralelo entre essas duas estruturas. Embora os impactos ambientais causados por linhas de energia não sejam um tema recente, com os primeiros estudos publicados ainda na década de 1920 (Michener 1928), esse tópico tem recebido menos atenção científica quando comparado com rodovias. Portanto, uma síntese/análise conjunta sobre como o ambiente e seus componentes bióticos podem responder à presença desses dois sistemas de transporte se torna útil e oportuna. Essa comparação permite, por exemplo, a identificação de ensinamentos que a Ecologia de Estradas pode trazer à 'Ecologia de Linhas de energia' estimulando novas pesquisas em relação a impactos pouco estudados para as LTs e LDs e facilitando sua predição para instalação de empreendimentos futuros.

Como minha trajetória moldou a tese

Meu interesse sobre como as linhas de energia impactam a biodiversidade não se iniciou com meu doutorado. Ainda na graduação, após finalizar uma bolsa de iniciação científica com zoologia de invertebrados, tanto a ornitologia quanto a conservação da biodiversidade despertaram grande curiosidade em mim e senti a necessidade de buscar uma experiência aplicada para complementar minha formação como bióloga e que pudesse contemplar esses temas. Essa busca então resultou em um estágio que durou dois anos na Companhia Estadual de Energia Elétrica do Rio Grande do Sul (CEEE). Minha tarefa era auxiliar a minha chefe bióloga em seus trabalhos, a maioria relacionados ao monitoramento de avifauna em linhas de transmissão e a elaboração dos respectivos relatórios. Ao longo desse estágio tive oportunidades únicas de estar em campo e ter meus primeiros contatos com aves colididas ou eletrocutadas, diferenciar seus sinais de morte, observar e estudar seu comportamento, e claro, encontrar muitas perguntas ainda sem respostas sobre quais espécies, como e por que as linhas de energia impactam a avifauna. Além disso, tive meu primeiro contato com as diferentes fases, documentos e produtos do licenciamento ambiental dessas estruturas, na época um universo complexo e novo para mim. Perceber que sempre me senti à vontade e curiosa com essa temática foi decisivo para buscar aprofundar meu conhecimento sobre a interação das linhas de energia com a biodiversidade e seguir estudando essa relação durante as fases seguintes da minha formação como bióloga e pesquisadora.

Com isso, eu estava decidida a encontrar uma resposta para alguma das minhas perguntas como tema central da minha monografia no final da graduação. Restava, porém, encontrar um orientador que também abraçasse a temática e que tivesse a mesma curiosidade que eu. Nesse momento o Prof. Andreas Kindel entrou na minha jornada acadêmica e profissional e junto com ele, o Núcleo de Ecologia de Rodovias e Ferrovias (NERF). O NERF é um grupo que atua fortemente na transferência dos resultados de suas pesquisas com rodovias e ferrovias e sua adoção nos instrumentos que normatizam o licenciamento ambiental, fazendo com que possam ser replicados os procedimentos de difusão que vêm sendo praticados no laboratório nos últimos anos (e.g. Kindel et al. 2017; FEPAM 2018).

O tema do meu Trabalho de Conclusão de Curso foi analisar a eficácia de sinalizadores de avifauna com base no comportamento de voo de aves, considerando que diferentes grupos possuem distintos padrões de voo e capacidade de mobilidade e reação a obstáculos (Biasotto et al. 2017). A resposta desse trabalho indicou, por exemplo, que possivelmente nenhum sinalizador específico seja igualmente eficaz para todos os grupos de aves ou em todas as situações, salientando a importância de se executar estudos dirigidos às espécies prioritárias em relação às colisões com os cabos de energia e um sistema de mitigação com múltiplos modelos de sinalizadores.

Em 2015 ingressei no mestrado junto ao Programa de Pós-Graduação em Ecologia na UFRGS. Ao longo de dois anos pude aprender diversas ferramentas, análises e me aprofundar sobre as questões do licenciamento ambiental das linhas, desde sua fase de Triagem, Escopo, Termo de Referência (TR) até a emissão de suas Licenças Ambientais e seus documentos relacionados. Foi nesse momento que também reconheci as principais fragilidades no processo de planejamento locacional das linhas, que acredito serem uma questão substancial por trás dos conflitos entre os diferentes setores de planejamento e licenciamento ambiental. Um exemplo dessas limitações seria o conteúdo apresentado nos TRs que perpetuavam uma abordagem exaustiva, exigindo a amostragem de variáveis desvinculadas dos potenciais impactos desses empreendimentos e com desenhos amostrais inadequados. Contribuíam para a manutenção dessa prática inúmeras razões, porém, suspeitei que a ausência de uma compilação e descrição dos potenciais impactos contribuía parcialmente para essa tradição. Motivada por esse cenário, o tema da minha dissertação de mestrado foi listar e descrever os potenciais efeitos ambientais causados pelas LTs, sua natureza e os componentes bióticos afetados através de uma revisão sistemática. Também estruturei um modelo conceitual para apoiar o processo de definição do escopo dos estudos e, com isso, contribuir para sua qualificação bem como das decisões tomadas durante o licenciamento de LTs (Biasotto 2017; Biasotto and Kindel 2018).

Ingressei no doutorado em 2017 e, ainda intrigada com a forma como as linhas são planejadas e convicta das fragilidades em relação à consideração das variáveis ambientais, elaborei um projeto que tinha como principal objetivo criar procedimentos e produtos que possibilitassem que os impactos sobre a biodiversidade fossem reconhecidos e dimensionados em fases iniciais de planejamento dos empreendimentos. O uso desses instrumentos permitiria explorar estratégias de evitamento de impactos e, para o caso de linhas já implantadas, o planejamento de ações de mitigação, além de possivelmente abreviar o tempo do processo de licenciamento e implantação das estruturas.

Motivada principalmente pela prevenção da perda e degradação de habitat, considerada um aspecto fundamental para a conservação da biodiversidade, e pela busca por diminuição de conflitos relacionados ao delineamento das rotas, elaborei o **Capítulo 1:**

'Traçando linhas de energia no Brasil: em direção a infraestruturas mais sustentáveis para evitar impactos e conflitos na fase de planejamento'. Nesse capítulo proponho uma abordagem para traçar rotas de linhas de transmissão que causem menor impacto ambiental através da incorporação de múltiplas variáveis ambientais relacionadas à integridade da vegetação pouco antropizada e simulação da variação na valoração das mesmas no processo de planejamento dessas infraestruturas. O objetivo geral é qualificar a escolha do melhor traçado de LTs na Avaliação de Impacto Ambiental, reconhecendo alguns dos principais potenciais impactos já nas fases pré-projeto ou na implantação, garantindo o máximo de impactos evitados. Usando uma descrição detalhada de todos os procedimentos metodológicos, desde a justificativa dos critérios até a seleção final da rota, apresento um fluxograma transparente e replicável para a consideração de um conjunto de critérios ambientais. Além disso, para identificar a rota mais adequada, usamos métricas quantitativas visando permitir decisões menos subjetivas. Ao mesmo tempo, após a obtenção de cinco cenários de rotas diferentes, propomos um método para identificar corredores de LT que possam ser segmentados de acordo com um grau de áreas coincidentes-divergentes entre as perspectivas ambiental e de engenharia, permitindo a tomada de decisões com menos conflito entre esses dois componentes do planejamento.

Instigada com os registros de aves eletrocutadas que observei durante meus campos na graduação, somados à completa ausência de informação sobre eletrocussões no Brasil, decidi que esse impacto merecia um capítulo específico na minha tese. No entanto, apesar de existirem uma série de métodos robustos possíveis para avaliar o impacto das eletrocussões, a ausência de informações biológicas, de mortalidade e de recursos para execução de campos tornava o capítulo desafiador, fazendo com que considerássemos muitos caminhos até chegarmos na proposta final que seria trabalhar com as eletrocussões em uma escala nacional. A concretude dessa ideia foi alcançada através de duas etapas muito importantes: primeiro, consegui, via Lei de Acesso à Informação, acesso a todos os dados espaciais das linhas de energia de alta, média e baixa tensão do Brasil e, segundo, realizei um doutorado-sanduíche através do Programa de Internacionalização da CAPES (PRINT) junto ao grupo CIBIO (Centro de Investigação em Biodiversidade e Recursos Genéticos) em Lisboa, Portugal. A colaboração com esse centro de pesquisa e sua rede de cientistas foi importantíssima e implicou em abreviar a transferência de conhecimento empregada no estudo das interações entre infraestruturas de energia e biodiversidade para a realidade brasileira, resultando no **Capítulo 2: 'Risco de eletrocussão de aves em linhas de energia: uma abordagem para priorizar espécies e áreas para conservação e mitigação de impacto'**. Nesse capítulo proponho um modelo conceitual que permite uma avaliação preliminar da distribuição espacial da exposição e da suscetibilidade das aves, que combinadas fornecem o risco potencial de eletrocussão. A estrutura é baseada em informações já disponíveis, incluindo variáveis como a densidade de infraestruturas elétricas dentro da área de distribuição das espécies e características morfológicas e comportamentais das espécies associadas a um maior risco de eletrocussão. A abordagem permite reconhecer regiões e espécies-alvo que devem receber atenção especial em avaliações ambientais, ajudando a promover situações de ganho ambiental e econômico que irão simultaneamente prevenir fatalidades de aves e interrupções no fornecimento de energia.

Logo após retornar do doutorado sanduíche, já com os primeiros resultados do capítulo 2, fui convidada para integrar um grupo de estudos composto por profissionais de diferentes setores que tinha como objetivo auxiliar a Companhia de Energia Elétrica da Bahia (COELBA) a encontrar soluções para mitigar eletrocussões de *Anodorhynchus leari (*Arara-azul-de-lear). *A. leari* foi indicada em meu capítulo 2 como umas das espécies prioritárias em relação ao risco de eletrocussão. A arara-azul-de-lear é uma espécie endêmica do bioma Caatinga, do sertão brasileiro, globalmente ameaçada de extinção (categoria EN na Lista Vermelha da IUCN) e tem uma área de distribuição extremamente restrita e exposta a diferentes perturbações antrópicas (Pacífico 2020). Das diferentes ameaças à espécie, o impacto das eletrocussões ainda não é bem reconhecido. Porém, a partir de 2017 os registros de morte por eletrocussão se tornaram mais frequentes, chamando atenção da população local e dos grupos de conservação da espécie. Como um dos primeiros passos para divulgar a problemática sobre as eletrocussões da arara-azul-de-lear e incentivar urgentemente que sejam instaladas mitigações, optamos por escrever juntos um primeiro trabalho descrevendo possíveis padrões dessas mortalidades, discutindo ações necessárias para melhor compreender o impacto das eletrocussões na população de araras e indicando possíveis mitigações eficazes aos Psitacídeos. O **Capítulo 3: 'Eletrocussões em linhas de energia como um impacto negligenciado para espécies ameaçadas: preocupações sobre a conservação da arara-azul-de-lear (*Anodorhynchus leari*, Aves, Psittacidae)'** tem como principal objetivo promover o reconhecimento das eletrocussões como uma ameaça à espécie e motivar uma ampla divulgação dessas fatalidades, explorando brevemente algumas hipóteses sobre as causas e padrões dos registros das fatalidades ao longo dos últimos anos e possíveis alternativas de mitigação.

Convidada para escrever um capítulo sobre linhas de energia para o livro 'Ecologia de Estradas: Síntese e Perspectivas' que contaria com uma seção específica de tópicos emergentes em Ecologia de Estradas, achei que uma comparação entre os impactos de rodovias e linhas de energia poderia se enquadrar como o último capítulo da minha tese. Essa também seria uma ótima oportunidade para identificar algumas das lacunas de pesquisa que futuramente poderiam auxiliar no reconhecimento de efeitos e na predição de impactos pouco estudados para as linhas. Ainda, além da proposta estar alinhada com a continuidade da minha trajetória com as linhas de energia, se enquadraria perfeitamente com a minha trajetória coletiva, como integrante do NERF, onde colaboro em vários trabalhos sobre impactos de rodovias e ferrovias. Com isso, finalizo essa tese com o **Capítulo 4: 'Infraestruturas lineares e os impactos sobre a biodiversidade: uma breve síntese sobre as diferenças e semelhanças entre estradas e linhas de energia'**. Neste capítulo, primeiro descrevo os principais aspectos estruturais e funcionais de estradas e linhas de energia e reviso brevemente as semelhanças e dissimilaridades nos tipos e magnitude de impactos sobre a biodiversidade (seção 1). A partir disso, na seção 2, destaco algumas lacunas de conhecimento que, quando preenchidas, poderão fortalecer nossa capacidade de predizer, prevenir ou remediar os impactos dessas infraestruturas lineares que co-ocorrem regularmente ao longo das paisagens.

Os capítulos e produtos que foram desenvolvidos no âmbito dessa tese de doutorado pretenderam apresentar abordagens e novas informações para a melhor consideração dos impactos ambientais no planejamento das linhas de energia no Brasil e para a mitigação de seus efeitos sobre a biodiversidade, revisitando o que propõe a Hierarquia de Mitigação. Complementarmente, essa tese pretendeu identificar e suprir algumas das lacunas de conhecimento em relação a espécies prioritárias e a impactos emergentes e, portanto, ainda pouco investigados. Os capítulos individuais dessa tese são:

Capítulo 1: Traçando linhas de energia no Brasil: em direção a infraestruturas mais sustentáveis para evitar impactos e conflitos na fase de planejamento

Routing power lines in Brazil: towards an environmental and engineering friendly framework for avoiding impacts and conflicts in the planning phase

Capítulo 2: Risco de eletrocussão de aves em linhas de energia: uma abordagem para priorizar espécies e áreas para conservação e mitigação de impacto

Risk of bird electrocution in power lines: a framework for prioritizing species and areas for conservation and impact mitigation

Capítulo 3: Eletrocussões em linhas de energia como um impacto negligenciado para espécies ameaçadas: preocupações sobre a conservação da Arara-azul-de-lear (*Anodorhynchus leari*, Aves, Psittacidae)

Power line electrocution as an overlooked threat to endangered species: concerns about the conservation of the Lear's Macaw (Anodorhynchus leari, Aves, Psittacidae)

Capítulo 4: Infraestruturas lineares e os impactos sobre a biodiversidade: uma breve síntese sobre as diferenças e semelhanças entre estradas e linhas de energia

Linear infrastructures and impacts on biodiversity: a brief synthesis about similarities and differences between Roads and Power lines

Capítulo 1

Traçando linhas de energia no Brasil: em direção a infraestruturas mais sustentáveis para evitar impactos e conflitos na fase de planejamento

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Chapter 1 - Routing power lines in Brazil: towards an environmental and engineering friendly framework for avoiding impacts and conflicts in the planning phase

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HIGHLIGHTS

- Systematic planning allows transparency, replicability, and methodological credibility in routing power lines.
- Impact avoidance is achieved with better environmental considerations in the power line planning phase.
- We identified the route segments where a consensus between engineering and environmental considerations exists.
- The early identification of coincidence areas between environmental and engineering perspectives can reduce risk and optimize debates.

ABSTRACT

Building new power transmission lines (TLs) is fundamental to supply the growing energy demand worldwide. Lessons learned from past projects drive the current planning processes to consider early assessments to avoid environmental impacts. Usually, TL impact assessments focus less on the first level of the mitigation hierarchy (impact avoidance) and more on the inferior levels (minimization, restoration and compensation). Thus, designing TLs routes that avoid adverse environmental effects becomes an essential step and an important challenge. In many countries, the environmental perspective is still poorly considered, and it is usually incorporated too late into the project, causing conflicts in the evaluation due to divergent opinions among stakeholders. These limitations have legal implications and risk decisions that cause delays in Environmental Impact Assessments and, consequently, in project implementation. Identifying conflicting areas early in the planning process is essential to avoid adding cost and delay to the project. To overcome these limitations, we proposed a decision workflow of route design in which we used the hypothetical planning of a TL located in southern Brazil as a case study. Our workflow includes: i) the proposal of alternative routes using Geographic Information System and Least Cost Path Analysis based on two sets of fuzzy criteria – engineering and environmental; ii) an experimental approach with gradual variation among five scenarios that integrate engineering and environmental perspectives (varying the environmental map influence on the final route from 90 to 75, 50, 25 and 10%), based on Spatial Multi-criteria Analysis and Analytic Hierarchy Process and, later, compared by eight evaluation metrics; and iii) identification of route segments charaterized by consensus between engineering and environmental perspectives, using a moving window analysis. As expected, our findings show that the scenarios with higher influence of environmental criteria achieved better performances in all environmental metrics. Furthermore, the spatial convergence among segments of all five modeled alternatives demonstrates three stretches that meet all the criteria. These high coincidence sites represent less conflict between environmental and engineering perspectives. We recommend that impact assessment of power lines should start at the planning phase, taking advantage of the first level of the mitigation hierarchy (impact avoidance). This will represent a gain in effectiveness of the impact assessment outcomes, a better focus on residual impacts during the following phases, a decrease in conflict level during the licensing process, and a potential reduction in time to project implementation.

Keywords: decision support, habitat loss, linear infrastructures, mitigation hierarchy, multicriteria analysis.

1.Introduction

According to the International Energy Agency (2018), global energy consumption has nearly doubled in the last decade, and the installation of new power transmission lines (TLs) was fundamental to supply this demand. As TLs are extensive structures that modify the environment, their diverse effects on biodiversity (Biasotto and Kindel, 2018) should be recognized early to design more sustainable routes, avoiding impacts (Kiesecker et al., 2011) and, consequently, reducing conflict and risky decisions in environmental licensing.

The best opportunity to prevent environmental impacts of TL grid expansion is to follow the mitigation hierarchy (Ekstrom et al., 2015; Phalan et al., 2018). According to this approach, impact avoidance should be the priority (e.g., by carefully locating associated infrastructures to sites away from biodiversity-relevant areas), followed by minimization, restoration, and lastly, compensation for residual impacts (Villarroya et al., 2014).

As a common practice in different types of infrastructures, the environmental perspectives are incorporated too late into the design process, restricting opportunities to influence the decision-making in the initial project phase (Karlson et al., 2016; Khera and Kumar, 2010; Malvestio et al., 2018) and so avoiding impacts. Further, there are conflicts of interest in the valuation of the different aspects of a project, and the environmental criteria tend to be overlooked in comparison to engineering, economic and political issues (Malvestio et al., 2018). The locational alternatives proposed in environmental Impact Assessments (EIA) often solely represents the interest of the project proponent (Effat and Hassan, 2013), whose choices reflect the most feasible option nearly exclusively from an economic appreciation (Warner and Diab, 2002).

These weaknesses have legal implications and imply decisions that can cause a delay in EIA delivery, in the environmental licensing process, and consequently, in project approval and implementation (Cardoso and Hoffmann, 2019; Fonseca et al., 2017; Lima and Magrini, 2010). Beyond the uncertainties involving public energy policy, in Brazil, for example, the electricity sector has been perceived as risky by international investors, mainly due to delays in the project implementation caused by regulatory obstacles related to environmental licensing and to unpredictable high monetary costs (Cardoso and Hoffmann, 2019). According to Bayer et al. (2018), the major delay in the implementation of power generation plants is associated with the lack of an available transmission grid. At the same time, there is a conflict in TL environmental licensing in which energy agencies want to prioritize upholding legislation and good environmental practices while entrepreneurs want environmental licenses to be issued quickly to fulfill the concession deadlines (Cardoso and Hoffmann, 2019).

A reasonable way to overcome these limitations is to adopt a planning framework able which is to decrease subjectivity regarding how alternative locations are outlined and to improve the representativeness of environmental variables in the route selection process (Duarte et al., 2017; Landim and Sánchez, 2012). Methods used for TL routing should follow a systematic flowchart that allows transparency, replicability, and methodological credibility (Berberian et al., 2015; Fisher, 2010). Multicriteria Analysis (MCA) is frequently used to support complex decision-making situations with conflicting goals, comparing scenarios or alternatives against a set of explicitly defined criteria that account for the most relevant aspects in a process (Esmail and Geneletti, 2018; Gonzalez and Enríquez-de-Salamanca, 2018). Other than optimizing criteria and ranking the alternatives, the MCA coupled to Geographic Information System (GIS) enables to add of geospatial intelligence into the decision-making framework (Nobrega et al., 2009), in this case making the alternatives evident and traceable, for example, through explicit spatial variables and enabling a quantitative assessment of all location alternatives (Pullin et al., 2016; Sutherland et al., 2018). However, this approach may be limited as a consequence of different weighting schemes, which could be subject to manipulation if not used in a participatory and transparent way (Esmail and Geneletti, 2018; Gonzalez and Enríquez-de-Salamanca, 2018; Pullin et al., 2016).

Our objective here was to present a systematic approach to compare alternative routes of power lines and indicate the route with the lowest environmental impact, focusing on the avoidance of forest loss. We present the planning and evaluation stages in a framework to assess different scenarios, allowing the comparison of alternative routes against a set of explicitly defined criteria. Specifically, we propose a workflow which includes: i) modelling of alternative routes using GIS and Least Cost Path Analysis (LCPA) based on two sets of criteria – engineering and environmental – explicitly and clearly presented; ii) scenarios with varying influence of those criteria, compared through spatial multicriteria analysis and Analytic Hierarchy Process (AHP), therefore allowing more objective information about the relative influence of different criteria upon the resulting routes; iii) quantitative evaluation of resulting routes, allowing for the comparison of alternative routes and identification of the best option.

Additionally, our procedure allows identifying the route segments where a consensus between engineering and environmental considerations exists. Similarly, the procedure identifies geographic-divergent segments, enabling the early identification of areas with potential conflicts where impact minimization needs to be negotiated. In spite GIS and multicriteria analysis being successfully used to support planning processes of linear infrastructures (Broniewicz and Ogrodnick 2020), the methodological approach presented in this paper is innovative by introducing a method that explicitly deals with the two impact prevention steps of the Mitigation Hierarchy.

To demonstrate the application of this workflow, we use as a case study a hypothetical route planning of a power line located in southern Brazil. Using Brazil as a scenario to our framework application is strategic, as it can be an opportunity to improve its TLs environmental licensing processes. In Brazil, TL projects are awarded to energy companies before assessing their environmental feasibility through EIA. Such practice is in total conflict with the logic of prioritizing the prevention of impacts, which is implied by the mitigation hierarchy and ordered by environmental regulations (Cardoso Júnior et al., 2014). Indeed, the current assessment workflow is generic in the initial planning phases, therefore it does not qualify the projects as environmentally feasible (Cardoso Jr., 2014). Despite being presented here in a Brazilian context, the proposed workflow could be adapted and replicated anywhere conflicting perceptions on TL route selection are expected.

2. Methods

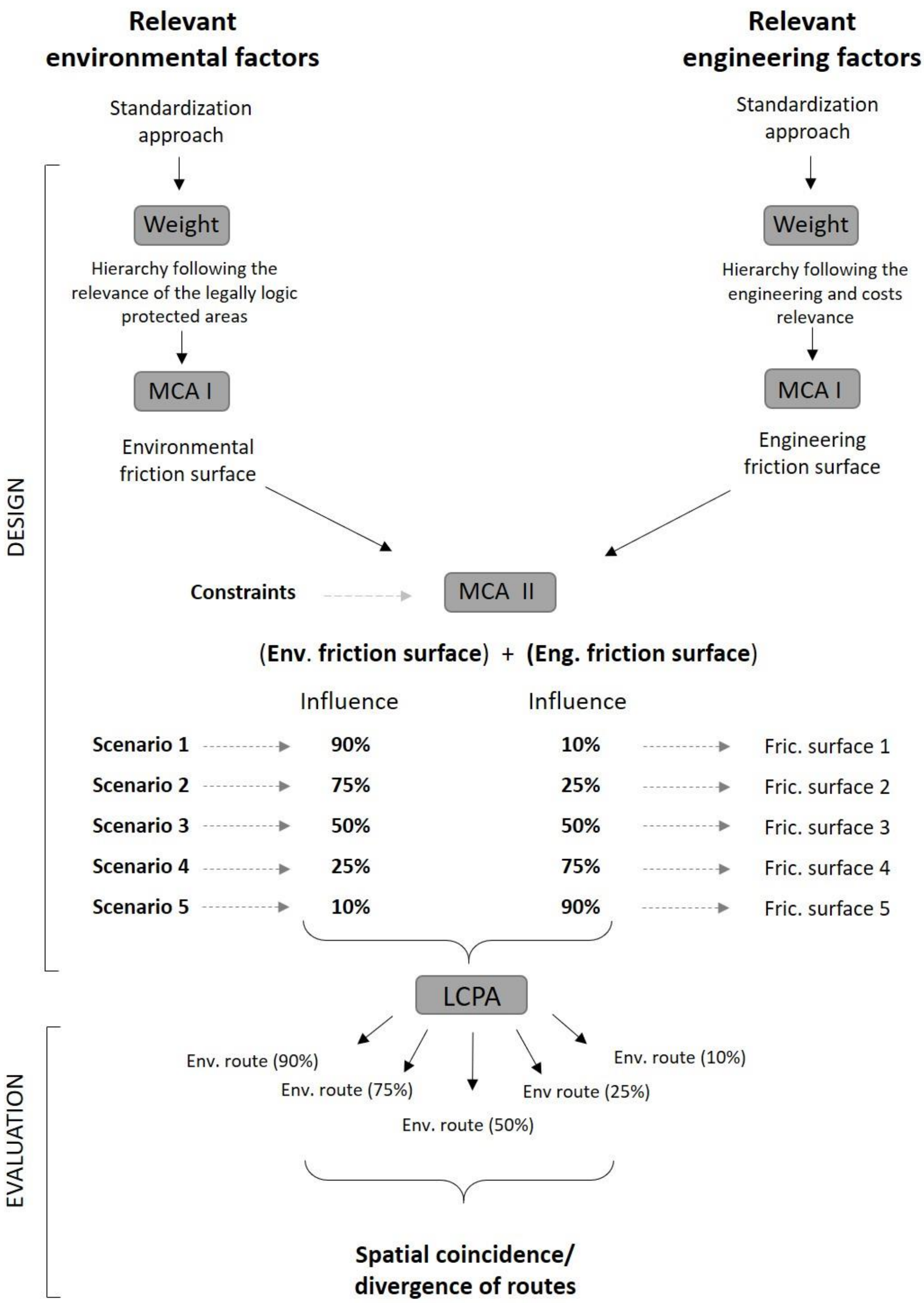

Figure 1. Overall method workflow. The approach is centered on Multicriteria Analysis (MCA) and GIS techniques and consists of design and evaluation stages, integrating environmental and engineering criteria. LCPA = Least Cost Path Analysis.

2.1 Criteria definition and spatialization

We defined two sets of criteria: environmental (5 criteria) and engineering criteria (8 criteria). All selected criteria were suitable for spatial representation as GIS layers, allowing spatially explicit TL route modelling. To identify the relevant criteria for the TL route planning we reviewed specialized literature (e.g., Araújo, 2016; Bagli et al., 2011; Campos et al., 2014; Lima et al., 2013; Shandiz et al., 2018). We also consulted environmental analysts of the Brazilian Institute of the Environment and Renewable Natural Resources, the national environmental licensing agency. Table 1 summarizes the overall ruleset, including the description of each input data and justification for each criterion.

The criteria were set as either constraints or factors. Constraints are Boolean criteria that restrict the geographic space available for projecting TL routes (0 = not available to routes; 1 = available) (Eastman, 2016). We considered that legally protected areas (category 1 according to the International Unit for Conservation of Nature - IUCN) and urban settlements were not available to TL so any projected route must avoid or bypass these areas.

Factors are criteria that define some degree of suitability for all geographic features (Eastman, 2016). All criteria were spatialized as friction maps. A standardization approach of the friction map for each criterion was computed using fuzzy membership (Jiang and Eastman, 2000) or reclassification approach in order to convert original pixel values of each criterion into friction values ranging between 1 (low friction – most suitable) and 255 (high friction – less suitable) (Table 1). For practical reasons, pixel values equal 0 are considered Null, preventing these areas from being considered in the process.

Table 1. Description of environmental and engineering criteria for power line installation and their respective justification, standardization method, and weights applied in the Analytical Hierarchy Process (AHP). NA (Not Applicable); constraints do not weight because they are incorporated lastly in MCA, to "mask out" unsuitable areas.

Criteria	Justification and source	Description of the input data	Standardization method (1 - 255)	Weights (AHP)
Constraints				
Urban settlements	Human health and safety. Not install infrastructure in areas classified as urban. Specialized literature.	Urban class	Boolean	NA
Protected areas – type I (IUCN)	Not install infrastructure in legally protected areas, where any direct consumptive human intervention is forbidden. Specialized literature.		Boolean	NA

Environmental factors				
Distance from protected areas – type VI (IUCN)	The farther, the better. Reduces effects on officially protected areas (mostly public) and whose main objective is to reconcile nature conservation with the sustainable use of natural resources. Specialized literature.		Fuzzy membership function, negative linear (abc = 1; d = maximum distance value)	0.1524
Permanent preservation areas (PPA)	Avoid impact on PPA. PPA are legally defined in Brazilian law to protect water resources, landscape, geological stability, biodiversity, and other aspects. Brazilian Native Vegetation Protection Law 2012 (Law n° 12.651/2012).	Landscape slopes > 45°; riparian buffers of 30, 50 and 100 m for intermittent, perennial, and higher-order water bodies, respectively.	Reclassification (1 or 255)	0.3899
Distance from forest remnants	The farther from forest patches, the better. Reduces environmental impact on Atlantic Forest remnants, which are protected by Brazilian Atlantic Rainforest Law 2006 (Law n° 14.128/2006).	Forest fragments > 5ha (minimum mapped area).	Fuzzy set membership function, negative linear (abc = 1; d = maximum distance value)	0.3899
Distance from existing linear structures	The closer, the better. Install infrastructures close to other installations to minimize fragmentation, and new disturbances. Specialized literature.	Transmission lines, railways, and state and federal paved roads.	Fuzzy set membership function, sigmoidal monotonically increasing (a = 1; b,c,d = 500) 500m threshold.	0.0679
Engineering Factors				
Slope	Avoid installing infrastructures in areas with steep slopes and requiring higher-cost towers (self-supporting towers and increasing height of the towers). Specialized literature.	Terrain slope (in %).	Fuzzy set membership function, sigmoidal monotonically increasing (a = 20%; b,c,d = 75%)	0.1428
All type accesses	Avoid installing infrastructure in areas that require higher-cost towers (self-supporting towers and increasing height of the towers). Avoids installing TLs that cross accesses. Consulting experts.	All types of access; paved and unpaved roads, railways.	Reclassification (1 or 255)	0.1428
Proximity to accesses	The closer, the better. Parallelism with other linear developments. Install infrastructures close to places with roads to avoid opening new accesses. Consulting experts.	All types of road access; paved and unpaved roads.	Fuzzy set membership function, positive linear (a = 1; b,c,d = 500)	0.1428
Existing linear structures	Avoid installing infrastructure in areas that require higher-cost towers (self-supporting towers and increasing height of the towers). Consulting experts.	Transmission lines, railways and state and federal paved roads. Avoid installing the project that crosses these infrastructures.	Reclassification (1 or 255)	0.1428
Proximity to existing linear structures	The closer, the better. Parallelism with other linear developments. Install infrastructures next to other installations to reduce costs with opening new accesses and maintenance. Specialized literature.	Transmission lines, railways, and state and federal paved roads.	Fuzzy set membership function, sigmoidal monotonically increasing (a = 1; b,c,d = 500)	0.1428

Forestry	Reduce right-of-way clearing or tower rising. Avoid installing infrastructures in areas that require a wider corridor or higher-cost towers. Specialized literature.		Reclassification (1 or 255)	0.1428
Streams	Prevent LCPA algorithm to follow the course of streams and rivers when processing routes. Specialized literature.	Intermittent, perennial, and higher-order rivers and lakes.	Reclassification (1 or 255)	0.1428

2.2 Design stage - Multicriteria Analysis and least-cost definition of alternative routes

Environmental and engineering factor maps were aggregated with Multicriteria Analysis using the Weighted Linear Combination rule (Eastman, 1999) in two different hierarchical steps: [1] integration of the factor sets to compute two cumulative friction surfaces, and [2] integration of the friction surfaces to compute the five different scenarios (Fig. 1).

2.2.1 Computing the cumulative friction surfaces

The friction maps represent the geographic variables after replacing the pixel values with the correspondent standardized values. Thus, all 4 friction maps of the environmental factors were integrated into a single cumulative friction surface (MCA I in Fig. 1). Similarly, a single friction surface was computed from the integration of the 7 friction maps from engineering factors.

The integration method used the Analytic Hierarchy Process (AHP) (Saaty, 1987), which computes the relative importance of the criteria (weighting). The procedure uses pairwise comparisons designed to reduce complexity and allow a consistency ratio analysis (Supplementary Material, Table S1) to assure the legitimacy of decision making when different stakeholders are involved (Esmail and Geneletti, 2018).

For the environmental criteria, we adopted a hierarchy of weights based on the Brazilian environmental legislation and for simplicity we adopted equal weights for engineering criteria. Because distinct weights were assigned to each environmental criterion, the consistency ratio of the judgments involved in the assignment of weights was tested and was acceptable (Saaty, 1987) (Supplementary Material, Table S2). Since the sum of factor weights must be equal to one, the resulting suitability map has the same range of values as the used standardized factor maps (1 - 255).

2.2.2 Computing the scenarios

After computing the friction surfaces, the next step consisted of integrating both environmental and engineering cumulative results into a single surface to represent each scenario. We included the constraints factors here. In the second round of MCA analysis (MCA

II in Fig. 1), we gradually varied the weights of the engineering and environmental cumulative surfaces to obtain five scenarios, which represent gradients of the relative influence of environmental friction *vs.* engineering friction surfaces.

The resulting surfaces for each five-scenario served as a reference for computing the TL routes through the Least Cost Path Analysis (LCPA) approach using the Pathway algorithm in TerrSet (Eastman, 2016). This tool allows finding the path between two targets that presents the lowest cumulative sum of the pixel's values from one point to another over a cost surface that defines how difficult it is to pass through each cell (Eastman, 2016). These resulting TL routes are not final designs but consist of the main routes that will guide more focused and ground surveyed studies of the power line to be installed.

2.3 Evaluation stage

Environmental and engineering metrics (Table 2) were used to quantitatively assess and compare the performance of the five alternative routes, and to select the best option.

Table 2. Metrics used to evaluate the performance of each modelled power line route.

Metric	**Description and suitability**
Length (km)	The total extension of TL route. Longer TL tend to increase engineering costs.
Forested area loss (ha)	When a TL route intercept forested area there is habitat degradation and/or habitat loss. Larger losses decrease project feasibility from the environmental perspective.
Permanent Preservation Area loss (PPA) (ha)	When a TL intercepts PPA, there is degradation and/or habitat loss of this class. Larger losses decrease project feasibility from the environmental perspective.
Average distance from forested fragments (m)	The average distance of each route pixel to the nearest forest pixel. Larger average distances, correspond to lower environmental degradation and larger project feasibility from the environmental perspective.
Average distance from linear structures (m)	The average distance of each route pixel to the nearest linear infrastructure pixel. From the engineering perspective, parallel TLs are desirable for both construction and maintenance. Lower average distances increase the project feasibility.
Average distance from road access (m)	The greater the average distance, the lower the feasibility.
Average slope (%)	From the engineering perspective, it is desirable to occupy flat terrain to build linear structures. Steeper slopes decrease project feasibility.
Number of linear structure crossings	The number of times a TL crosses linear infrastructures. Higher crossing numbers decrease project feasibility.

We also evaluated the spatial convergence of the output TL routes to check areas with less conflict between environmental and engineering perspectives. We assume the lowest potential conflicting areas correspond to landscape locations, or pixels, that present coincidence in all five alternative routes. In practice, the decision on routing in these areas is supported by both environmental and engineering perspectives, even each route has been computed using different weights. On the other hand, areas with the highest potential for conflict correspond to areas without overlap among the routes.

To identify the route overlapping, we overlaid and summed the five Boolean maps corresponding to the delivered TL routes, thus ranging from 1 (minimum) to 5 (maximum) overlap. Then, we used a moving window analysis (Filter algorithm in TerrSet) and assigned to a central pixel the sum of the neighboring pixels in a 3x3 window. This procedure resulted in a new output map. The route coincidence value of each pixel was classified with three classes: low coincidence (sum ≤ 5), intermediary coincidence (5 < sum ≤ 10), and high coincidence (sum >10). We chose this approach because it attenuates the effect of the slight differences in spatial location between different TL scenarios and allows for the definition of TL corridors (3x3 pixels routes) instead of TL routes (single-pixel routes). By using TL corridors, we allow that finer scale routing of TL, which is necessary for the executive engineering project, can be subject to adjustment after field assessment of both engineering and environmental factors that were not considered in the large-scale routing procedure. Although this early planning approach does not present a ground resolution for consideration of the more specific engineering issues, the output map allows engineers to tune the TL alignment blending other technical considerations such as straightness into the project.

2.4 Study case

To demonstrate the application of the proposed workflow, we set a hypothetical case study with the goal of finding the best route for implementing a TL using the environmental and engineering criteria listed above. The study corridor is in southern Brazil and connect the Muitos Capões municipality (51°22' 09" W, 28° 34' 59"S) to a destination point in Nova Santa Rita municipality (51° 20' 02" W, 29° 49' 20"S). The method was applied to a hypothetical 40-km wide macro-corridor (Supplementary Material Figure S1). The slope in the region varies from 0 to 290.9%, with narrow valleys with steep slopes, high hydrological density, and the presence of protected areas and important Atlantic Forest remnants.

The criteria were individually spatialized as friction raster maps with 30 x 30 m cell resolution. Supplementary Material Table S3 summarizes the information about the original spatial data used and their spatialization are shown in Supplementary Material Figure S2. Constraint and factor layers were created in ArcGIS 10.3 (ESRI 2015), while standardization, weighting, aggregation, LCPA, and other analyses were computed using TerrSet (Eastman, 2016).

3. Results

3.1 Multicriteria analysis and alternative scenarios

The two friction surfaces resulting from the AHP solutions, and MCA I simulations are represented in Figure 2. Overall, the environmental friction surface had a larger part of the landscape studied with high friction values, in contrast to the engineering friction surface (Fig. 2). These higher values represent specific sites that should be avoided and are characterized mainly by the overlap of permanent preservation areas and the forest fragments remnants. In the MCA II, the gradual weighting among scenarios showed scenario 1, with a better influence of environmental variables, with overall higher pixel values for LCPA algorithm (Fig. 2). In the engineering surface, friction values to TL routing were generally lower than in the environmental friction surface (Fig. 2).

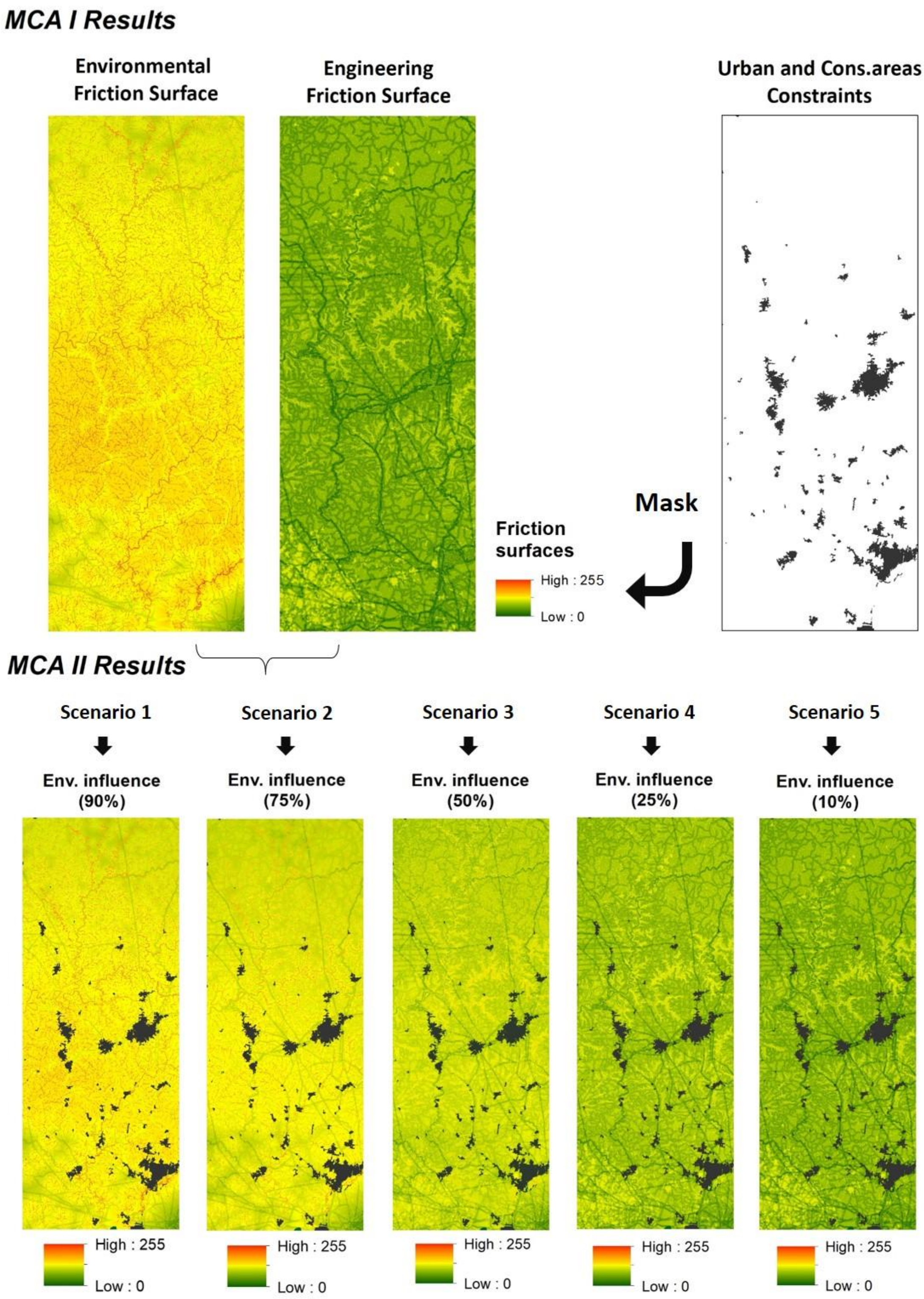

Figure 2. Friction surfaces resulting from multicriteria analysis simulations of scenarios with the increasing influence of environmental friction surface. Warmer colors (red) represent higher unsuitability for TL route location (higher values) and colder colors (green) represent sites with lower unsuitability.

3.2 Route comparison

The routes with the lower environmental influence (Env Route 50%, 25% e 10%) resulted in greater extension and lower linearity (Fig. 3). In comparison, the routes that had the greatest influence of environmental variables (Env Route 75% and 90%) were shorter and more linear (Fig. 3). None of the five scenarios was satisfactory for all the eight metrics evaluated (Fig. 4). According to the radar diagrams, the best scenario was Env. Route 75% (scenario 2) for most metrics (Fig. 4b). This scenario showed the greater mean distance from forest cover and less habitat loss than the scenario with the greatest influence of environmental variables (Env. Route 90%; scenario 1).

Overall, as expected, the routes with the higher influence of the environmental criteria achieved better performances in all environmental metrics, and in two engineering criteria. The detailed values of each metric in the five power line routes are shown in Supplementary Material, Table S4.

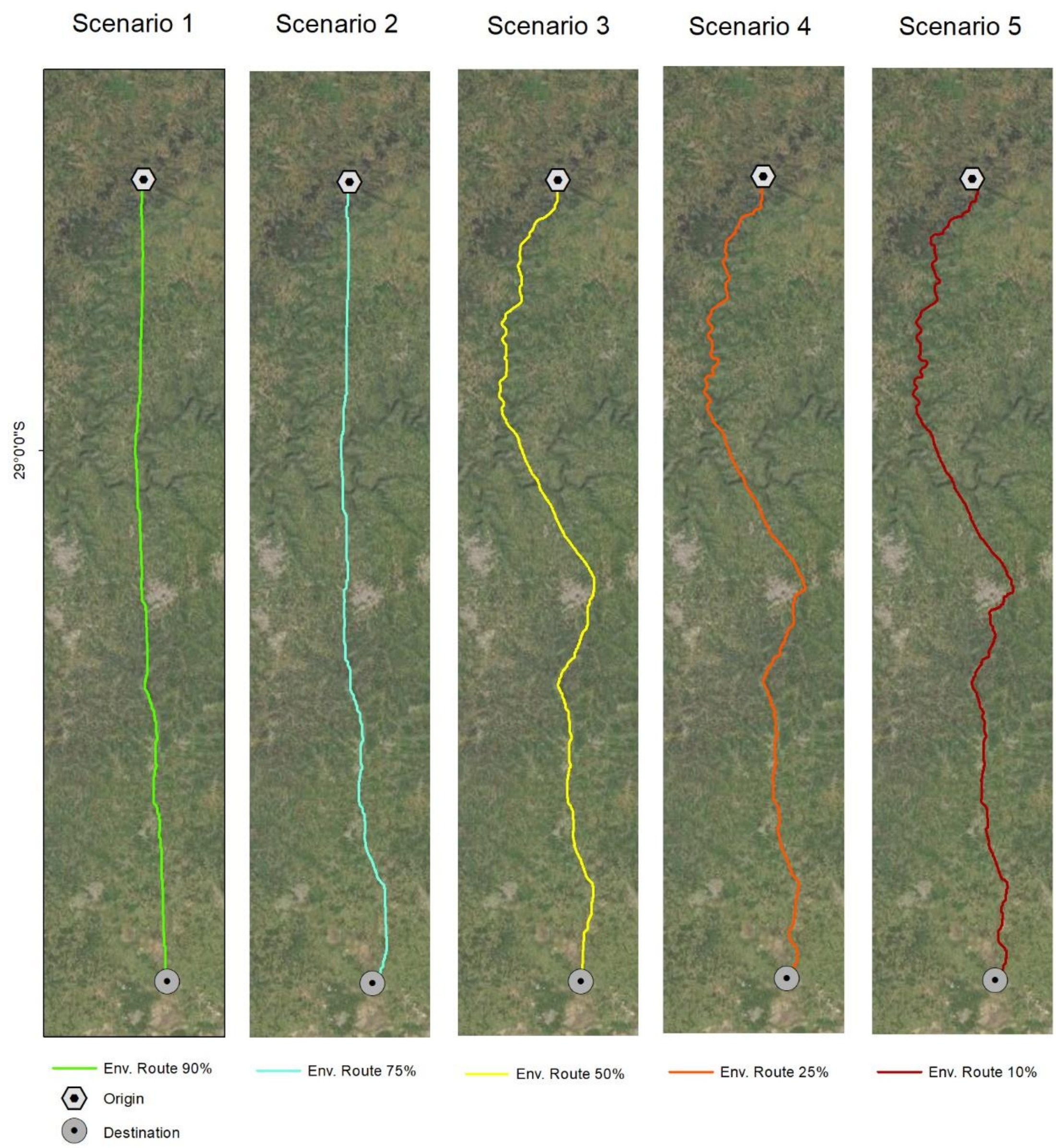

Figure 3. Power line routes resulting from five different scenarios with decreasing environmental criteria influence.

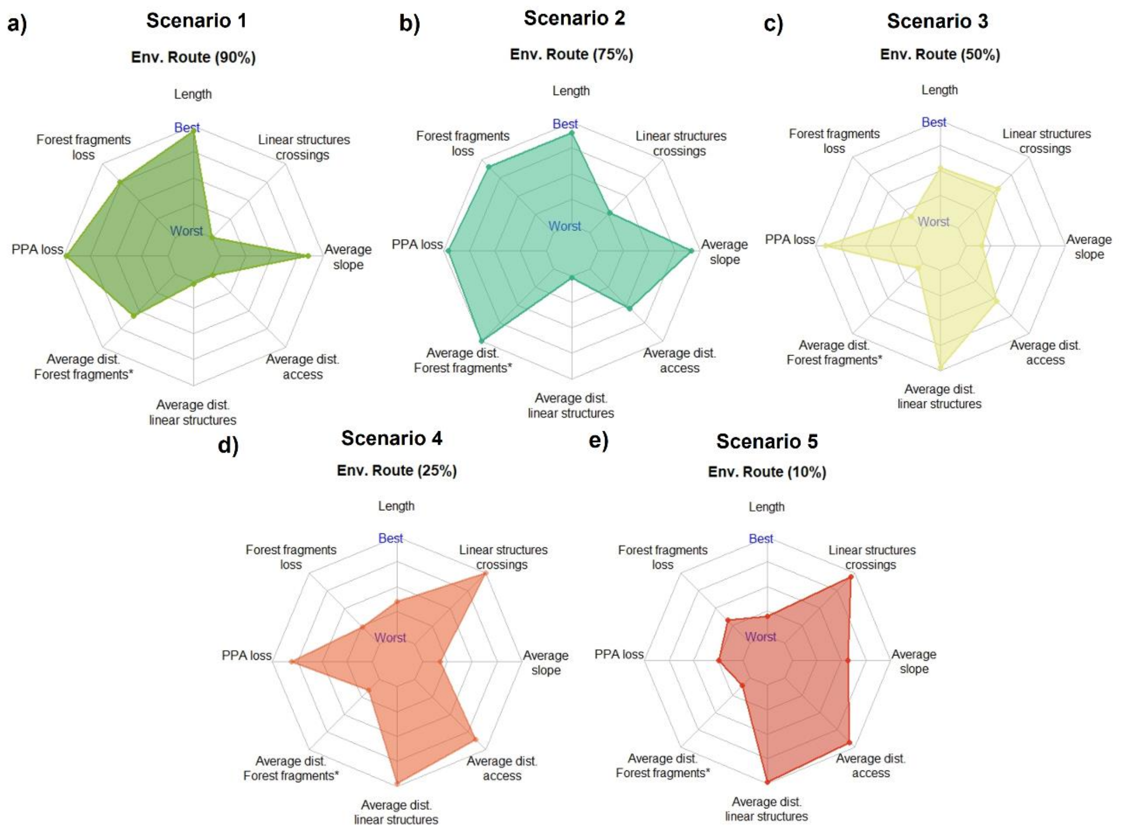

Figure 4. Environmental and engineering metrics are represented in a scale of suitability for power line installation (worst to best from the center outwards) under the five different scenarios of environmental influence. Each metric was normalized to 0 -> 1 values (representing worst -> best) according to the minimum and maximum values. The values representing 'Average distance from forest fragments' metric were multiplied by -1 so that it had the same logical representation in the radar diagrams as the other metrics (the greater the average distance from forest fragments, the better the project's suitability). The diagrams allow an overall assessment of each route (the larger the filled area in the radar, the most suitable is the route) and an interpretation of each alternative's strengths and weaknesses, based on each metric's performances. The colors represent the identification of each scenario.

3.3 Route coincidence

The spatial convergence between segments of all 5 modeled alternatives demonstrates the existence of three stretches that meet both environmental and engineering criteria (Fig. 5). Throughout the study area the 5 scenarios resulted in only 1 to 3 route alternatives (Fig. 5). The spatial convergence showed 29,7% and 5,3% of the pixels had intermediate and higher routes coincidence values, respectively, typically concentrated along the mid-southern part of the study area (Fig. 5). These coincidences of TL routes segments represent less conflict between environmental and engineering perspectives. More than half of the routes' pixels (65%) presented low coincidence values (Fig. 5), representing segments of potential conflicts between engineering and environmental perspectives.

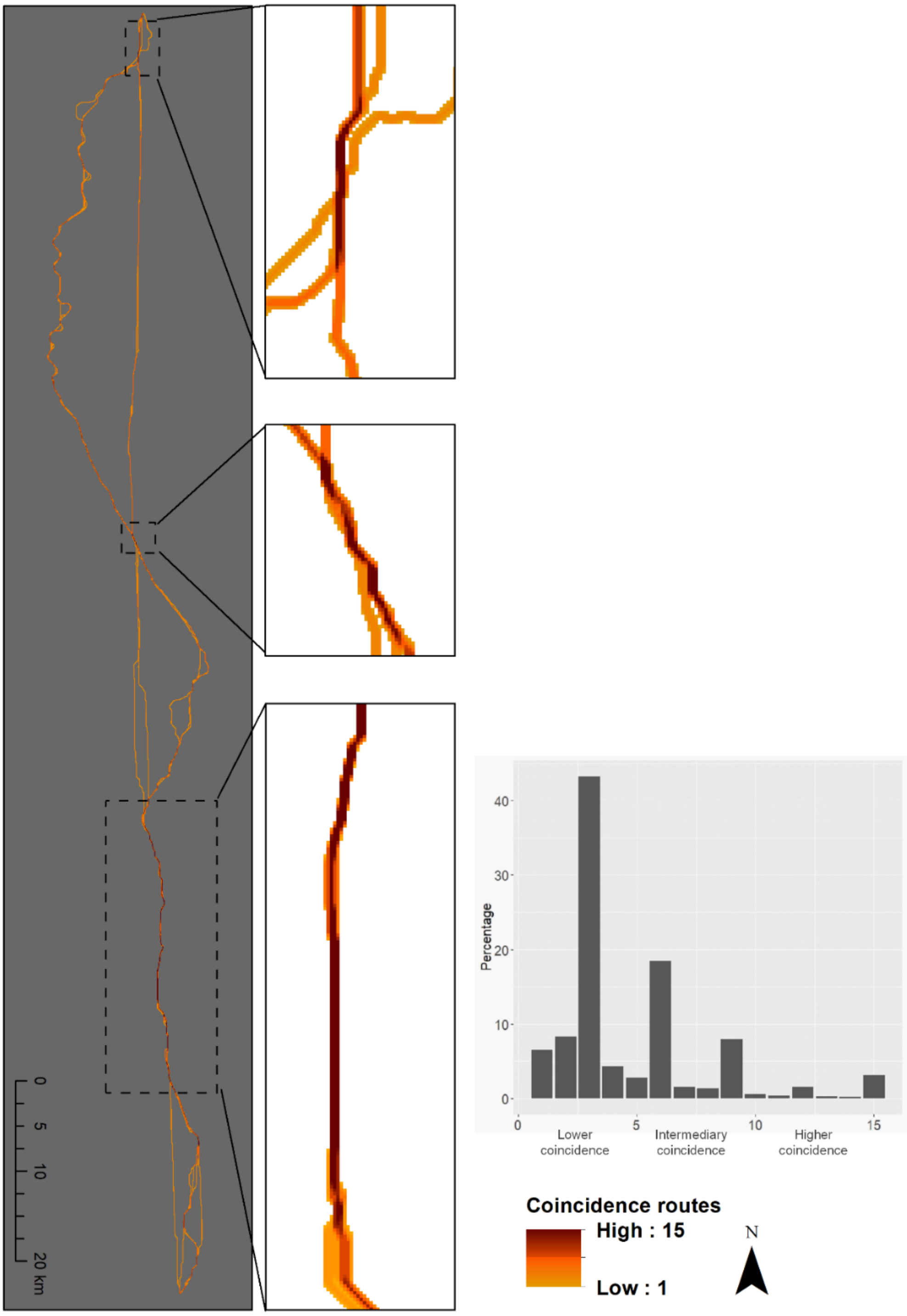

Figure 5. Coincidences and divergences along route corridors based on 3 x 3 moving window analysis. Route corridors presenting high degree of coincidence between alternative routes are highlighted on map. Histogram shows the percentage of pixels in each class of route coincidence (1 - 15), where 1 means less overlap and 15 means higher overlap of routes in that segment.

4. Discussion

Using a detailed step-by-step description of all methodological procedures, from criteria justification to final route selection, we presented a transparent, replicable, and testable workflow for introducing a diverse set of environmental criteria, meant to avoid or minimize habitat loss and degradation, early in the power line planning. Further, to identify the most suitable route, we used quantitative metrics to allow a less subjective decision. At the same time, after obtaining five different route alternatives, we proposed a methodology to identify TL corridors that can be segmented according to a degree of coincidence-divergence based on environmental and engineering criteria, enabling decision making with less conflict and precisely showing where there is divergence between environmental and engineering perspectives in route location.

To guarantee transparency and replicability to TL planning, we proposed and executed a workflow with at least ten different steps. Using the AHP procedure and different scenarios in MCA, we explicit our decisions and the potential influence of different weightings of environmental variables in contrast to the engineering variables. It is important to highlight that there are no fixed guidelines in MCA to indicate how a problem should be structured, and variables, criteria, and weights may change depending on the context in which they are introduced (Esmail and Geneletti, 2018). Although this flexibility is important to enable an adaptive management perspective, a systematic procedure, as proposed in our workflow, decreases the risk of results manipulation, contributing to information, transparency, credibility, auditability and eventually agility in EIA decisions.

Overall, the common practice is that environmental impacts are considered only superficially in TL planning phase (Cardoso Jr., 2014). To promote a more sustainable routing, we focused our approach in the planning process improvement through better robustness in environmental representation, aiming to prioritize the less habitat loss regarding the other impacts on biodiversity. We reached this through the preservation of the areas *in situ* (e.g., conservation areas, forest remnants, and PPAs), taking decisions considering the IUCN category of Strict Nature Reserve an exclusion criterion for TL routing, and in the AHP, equating the importance between PPAs and remnant forest fragments.

Unexpectedly, the best scenario was Env. Route 75% (scenario 2) for most environmental metrics. Besides having excluded the conservation areas from TL routing possibility, scenario 2 was characterized by greater distance from forest fragments and a smaller habitat loss than the scenario with the most significant influence of environmental variables (scenario 1, Env. Route 90%). Further, our results demonstrate that short routes may be the most suitable alternative even when environmental criteria strongly influence the route conception process. Short routes are a desirable property from the economic and technical perspectives since they possibly are less costly and are less prone to energy losses (Kishore and Singal, 2014; Lima et al., 2013). Nonetheless, this ‘least cost’ is true under at least two conditions: when engineering costs in unsuitable landscapes are low and when the environmental costs (management, restoration, monitoring) are also low. Together, these two conditions characterize a potential win-win situation, and they also highlight the importance of including environmental criteria and analyzing environmental costs (as monetary costs) of different route alternatives.

According to the mitigation hierarchy, avoidance is the first and most important step, and the best opportunity to maximize ecological and economic effectiveness is to start considering avoidance as early as possible in the planning process (Ekstrom et al. 2015). Our framework considered more robustly some environmental variables as habitat loss and degradation. However, the consideration about the achieved avoidance in this study is limited only to our impact representation by the criteria and did not apply to other important impacts that may also be incorporated into this planning phase as additional criteria. For example, a further necessary development in this approach is to differentiate the quality of remnant patches and their importance for landscape connectivity, as shown by Bergès et al., (2020). Further, impacts on biodiversity as bird collisions and electrocutions can also be anticipated, and therefore avoided, with similar approaches to those proposed by D’Amico et al. (2019) and Pérez-García et al. (2017), respectively.

Through moving window analysis, the overlap of five scenarios identified three potential corridors. Together they showed three convergence segments, representing just over 30% of corridors with higher coincidence. We can consider these specific sites as early identification of consensus areas between engineering and environmental criteria. The TL routing from these coincident points possibly reduces the risk of decision-making in environmental licensing, as they represent less conflict between environmental and engineering perspectives. On the other hand, when low coincidence corridors are present in the study area, TL planning along these landscapes involves a more risky and complex decision-making, corresponding to higher conflict between both perspectives, unless further information and analysis are used. This could be achieved, for example, by adding criteria to the route modeling analysis (Design stage) and re-running the corridor coincidence analysis.

Alternatively, the decision about the most suitable alternative could be drawn only after an environmental and engineering assessments provided by finer scale studies based on new field data. Moreover, the recognition of potential conflict areas is especially important because the cost of altering a project is lower early in the planning process before decisions about locations and technologies are locked in, and the range of feasible alternatives is narrowed (Phalan et al., 2018).

The early identification of high coincidence sections in the planning phase implies less risky decisions and allows the selection of TL route segments that can comply with mitigation hierarchy steps. The identification of coincidence areas also corresponds to places where the avoidance limits of locational alternatives have been achieved, so that impact studies and route refinement can focus on the other steps of the mitigation hierarchy (more detailed assessments focusing on minimization, restoration, and compensation of the remaining impacts). In lower coincidence areas, the route definition can be made based on the metrics evaluated, using as much as possible, the scenarios with most impact avoidance or new scenarios where it is still possible to improve the design through new modeling and metric analysis.

Improvement of our approach will depend on the resolution, quality, and availability of the data for producing spatial criteria which, the more refined and better represented in the initial planning phases, will ensure more significant optimization in reducing environmental impacts. Also, in further developments, we recommend incorporating quality control methods such as sensitivity analyses that aim to measure uncertainties regarding the set of weights in the routing process (Chen et al., 2010).

There are advantages in early impact assessment and in objectively considering environmental aspects in choosing the best layout of power lines (Dalloz et al., 2017). The more environmentally qualified the route selection in the planning phase, the less probability of a risky decision. By incorporating both environmental and engineering perspectives together in the workflow of impact assessment, and thereby anticipating different route alternatives that can be qualitatively and quantitatively compared, we are improving the TL routing process. Therefore, we recommend that impact assessment of TL should start at the planning phase, taking advantage of the first level of the mitigation hierarchy (impact avoidance). This practice will represent a gain in effectiveness of the impact assessment outcomes, a better focus on residual impacts during the following phases, a decrease in conflict level during the licensing process, and a potential reduction in time to project implementation.

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Supplementary materials – Chapter 1.

Table S1. Saaty´s pairwise rating scale know as Analytical Hierarchy Process (AHP).

Rating Scale - Intensity of Importance								
1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
*Less Importan*t								*More important*

Table S2. Environmental factors scoring according to the Saaty scale. Consistency ratio = 0.02 (CR ratings smaller than 0.1 are acceptable, Saaty 1987). For Multi-Criteria Evaluation using a weighted linear combination it is necessary that the sum of all weights = 1

Environmental factors	Permanent preservation areas (PPA)	Distance from forest fragments	Distance from protected areas - Sustainable use of natural resources	Distance from existing linear structures	***Weight***
Permanent preservation areas (PPA)	1	–	–	–	0.3899
Distance from forest fragments	1	1	–	–	0.3899
Distance from protected areas - Sustainable use of natural resources	1/3	1/3	1	–	0.1524
Distance from existing linear structures	1/5	1/5	1/3	1	0.0679

Table S3. Spatial data used in criteria spatialization. (*) Transmission lines spatial data provided by the Brazil's Access to Information Law.

Data	Source	Type of original data	Scale / resolution	Final data	Total area/total length data in study area
Urban settlements (ha)	Hasenack and Weber (2010)	Vector, polygon	1:50.000		46901.93
Protected áreas (ha)	MMA (2011)	Vector, polygon	1:100.000		2894.67
Forest fragments (ha)	SOS MA (2009)	Vector, polygon	1:50.000		130116.02
Linear structures (km)	Hasenack and Weber (2010) and other*	Vector, polyline	1:50.000		3790.43
Slope (%)	Digital elevation model (NASA 2018)	Raster	30 m	Raster, (30 m) UTM, SIRGAS 2000	0 – 290.96
Access (km)	Hasenack and Weber (2010), updated.	Vector, polyline	1:50.000		17834.06
Forestry (ha)	Hasenack and Weber (2010)	Vector, polygon	1:50.000		59479.24
Hydrography (km)	Hasenack and Weber (2010)	Vector, polyline	1:50.000		93243378.77

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Table S4. Performance of the five-power line alternative routes based on environmental and engineering metrics.

Metrics	**Env. route (10%)**	**Env. route (25%)**	**Env. route (50%)**	**Env. route (75%)**	**Env. Route (90%)**	**Min - max**
Length (km)	172.12	165.94	158.86	144.05	141.74	141 - 172.12
Forest area loss (ha)	53.82	57.87	61.92	24.93	32.31	24.93 - 61.92
Permanent Preservation Area loss (P SPA) (ha)	55.26	21.51	15.75	12.51	11.07	11.07 - 55.26
Average distance from forest fragments (m)	750.07	762.46	723.15	1147.7	944.63	723.1 - 1147.7
Average distance from linear structures (m)	320.67	353.46	350.62	2080.84	2064.56	320.6 - 2080.8
Average distance from road access (m)	120.19	131.17	179.09	178.22	258.02	120.1 - 258.0
Average terrain slope (%)	19.62	21.93	22.07	17.5	17.92	17.50 - 22.07
Number of linear structure crossings	147	141	194	229	262	141 - 262

Supplementary Material – Figure S1

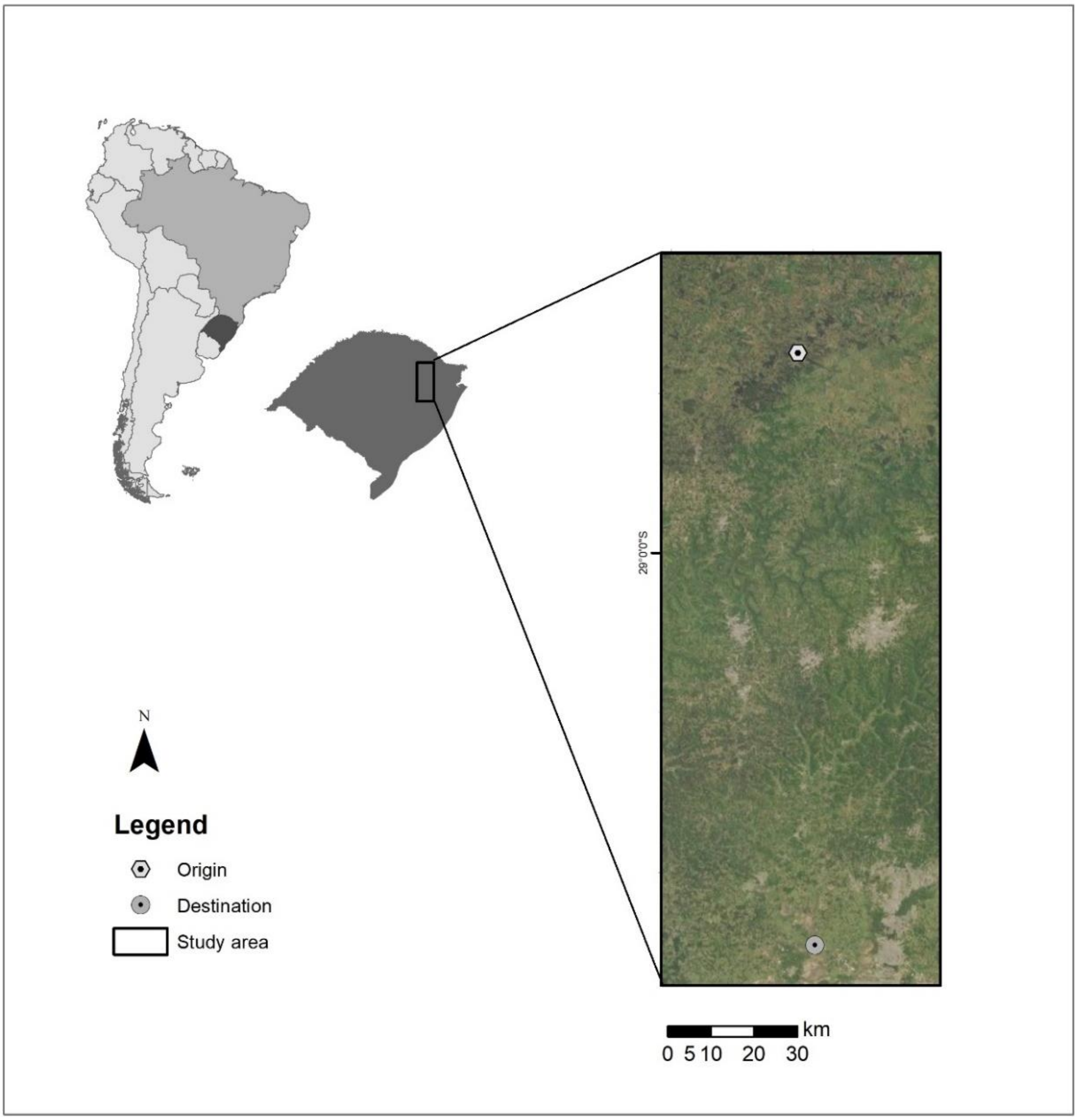

Figure S1. Study area where the systematic method presented in the workflow was applied.

Supplementary Material – Figure S2

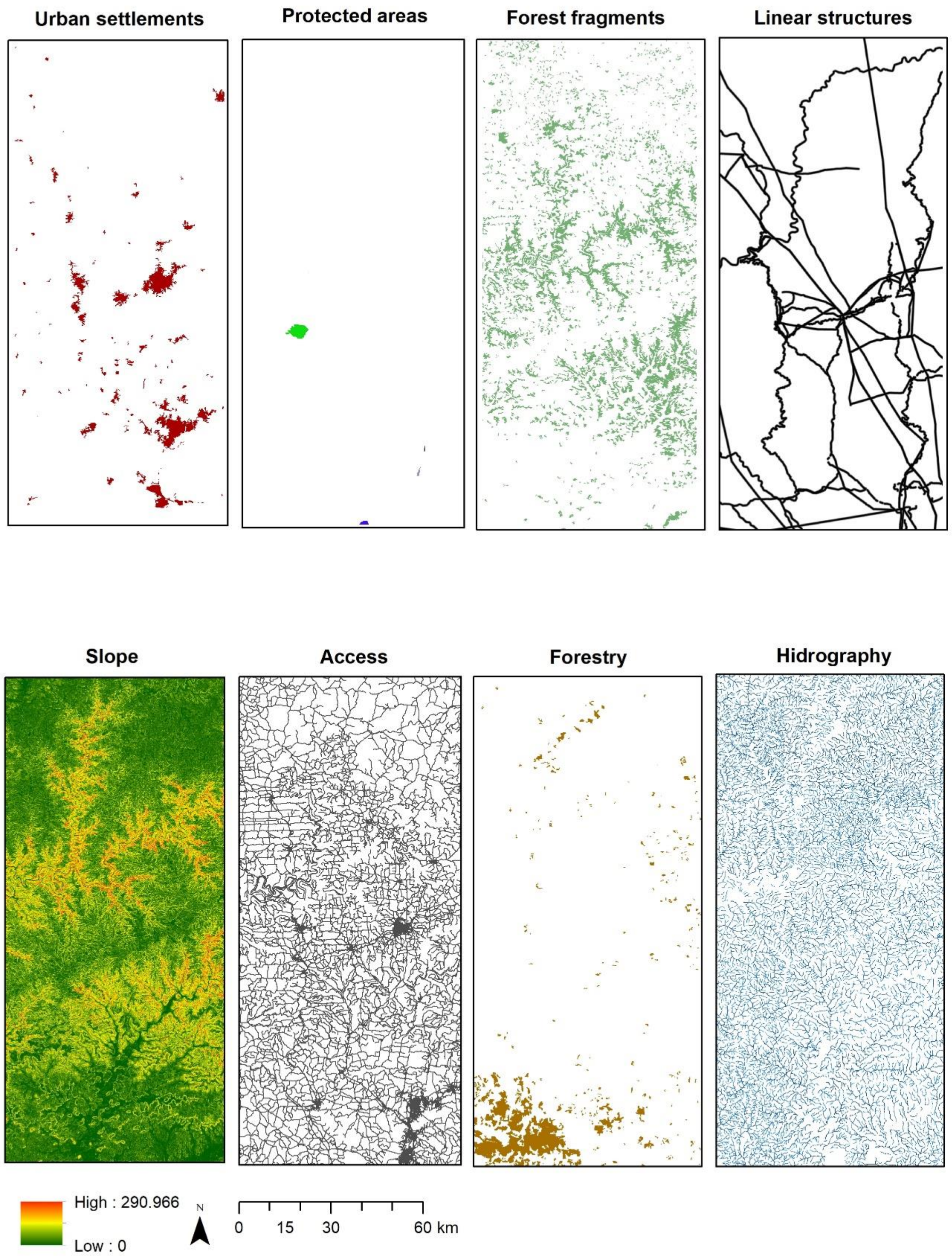

Figure S2. Spatial data used in environmental and engineering criteria spatialization.

Capítulo 2

Risco de eletrocussão de aves em linhas de energia: uma abordagem para priorizar espécies, áreas para conservação e mitigação de impacto

Larissa D. Biasotto, Francisco Moreira, Glayson Bencke,

Marcello D'Amico, Andreas Kindel & Fernando Ascensão

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Chapter 2 - Risk of bird electrocution in power lines: a framework for prioritizing species and areas for conservation and impact mitigation

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AUTHOR CONTRIBUTIONS

Conception and design were conducted by LB, FM, MD, AK, and FA. Data collection was performed by LB and GAB. Data preparation and analysis were performed by LB and FA. The first draft of the manuscript was written by LB. All authors commented and critically reviewed this and subsequent versions of the manuscript. All authors read and approved the final manuscript.

ABSTRACT

Electrocution on power lines is an important human-related cause of bird mortality and an important conservation issue worldwide. Besides impacts on bird populations, electrocutions cause power outages, resulting in damage to power line network integrity. However, there is a general lack of knowledge on the risk of bird electrocution, especially in developing countries. Generating information over large scales without resorting to local mortality data can be useful for the development of regional management strategies, particularly in countries where electrocution is poorly documented. Here, we developed a framework to model the risk of bird electrocution as an interaction between the species-specific exposure to power lines (pole density within a species distribution range) and susceptibility (morphological and behavioral traits associated with electrocution hazards). We applied this framework to Brazil, identifying 283 species that face a risk of electrocution, of which 38 were classified as higher risk, mostly raptors (76%). The Pantanal (a large wetland biome) concentrates the greatest cumulative susceptibility due to the high number of species vulnerable to electrocution (i.e., large species using power lines for perching or nesting), while the Atlantic Forest region has a higher risk for electrocution, due to the spatial overlap between the presence of vulnerable species and high exposure to power lines. Furthermore, our study identified spatial patterns of bird electrocution, highlighting priority areas for electrocution susceptibility and electrocution risk to be further investigated, and where measures to mitigate bird electrocutions should be applied on new and existing power lines. Our framework allows a preliminary assessment aimed at identifying areas of higher risk of electrocution, to highlight species vulnerable to this threat, and to improve power line routing. This approach can be replicated to other understudied areas of the world where the same information is available.

Keywords: Avian conservation, energy distribution, linear infrastructures, electric utility, pylon management, pole retrofitting.

RESUMO:

Eletrocussões em linhas de energia são uma importante causa de mortalidade de aves e um problema de conservação em muitos países. Além de impactos populacionais em aves, podem causar interrupções no fornecimento de energia, resultando em prejuízos econômicos. No entanto, existe uma carência de informação sobre eletrocussões em aves, sobretudo em países em desenvolvimento. Gerar informações em grandes escalas espaciais sem recorrer à coleta de dados de fatalidades pode ser útil para o desenvolvimento de estratégias regionais de gestão, particularmente em países onde as eletrocussões são mal documentadas. Desenvolvemos um modelo conceitual para estimar o risco de eletrocussão de aves como resultado da interação entre exposição às linhas de energia (densidade de postes dentro da área de distribuição de uma espécie) e suscetibilidade (atributos morfológicos e comportamentais associados ao risco de eletrocussão). Aplicamos essa abordagem para o Brasil e identificamos 283 espécies que estão sujeitas a risco de eletrocussão, sendo 38 classificadas como prioritárias para a conservação, a maioria rapinantes. O Pantanal é o bioma que concentra a maior suscetibilidade acumulada, devido à presença de muitas espécies vulneráveis à eletrocussão, enquanto a Mata Atlântica figura com o maior risco de eletrocussão devido à alta suscetibilidade e exposição. Nosso modelo conceitual pode ser útil como avaliação preliminar para identificar áreas de alto risco de eletrocussão e espécies mais vulneráveis, bem como para elaborar diretrizes para qualificar o licenciamento ambiental de linhas de energia. Além disso, nosso estudo permitiu identificar padrões espaciais de eletrocussões de aves, revelando áreas prioritárias para investigação adicional tanto da suscetibilidade quanto do risco de eletrocussão, ou onde medidas de mitigação devam ser aplicadas em linhas de energia novas ou já existentes. Essa abordagem pode ser replicada em

outras áreas geográficas do mundo com o mesmo tipo de informação disponível e onde eletrocussões sejam negligenciadas.

Palavras-chave: Conservação de aves, distribuição de energia, eletroplessão, infraestruturas lineares, mitigação de postes, renovação de postes.

1. Introduction

Access to electricity is essential to meet basic human needs, boost economic growth and foster development. Today, almost all regions of the globe are crossed by transmission networks, which are continually expanding to underserved regions (Jenkins, Smallie, & Diamond, 2010). However, despite their benefits to humans, power lines can pose a serious threat to birds by causing direct mortality due to collision with wires and electrocution (Bernardino *et al.*, 2018; Biasotto & Kindel, 2018; D'Amico *et al.*, 2018). Such mortality can have negative effects on population dynamics and demography, thus potentially affecting the persistence of species over time. Population-level impacts caused by power lines have been demonstrated, for example, for the Cape vulture *Gyps coprotheres* (Boshoff *et al.*, 2011), Bonelli's eagle *Hieraaetus fasciatus* (Hernández-Matías *et al.*, 2015), and Ludwig's bustard *Neotis ludwigii* (Shaw *et al.*, 2015), and for a number of other raptor species as reviewed by Slater *et al.* (2020). Bird electrocutions may also affect human populations, as they can cause power outages (Burgio *et al.*, 2014; Reed *et al.*, 2014) and wildfire ignitions (Guil *et al.*, 2018), resulting in economic losses for companies and customers (Maricato *et al.*, 2016). Thus, assessing the risk of bird electrocution is relevant from both a biodiversity conservation and an economic perspective.

Identifying both species and areas most prone to electrocution events is essential to mitigate the impacts of existing power lines and to improve the planning of new energy corridors. However, the systematic collection of bird-electrocution data along power lines has been primarily performed at a local scale, and mainly for the identification of high-risk structures (Tintó, Real, & Mañosa 2010; Guil *et al.* 2011; Dixon *et al.*, 2017). Upscaling these surveys from the local scale to larger management areas (at the regional or country level) can be difficult to achieve due to the high amount of resources and time required. The alternative of multiple surveys conducted on a local scale, if not coordinated, may fail to identify where mitigation and conservation efforts are most needed by overlooking areas and species with higher electrocution risk (Dwyer *et al.*, 2016). Therefore, generating sound information at large scales without performing extensive fieldwork would be highly useful for identifying those areas where to develop site-based management strategies (D'Amico *et al.*, 2019). This can be particularly important in countries where electrocution events are poorly documented and where power line grids are expanding rapidly (Eccleston & Harness, 2018).

Here, we suggest a framework for an initial risk assessment, at a large scale, using already available data on bird species and power line networks. The framework is based on the combination of two types of species-specific information, namely exposure to power lines and susceptibility to electrocution which, when combined, provide an integrated measure of the electrocution risk (Fig.1). Exposure is defined as the likelihood for the individuals of a target species to encounter an electric pole and is assumed to increase proportionally with increasing pole density (Dwyer *et al.*, 2016). That is, when a species inhabits a geographic range with a high pole density, that species has a high overall exposure, and consequently the probability of electrocution occurring increases (Dwyer *et al.*, 2020). Species susceptibility to electrocution is mainly influenced by intrinsic behavioral and morphological traits (Bevanger, 1998; Janss, 2000). Birds using power line structures as poles and wires for perching (Prather & Messmer, 2010) and nesting (Morelli *et al*., 2014; Moreira *et al*., 2018) are supposed to be more susceptible. Susceptibility also increases with body size (Dwyer *et al*., 2015), as electrocution occurs when a bird simultaneously touches two-phase conductors or one conductor and a ground wire device on a pole (Janss, 2000). Similar frameworks estimating risk as a combination of exposure and susceptibility have been previously proposed to address other impacts related to linear infrastructures, such as roadkills (Visintin, van der Ree, & McCarthy, 2016; Morelli, Benedetti, & Delgado, 2020) and collision with power lines (D'Amico *et al.*, 2019).

Our framework allows a preliminary assessment of potential electrocution risk for whole bird communities over broad geographical scales (regional to continental, but potentially also applicable at a global scale). We applied this framework to Brazil, the largest megadiverse country, and for which no specific study or standardized assessment of bird electrocution has been conducted to date. With rare exceptions, bird electrocution has been largely neglected in the Neotropics (Galmes *et al.*, 2017). In Brazil, all information consists of a few published casualty records and some anecdotal reports available in the scientific or grey literature. However, the country has a high species richness in taxonomic or functional groups known to be affected by electrocutions elsewhere, and there is no reason to suspect that such casualties do not occur in a similar way in Brazil. Electrocution also represents a threat to mammals, a group for which fatality events are far better documented in Brazil (Lokschin et al. 2007; Corrêa et al. 2018). Together, this evidence suggests that bird electrocution, although currently underreported, is a real issue that potentially affects many species in Brazil. Therefore, it is necessary to increase our ability to understand potential electrocution risk patterns across Brazilian regions. Here, we aimed to answer the following questions: 1) How is the overall bird susceptibility to electrocution spatially distributed? 2) How is the potential overall risk of bird electrocution spatially distributed? 3) Which species may face a higher risk of electrocution and, therefore, should receive special attention for conservation and mitigation?

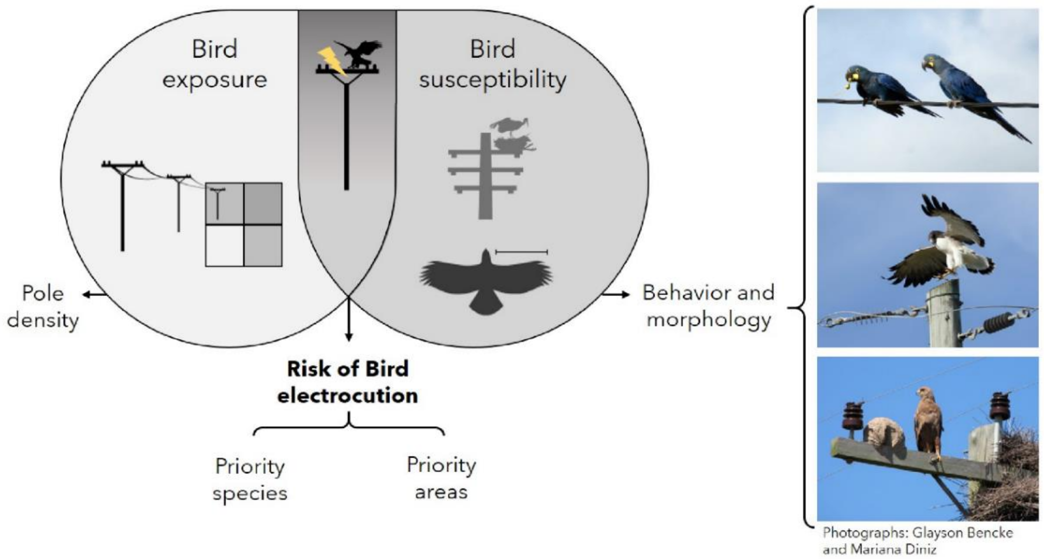

Figure 1. General framework to assess the risk of bird electrocutions. Exposure is measured as the density of electrical infrastructure within the species distribution and susceptibility is related to the morphological and behavioral traits associated with a higher risk of electrocution. This approach allows identifying species and areas with higher electrocution risk.

2. Methods

2.1 Study area

Brazil has a large land area (>8.5 M km^2), about half of South America. Both human population growth and urbanization rates are unevenly distributed across the country and demand an extensive and growing energy network (MME, 2019). Thousands of kilometers of power lines traverse the six Brazilian biomes (Fig.2), regions with distinct environments defined according to the prevailing climate and vegetation type: Amazon (tropical rainforests), Atlantic Forest (coastal rainforests), Caatinga (seasonally dry forests), Cerrado (tropical savannas), Pampa (subtropical/temperate grasslands), and Pantanal (tropical wetlands) (IBGE, 2019). This environmental heterogeneity affords an exceptional diversity of birds, accounting for almost 20% of the world's bird species richness (Jetz, Thomas, & Joy, 2012).

2.2 Power line information

We used the georeferenced database on the distribution of poles at the country level (updated through November 2018) available from the Brazilian Electricity Regulatory Agency (ANEEL). We selected structures from medium-voltage power lines (1-44 kV, n=30,665,490 poles) as these are the most likely to cause bird electrocutions, because the distance between the electrical components (wire-wire and pole-wire) matches the wingspan of several bird species (APLIC, 2006; Lehman *et al.*, 2007; Eccleston & Harness, 2018). Throughout the text we apply the term 'pole' to designate all the structures used to support medium-voltage power lines in Brazil, regardless of their material or specific configuration, as there is no information available that allows to explicitly distinguish between the different structures (such as wood poles or pylons).

2.3 Bird species information

We used the spatial data available from BirdLife International and Handbook of the Birds of the World (www.birdlife.org/datazone; BirdLife v10, 2017) to obtain georeferenced polygons corresponding to the geographic range of each species. We excluded marine, insular, extinct, and vagrant species according to the latest checklist of Brazilian birds published by the Brazilian Ornithological Records Committee – CBRO (Piacentini *et al*., 2015). We reconciled the BirdLife and CBRO datasets for taxonomic inconsistencies (e.g., use of different scientific names for the same species or the adoption of divergent species limits for certain taxa). Whenever a species in BirdLife was treated as two or more distinct species on the CBRO checklist, we treated them as a single species in our analyses. This resulted in a working list of 1,668 regularly occurring continental species (87% of the Brazilian species).

Wingspan is often selected as an indicator of morphological susceptibility to electrocution in birds (Bevanger, 1998), but it is not available for most Brazilian species. We used wing length as a proxy because this measure often represents the overall body size better than other univariate traits (e.g. Wiklund, 1996), and because it correlates well with wingspan in a wide variety of bird groups (see Supplementary Material, Figure S1). For the species for which we could not obtain accurate wing-length data in the literature (n = 30, all passerines), we estimated missing values using a linear model relating ‘wing length’ ~ ‘body length’ (see Supplementary Material, Figure S2).

To assess the behavioral susceptibility to electrocution, we classified each species according to its use of poles and wires for perching or nesting. First, we searched for evidence of perching or nesting on cables and poles in the online photographic archive of Brazilian birds WikiAves (www.wikiaves.com.br). This citizen-science platform currently encompasses over 3 million photographic records of Brazilian birds from all over the country. For each species, photographs were inspected until unequivocal evidence of perching and/or nesting on poles or wires was found (if any). This meant that, to be accepted, a record had to clearly show one or more individuals of the species perched on a power wire or pole, or with an active nest built on a pole or its associated structures (transformers, cable supports, etc.). To facilitate the search for images of nesting behavior, we filtered photographs with content ‘nest’ or main actions ‘incubating’, ‘caring for/feeding offspring’ or ‘building nest’ using the website built-in advanced search tool. For species poorly represented in the WikiAves database (e.g., rare or restricted-range species) and lacking evidence of the use of power line structures, the potential for perching/nesting on poles or wires was assessed by one of us (G.A.B) based on his extensive field experience with Brazilian birds and using evidence accumulated for phylogenetically related species sharing similar behavior and habitat preferences.

2.4 Modelling framework and analysis

The framework here proposed allows obtaining independent and complementary maps of susceptibility, exposure and risk as defined in Fig. 1. We used raster information with the same extent (Brazilian territory) and a 50 x 50 km resolution (n = 3,419 cells). This resolution is suitable for our purposes since 76% of the 98 Brazilian energy companies manage areas larger than 2,500 km² (equivalent to our pixel of 50 x 50 km). In addition, this resolution is recommended for continental or broad-scale analysis (Hawkins *et al.*, 2008). Therefore, it can be assumed as an appropriate scale for regional mitigation planning and management. We conducted the analyses at the biome level because each Brazilian biome contains a distinct bird assemblage and has unique drivers affecting biodiversity (Souza *et al.*, 2020). These drivers (land-use and land-cover changes) directly influence the rates of urbanization and expansion of the energy network. There are also several legal and conservation planning instruments that have been developed and/or are applied at the biome level and need to be complied by energy companies. The delimitation of Brazilian biomes followed IBGE (2019).

We started by building an overall exposure map based on the electricity pole distribution at the country level (see section 2.2), described as the density of medium voltage poles per unit area (50 x 50 km grid cell or km²) (Fig. 2, step 1). The value of pole density was log-transformed to reduce the importance of the few cells containing very large urban areas and correspondingly very high pole densities. We derived species-specific exposure maps (Fig. 2, step 2) for the subset of behaviorally susceptible species (i.e., those species identified as using cables and/or poles; see 2.3) by clipping the overall exposure map with the polygon of distribution of each species.

Similarly, we built species-specific susceptibility maps (Fig. 2, step 3A) by using the wing length (in mm) as a susceptibility indicator and assigning this value to each pixel of each individual species map. We then obtained the overall susceptibility map for Brazil by summing all species-specific susceptibility maps (Fig. 2, step 3B). We chose to work with the cumulative susceptibility because we assume that all species using power line structures have some risk of electrocution, even the small ones. Thus, this metric indicates the accumulated susceptibility for each pixel, considering only those species that use power line structures. From this overall susceptibility map, we estimated the median value of susceptibility for each biome.

Using these information layers, we further derived species-specific maps of electrocution risk by multiplying the species morphological susceptibility (i.e. wing length) and exposure maps (Fig. 2, step 4A). To obtain the map of overall electrocution risk in Brazil (Fig. 2, step 4B), we multiplied the overall exposure map by the overall susceptibility map, from which we also extracted the median risk for each biome. The species-specific maps of electrocution risk were used to rank species according to their median risk (within their respective distribution ranges) (Fig. 2, step 5). To identify the subset of species potentially most affected by electrocution (i.e., with higher median risk values), we split the ranking into different classes using the method proposed by (Jiang, 2013) for data with heavy-tailed distributions. The method partitions the class intervals and so establishes the number of classes through an iterative multistep approach. The first step splits data values around the mean into two parts (head and tail); the next step splits the above-average values again into head and tail by the new mean, and so on until the head values are no longer heavy-tailed. Each mean corresponds to the upper limit of a class. This approach resulted in three classes, interpreted by us as species with 'higher', 'intermediate' and 'lower" electrocution risk, respectively (Fig. 2, step 6). We used this objective classification to reduce arbitrariness in the assignment of classes, as we do not have data to establish a clear relationship between risk level and priority level, which should ideally be defined on a local or case-by-case basis. We considered higher-risk species to be of greatest concern for conservation and mitigation actions at the national scale.

Finally, the overall exposure map, the species-specific maps, and the final susceptibility map were normalized to 0-1 values according to the minimum and maximum values in each map, with 0 being assigned to the grid cells with the lowest observed value and 1 to the grid cells with the highest observed value. This facilitates comparisons since all maps are on the same scale and ensured that the values of the input maps (exposure and susceptibility) had equal weights when multiplied to produce the risk map. We performed all spatial analyses in R environment (R Core Team, 2020) and the R packages 'sf' (Pebesma, 2018), 'fasterize' (Ross *et al.*, 2020), 'raster' (Hijmans *and* van Etten., 2020), 'classInt' (Bivand 2020a), and 'rgdal' (Bivand *et al*., 2020b). Map layouts were made using ArcGIS 10.3 (ESRI, 2015).

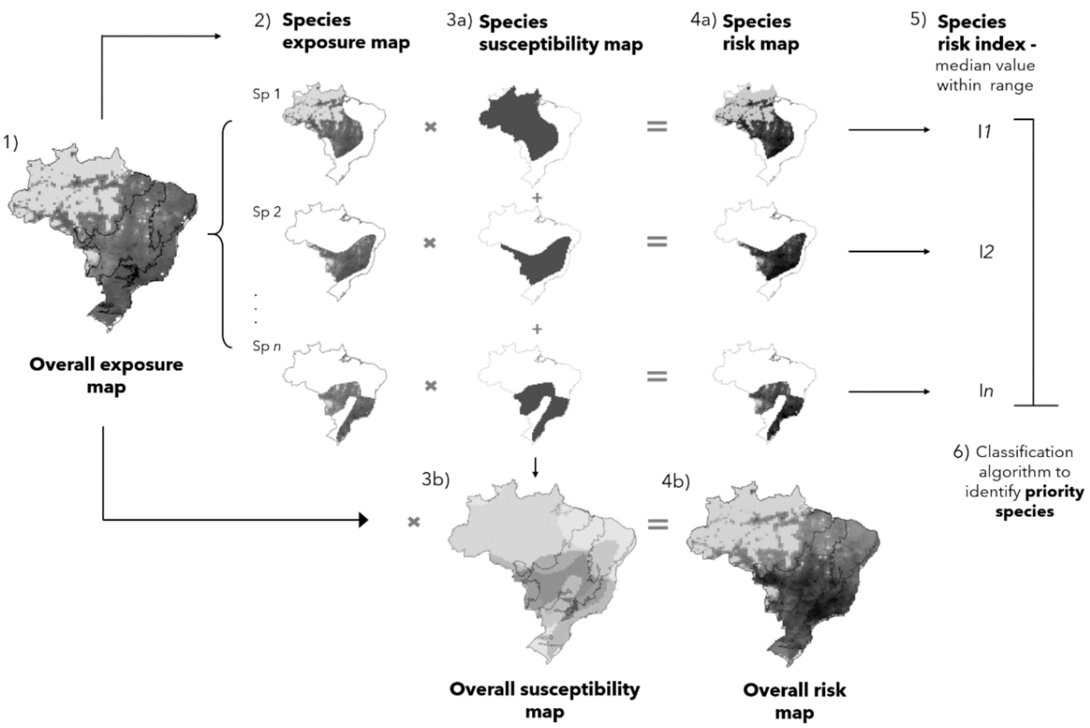

Figure 2. Workflow to identify target species and areas for bird electrocution prevention/control in eight steps. (1) Identification of geographic areas with high pole density – overall exposure map. (2) Obtaining species-specific exposure maps by overlaying the species distribution areas with the overall exposure map. (3a) Insertion of the wing length value in the raster maps of the species distribution to generate the species-specific susceptibility maps. (3b) Cumulative map of susceptibility by summing up all species-specific susceptibility maps. (4a) Species risk maps obtained by multiplying species-specific susceptibility and exposure maps. (4b) Identification of areas with higher risk of bird electrocution by multiplying the

overall exposure and overall susceptibility maps. (5) Extraction of median value within species risk maps. (6) Identification of higher risk species.

3. Results

Pole density across the country ranged from 0 to 260 poles/km² (Table 1). Extensive areas in the Amazon (more than half of the biome's land surface) and Pantanal, and a few areas in the Cerrado, had very low pole densities (Fig. 3a). The Atlantic Forest, Pampa, Caatinga and the rest of the Cerrado had considerably higher and more homogeneous pole densities (Fig. 3a).

Table 1. Pole density of medium voltage power lines (1 - 44 kV) in the six Brazilian biomes. Biomes are arranged by the median pole density.

Biome	Range pole density / km²	Mean (± SD) pole density / km²	Median pole density / km²
Atlantic Forest	0.5 – 259.8	13.1 ± 19.8	9.7
Pampa	0.5 – 68.3	6.0 ± 7.8	4.5
Caatinga	0.1 – 25	4.4 ± 3.3	3.6
Cerrado	0.0 – 63.8	3.8 ± 4.7	2.6
Pantanal	0.0 – 5.4	0.6 ± 1.0	0.1
Amazon	0.0 – 48.4	0.8 ± 2.3	0.0

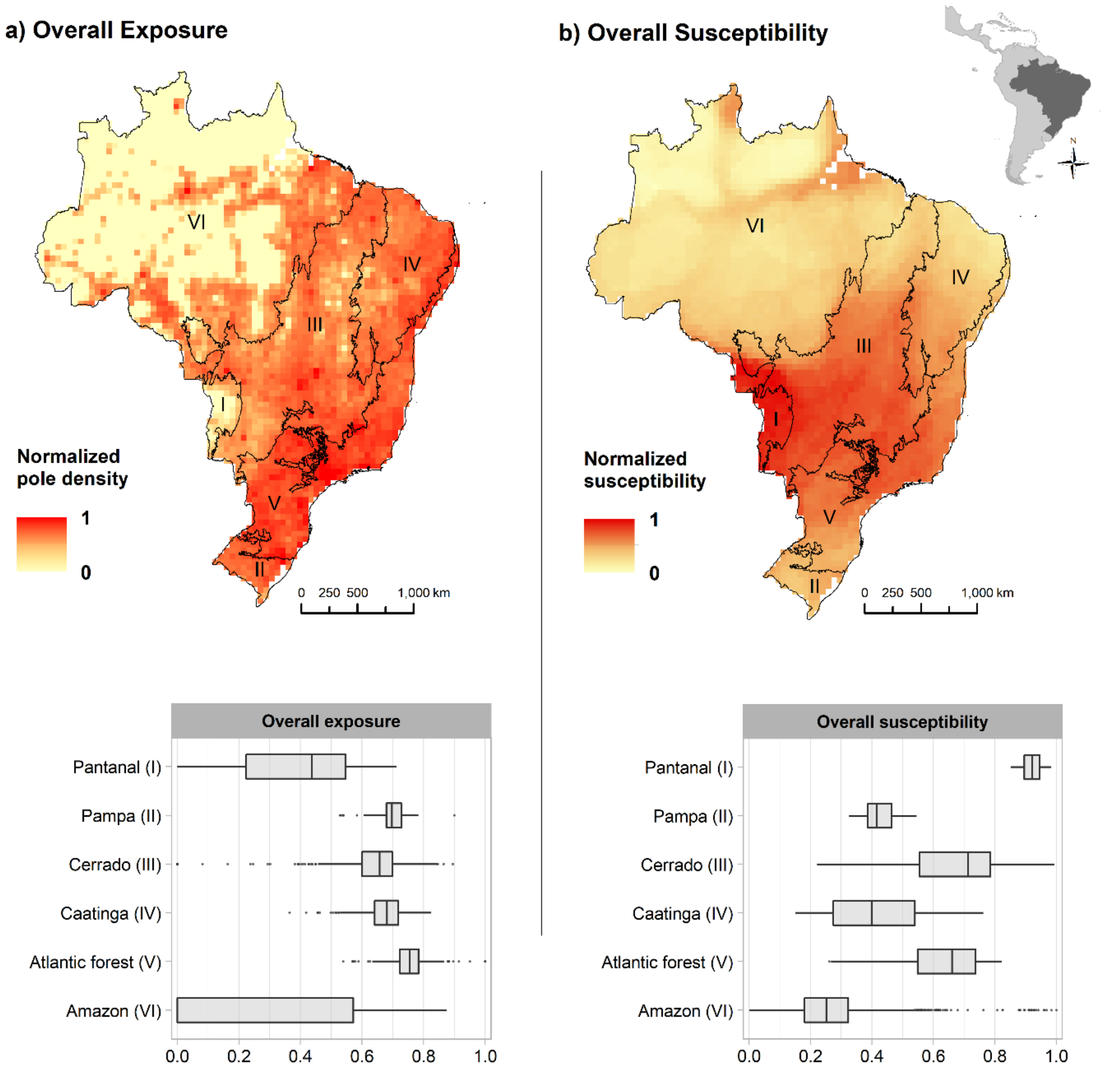

Figure 3. Summary results for exposure and susceptibility to electrocution, for 283 species with behavioral characteristics associated with a higher risk of electrocution: a**)** Overall exposure map based on pole density of medium voltage power lines (1 - 44 kV) (raw values of pole density were log transformed to reduce the high relative weight of a few areas in the Atlantic Forest, (see Table 1); b**)** overall susceptibility map based on distribution area and wing length. In both panels, pixel values were normalized to a 0-1 scale. Boxplots represent the interquartile range (IQR; box), the median (vertical bar), the 1.5 * IQR interval (whiskers) and the outliers (dots).

We found direct evidence of the use of power lines for perching and/or nesting for 242 bird species, and we further identified another 41 species that potentially use power line structures, totaling 283 species (Supplementary Material, Table S1). Pantanal was the biome with the highest cumulative bird susceptibility to electrocution (Fig. 3b). Some areas of Cerrado adjacent to Pantanal also showed high cumulative susceptibility (Fig. 3b). At the other extreme, the Amazon showed the lowest median of cumulative susceptibility (Fig. 3b). The overall pattern does not change when only species with direct evidence of the use of power line structures are included in the analyses (242 species) (see Supplementary Material, Figure S3). The Atlantic Forest showed the highest electrocution risk (median values), followed in order by Cerrado, Pantanal, Pampa, Caatinga and Amazon (Fig. 4).

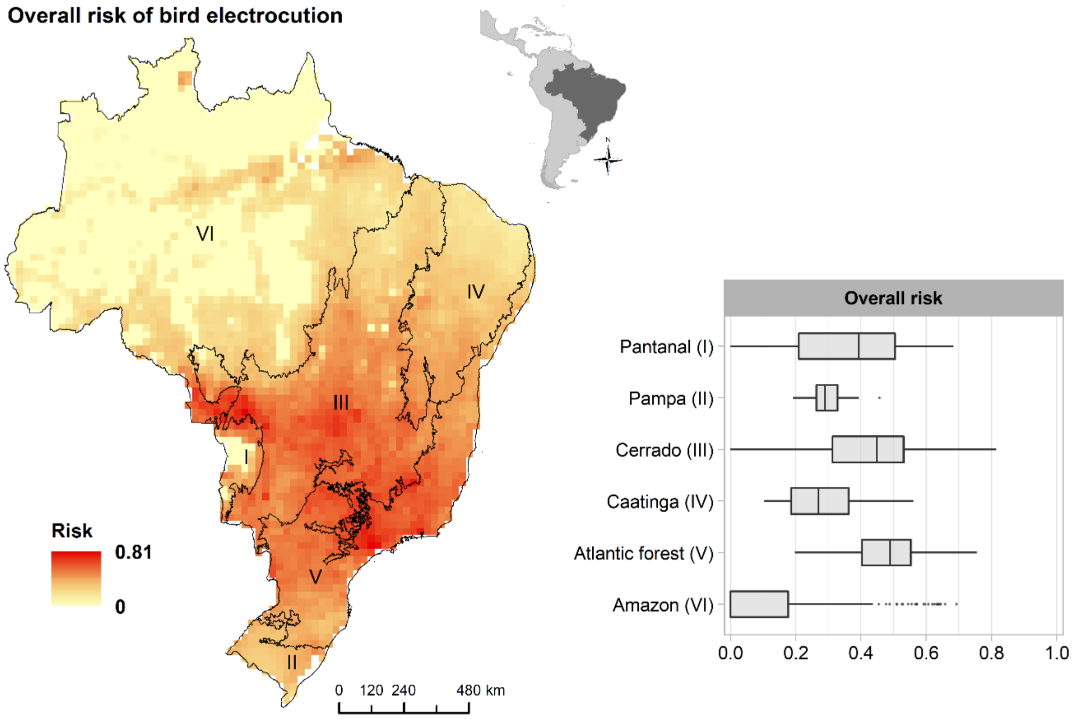

Figure 4. Overall risk of bird electrocution relating power pole density to bird susceptibility map. Boxplots represent the interquartile range (IQR; box), the median (vertical bar), the 1.5 * IQR interval (whiskers) and the outliers (dots).

We identified 38 species with higher electrocution risk (13% of the analyzed species) (Fig. 5), having a median risk ranging between 0.25 and 0.57. Most of the higher risk species were raptors (76%). The three species with the highest risk values were the jabiru *Jabiru mycteria* (a very large stork), the black-chested buzzard-eagle *Geranoetus melanoleucus* and the crowned eagle *Urubitinga coronata.* The risk within each species range was highly variable across species, but some species such as the black-chested buzzard-eagle and the crowned eagle had a small interquartile range over high-risk values, denoting a high pole density across their entire distribution ranges (Fig. 5). Of the remaining species, 51 were classified as 'intermediate risk' (18%; 0.10-0.25) and 194 as 'lower risk' (67%; 0.00-0.10) (Supplementary Material, Figure S4).

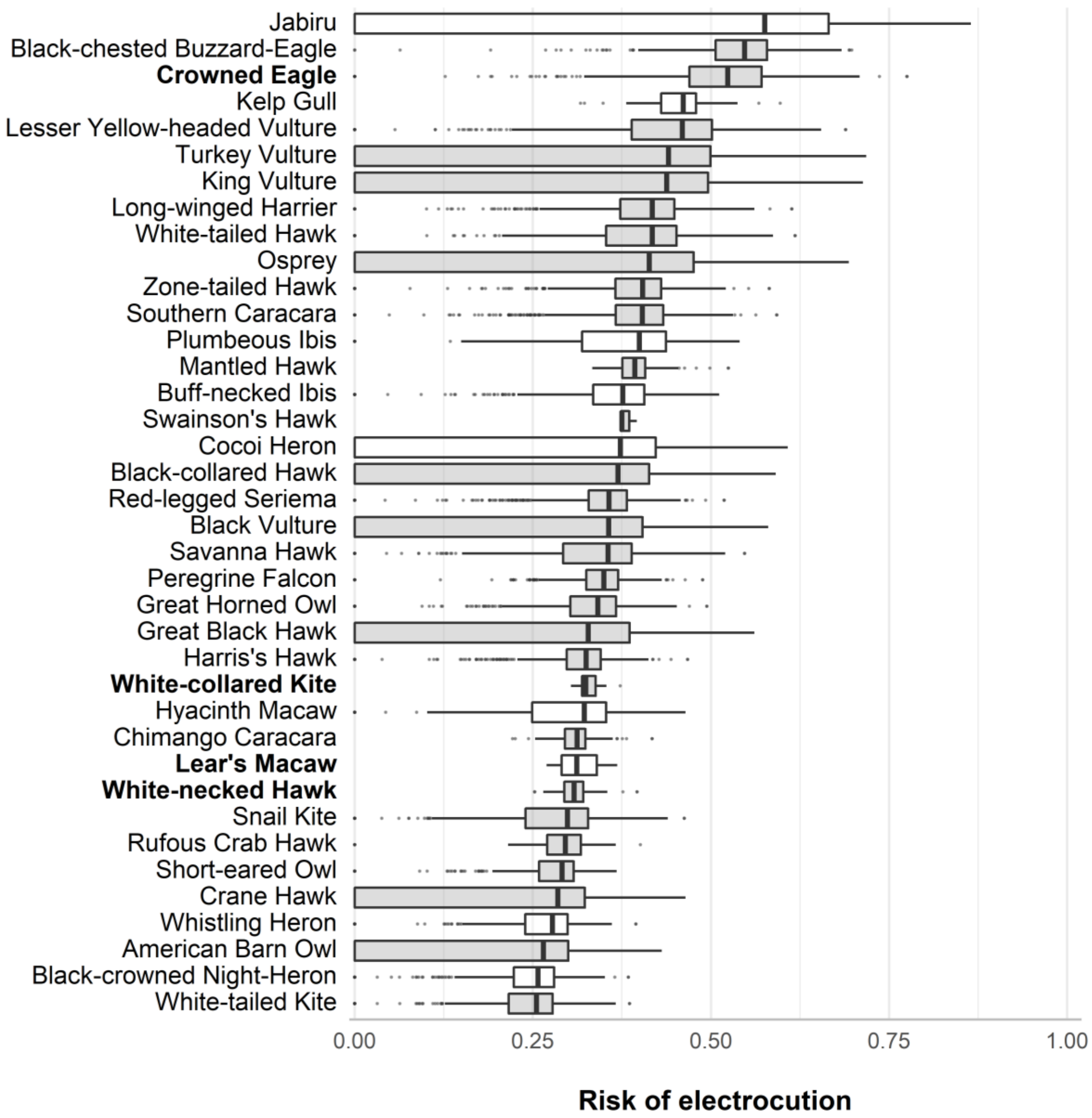

Figure 5. Variation in electrocution risk for 38 bird species with higher risk of electrocution. Boxplots represent the interquartile range (IQR; box), the median (vertical bar), the 1.5 * IQR interval (whiskers) and the outliers (dots). Grey boxes represent raptor species. Common names in bold represent globally threatened species according to the IUCN Red List of Threatened Species (BirdLife International, 2020).

4. Discussion

Electrocution is probably one of the main causes of human-induced bird mortality (Loss *et al.*, 2015; Slater *et al.*, 2020), but for many regions in the world there is still no information on the extent of this impact. We provided a framework that allows a preliminary assessment of the spatial distribution of bird exposure and susceptibility, which combined provide the potential risk of electrocution. The framework is based on available information, including the density of electrical infrastructures within a species' range, and morphological and behavioral traits associated with a higher risk of electrocution.

The application of the framework to Brazil indicated the Atlantic Forest as the biome with the highest risk of bird electrocution, a condition resulting from a high pole density combined with a high number of susceptible species occurring therein. The Atlantic Forest concentrates more than 60% of the Brazilian human population (Ribeiro *et al.*, 2009; Scarano & Ceotto, 2015), so it is not surprising that it has the highest pole density. The most cost-effective method to reduce bird electrocution in areas that already accommodate such a dense electrical network is the adoption of mitigation measures in strategic sites, including the retrofitting of wood poles (Dwyer *et al.*, 2017) or pylons (Chevallier *et al.*, 2015; Dixon *et al.*, 2019) whose design poses a risk of electrocution. In areas classified as higher risk, under our framework, such as the Atlantic Forest, a more focused investigation can be applied to search for data on fatalities or power system failures assigned to electrocutions, and to evaluate the relationship between landscape composition and electrocution events (*e.g*. Hernández-Matías *et al*., 2020). The pole location and configuration are important in determining the risk of mortality at the local scale (Mojica *et al*., 2018) and to inform the best mitigation interventions. Our approach indicates where electric companies and conservation biologists can focus their attention to perform detailed assessments aimed at identifying high-risk poles. For example, it is known that a combination of high pole density, prey abundance, and few natural perches can increase electrocution risk for some raptor species (Pérez-García *et al.*, 2011).

Our results also showed that the Pantanal and surrounding areas concentrate the highest cumulative susceptibility (i.e., the highest concentration of species vulnerable to electrocution). Although this biome and the Amazon currently experience high rates of agricultural expansion, they still have relatively few energy infrastructures (Souza *et al.*, 2020), including power lines. However, the Pantanal can become a central area for future projects of infrastructure expansion that will connect the Amazon to central Brazilian regions (Hyde, Bohlman, & Valle, 2018; Vilela *et al.*, 2020). Our results indicate that the routing of new power lines through the Pantanal can lead to a significant increase in the risk of electrocution for susceptible species. Consequently, we recommend that these new facilities be carefully planned and, if it is not possible to avoid the most sensitive areas, the new power lines should at least be built with appropriate mitigation measures and considering the behavior and morphology of the most susceptible species.

Thirty-eight bird species were ranked as higher risk of electrocution in our study. Specific guidelines for protection against electrocution should be delineated for these species, which should further receive special attention during the environmental licensing of new power lines. We found that birds of prey predominate among our higher risk species. In particular, the globally threatened crowned eagle, white-collared kite *Leptodon forbesi*, and white-necked hawk *Amadonastur lacernulatus*, are of special concern because the electrocution of even a few individuals can potentially cause serious population-level impacts. Raptors are top predators and are well known for using cables and poles to perch (Slater *et al.*, 2020). Overall, they have a delayed maturity, low fertility rates and smaller population sizes, thus electrocution events may have severe implications for their population dynamics and persistence over time (Eccleston & Harness, 2018; De Pascalis *et al.*, 2020; Slater *et al.*, 2020). In our ranking, the black-chested buzzard-eagle and the endangered crowned eagle occupied the top positions. These results are in line with studies performed in neighboring semiarid areas of central Argentina, where the former species accounts for numerous electrocution records (Ibarra & De Lucca, 2015) and the latter has been shown to be disproportionately affected by electrocution considering its low population density (Galmes *et al*., 2017; Sarasola, Galmes, & Watts, 2020).

Likewise, parrots (order Psittaciformes), represented in our higher-risk class by the endangered Lear's Macaw *Anodorhynchus leari* and Hyacinth Macaw *Anodorhynchus hyacinthinus*, stand out for their curiosity and social behavior when interacting with power line structures (Seibert, 2006). They often peck the structures and interact closely with pole elements like jumpers and energized wires, and most commonly in small flocks. Galmes *et al.* (2017) reported at least two species of parrots in Argentina as victims of electrocution, suggesting that this is indeed an important mortality factor for this group, at least in certain regions. In general, parrots are long-lived birds, and many species have naturally restricted ranges and are threatened with extinction (Berkunsky *et al.*, 2017). We strongly recommend that particular attention be paid to these threatened macaws and parrots, for example by carefully considering the pole design to be used, ideally tailored for both raptors and for this group, since measures to mitigate the electrocution of raptors may not be sufficient or suitable for parrots.

Further developments of the framework

We acknowledge some limitations of our framework and reinforce that it should be considered a first approach to identify regions and species that need more attention and should be targeted for a more in-depth data collection process. We highlight some features that could be refined to improve the effectiveness of the framework.

First, some authors argue that the use of pole density as a single surrogate for bird exposure to electrocution can compromise the results because this approach ignores habitat availability and configuration in hazard pole arrangement (Pérez-García *et al.*, 2017; Hernández-Lambraño, Sánchez-Agudo, & Carbonell, 2018). In our study, we used pole density as a proxy for exposure to electrocution because there is no systematic information on electrocution hazards for any part of the Brazilian territory (and for many other countries), thus preventing approaches that identify the most problematic pole configurations. Yet, it has been shown that the probability of electrocution increases with pole density (Guil *et al.*, 2011, 2015; Dwyer *et al.*, 2020). We strongly recommended that future replications of our framework include information about pole/pylon configuration whenever available, in order to refine the electrocution risk as it is influenced by grounding, pole and crossarms material, conductor and wire arrangement, insulators, exposed jumpers and other technical elements (Tintó *et al.*, 2010; Dwyer *et al.*, 2017).

Second, the use of the wing length and perching/nesting behaviors as the sole predictors of susceptibility may seem reductionist. These traits, however, can be easily obtained, allowing a preliminary assessment of a vast pool of species as ours, similarly to previous approaches that looked at the risk of bird collision with wires and wind turbines (Beston etl., 2016; Santangeli *et al.*, 2018; D'Amico *et al.*, 2019). Our framework also does not integrate information on species abundance, or species-specific patterns of frequency and temporal use of the infrastructures. Resident species, for example, can have higher temporal exposure to poles than migratory species. On the other hand, a migratory species that spends its non-breeding period in low-risk areas might at least theoretically be significantly affected if it passes through high-risk areas during migration. While the inclusion of such information would greatly improve the ability to identify higher risk areas at finer resolutions or with larger confidence, we currently have no information about these species' traits. However, this information may be available at smaller scales or for some target species or groups.

Third, although we have explicitly indicated species that should receive special attention, we recommend caution when interpreting the terms 'intermediate' and 'lower' risk, as our rating provides a value that can only be used for comparisons within our species pool. All 283 species analyzed face some risk of electrocution, due to their use of energy structures. Some smaller species, despite their size, show gregarious nesting behavior or build bulky nests of sticks. The monk parakeet *Myiopsitta monachus*, for example, builds large communal nests that greatly increase the risk of electrocution and power outages (Burgio *et al.*, 2014).

Fourth, we were unable to verify or validate our results because bird electrocutions are underreported and under-studied in Brazil. We hope that our results will stimulate hypothesis testing and encourage electrocution surveys aimed at higher risk areas and species to further improve the framework. Finally, the grid resolution used here is rather coarse for mitigation planning and routing at local scales. For example, it is not appropriate to indicate the most suitable corridors for new power lines or to identify specific poles to be mitigated. However, our spatial scale is applicable for planning the expansion of the energy network, especially in countries where there is a long distance between the power plants and the main energy consuming regions, such as Brazil (Cardoso Júnior *et al.*, 2014). The outcomes of our framework can be "fine-tuned" following a systematic process of data refinement. The bird distribution and pole configuration databases are key elements to be improved for fine-scale studies.

Conclusion

Our framework allows recognizing target regions and species to receive special attention in bird electrocution assessments, fostering win-win situations that will simultaneously prevent bird fatalities and power outages. We recommend refining the scale in higher-risk regions and for higher-risk species. The method proposed here can be replicated in any geographical area of the world where bird electrocutions are poorly studied and where information on birds and power lines is available.

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Supplementary Material – Chapter 2

Supplementary Material – Figure S1

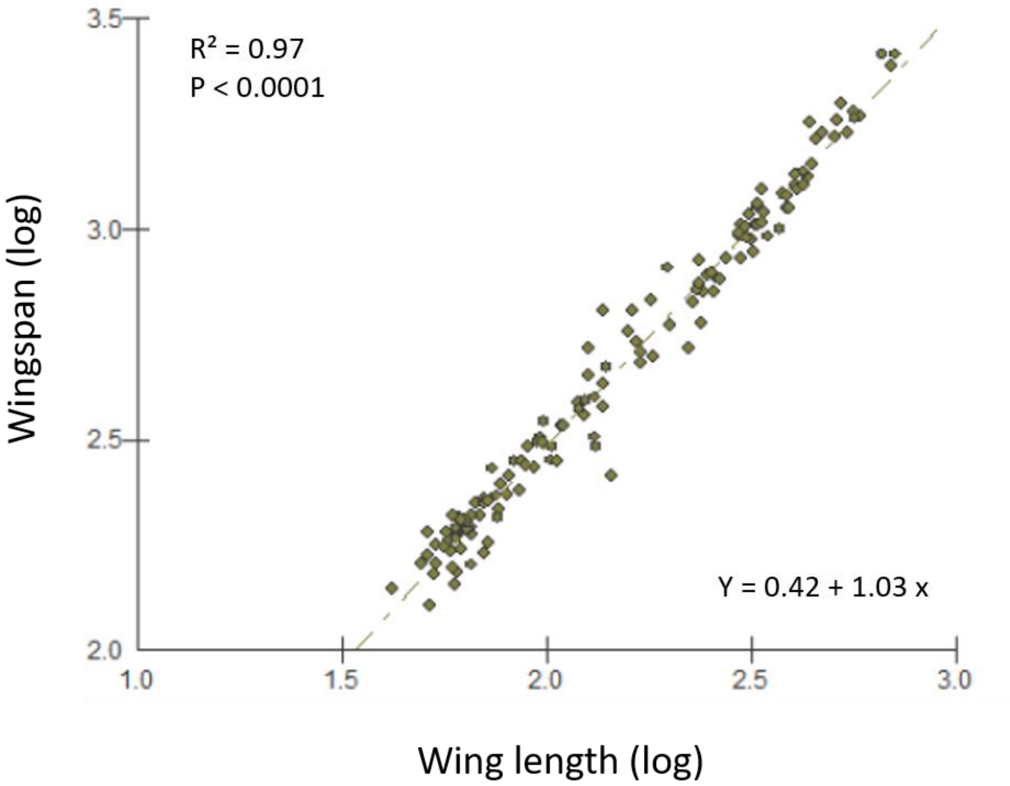

Figure S1. Linear regression model relating wingspan (dependent variable) and wing length (independent variable) for 129 species of Brazilian birds belonging to 36 taxonomic families.

Supplementary Material – Figure S2

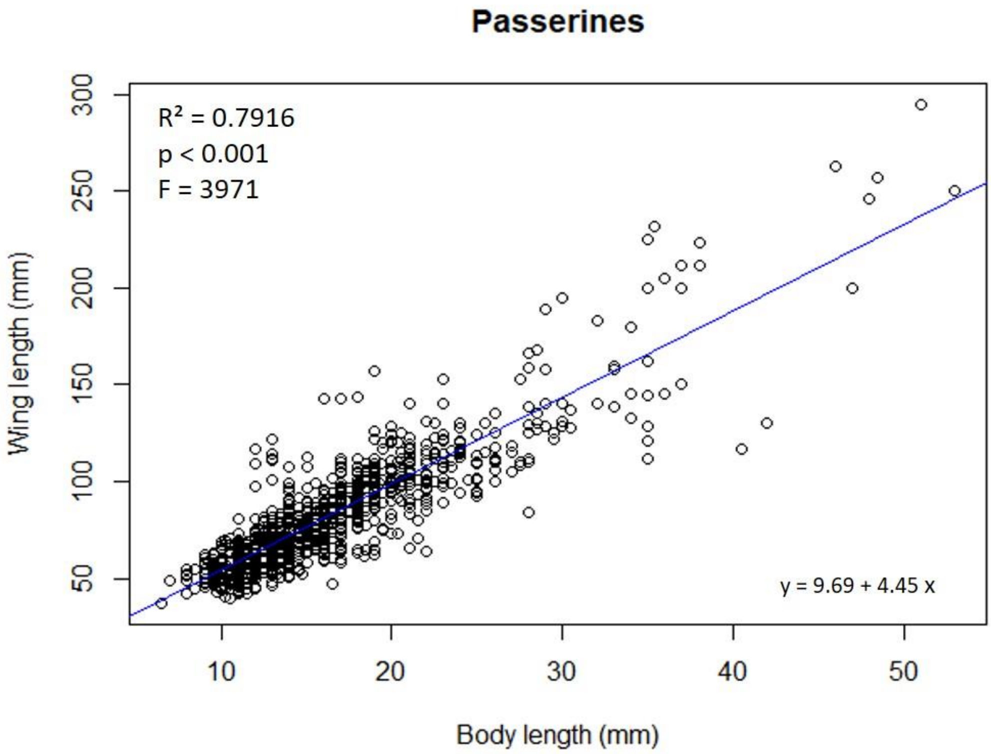

Figure S2. Linear model relating bird Wing length ~ Body Length measures. We obtained body length data from Handbook of the Birds of the World, and wing length from different bibliographic references to 1022 Passerines species.

Supplementary Material – Figure S3

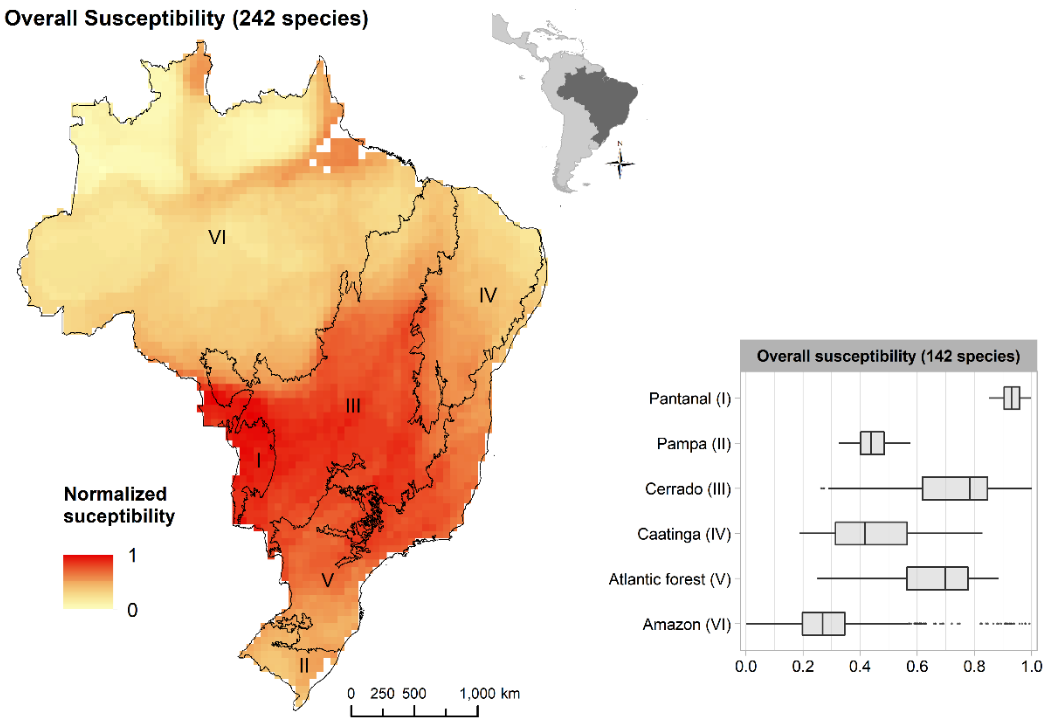

Figure S3. Map of electrocution susceptibility for 242 species of Brazilian birds that had their use of poles or wires for perching or nesting confirmed by examination of WikiAves photographs.

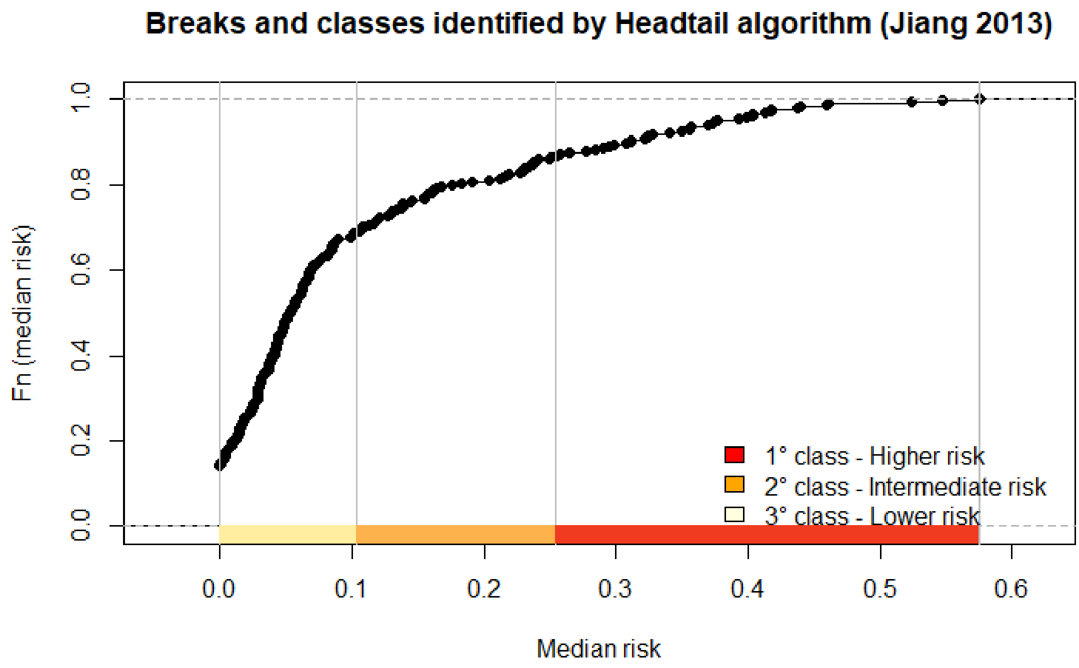

Figure S4. Classes and class intervals of bird electrocution risk as defined by the application of the clustering algorithm scheme of Jiang (2013) for data with a heavy-tailed distribution. The three resulting classes are interpreted as 'higher risk' (red bar, 0.25 to 0.57), 'intermediate risk' (orange bar, 0.10 to 0.25) and 'lower risk' (light yellow bar, 0.00 to 0.10) of electrocution. We consider high-risk species as priority for conservation and mitigation action.

Supplementary Material Table S1. Information on susceptibility and risk of electrocution for 283 Brazilian bird species.

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
1	Jabiru	*Jabiru mycteria*	Ciconiidae	Ciconiiformes	715	1	0	0	2	5312	0.575	Higher
2	Black-chested Buzzard-Eagle	*Geranoaetus melanoleucus*	Accipitridae	Accipitriformes	566	0.775	0	2	0	16959.2	0.547	Higher
3	Crowned Eagle	*Urubitinga coronata*	Accipitridae	Accipitriformes	566	0.775	0	2	0	16774.9	0.524	Higher
4	Kelp Gull	*Larus dominicanus*	Laridae	Charadriiformes	448	0.597	0	2	0	48269.3	0.461	Higher
5	Lesser Yellow-headed Vulture	*Cathartes burrovianus*	Cathartidae	Cathartiformes	509	0.689	0	2	0	13401	0.460	Higher
6	Turkey Vulture	*Cathartes aura*	Cathartidae	Cathartiformes	528	0.718	0	2	0	8914.8	0.440	Higher
7	King Vulture	*Sarcoramphus papa*	Cathartidae	Cathartiformes	525	0.713	0	1	0	8914.8	0.438	Higher
8	Long-winged Harrier	*Circus buffoni*	Accipitridae	Accipitriformes	459	0.614	0	2	0	14863.6	0.418	Higher
9	White-tailed Hawk	*Geranoaetus albicaudatus*	Accipitridae	Accipitriformes	462	0.618	0	2	2	14062.1	0.418	Higher
10	Osprey	*Pandion haliaetus*	Pandionidae	Accipitriformes	512	0.694	0	1	2	7947.6	0.413	Higher
11	Zone-tailed Hawk	*Buteo albonotatus*	Accipitridae	Accipitriformes	438	0.582	0	1	0	17077.5	0.404	Higher
12	Southern Caracara	*Caracara plancus*	Falconidae	Falconiformes	445	0.593	0	2	2	14683.7	0.404	Higher
13	Plumbeous Ibis	*Theristicus caerulescens*	Threskiornithidae	Pelecaniformes	450	0.600	0	2	0	13038.6	0.399	Higher
14	Mantled Hawk	*Pseudastur polionotus*	Accipitridae	Accipitriformes	400	0.525	0	2	0	32241.6	0.393	Higher
15	Buff-necked Ibis	*Theristicus caudatus*	Threskiornithidae	Pelecaniformes	429	0.568	0	2	0	11010.6	0.376	Higher
16	Swainson's Hawk	*Buteo swainsoni*	Accipitridae	Accipitriformes	427	0.565	0	1	0	8533	0.375	Higher
17	Cocoi Heron	*Ardea cocoi*	Ardeidae	Pelecaniformes	455	0.608	0	2	0	8914.8	0.373	Higher

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
18	Black-collared Hawk	*Busarellus nigricollis*	Accipitridae	Accipitriformes	444	0.591	0	2	0	9438.4	0.369	Higher
19	Red-legged Seriema	*Cariama cristata*	Cariamidae	Cariamiformes	396	0.519	0	2	0	15907.2	0.357	Higher
20	Black Vulture	*Coragyps atratus*	Cathartidae	Cathartiformes	437	0.580	0	2	0	8914.8	0.356	Higher
21	Savanna Hawk	*Heterospizias meridionalis*	Accipitridae	Accipitriformes	415	0.547	0	2	2	11033.9	0.355	Higher
22	Peregrine Falcon	*Falco peregrinus*	Falconidae	Falconiformes	376	0.488	0	2	0	20915.2	0.349	Higher
23	Great Horned Owl	*Bubo virginianus*	Strigidae	Strigiformes	380	0.494	0	1	0	16310	0.341	Higher
24	Great Black Hawk	*Urubitinga urubitinga*	Accipitridae	Accipitriformes	424	0.561	0	2	0	8420	0.327	Higher
25	Harris's Hawk	*Parabuteo unicinctus*	Accipitridae	Accipitriformes	362	0.467	2	2	0	16696.5	0.324	Higher
26	White-collared Kite	*Leptodon forbesi*	Accipitridae	Accipitriformes	338	0.431	1	0	0	30901.3	0.324	Higher
27	Hyacinth Macaw	*Anodorhynchus hyacinthinus*	Psittacidae	Psittaciformes	404.2	0.531	2	1	0	5274.5	0.322	Higher
28	Chimango Caracara	*Milvago chimango*	Falconidae	Falconiformes	329	0.417	0	2	0	33820	0.312	Higher
29	Lear´s Macaw	*Anodorhynchus leari*	Psittacidae	Psittaciformes	385.6	0.503	2	1	0	7832	0.311	Higher
30	White-necked Hawk	*Amadonastur lacernulatus*	Accipitridae	Accipitriformes	315	0.396	1	1	0	64520.1	0.307	Higher
31	Snail Kite	*Rostrhamus sociabilis*	Accipitridae	Accipitriformes	359	0.463	2	0	0	10715.9	0.299	Higher
32	Rufous Crab Hawk	*Buteogallus aequinoctialis*	Accipitridae	Accipitriformes	332	0.422	0	1	0	28921.8	0.295	Higher
33	Short-eared Owl	*Asio flammeus*	Strigidae	Strigiformes	323	0.408	2	1	0	17507.8	0.291	Higher
34	Crane Hawk	*Geranospiza caerulescens*	Accipitridae	Accipitriformes	360	0.464	0	1	0	8914.8	0.285	Higher
35	Whistling Heron	*Syrigma sibilatrix*	Ardeidae	Pelecaniformes	314	0.395	0	1	0	20325.1	0.277	Higher
36	American Barn Owl	*Tyto furcata*	Tytonidae	Strigiformes	338	0.431	0	1	0	8914.8	0.264	Higher

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
37	Black-crowned Night-Heron	*Nycticorax nycticorax*	Ardeidae	Pelecaniformes	307	0.384	2	2	0	13771.9	0.257	Higher
38	White-tailed Kite	*Elanus leucurus*	Accipitridae	Accipitriformes	308	0.386	2	2	0	12365.9	0.255	Higher
39	Gray-headed Kite	*Leptodon cayanensis*	Accipitridae	Accipitriformes	338	0.431	2	0	0	8116.2	0.250	Intermed
40	Striped Owl	*Asio clamator*	Strigidae	Strigiformes	294	0.365	0	1	0	15597.6	0.249	Intermed
41	Short-tailed Hawk	*Buteo brachyurus*	Accipitridae	Accipitriformes	315	0.396	2	1	0	8897.6	0.242	Intermed
42	Large-billed Tern	*Phaetusa simplex*	Sternidae	Charadriiformes	312	0.392	0	1	0	8939.3	0.240	Intermed
43	Yellow-headed Caracara	*Milvago chimachima*	Falconidae	Falconiformes	309	0.387	0	2	0	8915.4	0.238	Intermed
44	Plumbeous Kite	*Ictinia plumbea*	Accipitridae	Accipitriformes	320.5	0.405	2	0	0	8389	0.237	Intermed
45	Aplomado Falcon	*Falco femoralis*	Falconidae	Falconiformes	282	0.347	0	2	0	14378.5	0.236	Intermed
46	Neotropic Cormorant	*Nannopterum brasilianus*	Phalacrocoracida e	Suliformes	305	0.381	0	1	0	8939.3	0.234	Intermed
47	White-rumped Hawk	*Parabuteo leucorrhous*	Accipitridae	Accipitriformes	253	0.303	2	0	0	39302.6	0.231	Intermed
48	Blue-and-yellow Macaw	*Ara ararauna*	Psittacidae	Psittaciformes	378.3	0.492	0	2	0	3895.3	0.230	Intermed
49	Mississippi Kite	*Ictinia mississippiensis*	Accipitridae	Accipitriformes	315	0.396	1	0	0	4303.8	0.229	Intermed
50	Hook-billed Kite	*Chondrohierax uncinatus*	Accipitridae	Accipitriformes	321	0.405	2	0	0	6087.8	0.227	Intermed
51	Laughing Falcon	*Herpetotheres cachinnans*	Falconidae	Falconiformes	294	0.365	0	2	0	8225.1	0.219	Intermed
52	Roadside Hawk	*Rupornis magnirostris*	Accipitridae	Accipitriformes	287	0.354	2	2	2	8939.3	0.217	Intermed
53	Picazuro Pigeon	*Patagioenas picazuro*	Columbidae	Columbiformes	260	0.313	2	2	1	15325.8	0.215	Intermed
54	Common Potoo	*Nyctibius griseus*	Nyctibiidae	Nyctibiiformes	282	0.347	0	2	0	8915.4	0.213	Intermed
55	Toco Toucan	*Ramphastos toco*	Ramphastidae	Piciformes	255	0.306	2	2	0	15016.6	0.204	Intermed

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
56	Gray-lined Hawk	*Buteo nitidus*	Accipitridae	Accipitriformes	275	0.336	2	2	0	5503.2	0.190	Intermed
57	Scaled Chachalaca	*Ortalis squamata*	Cracidae	Galliformes	215	0.245	2	0	0	27953.8	0.182	Intermed
58	Turquoise-fronted Parrot	*Amazona aestiva*	Psittacidae	Psittaciformes	225	0.260	2	0	0	12349.6	0.176	Intermed
59	Rufous-thighed Kite	*Harpagus diodon*	Accipitridae	Accipitriformes	222	0.256	2	0	0	13249	0.168	Intermed
60	Blue-winged Macaw	*Primolius maracana*	Psittacidae	Psittaciformes	215.5	0.246	0	2	0	12302	0.164	Intermed
61	Ringed Kingfisher	*Megaceryle torquata*	Alcedinidae	Coraciiformes	226	0.262	2	1	0	9184.5	0.162	Intermed
62	Yellow-billed Teal	*Anas flavirostris*	Anatidae	Anseriformes	202	0.226	0	1	0	21579.9	0.161	Intermed
63	Bat Falcon	*Falco rufigularis*	Falconidae	Falconiformes	229	0.267	0	2	1	8249.3	0.160	Intermed
64	Spot-winged Pigeon	*Patagioenas maculosa*	Columbidae	Columbiformes	206	0.232	2	2	1	12301.2	0.157	Intermed
65	American Kestrel	*Falco sparverius*	Falconidae	Falconiformes	207	0.233	2	2	2	12983.2	0.156	Intermed
66	Chaco Chachalaca	*Ortalis canicollis*	Cracidae	Galliformes	257	0.309	2	0	0	3004.1	0.155	Intermed
67	Burrowing Owl	*Athene cunicularia*	Strigidae	Strigiformes	200	0.223	1	2	0	17364.4	0.154	Intermed
68	Curl-crested Jay	*Cyanocorax cristatellus*	Corvidae	Passeriformes	200	0.223	2	1	0	12851.4	0.145	Intermed
69	Common Nighthawk	*Chordeiles minor*	Caprimulgidae	Caprimulgiformes	208	0.235	2	0	0	8914.8	0.144	Intermed
70	Greater Ani	*Crotophaga major*	Cuculidae	Cuculiformes	205	0.230	2	0	0	8211.5	0.139	Intermed
71	Guira Cuckoo	*Guira guira*	Cuculidae	Cuculiformes	187	0.203	2	2	0	14356.3	0.138	Intermed
72	Lineated Woodpecker	*Dryocopus lineatus*	Picidae	Piciformes	202	0.226	0	2	0	8908.2	0.138	Intermed
73	Yellow-faced Parrot	*Alipiopsitta xanthops*	Psittacidae	Psittaciformes	193.9	0.214	2	0	0	7890.1	0.137	Intermed
74	Lesser Nighthawk	*Chordeiles acutipennis*	Caprimulgidae	Caprimulgiformes	188	0.205	2	0	0	10993.2	0.134	Intermed

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
75	Golden-capped Parakeet	*Aratinga auricapillus*	Psittacidae	Psittaciformes	170	0.177	2	2	0	25172.9	0.130	Intermed
76	Upland Sandpiper	*Bartramia longicauda*	Scolopacidae	Charadriiformes	181	0.194	0	1	0	12716.4	0.129	Intermed
77	Campo Flicker	*Colaptes campestris*	Picidae	Piciformes	177	0.188	2	2	1	15252.1	0.129	Intermed
78	Pale-vented Pigeon	*Patagioenas cayennensis*	Columbidae	Columbiformes	190	0.208	2	2	0	8899.3	0.127	Intermed
79	Tropical Screech-Owl	*Megascops choliba*	Strigidae	Strigiformes	181	0.194	2	1	0	9258.3	0.121	Intermed
80	White-eyed Parakeet	*Psittacara leucophthalmus*	Psittacidae	Psittaciformes	183	0.197	2	2	0	10077.6	0.120	Intermed
81	White Woodpecker	*Melanerpes candidus*	Picidae	Piciformes	167	0.173	0	2	0	15819.4	0.119	Intermed
82	Crimson-crested Woodpecker	*Campephilus melanoleucos*	Picidae	Piciformes	190	0.208	0	2	0	4760.5	0.117	Intermed
83	Great Potoo	*Nyctibius grandis*	Nyctibiidae	Nyctibiiformes	402	0.528	0	2	0	6438.1	0.116	Intermed
84	Purple Martin	*Progne subis*	Hirundinidae	Passeriformes	157	0.158	2	2	0	20663.6	0.113	Intermed
85	Pearl Kite	*Gampsonyx swainsonii*	Accipitridae	Accipitriformes	167	0.173	2	2	1	8195.1	0.108	Intermed
86	Ringed Teal	*Callonetta leucophrys*	Anatidae	Anseriformes	186	0.202	0	1	0	10400.7	0.108	Intermed
87	Jandaya Parakeet	*Aratinga jandaya*	Psittacidae	Psittaciformes	158.6	0.160	2	2	0	9102.7	0.107	Intermed
88	Monk Parakeet	*Myiopsitta monachus*	Psittacidae	Psittaciformes	158	0.159	2	2	2	11230.2	0.105	Intermed
89	Scaled Pigeon	*Patagioenas speciosa*	Columbidae	Columbiformes	198	0.220	2	1	0	6912.4	0.105	Intermed
90	Peach-fronted Parakeet	*Eupsittula aurea*	Psittacidae	Psittaciformes	155	0.155	2	1	0	10229	0.102	Lower
91	Giant Cowbird	*Molothrus*	Icteridae	Passeriformes	180	0.193	2	2	0	7690.2	0.102	Lower

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
		oryzivorus										
92	Eared Dove	*Zenaida auriculata*	Columbidae	Columbiformes	150	0.147	2	2	1	14622	0.100	Lower
93	Smooth-billed Ani	*Crotophaga ani*	Cuculidae	Cuculiformes	159	0.161	2	1	0	8921.7	0.099	Lower
94	Scarlet-throated Tanager	*Compsothraupis loricata*	Thraupidae	Passeriformes	140	0.132	2	0	0	10378.4	0.089	Lower
95	Green-barred Woodpecker	*Colaptes melanochloros*	Picidae	Piciformes	137	0.128	0	2	1	15633.1	0.088	Lower
96	Cactus Parakeet	*Eupsittula cactorum*	Psittacidae	Psittaciformes	138.3	0.130	2	0	0	8811.8	0.087	Lower
97	Double-toothed Kite	*Harpagus bidentatus*	Accipitridae	Accipitriformes	234	0.274	1	0	0	4637.5	0.086	Lower
98	Gray Monjita	*Xolmis cinereus*	Tyrannidae	Passeriformes	140	0.132	2	1	2	11594	0.086	Lower
99	Gray-breasted Martin	*Progne chalybea*	Hirundinidae	Passeriformes	144	0.138	2	2	2	8914.8	0.085	Lower
100	Yellow-rumped Marshbird	*Pseudoleistes guirahuro*	Icteridae	Passeriformes	130	0.117	2	2	0	21765.7	0.085	Lower
101	Brown Cacholote	*Pseudoseisura lophotes*	Furnariidae	Passeriformes	135	0.125	2	1	1	9066.1	0.085	Lower
102	Brown-chested Martin	*Progne tapera*	Hirundinidae	Passeriformes	143	0.137	2	2	1	8914.8	0.084	Lower
103	Plain Parakeet	*Brotogeris tirica*	Psittacidae	Psittaciformes	124.4	0.109	2	2	2	45989.6	0.082	Lower
104	Streamer-tailed Tyrant	*Gubernetes yetapa*	Tyrannidae	Passeriformes	130	0.117	2	1	0	17914.2	0.082	Lower
105	Ruddy Ground-Dove	*Columbina talpacoti*	Columbidae	Columbiformes	140	0.132	2	2	1	8917.6	0.081	Lower
106	Black-fronted Nunbird	*Monasa nigrifrons*	Bucconidae	Galbuliformes	139	0.131	2	0	0	5408.4	0.078	Lower
107	Amazon Kingfisher	*Chloroceryle amazona*	Alcedinidae	Coraciiformes	135	0.125	2	0	0	8914.8	0.076	Lower

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
108	Chalk-browed Mockingbird	*Mimus saturninus*	Mimidae	Passeriformes	125	0.110	2	2	1	15023.7	0.075	Lower
109	Chopi Blackbird	*Gnorimopsar chopi*	Icteridae	Passeriformes	124	0.108	2	1	0	15918.2	0.074	Lower
110	Crested Black-Tyrant	*Knipolegus lophotes*	Tyrannidae	Passeriformes	119	0.101	2	1	0	26542.7	0.073	Lower
111	Screaming Cowbird	*Molothrus rufoaxillaris*	Icteridae	Passeriformes	120	0.102	2	2	0	18438.3	0.071	Lower
112	Cattle Tyrant	*Machetornis rixosa*	Tyrannidae	Passeriformes	120	0.102	2	2	0	17470.3	0.071	Lower
113	White-rumped Swallow	*Tachycineta leucorrhoa*	Hirundinidae	Passeriformes	122	0.105	2	2	2	13684.5	0.069	Lower
114	Nanday Parakeet	*Aratinga nenday*	Psittacidae	Psittaciformes	179	0.191	2	1	0	933.1	0.069	Lower
115	Barn Swallow	*Hirundo rustica*	Hirundinidae	Passeriformes	126	0.111	2	0	0	8914.8	0.068	Lower
116	Chilean Swallow	*Tachycineta leucopyga*	Hirundinidae	Passeriformes	117	0.097	2	0	0	19980.9	0.067	Lower
117	White-rumped Monjita	*Xolmis velatus*	Tyrannidae	Passeriformes	120	0.102	2	1	0	11619.3	0.067	Lower
118	Brown-and-yellow Marshbird	*Pseudoleistes virescens*	Icteridae	Passeriformes	114	0.093	2	1	0	25003.8	0.067	Lower
119	Great Rufous Woodcreeper	*Xiphocolaptes major*	Dendrocolaptidae	Passeriformes	145	0.140	0	1	0	2389.5	0.067	Lower
120	Yellow-chevroned Parakeet	*Brotogeris chiriri*	Psittacidae	Psittaciformes	120.2	0.102	2	0	0	10949	0.067	Lower
121	Tropical Mockingbird	*Mimus gilvus*	Mimidae	Passeriformes	115	0.094	2	1	0	17022.4	0.065	Lower
122	Rufous-bellied Thrush	*Turdus rufiventris*	Turdidae	Passeriformes	113.8	0.093	2	0	0	17603.3	0.065	Lower
123	Scarlet-headed Blackbird	*Amblyramphus holosericeus*	Icteridae	Passeriformes	110	0.087	2	0	0	22200	0.063	Lower

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
124	Tropical Kingbird	*Tyrannus melancholicus*	Tyrannidae	Passeriformes	120.5	0.103	2	2	2	8914.8	0.063	Lower
125	Pale-breasted Thrush	*Turdus leucomelas*	Turdidae	Passeriformes	115.26	0.095	2	0	0	12290.8	0.063	Lower
126	Cliff Swallow	*Petrochelidon pyrrhonota*	Hirundinidae	Passeriformes	113	0.091	2	0	0	15607.5	0.063	Lower
127	Blue-and-white Swallow	*Pygochelidon cyanoleuca*	Hirundinidae	Passeriformes	112	0.090	2	2	1	16051.1	0.062	Lower
128	Sayaca Tanager	*Tangara sayaca*	Thraupidae	Passeriformes	112	0.090	2	2	2	15333.8	0.062	Lower
129	Caatinga Cacholote	*Pseudoseisura cristata*	Furnariidae	Passeriformes	112	0.090	2	2	2	12047.8	0.061	Lower
130	Scimitar-billed Woodcreeper	*Drymornis bridgesii*	Dendrocolaptidae	Passeriformes	112	0.090	0	1	1	8764.4	0.061	Lower
131	Rufous Hornero	*Furnarius rufus*	Furnariidae	Passeriformes	110	0.087	2	2	2	16914.9	0.060	Lower
132	Campo Troupial	*Icterus jamacaii*	Icteridae	Passeriformes	110	0.087	2	2	2	13744.1	0.060	Lower
133	White-browed Meadowlark	*Sturnella superciliaris*	Icteridae	Passeriformes	108	0.084	2	1	0	16836.8	0.058	Lower
134	Creamy-bellied Thrush	*Turdus amaurochalinus*	Turdidae	Passeriformes	109.3	0.086	2	0	0	13075.2	0.058	Lower
135	Red-crested Cardinal	*Paroaria coronata*	Thraupidae	Passeriformes	108	0.084	2	0	0	13307.8	0.057	Lower
136	Spectacled Thrush	*Turdus nudigenis*	Turdidae	Passeriformes	121.3	0.104	2	0	0	5161.9	0.057	Lower
137	Southern Rough-winged Swallow	*Stelgidopteryx ruficollis*	Hirundinidae	Passeriformes	114	0.093	2	2	0	8914.8	0.057	Lower
138	White Monjita	*Xolmis irupero*	Tyrannidae	Passeriformes	108	0.084	2	2	2	11419.4	0.057	Lower
139	Fork-tailed Flycatcher	*Tyrannus savana*	Tyrannidae	Passeriformes	117	0.097	2	2	2	8226	0.056	Lower
140	Great Kiskadee	*Pitangus sulphuratus*	Tyrannidae	Passeriformes	111.2	0.089	2	2	2	8912.4	0.054	Lower
141	Bank Swallow	*Riparia riparia*	Hirundinidae	Passeriformes	111	0.088	2	0	0	8831.5	0.054	Lower

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
142	Palm Tanager	*Tangara palmarum*	Thraupidae	Passeriformes	110	0.087	2	1	1	8790.2	0.053	Lower
143	Great Pampa-Finch	*Embernagra platensis*	Thraupidae	Passeriformes	99	0.070	2	0	0	29787.8	0.053	Lower
144	Scaled Dove	*Columbina squammata*	Columbidae	Columbiformes	103	0.076	2	2	2	13809.5	0.052	Lower
145	Golden-billed Saltator	*Saltator aurantiirostris*	Thraupidae	Passeriformes	104	0.078	2	0	0	6060.4	0.051	Lower
146	Chestnut-capped Blackbird	*Chrysomus ruficapillus*	Icteridae	Passeriformes	101	0.073	2	0	0	16728.1	0.051	Lower
147	White-winged Swallow	*Tachycineta albiventer*	Hirundinidae	Passeriformes	108	0.084	2	0	0	8451.5	0.051	Lower
148	Narrow-billed Woodcreeper	*Lepidocolaptes angustirostris*	Dendrocolaptidae	Passeriformes	100.9	0.073	0	1	1	12654.7	0.049	Lower
149	Brown-crested Flycatcher	*Myiarchus tyrannulus*	Tyrannidae	Passeriformes	102	0.075	1	0	0	10687.1	0.049	Lower
150	Pale-legged Hornero	*Furnarius leucopus*	Furnariidae	Passeriformes	105	0.079	2	1	1	6033.8	0.049	Lower
151	Blue-and-yellow Tanager	*Pipraeidea bonariensis*	Thraupidae	Passeriformes	95	0.064	2	0	0	33056.6	0.048	Lower
152	Grayish Saltator	*Saltator coerulescens*	Thraupidae	Passeriformes	110	0.087	2	0	0	4018.8	0.048	Lower
153	Swainson's Flycatcher	*Myiarchus swainsoni*	Tyrannidae	Passeriformes	104	0.078	2	0	0	8917.5	0.048	Lower
154	Shiny Cowbird	*Molothrus bonariensis*	Icteridae	Passeriformes	101.36	0.074	2	2	0	10875.7	0.048	Lower
155	Picui Ground-Dove	*Columbina picui*	Columbidae	Columbiformes	103	0.076	2	2	1	7083.7	0.048	Lower
156	Variegated Flycatcher	*Empidonomus varius*	Tyrannidae	Passeriformes	102.7	0.076	2	0	0	8914.8	0.047	Lower
157	Grayish Baywing	*Agelaioides badius*	Icteridae	Passeriformes	95	0.064	2	1	2	26363.1	0.046	Lower

ID Rank	Common names	Species	Family	Order	Wing length (mm)	Wing length Norm.	Behavior wires*	Behavior poles*	Behavior nesting*	Mean number of poles	Electrocution risk (median)	Classes of risk
158	Wing-banded Hornero	*Furnarius figulus*	Furnariidae	Passeriformes	96	0.066	2	2	2	12354.9	0.044	Lower
159	Rufous Cacholote	*Pseudoseisura unirufa*	Furnariidae	Passeriformes	106	0.081	1	1	1	3717.3	0.044	Lower
160	White-winged Parakeet	*Brotogeris versicolurus*	Psittacidae	Psittaciformes	121.3	0.104	2	0	0	2815.2	0.044	Lower
161	Pale Baywing	*Agelaioides fringillarius*	Icteridae	Passeriformes	95	0.064	2	2	2	11285	0.044	Lower
162	Diademed Tanager	*Stephanophorus diadematus*	Thraupidae	Passeriformes	90.96	0.058	2	0	0	31061.2	0.044	Lower
163	Black-throated Saltator	*Saltatricula atricollis*	Thraupidae	Passeriformes	95	0.064	2	0	0	11849	0.043	Lower
164	Yellow-bellied Elaenia	*Elaenia flavogaster*	Tyrannidae	Passeriformes	95	0.064	2	0	0	11995	0.042	Lower
165	Swallow-winged Puffbird	*Chelidoptera tenebrosa*	Bucconidae	Galbuliformes	110	0.087	2	0	0	4803.1	0.042	Lower
166	Yellow-winged Blackbird	*Agelasticus thilius*	Icteridae	Passeriformes	92	0.060	2	0	0	24742.6	0.042	Lower
167	Firewood-Gatherer	*Anumbius annumbi*	Furnariidae	Passeriformes	90	0.057	2	2	2	25788.2	0.042	Lower
168	White-lined Tanager	*Tachyphonus rufus*	Thraupidae	Passeriformes	95	0.064	2	0	0	9428.1	0.042	Lower
169	Swallow Tanager	*Tersina viridis*	Thraupidae	Passeriformes	97	0.067	2	0	0	10796.3	0.042	Lower
170	Social Flycatcher	*Myiozetetes similis*	Tyrannidae	Passeriformes	97	0.067	2	2	2	9891.4	0.041	Lower
171	Brazilian Tanager	*Ramphocelus bresilius*	Thraupidae	Passeriformes	87.2	0.053	2	0	0	38638.6	0.040	Lower
172	Short-crested Flycatcher	*Myiarchus ferox*	Tyrannidae	Passeriformes	95	0.064	2	0	0	8352.7	0.039	Lower
173	Little Woodpecker	*Veniliornis passerinus*	Picidae	Piciformes	96	0.066	0	1	1	7337.9	0.039	Lower

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174	Common Ground-Dove	*Columbina passerina*	Columbidae	Columbiformes	93	0.061	2	1	1	7254.5	0.038	Lower
175	Blue-winged Parrotlet	*Forpus xanthopterygius*	Psittacidae	Psittaciformes	90	0.057	2	2	2	12962.3	0.038	Lower
176	White-throated Kingbird	*Tyrannus albogularis*	Tyrannidae	Passeriformes	109	0.085	2	1	1	4195.1	0.037	Lower
177	Yellow-browed Tyrant	*Satrapa icterophrys*	Tyrannidae	Passeriformes	90	0.057	2	0	0	11925.3	0.037	Lower
178	Black Jacobin	*Florisuga fusca*	Trochilidae	Apodiformes	85	0.049	2	0	0	39562.8	0.037	Lower
179	Rusty-margined Flycatcher	*Myiozetetes cayanensis*	Tyrannidae	Passeriformes	94	0.063	2	0	0	6492.3	0.037	Lower
180	Crowned Slaty Flycatcher	*Griseotyrannus aurantioatrocrist atus*	Tyrannidae	Passeriformes	98	0.069	1	0	0	4287.1	0.037	Lower
181	Red-cowled Cardinal	*Paroaria dominicana*	Thraupidae	Passeriformes	87	0.052	2	0	0	11842.7	0.036	Lower
182	Large Elaenia	*Elaenia spectabilis*	Tyrannidae	Passeriformes	90.8	0.058	1	0	0	5459	0.034	Lower
183	Rufous-tailed Jacamar	*Galbula ruficauda*	Galbulidae	Galbuliformes	86	0.051	2	0	0	9724.3	0.033	Lower
184	Velvety Black-Tyrant	*Knipolegus nigerrimus*	Tyrannidae	Passeriformes	82	0.045	2	0	0	25747.6	0.032	Lower
185	Long-tailed Tyrant	*Colonia colonus*	Tyrannidae	Passeriformes	84	0.048	2	1	0	11929.7	0.031	Lower
186	Piratic Flycatcher	*Legatus leucophaius*	Tyrannidae	Passeriformes	88.9	0.055	1	0	0	8319.9	0.031	Lower
187	Spot-backed Puffbird	*Nystalus maculatus*	Bucconidae	Galbuliformes	83	0.046	2	0	0	9918.4	0.031	Lower
188	Red-crested Finch	*Coryphospingus cucullatus*	Thraupidae	Passeriformes	82	0.045	2	0	0	17110.6	0.031	Lower
189	Silver-beaked	*Ramphocelus*	Thraupidae	Passeriformes	88	0.054	2	0	0	6203.3	0.030	Lower

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	Tanager	*carbo*										
190	Green Kingfisher	*Chloroceryle americana*	Alcedinidae	Coraciiformes	85	0.049	2	0	0	8939.3	0.030	Lower
191	Orange-backed Troupial	*Icterus croconotus*	Icteridae	Passeriformes	107	0.082	2	1	1	2423.6	0.030	Lower
192	Greater Thornbird	*Phacellodomus ruber*	Furnariidae	Passeriformes	83	0.046	1	2	2	7381.2	0.029	Lower
193	Hellmayr's Pipit	*Anthus hellmayri*	Motacillidae	Passeriformes	78.1	0.039	2	1	0	41442.6	0.029	Lower
194	Saffron Finch	*Sicalis flaveola*	Thraupidae	Passeriformes	80.3	0.042	2	2	2	15671	0.029	Lower
195	Lark-like Brushrunner	*Coryphistera alaudina*	Furnariidae	Passeriformes	81	0.043	0	1	0	8533	0.029	Lower
196	Yellow-billed Nunbird	*Monasa flavirostris*	Bucconidae	Galbuliformes	110	0.087	2	0	0	2427.8	0.029	Lower
197	House Sparrow	*Passer domesticus*	Passeridae	Passeriformes	80	0.042	2	2	2	14455.5	0.028	Lower
198	Lesser Kiskadee	*Philohydor lictor*	Tyrannidae	Passeriformes	90	0.057	2	0	0	4309.7	0.028	Lower
199	Plain-breasted Ground-Dove	*Columbina minuta*	Columbidae	Columbiformes	80.1	0.042	2	1	1	13453.3	0.028	Lower
200	White-eared Puffbird	*Nystalus chacuru*	Bucconidae	Galbuliformes	80	0.042	2	0	0	14515.2	0.028	Lower
201	Natterer's Striolated Puffbird	*Nystalus striolatus*	Bucconidae	Galbuliformes	90	0.057	2	0	0	3257.6	0.027	Lower
202	Swallow-tailed Hummingbird	*Eupetomena macroura*	Trochilidae	Apodiformes	78	0.039	1	0	0	15031.8	0.026	Lower
203	Rufous-collared Sparrow	*Zonotrichia capensis*	Passerellidae	Passeriformes	78.1	0.039	2	0	0	11970.9	0.026	Lower
204	Vermilion Flycatcher	*Pyrocephalus rubinus*	Tyrannidae	Passeriformes	80	0.042	2	1	0	9465.4	0.025	Lower
205	Masked Water-Tyrant	*Fluvicola nengeta*	Tyrannidae	Passeriformes	76	0.036	2	1	2	16602.7	0.025	Lower

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206	Thrush-like Wren	*Campylorhynchus turdinus*	Troglodytidae	Passeriformes	90	0.057	0	2	2	3608.7	0.024	Lower
207	White-fronted Nunbird	*Monasa morphoeus*	Bucconidae	Galbuliformes	120	0.102	1	0	0	2627	0.024	Lower
208	Hooded Siskin	*Spinus magellanicus*	Fringillidae	Passeriformes	75	0.034	2	2	0	15667.5	0.023	Lower
209	Lesser Hornero	*Furnarius minor*	Furnariidae	Passeriformes	82	0.045	1	1	1	3545.7	0.023	Lower
210	Wedge-tailed Grass-Finch	*Emberizoides herbicola*	Thraupidae	Passeriformes	73.3	0.032	2	0	0	16447.4	0.022	Lower
211	Three-toed Jacamar	*Jacamaralcyon tridactyla*	Galbulidae	Galbuliformes	70	0.027	2	0	0	47063.4	0.021	Lower
212	Black-and-rufous Warbling-Finch	*Poospiza nigrorufa*	Thraupidae	Passeriformes	69	0.025	1	1	0	23914.8	0.018	Lower
213	Green-rumped Parrotlet	*Forpus passerinus*	Psittacidae	Psittaciformes	81.2	0.043	2	2	1	1648.8	0.018	Lower
214	Brown Jacamar	*Brachygalba lugubris*	Galbulidae	Galbuliformes	72	0.030	2	0	0	5516.4	0.018	Lower
215	Long-tailed Ground-Dove	*Uropelia campestris*	Columbidae	Columbiformes	70	0.027	2	1	0	7306.4	0.017	Lower
216	Masked Yellowthroat	*Geothlypis aequinoctialis*	Parulidae	Passeriformes	69	0.025	2	0	0	14743	0.017	Lower
217	Pileated Finch	*Coryphospingus pileatus*	Thraupidae	Passeriformes	68	0.024	2	0	0	12264	0.016	Lower
218	Pink-legged Graveteiro	*Acrobatornis fonsecai*	Furnariidae	Passeriformes	67.8	0.023	1	0	0	9176	0.016	Lower
219	Double-collared Seedeater	*Sporophila caerulescens*	Thraupidae	Passeriformes	68.5	0.024	2	0	0	11321.8	0.015	Lower
220	Cinereous Warbling-Finch	*Microspingus cinereus*	Thraupidae	Passeriformes	67	0.022	2	1	0	12142.9	0.015	Lower
221	Black-throated Mango	*Anthracothorax nigricollis*	Trochilidae	Apodiformes	69	0.025	2	0	0	9539.6	0.015	Lower

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222	Bananaquit	*Coereba flaveola*	Thraupidae	Passeriformes	67	0.022	2	0	0	10491	0.014	Lower
223	Grassland Sparrow	*Ammodramus humeralis*	Passerellidae	Passeriformes	66	0.021	2	0	0	13231.2	0.014	Lower
224	Chotoy Spinetail	*Schoeniophylax phryganophilus*	Furnariidae	Passeriformes	66	0.021	1	1	0	9813.8	0.014	Lower
225	White-vented Violetear	*Colibri serrirostris*	Trochilidae	Apodiformes	64	0.018	1	0	0	19374.7	0.012	Lower
226	Tufted Tit-Spinetail	*Leptasthenura platensis*	Furnariidae	Passeriformes	64	0.018	0	0	1	8884.4	0.012	Lower
227	Hyacinth Visorbearer	*Augastes scutatus*	Trochilidae	Apodiformes	62	0.014	2	0	0	14593.2	0.010	Lower
228	Stripe-breasted Starthroat	*Heliomaster squamosus*	Trochilidae	Apodiformes	61	0.013	1	0	0	17388.8	0.009	Lower
229	Orange-fronted Yellow-Finch	*Sicalis columbiana*	Thraupidae	Passeriformes	62	0.014	2	1	1	6240.5	0.009	Lower
230	Striolated Tit-Spinetail	*Leptasthenura striolata*	Furnariidae	Passeriformes	60	0.011	0	0	1	25898.4	0.009	Lower
231	Rusty-collared Seedeater	*Sporophila collaris*	Thraupidae	Passeriformes	60	0.011	1	0	0	15214.6	0.008	Lower
232	White-bellied Seedeater	*Sporophila leucoptera*	Thraupidae	Passeriformes	59	0.010	2	0	0	13678.3	0.007	Lower
233	Sapphire-spangled Emerald	*Amazilia lactea*	Trochilidae	Apodiformes	57	0.007	2	0	0	25203	0.005	Lower
234	Ruby-topaz Hummingbird	*Chrysolampis mosquitus*	Trochilidae	Apodiformes	57	0.007	1	0	0	9315.4	0.004	Lower
235	Lined Seedeater	*Sporophila lineola*	Thraupidae	Passeriformes	57.16	0.007	2	0	0	7910.9	0.004	Lower
236	Yellow-bellied Seedeater	*Sporophila nigricollis*	Thraupidae	Passeriformes	56.5	0.006	2	0	0	13099.6	0.004	Lower
237	Blue-tufted Starthroat	*Heliomaster furcifer*	Trochilidae	Apodiformes	56.5	0.006	2	0	0	11796.5	0.004	Lower

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238	Gilded Hummingbird	*Hylocharis chrysura*	Trochilidae	Apodiformes	56	0.005	2	0	0	15992.2	0.004	Lower
239	Dark-throated Seedeater	*Sporophila ruficollis*	Thraupidae	Passeriformes	55.3	0.004	1	0	0	13203.9	0.003	Lower
240	Glittering-bellied Emerald	*Chlorostilbon lucidus*	Trochilidae	Apodiformes	55	0.004	2	0	0	16301.7	0.003	Lower
241	White-throated Seedeater	*Sporophila albogularis*	Thraupidae	Passeriformes	54	0.002	2	0	0	12657	0.002	Lower
242	Southern House Wren	*Troglodytes musculus*	Troglodytidae	Passeriformes	53	0.001	2	2	1	8914.8	0.001	Lower
243	White-chinned Sapphire	*Hylocharis cyanus*	Trochilidae	Apodiformes	54	0.002	2	0	0	5556.6	0.001	Lower
244	Greater Yellow-headed Vulture	*Cathartes melambrotus*	Cathartidae	Cathartiformes	533	0.725	0	1	0	2116.2	0.000	Lower
245	Crested Caracara	*Caracara cheriway*	Falconidae	Falconiformes	406	0.534	0	2	1	2866.4	0.000	Lower
246	White Hawk	*Pseudastur albicollis*	Accipitridae	Accipitriformes	379	0.493	2	2	0	2361.5	0.000	Lower
247	Long-tailed Potoo	*Nyctibius aethereus*	Nyctibiidae	Nyctibiiformes	345	0.442	0	2	0	8427.1	0.000	Lower
248	Black Caracara	*Daptrius ater*	Falconidae	Falconiformes	322	0.407	2	2	0	1782.8	0.000	Lower
249	Slender-billed Kite	*Helicolestes hamatus*	Accipitridae	Accipitriformes	287	0.354	2	0	0	2360.9	0.000	Lower
250	Broad-winged Hawk	*Buteo platypterus*	Accipitridae	Accipitriformes	272.6	0.332	2	1	0	1080.2	0.000	Lower
251	Chestnut-fronted Macaw	*Ara severus*	Psittacidae	Psittaciformes	231.5	0.270	0	2	0	2401.9	0.000	Lower
252	Red-shouldered Macaw	*Diopsittaca nobilis*	Psittacidae	Psittaciformes	173	0.182	2	1	2	1590.3	0.000	Lower
253	Sun Parakeet	*Aratinga solstitialis*	Psittacidae	Psittaciformes	154.3	0.154	2	2	2	1618.6	0.000	Lower

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254	Dusky-headed Parakeet	*Aratinga weddellii*	Psittacidae	Psittaciformes	143.6	0.138	2	2	0	1887.4	0.000	Lower
255	Southern Martin	*Progne elegans*	Hirundinidae	Passeriformes	143	0.137	2	2	0	1355.4	0.000	Lower
256	Brown-throated Parakeet	*Eupsittula pertinax*	Psittacidae	Psittaciformes	139.2	0.131	2	1	0	885.4	0.000	Lower
257	Oriole Blackbird	*Gymnomystax mexicanus*	Icteridae	Passeriformes	137	0.128	2	0	0	2209	0.000	Lower
258	Black Nunbird	*Monasa atra*	Bucconidae	Galbuliformes	134.5	0.124	2	0	0	780.4	0.000	Lower
259	Gray Kingbird	*Tyrannus dominicensis*	Tyrannidae	Passeriformes	124.5	0.109	2	1	1	561.6	0.000	Lower
260	Streaked Flycatcher	*Myiodynastes maculatus*	Tyrannidae	Passeriformes	119.1	0.101	2	0	0	1314.9	0.000	Lower
261	Great Jacamar	*Jacamerops aureus*	Galbulidae	Galbuliformes	118	0.099	2	0	0	1426.6	0.000	Lower
262	Eastern Meadowlark	*Sturnella magna*	Icteridae	Passeriformes	115.99	0.096	2	0	0	3368.2	0.000	Lower
263	Black-billed Thrush	*Turdus ignobilis*	Turdidae	Passeriformes	114.6	0.094	2	0	0	0	0.000	Lower
264	Olive-sided Flycatcher	*Contopus cooperi*	Tyrannidae	Passeriformes	111.35	0.089	2	0	0	4278.9	0.000	Lower
265	Eastern Kingbird	*Tyrannus tyrannus*	Tyrannidae	Passeriformes	110.1	0.087	2	0	0	2380.1	0.000	Lower
266	Sulphury Flycatcher	*Tyrannopsis sulphurea*	Tyrannidae	Passeriformes	110	0.087	2	0	0	2247.7	0.000	Lower
267	White-banded Swallow	*Atticora fasciata*	Hirundinidae	Passeriformes	108	0.084	2	0	0	1692.8	0.000	Lower
268	Cliff Flycatcher	*Hirundinea ferruginea*	Tyrannidae	Passeriformes	103	0.076	2	2	1	1.7	0.000	Lower
269	Carib Grackle	*Quiscalus lugubris*	Icteridae	Passeriformes	100	0.072	2	1	0	0	0.000	Lower
270	White-thighed Swallow	*Atticora tibialis*	Hirundinidae	Passeriformes	98	0.069	2	0	0	6781.2	0.000	Lower

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271	Black-collared Swallow	*Pygochelidon melanoleuca*	Hirundinidae	Passeriformes	97	0.067	2	0	0	3141.7	0.000	Lower
272	Blue-gray Tanager	*Tangara episcopus*	Thraupidae	Passeriformes	93	0.061	2	2	1	2064.5	0.000	Lower
273	Paradise Jacamar	*Galbula dea*	Galbulidae	Galbuliformes	91	0.058	2	0	0	1839.6	0.000	Lower
274	Purus Jacamar	*Galbalcyrhynchus purusianus*	Galbulidae	Galbuliformes	88	0.054	2	0	0	910.2	0.000	Lower
275	Red-capped Cardinal	*Paroaria gularis*	Thraupidae	Passeriformes	85.6	0.050	2	1	2	2168.4	0.000	Lower
276	Green-tailed Jacamar	*Galbula galbula*	Galbulidae	Galbuliformes	80	0.042	2	0	0	854.6	0.000	Lower
277	Bluish-fronted Jacamar	*Galbula cyanescens*	Galbulidae	Galbuliformes	75	0.034	2	0	0	687.5	0.000	Lower
278	White-chinned Jacamar	*Galbula tombacea*	Galbulidae	Galbuliformes	75	0.034	2	0	0	304.8	0.000	Lower
279	White-throated Jacamar	*Brachygalba albogularis*	Galbulidae	Galbuliformes	72	0.030	2	0	0	618.6	0.000	Lower
280	Bicolored Wren	*Campylorhynchus griseus*	Troglodytidae	Passeriformes	64	0.018	2	2	2	2259.8	0.000	Lower
281	Yellow-browed Sparrow	*Ammodramus aurifrons*	Passerellidae	Passeriformes	60	0.011	2	0	0	1867.5	0.000	Lower
282	Long-billed Starthroat	*Heliomaster longirostris*	Trochilidae	Apodiformes	58	0.008	1	0	0	1946.1	0.000	Lower
283	Ruddy-breasted Seedeater	*Sporophila minuta*	Thraupidae	Passeriformes	52.4	0.000	2	0	0	2621.7	0.000	Lower

* 0 (zero) for species that possibly don't have the specific behavior. No evidence on Wikiaves database and classified by expert knowledge as likely non-user. 1 (one) for species that possibly use the structures of the power lines - classification as a potential user by expert knowledge. 2 (two) for species with confirmed evidence of use behave of structures by WikiAves database (https://www.wikiaves.com.br).

Capítulo 3

Eletrocussões em linhas de energia como um impacto negligenciado para espécies ameaçadas: preocupações sobre a conservação da arara-azul-de-lear (*Anodorhynchus leari*, Aves, Psittacidae)

Larissa D. Biasotto, Erica Pacífico, Fernanda Paschotto, Thiago Filadelfo, Maíla Couto, Kilma Manso, Antonio Emanuel B.A. Souza, Luis Fábio Silveira, Fernando Ascensão, José Luis Tella & Andreas Kindel

Esse capítulo será submetido para a revista *Avian Conservation and Ecology* como *Short Communication* e está formatado conforme as normas da revista, com exceção das figuras, que se encontram inseridas ao longo do texto. Tem a primeira autoria compartilhada entre Larissa Biasotto e Erica Pacífico.

Chapter 3 - Power line electrocution as an overlooked threat to endangered species: concerns about the conservation of the Lear's Macaw (*Anodorhynchus leari*, Aves, Psittacidae)

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ABSTRACT

Electrocution constitutes a threat for small populations, potentially affecting the species persistence over time. Population-level impacts caused by electrocutions have been evidenced mainly for raptors, however, other avian taxa can also be affected. Parrots and macaws are vulnerable to electrocution, but few studies have been carried out with a focus on psittacine. Here we report electrocutions deaths of the endangered Lear's Macaw. Despite the underestimates, the number of recorded electrocutions we reported clearly highlights that this may be an important threat to this species. The electrocution affected adults, mostly during the breeding season and the number of electrocution fatalities decreased with increasing distances to the nearest roosting site. We highlight the importance to consider electrocution risk as a novel and overlooked threat for the Lear's Macaw. We emphasize the urgent need to systematically monitor electrocution fatalities and to apply effective and efficient mitigation measures, together with policy formulation aimed at reducing the impact of power lines along the species distribution area.

Keywords: avian conservation, distribution lines, electrical shock, pylon management, pole retrofitting.

1. Introduction

Power lines are infrastructures continuously expanding worldwide to supply human populations that lack access to electricity (Arderne et al. 2020). Poorly planned power line networks may represent a risk for biodiversity, both by crossing sensitive areas, resulting in habitat loss and degradation, and by promoting wildlife fatalities due to collision or electrocution. The presence of power lines can act as an ecological trap since, while providing perching or nesting opportunities on poles and wires, they may cause non-compensated deaths from collisions and electrocutions (Mainwaring 2015). Electrocution occurs when an animal simultaneously touches two-phase conductors or one conductor and a grounded device on a pole (Bevanger 1998). Electrocution events are therefore expected to be more common in distribution lines – low and medium voltage – due to the shorter distance between the electrified elements (Bevanger 1994, 1998). For the same reason, electrocution may be an important fatality source for larger-sized species that use poles or wires for displacement, perching and nesting sites, most notably for flying vertebrates like large birds and bats (Loss et al. 2015, Tella et al. 2020) but also, for arboreal mammals such as primates (Corrêa et al. 2018).

Electrocution constitutes a threat mainly for small populations, potentially affecting the species persistence over time (Eccleston and Harness 2018). Population-level impacts caused by electrocutions have been evidenced mainly for endangered raptors, such as the Cape Vulture *Gyps coprotheres* (Boshoff et al. 2011) and the Bonelli's Eagle *Aquila fasciata* (Hernández-Matías et al. 2015) and supposed for many other birds of prey as reviewed by Lehman et al. (2007) and Slater et al. (2020). However, other avian taxa like corvids and woodpeckers can also be affected (Bevanger 1998, Janss 2000).

While bird electrocution is "on the radar" of conservation efforts in many parts of the world (Boshoff et al. 2011, Dixon et al. 2013, Kemper et al. 2013, Loss et al. 2014, Ibarra J. De Lucca E. 2015, Guil et al. 2015), it remains understudied in the Neotropics (Galmes et al. 2017 Guil and Pérez-García 2022). Yet, it is expected a strong expansion of the energy grid for the next decades in this region (Kishore and Singal 2014). Furthermore, as tropical regions host a large proportion of the world bird species, the expansion of power line networks is expected to have detrimental effects on local populations of large and endangered birds (Biasotto et al. 2021).

Parrots (order Psitaciformes), and particularly macaws, are vulnerable to electrocution (Biasotto et al. 2021), but few studies focused on these birds. Overall, just anecdotal or occasional death by electrocution are reported for parrots. Galmes et al. (2017) documented at least two parrot species in Argentina as victims of electrocution. Losses of some Golden Parakeets *Guaruba guarouba*, a threatened species reintroduced in Belém (Brazil), were caused by electrocution (Vilarta et al. 2021). Further, it is known that the last wild Spix's Macaw *Cyanopsitta spixii* died due to electrocution (Juniper, 2004). The two large blue macaws, Hyacinth Macaw (*Anodorhynchus hyacinthinus*) and Lears' Macaw (*Anodorhynchus leari*), have been recently identified at high risk of electrocution due to their morphology and behavioral traits and to the high pole density within their distribution (Biasotto et al. 2021) adding a reason for concern about their population integrity.

The Lear's Macaw is endemic to the *Caatinga* biome (tropical dry forests in NE Brazil) and listed as globally Endangered by IUCN (Birdlife International 2020). While the population of Lear's Macaw has increased in the last 30 years due to active conservation efforts (Barbosa and Tella 2019), the loss of nesting (Pacífico et al. 2020) and foraging habitats constitutes a main threat for its long-term persistence. Continued deforestation and habitat degradation resulting from agricultural and livestock intensification (e. g. exotic pastures and crops; overgrazing), together with the expansion of mining and energy developments such as wind farms, hydroelectric power plants, coal power plants, illegal charcoal, and logging (Acosta-Salvatierra et al. 2017, Neri et al. 2019) are of particular importance. These land use changes associated with unsustainable practices in agriculture (de Andrade et al. 2015) also affect Lear's Macaw by reducing patch size, density, and survival of the Licuri Palm (*Syagrus coronata*), whose fruits are a key food resource for the specie (Silva-Neto et al. 2012).

Here we report macaws' deaths caused by electrocution, discussing the importance to consider electrocution risk as a novel and overlooked threat for the Lear's Macaw. We emphasize the urgent need to systematically monitor electrocution fatalities and to apply effective and efficient mitigation measures, together with policy formulation aimed at reducing the impact of power lines along the species distribution area.

2. Methods

2.1 Study area:

Caatinga is an ecoregion endemic to NE Brazil, a semiarid hinterland that presents a mosaic of different physiognomies with a broad range of woody plant densities (da Silva et al. 2017). It is characterized by a high inter-annual variability in rainfall, with droughts that can last for years. This biome is threatened by agriculture, farming, and illegal charcoal production. Moreover, inadequate land use has caused accelerated desertification processes in many areas (da Silva et al. 2017, Acosta-Salvatierra et al. 2017, Schulz et al. 2018). The Lear's Macaw population core areas are in the Raso da Catarina (RASO), where >99% of the individuals are concentrated and population numbers are increasing. Another almost extinct population of Lear's Macaw has been managed and monitored for its restoration since 2016 at the Protection Area of Boqueirão da Onça (BDO), 230 km west to the RASO population (Pacífico et al. 2014).

2.2 Electrocution records and field observations:

Macaws found dead were informed by locals; whenever possible we retrieved the carcass to confirm signs of electrocution and only confirmed electrocuted ones were counted for this study and the localities georeferenced. All specimens found in adequate conditions were deposited at Museu de Zoologia da Universidade de São Paulo (MZUSP), and when possible, tissue samples were also obtained and deposited at the same collection (SISBIO license nº 12.763). We briefly described the pole structure and their energized elements at the sites were the fatalities occurred. We also recorded the presence or absence of both Licuri Palm patches and natural perching structures (e. g. higher trees dead or alive) near the specific fatalities

During long-term surveys (2008 to 2021) in the Caatinga to investigate population dynamics and habitat use of Lear's Macaw, we often observed individuals perching on power lines and interacting with energy elements. We distinguished and documented some of these behaviors to identify potential reasons for electrocution.

2.3 Distribution of fatality events:

We created map layers with the following information: i) locations of macaw fatalities; ii) current range distribution of the species, that includes 11 municipalities at north of the state of Bahia (Rodelas, Paulo Afonso, Glória, Santa Brígida, Jeremoabo, Canudos, Euclides da Cunha, Monte Santo, Novo Triunfo, Sento Sé, Campo Formoso); iii) historical occurrence of the species, that includes Uauá, Curaçá, Umburanas municipalities, and peripheral potential feeding areas, that include another 6 municipalities (Cansanção, Quijingue, Cícero Dantas, Banzaê, Sítio do Quinto, Antas), as potential areas for the expansion of the species (pers. obs. E.P., Araujo et al. 2014, ICMBio 2019) ; iv) the six known communal roosting sites of the species: Toca Velha (Canudos) and Serra Branca (Jeremoabo), which are the main roosts, and Barreiras (Canudos), Baixa do Chico community (Glória), Barra do Tanque (Euclides da Cunha), and Logradouro Farm (Jeremoabo), which were recently discovered (T.F.; E.P. pers. obs); and v) the medium voltage (13,8 kV) power line grid provided by the Brazilian Electricity Regulatory Agency (ANEEL). We used ArcGIS 10.3.1 (ESRI, 2015) for building all maps, and the Path Distance tool to extract distance from each fatality record to the nearest roosting site.

3. Results

3.1. Electrocution records and field observations:

Lear's Macaw carcasses were recovered by villagers under the power lines and very close to the poles (Fig. 1a). Clear signs of electrocution were observed in all of them, such as burned areas on the body, beak, phalanges, and feathers (Fig. 1b, c, d). Some carcasses showed signs of predation after electrocution (Fig. 1e).

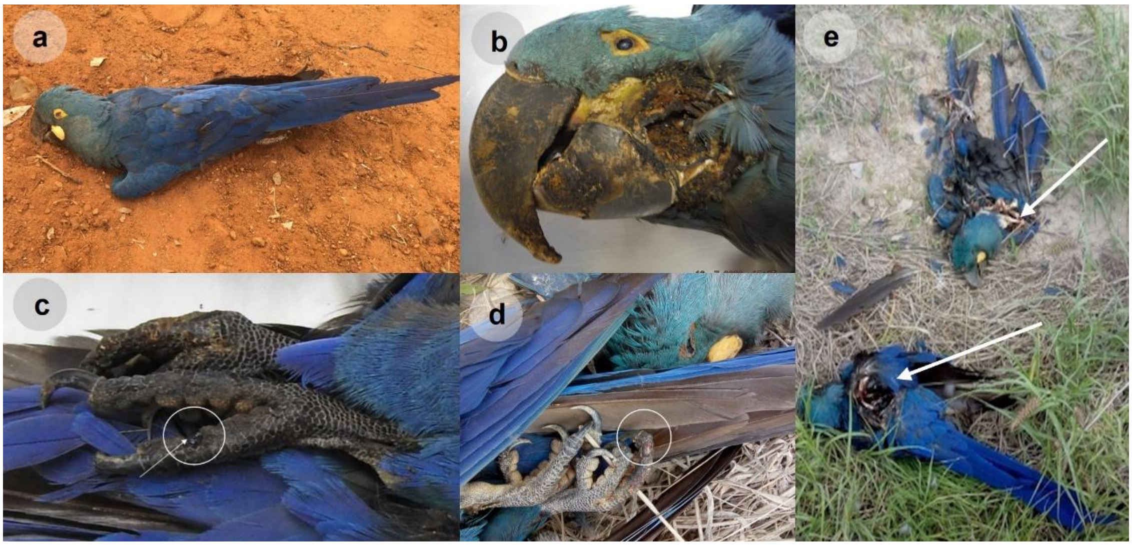

Figure 1. a) Dead Lear's Macaw found with signs of electrocution (Marlene Reis); **b)** Signs of electrocution in the Lear's Macaw carcass (Marlene Reis); **c)** Burned phalanges (necropsy report); **d)** Two Lear's Macaws with injuries in phalanges (José Amilton Dantas Alves); **e)** Two Lear's Macaws with signs of predation after electrocution (José Amilton Dantas Alves).

By June 2021 we compiled a total of 31 individuals found dead by electrocution (Fig. 2) (Supporting Information, Table S1). First electrocution was reported in 2008, and numbers increased after 2017 with a maximum of nine macaws in 2019. In the current year (2021), we recorded an increase in fatalities, with one dead macaw per month (six records until June). Two electrocution events involved two simultaneous deaths and one event killed three individuals at once. Fatalities mainly occurred (74%) during the breeding season (December – June) (Supporting Information, Table S1).

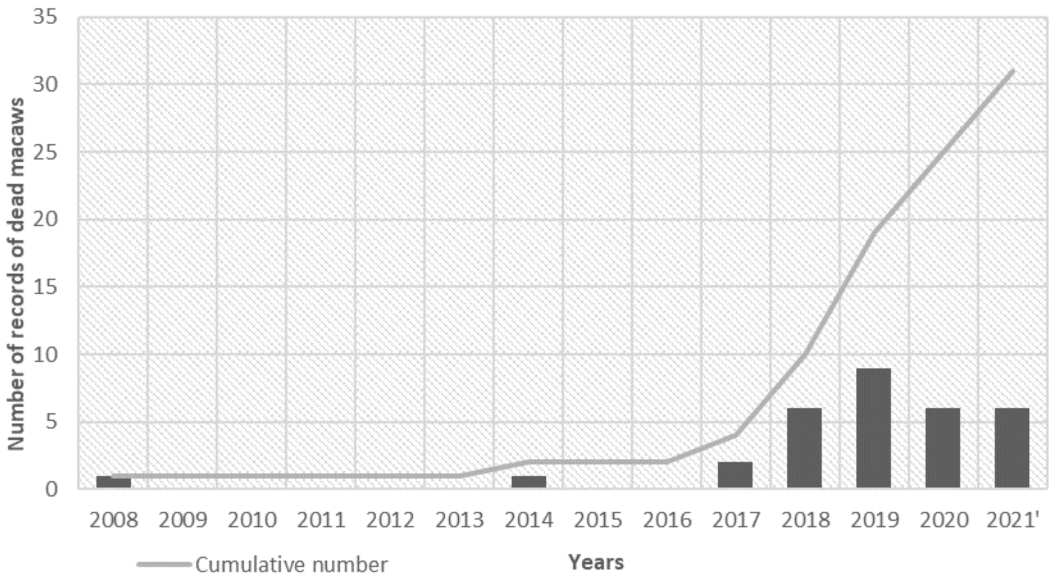

Figure 2. Records of Lear's Macaws electrocuted per year and accumulated along the observation period. Data updated until June 2021.

The recorded fatalities were more common on concrete pylons with two-phase or three-phase distribution corner configuration (structure carrying two different distribution lines, one of them underbuilt and perpendicularly arranged), with exposed wires, horizontally arranged in a crossarm, whose distance among the wires is less than 70 cm (Fig. 3 e). Some fatalities also occurred on poles containing pin type insulator, and other devices like transformers and exposed jumpers.

Macaws were recorded using power lines as perch to forage (Fig. 3 a), to perform sentinel behavior and to rest in locations still without electrocution records (Fig. 3b and c), pecking the power line structures, and interacting closely with pole elements (Fig. 3 a, b, c, d).

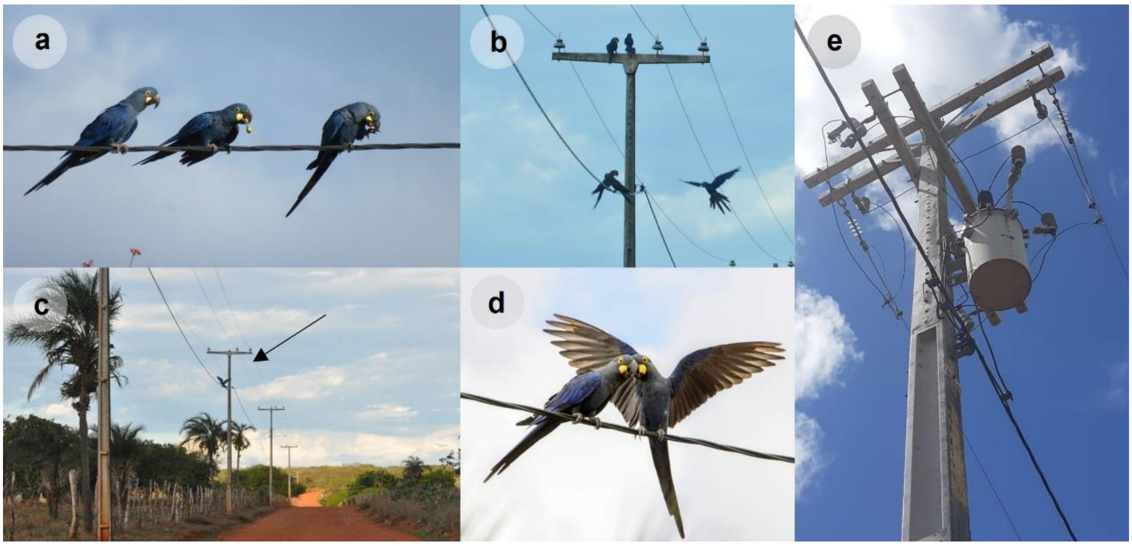

Figure 3. a) Lear's Macaws observed eating Licuri Palm fruits perched at power lines (Mariana Diniz); **b)** Lear's macaws perching at power line structures (Thiago Filadelfo); **c)** Lear's Macaw foraging in the Licuri Palm patches, using power line to sentinel behavior (black arrow) in the rural areas (Thiago Filadelfo); **d)** Pair of macaws interacting in energy cable (Dalila Mouta); **e)** Corner configuration pole most commonly causing macaw electrocutions.

3.2. Distribution of fatality events

We identified 13 electrocution localities (Fig. 4) and we observed macaws using power line structures for perching while foraging in the Licuri Palm patches in 10 of them. Most of the deaths were recorded at Euclides da Cunha municipality (58%) (Fig. 4c). By overlapping the grid of medium voltage lines with both sets of municipalities of potential and confirmed occurrence we observed that power lines were installed in all the current and the potential expansion areas of Lear's Macaw in RASO Ecoregion (Fig. 4c).

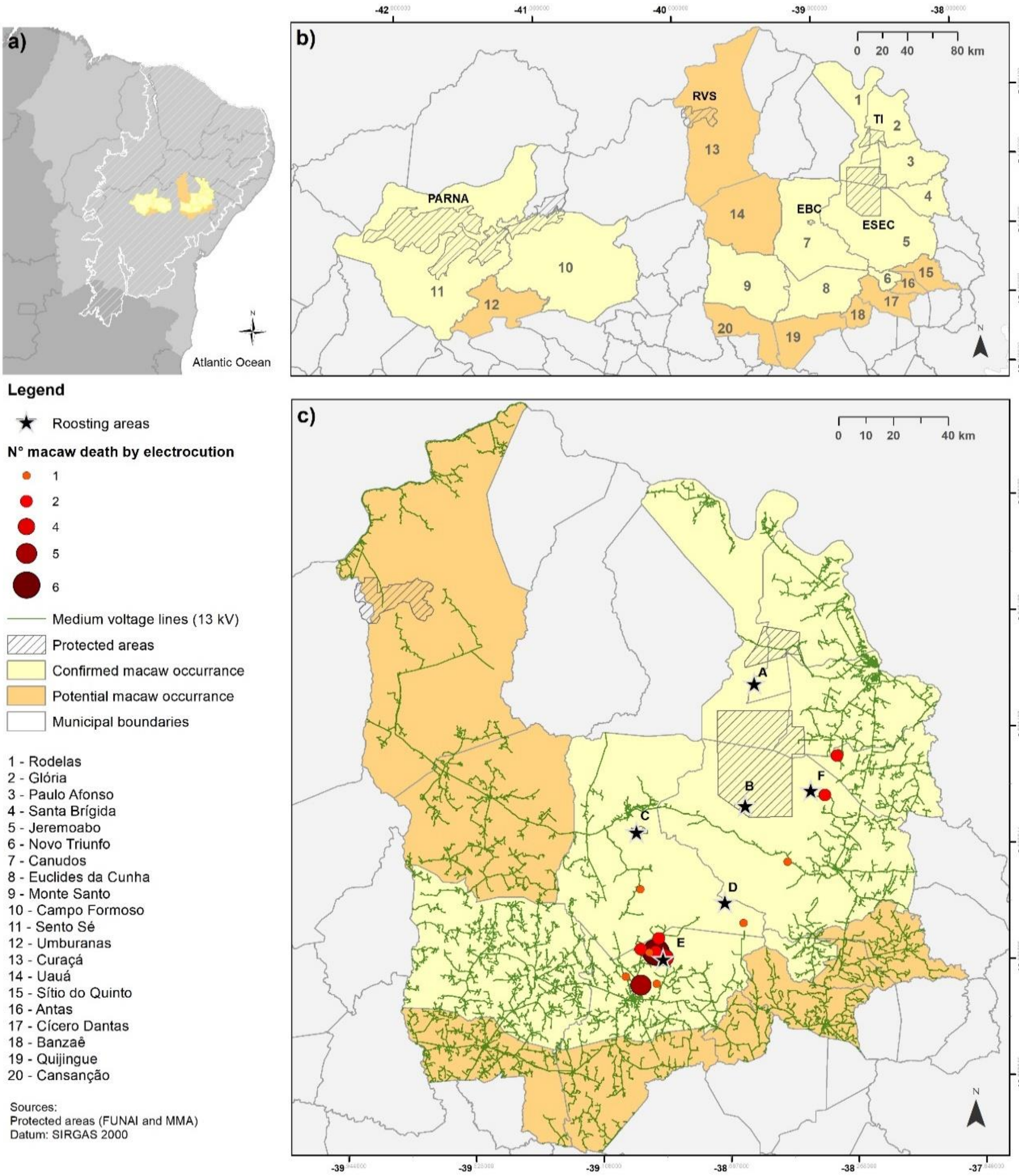

Figure 4. a) Northeast region of Brazil in light grey, with white line highlighting the Caatinga limits and colored patches the main areas of Lear's macaw areas of occurrence; **b)** Detail of the two known areas of occurrence of the Lear´s Macaw: the Boqueirão da Onça area (left) and the Raso da Catarina area (right), and the protected areas: PARNA (Boqueirão da Onça National Parque); RVS (Ararinha-Azul Wildlife Refuge); TI (Brejo do Burgo Indigenous land); ESEC (Raso da Catarina Ecological Station); EBC (Canudos Biological Station); **c)** Municipalities at Raso da Catarina area where the electrocutions occurred (red dots) and the known communal roosting sites of the species (black stars): A (Baixa do Chico community), B (Serra Branca), C (Toca Velha), D (Barreiras), E (Barra do Tanque) and F (Logradouro Farm).

The number of electrocution fatalities recorded decreased with increasing distances to the nearest roosting site (Fig. 5). Distances ranged from 0.89 km at Barra do Tanque to 25.67 km at Serra Branca communal roosts (Fig. 5).

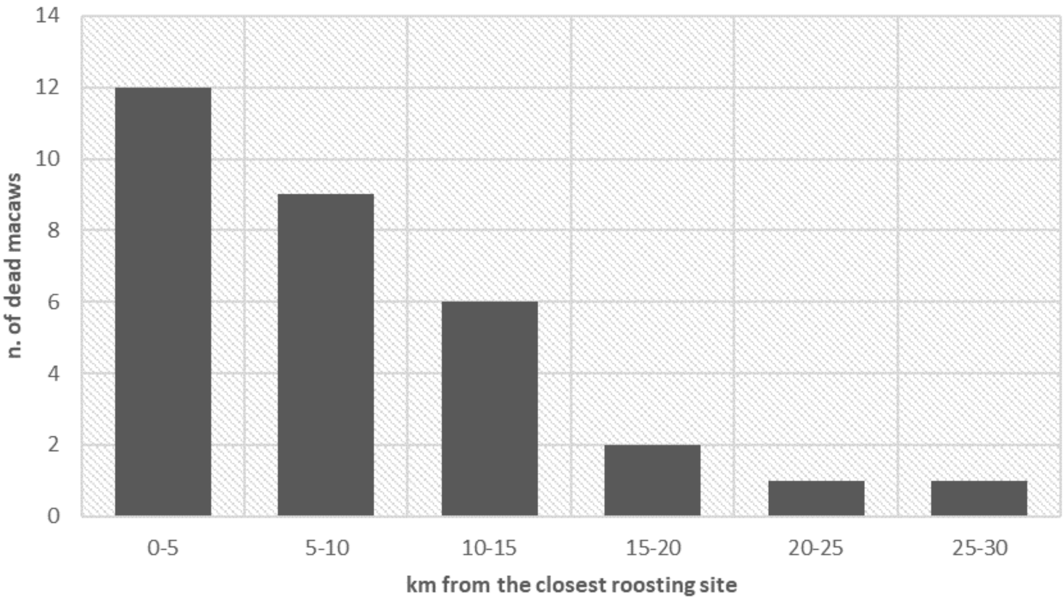

Figure 5. Distance (km) to the nearest communal roost sites of electrocuted Lear's Macaws.

4. Discussion

Our results are the first evidence that medium voltage power lines cause frequent fatalities to the globally Endangered and range-restricted Lear's Macaw. The increasing number of electrocutions we report indicate that this may currently be the major cause of human induced mortality for the species, being larger than the losses due to killing as a response of farmers to crop losses in the past (Barbosa and Tella 2019). Moreover, the fact that electrocution occurred mostly during the breeding season may seriously affect the population dynamics of the species.

Power lines may function as an ecological trap for this species, offering an apparent advantage by providing perching sites for foraging macaws, which however result in a higher risk of electrocution (Mainwaring 2015). Energy poles seem to offer an attractive alternative used for feeding and sentinel behaviors in increasing anthropogenic landscapes that are experiencing a progressive shortage of tall trees once used by macaws. Further, pairs and small flocks of Lear's Macaws have been observed perching on power lines, involved in intense social behaviors which include probing and pecking pole elements, increasing the probability of mortality events with more than one individual, as we recorded three times.

The increasing number of electrocutions is a warning signal and certainly deserves urgent attention. This apparent increase may result from both the expansion of the macaw's population (Barbosa and Tella 2019) and of the energy grid to rural areas, intensified since 2007 due to public incentives to universal access to energy (MME 2006). An additional cause could be the good and growing communication of locals with macaws' conservation groups, especially in Euclides da Cunha, thus increasing the detection and reporting of fatalities, and possibly explaining a higher concentration of the number of macaw's deaths in this municipality. Further, due to the communication improvement after energy availability in rural villages (e. g. internet admission, use of smartphones and apps) people can easier communicate the occurrence of fatalities. Finally, some energy breaks caused by electrocutions might take people to check the pole in front of their houses immediately resulting in carcass detection.

It is important to highlight that all fatalities were opportunistically recorded by villagers. Therefore, the number of carcasses reported to us surely underestimate actual numbers of electrocuted macaws. Spatial patterns may also be biased due to underreporting in remote and uninhabited areas. Additionally, scavenger's activity (Fig. 1e) may remove carcasses further reducing detection (Ponce et al. 2010, Bernardino et al. 2020). To obtain more accurate fatality estimates and explain their occurrence, we urgently need to conduct a systematic survey of carcasses accounting for imperfect detection (Borner et al. 2017, Barrientos et al. 2018) and investigate what are the technical, environmental, and biological covariates that can contribute to Macaw´s risk of electrocution. For example, confirm if the larger numbers of fatalities closer to roosting sites is a pattern and to what degree it is explained by a greater foraging and social activity in areas with Licuri patches closer to the roosting sites and/or by a higher density of risky poles. Answers to these questions would indicate priority areas for action.

Recommended conservation actions

Electrocution mitigations for Psittaciformes are a big challenge. Until now, solutions present in the scientific literature on electrocution mitigation, such as the installation of bird perch deterrents on energy poles and other avian-safety practices, primarily target raptors (APLIC 2006, Eccleston and Harness 2018). However, parrots and especially macaws have behavioral differences, standing out their curiosity and social behavior (Seibert, 2006). They often peck the structures and interact closely with pole elements, including playing around the energy conductors, jumpers, transformers, and most commonly doing this in pairs or flocks, as described here. Macaw's beaks are very strong, their bites easily destroying some deterrent structures like plastic spikes or insulator covers. Therefore, measures to mitigate the birds-of-prey electrocution may not be sufficient or suitable for parrots (Biasotto et al. 2021).

We recommend that mitigation efforts target on modifications of pole configurations and wire arrangements, such as increasing the distance between energized cables to at least 1.0 m (considering the Lear's Macaw wingspan) or eliminating the crossarms by using the vertical arrangement of wires with a minimum distance of 1.0 m among them (considering the Lear's Macaw body length). Alternative actions could be the insulation of energized elements, covering the jumpers, phase conductors, and transformer with resistant materials when the separation of wires is not feasible. Furthermore, the installation of other pole models like the wishbone design (APLIC 2006), a pole with alternate wires, may be encouraged. Since none of these possible solutions have ben ever tested, an experimental study, using a sampling design like progressive change BACIPS (Thiault et al. 2017), sufficiently replicated, should be used to evaluate their effectiveness.

We recommend that the retrofitting of hazardous poles should be started in areas closer to the six known roosting areas, mainly in Barra do Tanque, Serra Branca and Logradouro Farm, and after demonstrated effective, gradually be expanded to areas with confirmed pole occupancy by macaws in other municipalities. To be cost-efficient, since perhaps not all poles need interventions, such kind of mitigation program should be built following a pole occupancy survey (e.g., Moreira et al. 2018, García-Alfonso et al. 2021). However, as an emergency measure, poles with confirmed deaths should be immediately retrofitted.

Finally, it is extremely important that the proposed mitigation measures are applied when new power lines are installed over the entire Lear's Macaw distribution area. This is relevant considering the potential population expansion to new areas and the recent discovery of new roosting sites. During our long-term surveys we found three new roosting sites located in unprotected and human-disturbed areas (Baixa do Chico, Barreiras, and Logradouro farm). Moreover, although no records of electrocution were so far noticed for both Baixa do Chico and Boqueirão da Onça roosting areas, if happening, they could compromise the intensive conservation actions ongoing there, such as the reintroduction program for the recovery of the nearly extinct population in Boqueirão da Onça area.

We recommend urgency in all the above actions and, as soon as further information of an accurate estimate of Lear's macaw deaths due to electrocutions are available, a simulation study should be carried to better understand the potential outcomes of electrocutions onto the population's viability in the long term. The number of recorded electrocutions we reported in this study clearly highlights that this may be an important threat to this species that cannot be neglected hereafter.

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Supporting Information, Table S1 – Chapter 3.

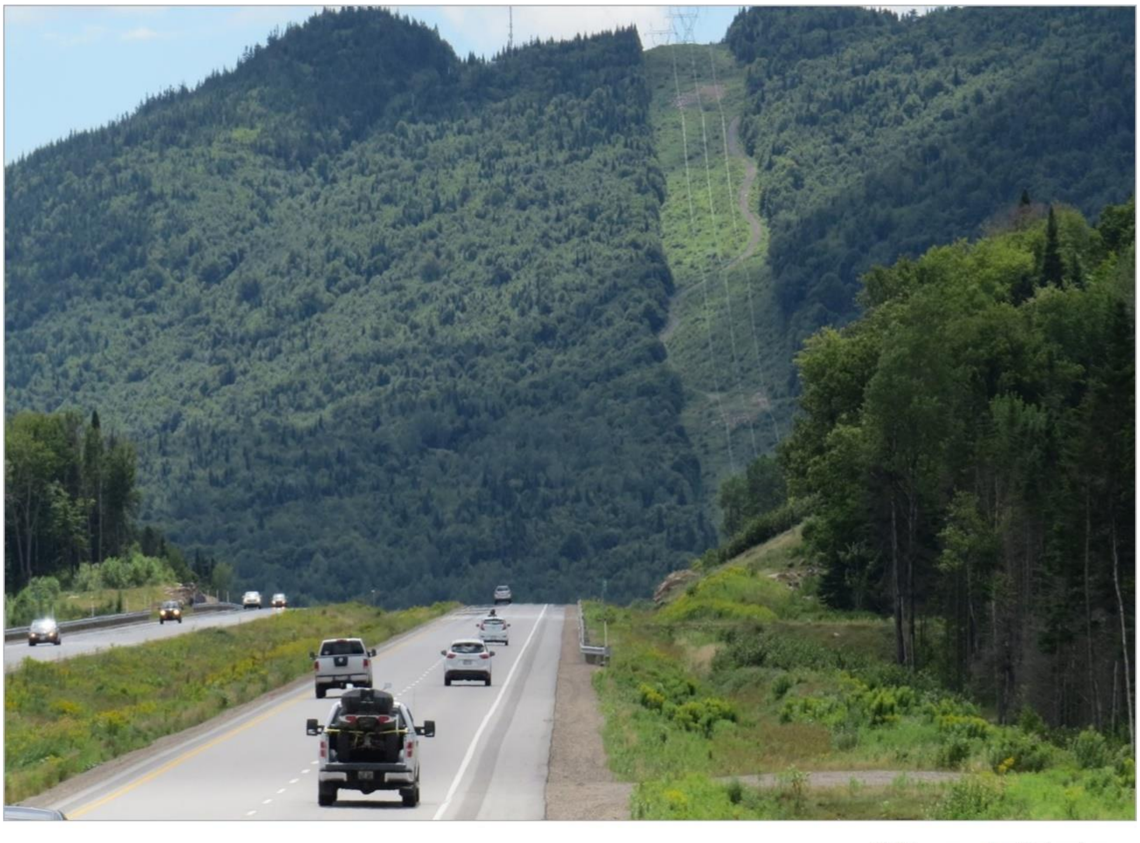
Table S1. Lear's Macaw electrocution data updated until June 2021. *AL*: *Anodorhynchus leari;* NA: Not Available.

Electrocution events	n° deaths	year	month	season	coordinates	municipality
*AL*001	1	2008	NA	NA	S10° 21.350' W38° 57.460'	Euclides da Cunha
*AL*002	1	2014	dec	breeding	S9° 49.967' W38° 22.850'	Jeremoabo
*AL*003	1	2017	jan	breeding	S10° 03.312' W38° 30.200'	Jeremoabo
*AL*004	1	2017	may	breeding	S10° 22.390' W38° 54.290'	Euclides da Cunha
*AL*005	1	2018	jan	breeding	S10° 15.475' W38° 38.901'	Canudos
*AL*006	1	2018	apr	breeding	S10° 21.180' W38° 56.170'	Euclides da Cunha
*AL*007	3	2018	may	breeding	S10° 22.390' W38° 54.290'	Euclides da Cunha
*AL*008	1	2018	dez	breeding	S10° 21.270' W38° 56.120'	Euclides da Cunha
*AL*009	1	2019	mar	breeding	S10° 18.519' W38° 55.581'	Canudos
*AL*010	1	2019	may	breeding	S10° 08.801' W38° 59.221'	Canudos
*AL*011	1	2019	oct	non-breeding	S10° 27.807' W38° 59.111'	Euclides da Cunha
*AL*012	1	2019	NA	NA	S10° 27.807' W38° 59.111'	Euclides da Cunha
*AL*013	1	2019	jan	breeding	S10° 21.270' W38° 56.120'	Euclides da Cunha
*AL*014	1	2019	fev	breeding	S10° 21.270' W38° 56.120'	Euclides da Cunha
*AL*015	2	2019	fev	breeding	S10° 21.270' W38° 56.120'	Euclides da Cunha
*AL*016	1	2019	dez	breeding	S10° 21.270' W38° 56.120'	Euclides da Cunha
*AL*017	1	2020	jun	late-breeding	S10° 27.807' W38° 59.111'	Euclides da Cunha
*AL*018	1	2020	jun	late-breeding	S10° 27.807' W38° 59.111'	Euclides da Cunha
*AL*019	1	2020	jun	late-breeding	S10° 27.807' W38° 59.111'	Euclides da Cunha
*AL*020	1	2020	jul	non-breeding	S9° 49.967' W38° 22.850'	Jeremoabo
*AL*021	2	2020	nov	early-breeding	S10° 20.654' W38° 59.105'	Euclides da Cunha
*AL*022	1	2021	fev	breeding	S9° 42.150' W38° 20.450'	Santa Brígida
*AL*023	1	2021	abr	breeding	S10° 18.519' W38° 55.581'	Canudos
*AL*024	1	2021	may	breeding	S10°27.553' W 38°55.948'	Euclides da Cunha
*AL*025	1	2021	may	breeding	S10° 21.180' W38° 56.170'	Euclides da Cunha
*AL*026	1	2021	may	breeding	S10° 26.127' W39° 02.080'	Euclides da Cunha
*AL*027	1	2021	may	breeding	S9° 42.150' W38° 20.450'	Santa Brígida

Capítulo 4

Infraestruturas lineares e os impactos sobre biodiversidade: semelhanças e diferenças entre estradas e linhas de energia

Larissa D. Biasotto, Francisco Moreira &
Andreas Kindel



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Chapter 4 - Linear infrastructures and impacts on biodiversity: a brief synthesis about similarities and differences between Roads and Power lines

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ABSTRACT

Even though the power line impacts on biodiversity are not an emerging topic, this subject has received far less attention when compared to Road Ecology. In the *section 1* of this chapter, we briefly remark the main aspects of the general structure of roads and power lines regarding their attributes, global extension, and effect zone, and we shortly review the similarities and differences in the top-five impact categories: attractiveness, wildlife mortality, barrier or filter effect, corridor effect, and lastly habitat quality and transformation. To address all key impacts from power lines on biodiversity, we synthesized and exemplified them with some examples. In the section 2, we identified some knowledge gaps that should be further explored in future studies.

Keywords: biodiversity, energy policy, environmental impacts, linear infrastructures, right of way.

Roads and power lines are certainly among the most pervasive human-made linear infrastructures on Earth. Despite their undeniable benefits to society, their construction and operation result in a large array of biodiversity impacts. Even though power line impacts are not an emerging topic, with the first's studies published in the 1920's (Michener 1928), this subject has received far less scientific attention when compared to Road Ecology.

In this chapter, we briefly remark the main aspects of the general structure of roads and power lines (section 1), shortly review the similarities and differences in the types and magnitude of their known impacts on biodiversity (section 1.1 to 1.5), and highlight some knowledge gaps that, if fulfilled, would strengthen our ability to prevent or remediate impacts of these linear infrastructures that regularly co-occur in most landscapes (section 2).

1. Similarities and differences in infrastructural aspects and in biodiversity impacts

A dataset obtained by Meijer et al. (2018) estimates that major roads cover over 21 million km of roads worldwide in 222 countries. Until now, at least 86% of the global population lives up to 2 km from a road (Wenz et al. 2020). For power lines, according to the Global Electric Power Transmission Network, until 2014 the global energy grid consisted of 5.5 million kilometers considering only the high-voltage transmission lines (above 69 kV). This is a large underestimation of the world power grid size as it does not include the low and medium voltage grids, the largest share of the power grid. Moreover, Arderne *et al.* (2020) estimated that 97% of the global population resides within 10 km of medium voltage lines (>10 kV) at present.

Each one of these linear infrastructures is very diverse and can be categorized by structural features and transport capacity. In the case of roads, the most important features are the number of lanes (width), surface type, traffic volume, and vehicle speed. For power lines, the most relevant traits include the energy transmission environment (overhead or underground) and if overhead, the voltage level (which distinguishes transmission and distribution lines), the type of supporting structures (e.g., towers, pylons or poles), and the number of circuits (wires). Many of those attributes are correlated, and regardless of whether a road or a power line, they will define the corridor width – Right of Way (RoW) - possibly one of the most important drivers of the abiotic and biotic changes on the landscape traversed.

Besides their huge length, the direct and indirect impacts of roads and power lines on biodiversity extend outwards from their main corridor, resulting in effect zones that correspond to an intensity gradient of irregular width, depending on the impact source and on the adjacent landscape (Fig. 1). The road-effect zone is better understood and is described as highly asymmetric between roadsides, depending mainly on traffic volume, environmental directional flows (e.g., wind, water), vegetation openness, topography, and species sensitivities (Forman and Deblinger 2000). Until now, effect zones were only estimated for roads (in the northern and temperate regions) remaining unknown for transmission and distribution power lines.

The most obvious effects of power lines on the environment are associated with the RoW, the zone below the overhead wires where vegetation is cleared and managed to avoid interferences with the structure and the risk of energy outages (Biasotto and Kindel 2018). The higher the voltage of a power line, the wider the RoW width. Also, there is no sinuosity due to almost mandatory linearity to minimize costs and energy losses.

The linear feature of roads and power lines result in general impacts common to both infrastructures, although the extent and intensity may differ and could be modulated by the surrounding environments. However, due to some structural and functional differences we also find some specific impacts of each one of these infrastructures. Below we will address some of the similarities and differences in five main impact categories common to both structures. To address all key-impacts from power lines on biodiversity, with less representation in the research agenda compared to roads, we synthesized and exemplified them with specific examples. In this chapter we do not make an exhaustive review (for more details on power line impacts, see Biasotto and Kindel 2018). For roads, we used some key review studies and the state of knowledge about impacts to contrast and compare with power lines.

Literature search on power line impacts on biodiversity

To describe and exemplify the impacts of power lines we searched for the most recently studies focused on power line impacts on biodiversity complementing the systematic review conducted by Biasotto and Kindel (2018), adding the last four years (2017 - 2020). We followed the same flowchart and used the same terms to conduct the review on Scopus© and ISI Web of Science© (see Biasotto and Kindel 2018 for more details). The review was updated in December 2020.

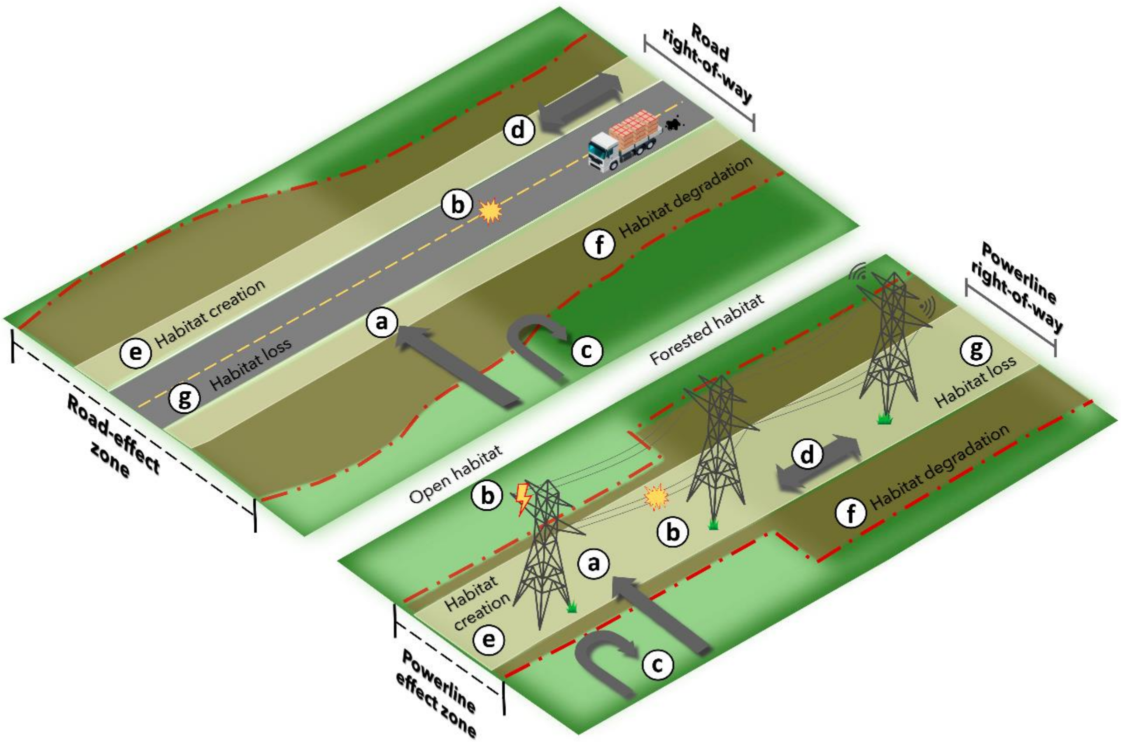

Fig 01. Overall structural similarities and differences of roads and power lines responsible for their impacts on biodiversity. **a)** Attractiveness to the road surface or to the power line corridor caused by resource provision; **b)** wildlife mortality by vehicle collision in roads and by overhead wire collision and electrocution on power lines; **c)** barrier or filter effect responsible for animal avoidance in roads and power line structures; **d)** corridor effect showing the possible displacement along RoWs of roads and power lines; and changes in environmental quality that depending on the species requirements, may be perceived as: **e)** habitat creation, **f)** disturbances like chemical pollution on roads and electromagnetic pollution on power lines responsible for habitat degradation, and, ultimately, as **g)** habitat loss caused by both roads and power line operation.

1.1. Attractiveness

Both roads and power lines can provide new resources or conditions that increase habitat quality and attract organisms towards them (Fig. 1a). Some species are attracted to the road surface by food availability (seed spills and carrion) (Fig. 2a), or for thermoregulation, which obviously can make them vulnerable to increased road mortality if they are not able to avoid incoming vehicles (Fahrig and Rytwinski 2009). Overhead wires, towers and pylons/poles may be used as perches by birds for foraging and nesting (e.g., Prather and Messmer 2010; Zhou et al. 2020) (Fig. 02 b and c) resulting in benefits at the population level for some species such as the White stork (*Ciconia ciconia*) (Moreira et al. 2018).

Fig 02. Examples of food and breed resource provided by roads and power lines. a) Black vulture (*Coragyps atratus*) attracted to the road surface by a carcass – Photo: Luisa Teixeira; b) A couple of White storks nesting on a high voltage energy tower – Photo: Larissa Biasotto; c) White-tailed Hawk (*Geranoaetus albicaudatus*) perching on distribution energy poles with bird nests – Photo: Glayson Bencke.

1.2. Wildlife mortality

Wildlife mortality is a common impact from roads and power lines although the mechanisms differ (Fig. 1b). Mortality due to vehicle-animal collision occurs when an individual attempts to cross a road or is attracted to the road surface (Fig. 3a). The most important road attributes that affect vehicle-animal collisions are, the traffic volume, vehicle speed, and the presence or not of mitigation measures. On power lines two mechanisms can result in animal fatalities: (i) collisions with overhead wires, mainly during restricted visibility or difficult flight conditions as high and irregular wind speeds, associated with both distribution and transmission power lines (Bevanger 1994, 1998) (Fig. 4b); (ii) electrocutions, due to a simultaneous touch onto two-phase conductors or one conductor and a ground wire device on a pole (Bevanger 1994, 1998) (Fig. 4 c and d). Therefore, for example, larger-sized birds using power line structures for perching or nesting are expected to be more susceptible to electrocution. Also, electrocution is more common in distribution lines due to of the shorter distance between the energized structures.

Overall, the number of fatalities caused by bird electrocution and collision with power lines probably are lower than those caused by roads. In the USA at least 5.63 million birds were killed annually by power line electrocution, 22.8 million by power line collisions, against 199.6 million by vehicle collisions (Loss et al. 2015).

Roads cause fatalities of a large variety of invertebrate and vertebrate groups. In contrast, power line impacts affect mainly birds, with some evidence of population-level impacts. For example, mortality from power line collisions seems to be unsustainable to a Ludwig's Bustard (*Neotis ludwigii*) population (Jenkins et al. 2011), whereas electrocutions could drive a population of Bonelli's Eagle *(Aquila fasciata*) to extinction (Hernández-Matías et al. 2015). Although bird are the main victims, there are also evidence of fatalities for mammals (Fig. 4 e and f), including primates (Katsis et al. 2018), carnivores (Kolnegari et al. 2018), and bats (Tella et al. 2020), and even rarely for reptiles (Fritts 2002).

Fig 03. a) Anteater (*Tamandua tetradactyla)* killed by collision with a vehicle on a road surface - Photo: Gabriela Schuck; b) Young Black-crowned Night-Heron (*Nycticorax nycticorax*) killed by collision with overhead wires – Photo: Larissa Biasotto; c) Endangered Lear's Macaw (*Anodorhynchus leari*) electrocuted on energy distribution poles – Photo: José Luiz Silva dos Santos; d) Shiny Cowbird (*Molothrus bonariensis*) stuck on an anchoring structure of wire on an energy pole - Photo: Glayson Bencke; e) Brown-howler monkey (*Alouatta guariba*) injured by electrical wires on distribution lines in Brazil – Photo: Gerson Buss; f) *Didelphis sp*. electrocuted on power lines with wires vertically arranged – Photo: Débora Glienke.

1.3. Barrier or filter effect

The presence of dynamic (vehicles on roads) or static (power lines wires) physical obstacles results in fatalities of some individuals that try to cross these infrastructures resulting in a barrier or filter effect (Fig. 1c). Additionally, individuals may respond to the presence of traffic and/or the RoW changing their behavior, avoiding crossing a busy highway or a power line, resulting in limited individual permeability and reduced gene flow, demonstrated until now only for roads (e.g., Holderegger and Di Giulio 2010).

Roads differ in barrier effect intensity depending primarily on the traffic volume, surface type, and the studied organism. Because of their static condition, it is expected that power lines have a milder barrier effect when compared to roads, however, this may not hold for species that avoid habitat clearings. Less expected, changes in flight behavior in open vegetation areas was demonstrated for tetranoids (Grouss sp.; Pruett *et al.* 2009), a particularly vulnerable bird group to collisions because their flying ability evolved without the presence of vertical structures such as energy towers (Kohl et al. 2019). Further, Silva et al. (2010) assessed the little bustard (*Neotis ludwigii*) higher avoidance of available habitat in the presence of high-tension power lines compared to roads.

Avoidance of power lines was also demonstrated for small arboreal mammals (Wilson et al. 2007) and for the red panda (Dendup et al. 2020). Side by side power line and road RoWs changed the local occurrence and density of ungulates by a higher risk of predation, poor foraging conditions, hindered movement, and decreased habitat (Bartzke et al. 2014).

1.4. Corridor effect

The RoW of roads and power lines and overhead wires may work as a corridor for animal movements, connecting functional habitats (Fig. 1d and Fig. 4a and 4b). For invertebrates, road verges are important stepping stones for population connectivity of the *Lycaena helle* butterfly (Modin and Öckinger 2020). Although there is evidence that road verges (Andersen et al. 2017) and power line RoWs (Smith et al. 2008) can be used as routes for carnivore displacements, this information had not been enough to measure and compare the potential of verges of both infrastructures function as corridors for wildlife (Ouédraogo et al. 2020). We could expect that the much lower disturbance levels on power line RoWs likely promote a more intense use of them as corridors when compared to roads.

Fig 04. a) Lowland tapir (*Tapirus terrestris*) moving along an unpaved road – Photo: Gabriela Schuck; b) Brown howler monkey using overhead distribution wires for displacement – Photo: João Cláudio Godoy.

1.5. Habitat quality and transformation

The implementation and operation of roads and power lines introduce changes to the environment that, depending on species requirements, may be perceived by some of them as an increase in habitat quality and ultimately as habitat creation (Fig. 1e). For other species, in the opposite direction, this disturbance on environmental conditions may result in habitat degradation (Fig. 1f) until there is no longer habitat at all to support certain species (habitat loss, Fig. 1g), splitting a former continuum into smaller pieces of habitat (fragmentation).

Depending on the frequency of vegetation mowing along the road and power line's RoW, clearings can create valuable habitat for native pollinators (e.g., Eldegard et al. 2017; Wagner et al. 2019). In agricultural landscapes, uncropped and unmanaged habitats under pylons or road margins are refuges for small mammals (Ouédraogo et al. 2020; Šálek et al. 2020). Conversely, these new open habitats along power line RoWs or along frequently disturbed road margins offer opportunities for the establishment of invasive species (Kurek et al. 2015). It may be expected that roads are stronger drivers of biological invasion than power lines due to a higher propagule pressure from transport by vehicles.

Roads and power lines can cause other effects on biodiversity on surrounding habitats triggered by different disturbances (Fig. 1f). The most common road disturbances are traffic noise, light, and chemical pollution. For power lines, the corona effect and the electromagnetic field are known disturbances. Corona ions are originated from overhead high-voltage power lines and, what is not widely known, also from motor vehicle emissions. Although their effect on wildlife is largely unknown, it seems that the concentration of these particles emitted by power lines is at least five times less than the concentration found near highways (Jayaratne et al. 2015). Some studies show that the continuous exposure to electromagnetic radiation (EMR) might induce behavioral changes in animals, governing, for example, orientation and movement in pollinators (Vanbergen et al. 2019). However, effects from EMR on organisms are still highly overlooked.

There is an ongoing debate in the literature about the effect of habitat loss (or habitat amount) and fragmentation on species richness (see Fahrig 2017 and studies that follow, for more details). For roads and moreover for power lines there is a lack of studies that appropriately measure and disentangle habitat loss and fragmentation processes and their direct effects on biodiversity. Few studies focus on habitat loss and fragmentation on species and population dynamic levels. Rare studies have been carried out investigating specifically the reduction of habitat suitability from power lines, as the abandonment of territories by the Bearded Vulture (Krüger et al. 2015) and the fragmentation by roadways and transmission lines for Greater Prairie-Chickens (Hovick et al. 2015).

2. Knowledge gaps and future studies

After the above synthesis highlighting similarities and differences on the types of impacts between roads and power lines, here we identify some research gaps that should be further explored by researchers and different stakeholders involved in the planning of projects and programs of both network expansions.

Comparative, cumulative and/or synergic cascading effects of these two linear infrastructures, from individual to population or community responses have been seldom evaluated. Carefully designed studies, planned before the implementation of new individual projects and grid expansions, or retrospective studies, using remote sensing, are highly in need to address these issues. The most robust sampling designs, like the progressive-change Before and After Control-Impact (BACI) or (BACIPS) (Thiault et al. 2017) have not been applied until now on biodiversity impact assessments of road infrastructures or power lines.

To ensure more sustainable projects, a common recommendation is to install, whenever it is possible, new power lines in parallel and close to existing roads or other linear infrastructures. This follows expected increased benefits of easier building and maintenance access, and decreased environmental impacts, through the side-by-side positioning of the RoWs. It is expected that this practice will result in a smaller effect zone due to less habitat loss and degradation. However, there is still a lack of scientific evidence that demonstrates the minimization of potential cumulative or synergistic impacts. For example, another possible undesired outcome could be an amplification of the barrier effect when these structures are adjacent. Similarly, more robust comparative studies that clearly differentiate the effects of each structure when present in the same landscape are also lacking.

Another issue that needs increased attention is a better understanding of the amount of anthropogenic versus non-anthropogenic mortality and their repercussion onto the population's viability in the long term. For both roads and power lines, priority study species or groups based on their higher risk of additive mortality from those infrastructures should be selected.

The well-described indirect deforestation effect (or other vegetation cover conversions) from new road building in tropical regions has still not been evaluated for power lines, although similar effects of these infrastructures could be expected. Power line construction largely depends on the opening of access roads, at least in pristine regions, and after these first cuts, it is reasonable to predict that a similar landscape change observed from new road constructions will follow, perhaps only slower. If this above mechanism is recognized, roadless areas should also be recognized and promoted as well as power line-less areas.

Highly biodiverse developing countries in Asia, Africa, and the neotropics will concentrate the forthcoming road and energy grid expansion probably affecting more remote and nearly pristine regions. The accumulated knowledge on the direct impacts of those infrastructures is not negligible and allows to support some decisions about what and how to mitigate in a large variety of contexts. Of urgency is the investigation of how those impacts could be incorporated into the route planning of these linear infrastructures, allowing for impact prevention by avoiding cutting, or the proximity to or the connectivity rupture of the most valuable habitats (e.g., Bergès et al. 2020).

We hope the research on the above-listed issues will allow for a more rigorous evaluation of the huge planned expansion, of the road and power line networks. The fulfillment of these knowledge gaps will strongly enable and qualify the impact prediction of those infrastructures, a key step to complying with the Mitigation Hierarchy and its emphasis on impact avoidance as the first option (Villarroya et al. 2014), including the cancelation of unsustainable projects.

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CONSIDERAÇÕES FINAIS

Enquanto a expansão do sistema de transporte de energia é seguramente uma necessidade para suprir a demanda energética, é preciso planejar a instalação dessas estruturas de modo que elas tenham o menor impacto possível no ambiente. Assim como outros países em desenvolvimento, o Brasil ocupa um lugar representativo no cenário de investimentos do setor energético, com uma previsão de milhares de quilômetros de novas linhas de transmissão e de distribuição de energia para serem instaladas até 2030 (Kishore and Singal 2014). Complementarmente, considerando que grande parte dos impactos ambientais persiste ao longo da operação das linhas de energia, é preciso também dar atenção à malha energética operando no país, promovendo ações adequadas de mitigação de seus impactos sobre a biodiversidade (Biasotto and Kindel 2018).

Minha tese de doutorado buscou qualificar o conhecimento e a pesquisa sobre as linhas de energia, contribuindo para a melhor integração dos aspectos ambientais no planejamento dessas infraestruturas, visando a mitigação de diferentes impactos. Adicionalmente, procurei ampliar o conhecimento sobre impactos pouco estudados em território nacional, como a eletrocussões de aves, e identificar importantes lacunas de conhecimento sobre o modo como as linhas podem influenciar a biodiversidade e o ambiente no qual estão inseridas.

No **Capítulo 1,** através de uma descrição detalhada dos procedimentos metodológicos, que abrange desde a justificativa dos critérios até a seleção final de uma rota, elaborei um modelo conceitual sistemático para ser aplicado no delineamento de rotas de linhas de transmissão de energia. A estrutura é ideal para ser aplicada na fase inicial de planejamento das LTs, priorizando ao máximo o evitamento de impactos como a perda e/ou degradação de hábitat. O modelo conceitual incluiu a proposição de rotas alternativas desenhadas com base em critérios ambientais e de engenharia através da utilização de Sistema de Informação Geográfica (SIG) e Análise de Caminho de Menor Custo. O pilar fundamental do modelo foi a proposição de uma abordagem experimental com variação gradual entre cinco cenários que integraram as perspectivas de engenharia e ambiental, variando a influência do mapa ambiental através de Análises Multicritério. Complementarmente, após a obtenção dos cinco cenários, mostrei que é possível a identificação de segmentos de rota com consenso entre as perspectivas de engenharia e ambiental através de uma análise de janela móvel aplicada à sobreposição de todos os cenários. A identificação dessas áreas de coincidência, além de indicar locais de maior ou menor conflito entre as perspectivas ambiental e de engenharia, também corresponde aos locais onde os limites de evitamento foram atingidos, permanecendo a aplicação das demais etapas da Hierarquia de Mitigação em estudos de impacto e processos de refinamento de rotas posteriores.

Contudo, reconheço que ainda são necessárias a incorporação de outros procedimentos no modelo conceitual que propus para tornar o processo de qualificação do planejamento das LTs mais real e concreto. Por exemplo, o refinamento das informações de base, como a inclusão de outros critérios e espacialização de outros impactos e a incorporação de métodos de controle de qualidade, como análises de sensibilidade, que devem medir as incertezas em relação ao conjunto de pesos atribuídos ao longo do processo de desenho das rotas. Ainda, entendo que soluções produzidas a partir de uma perspectiva exclusivamente biótica podem trazer desafios operacionais ou econômicos, exigindo outros esforços para acomodar o conjunto das exigências inerentes a estas infraestruturas. Da mesma forma, soluções técnicas que não considerem os aspectos ambientais adequadamente também podem não ser ambientalmente aceitáveis, algo que entendo que só poderá ser avaliado a partir de colaborações interdisciplinares e multi-institucionais.

No **Capítulo 2** desenvolvi um modelo conceitual específico para estimar o risco de eletrocussão de aves como resultado da interação entre dois processos: i) exposição das espécies às linhas de energia, onde considerei a densidade de postes dentro da área de distribuição de uma espécie e ii) suscetibilidade, onde considerei atributos morfológicos e comportamentais associados ao risco de eletrocussão. Mostrei que a partir da disponibilidade dessas informações, do uso de ferramentas simples e de análises espaciais básicas, podemos gerar uma avaliação preliminar para grandes escalas sem recorrer à coleta de dados de fatalidade. Ao aplicar esse modelo para o contexto brasileiro reconheci 283 espécies de aves brasileiras que estão mais sujeitas ao risco de eletrocussão, sendo que 38 foram classificadas como de atenção prioritária. Apesar da grande representatividade dos rapinantes, meus resultados também indicaram a necessária preocupação com os psitacídeos, grupo até então não contemplado em praticamente nenhum outro estudo sobre eletrocussões. Ainda, nesse capítulo identifiquei possíveis padrões espaciais de eletrocussões de aves, revelando áreas prioritárias para investigação adicional tanto da suscetibilidade quanto do risco de eletrocussão, ou onde a implantação de medidas de mitigação em linhas de energia já existentes deva ser avaliada em detalhe. Utilizar o Brasil como estudo de caso foi também estratégico, de modo que almejo que esse trabalho possa ser utilizado para o melhor reconhecimento desse impacto em território nacional e para a criação de diretrizes que normatizem o licenciamento ambiental de linhas de distribuição no que se refere à avaliação das eletrocussões da avifauna como um impacto ambiental. De forma mais ampla, a abordagem desenvolvida nesse capítulo também poderá ser adaptada para o estudo das eletrocussões em diferentes regiões do mundo, particularmente em países onde as eletrocussões são mal documentadas, uma vez que é extremamente útil para o desenvolvimento de estratégias regionais de gestão.

Com o **Capítulo 3** apresentei evidências de que uma das espécies indicadas como prioritárias em relação ao risco de eletrocussão no **Capítulo 2** está de fato morrendo por choque elétrico em redes de energia de média tensão. Apesar de ter tido acesso apenas a registros ocasionais de fatalidade, as 31 mortes reportadas demonstram que esta pode ser uma ameaça importante para esta espécie e que não pode ser negligenciada daqui por diante. Através de uma primeira análise exploratória dos locais de eletrocussão até agora registrados, indiquei que provavelmente as mortes por eletrocussão sejam mais frequentes em locais mais próximos das áreas de dormitório. Ainda, busquei levantar algumas hipóteses sobre o comportamento da espécie que podem estar contribuindo com sua maior suscetibilidade às eletrocussões. Por fim, descrevi possíveis práticas que serão efetivas para mitigar as eletrocussões da arara-azul-de-lear e que também poderão ser aplicadas a outras espécies de psitacídeos. Como por exemplo, o maior espaçamento entre os cabos levando em consideração a envergadura da espécie, remoção da cruzeta e disposição vertical dos cabos, encapamentos das estruturas energizadas com material resistente, além da instalação das novas LDs já mitigadas ou com implantação de novos postes com configuração do tipo Canadense (alternada). Por fim, recomendei que seja realizado um monitoramento sistemático com desenho amostral adequado para a investigação sobre quais são os aspectos relacionados às eletrocussões. Ainda, sugeri que deverão ser respondidas perguntas sobre quais são os locais prioritários para mitigação e qual a magnitude das eletrocussões e suas possíveis implicações populacionais a longo prazo.

Finalmente, com o **Capítulo 4** pude contrastar as semelhanças e diferenças entre estradas e linhas de energia principalmente no que se refere ao modo como afetam os organismos e ambientes nos quais estão inseridas. Para isso, nesse capítulo descrevi os principais aspectos estruturais e funcionais de cada uma dessas infraestruturas, dando um panorama geral sobre a dimensão e extensão dessas duas malhas no mundo e incluindo o conceito de zona de efeito, até o momento estudado apenas para alguns contextos geográficos para rodovias. Apesar de apresentar brevemente o estado da arte sobre ambas as infraestruturas, dei maior destaque às linhas de energia, para ressaltar o que sabe e o que ainda permanece desconhecido sobre seus impactos ambientais. Através de uma atualização da revisão sistemática conduzida em 2017 (Biasotto and Kindel 2018), procurei apresentar os principais e mais atuais conhecimentos referentes a cinco categorias comuns de impactos entre linhas e estradas: i) atratividade, presente em ambas, porém através da provisão de recursos totalmente diferentes; ii) mortalidade direta da fauna, representada por mecanismos de morte diferentes, e aparentemente maior para rodovias; iii) efeito barreira ou filtro, ainda pouco avaliado mas com efeito esperado menos intenso para as linhas devido a sua condição estática; iv) efeito corredor, proporcionado pelas duas estruturas porém possivelmente maior para linhas, uma vez que os níveis de perturbação são mais amenos e provavelmente possam promover o uso mais intenso do corredor pela fauna; e, por fim, v) qualidade e transformação do habitat. Essa última categoria de impacto revela mudanças causadas no ambiente que tanto podem promover a criação de novos habitats, bem evidenciado para as linhas, como a perturbação nas condições ambientais que resultariam em degradação do habitat, e em níveis mais severos, na perda de habitat. Essas duas últimas consequências são pouco investigadas nas duas áreas, principalmente sobre uma perspectiva de organismos. Na seção 2 do capítulo, pude brevemente discorrer sobre as principais lacunas e desafios para futuros estudos que envolvam essas duas estruturas, destacando principalmente: a falta de desenhos amostrais mais robustos para responder a magnitude de impactos; a ausência de evidências científicas que demonstrem a minimização dos impactos cumulativos e sinérgicos quando da instalação conjunta das duas estruturas; e a necessidade de uma melhor compreensão de como a mortalidade antropogênica repercute na viabilidade populacional de determinadas espécies.

Essa tese tem importantes contribuições sob a perspectivada Hierarquia de Mitigação de impactos, com algumas de suas diferentes etapas contempladas nos estudos aqui apresentados. Através dos dois primeiros capítulos, mostrei formas de evitamento de impactos, o primeiro visando a redução da perda de áreas importantes para a biodiversidade no planejamento de linhas e o segundo indicando áreas mais sensíveis a serem evitadas para instalação de futuras linhas, em virtude da maior suscetibilidade da avifauna às eletrocussões. Especificamente em relação à minimização de impactos, o capítulo 2 e 3 revelam onde e como podem ser despendidos esforços para a minimização do risco de eletrocussão em áreas com estruturas já instaladas, o segundo com foco na comunidade de aves e o terceiro com foco em uma espécie prioritária. Por fim, com o capítulo 4 identifiquei algumas lacunas de pesquisa cujo preenchimento pode ser fundamental para a melhor predição dos impactos das infraestruturas lineares sobre a biodiversidade, etapa necessária para posterior aplicação da Hierarquia de Mitigação. De maneira geral, minha tese explora abordagens que podem ser adaptadas e utilizadas em um contexto de tomada de decisão, referente tanto ao planejamento e expansão da malha quanto ao licenciamento ambiental dos projetos individuais. Ainda, valoriza a necessidade de maior investigação sobre as consequências ambientais causadas pela presença das linhas de energia, para que esse conhecimento se traduza em políticas públicas de mitigação de impactos.

Para finalizar, gostaria de aproveitar o espaço final dessas considerações para enfatizar que o conteúdo aqui apresentado é apenas uma parte do conhecimento e da prática que adquiri ao longo desse período de intenso estudo e dedicação. Além dos capítulos que apresentei, durante esses quatro anos junto ao Programa de Pós-Graduação em Ecologia da UFRGS tive a oportunidade de complementar minha trajetória como doutoranda através de diversas experiências que envolveram: a colaboração com outros trabalhos acadêmicos (Dasoler et al. 2020; Teixeira et al. 2020a, b); a revisão de trabalhos em periódicos científicos; a difusão de conhecimentos produzidos através de palestras, entrevistas, produção e organização de workshops voltados à qualificação de profissionais e de procedimentos do licenciamento ambiental de infraestruturas; e desempenhar atividades de ensino que incluíram, além de dar aulas, coorientação de Trabalhos de Conclusão de Curso (Da Costa 2018) e participação em bancas de monografia. Além disso, foram muitos os momentos em que pude me envolver no desenvolvimento de políticas públicas consensuadas com diversos atores sociais, voltadas à discussão de soluções técnicas e ambientais para mitigação de impactos e solução de conflitos envolvendo infraestruturas antrópicas e meio ambiente. Todas essas são atividades das quais me orgulho e que contribuíram grandiosamente para minha formação como ecóloga e pesquisadora. Com toda certeza, também retornam à sociedade o investimento direcionado à minha pesquisa, recurso tão precioso e escasso nos tempos atuais.

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