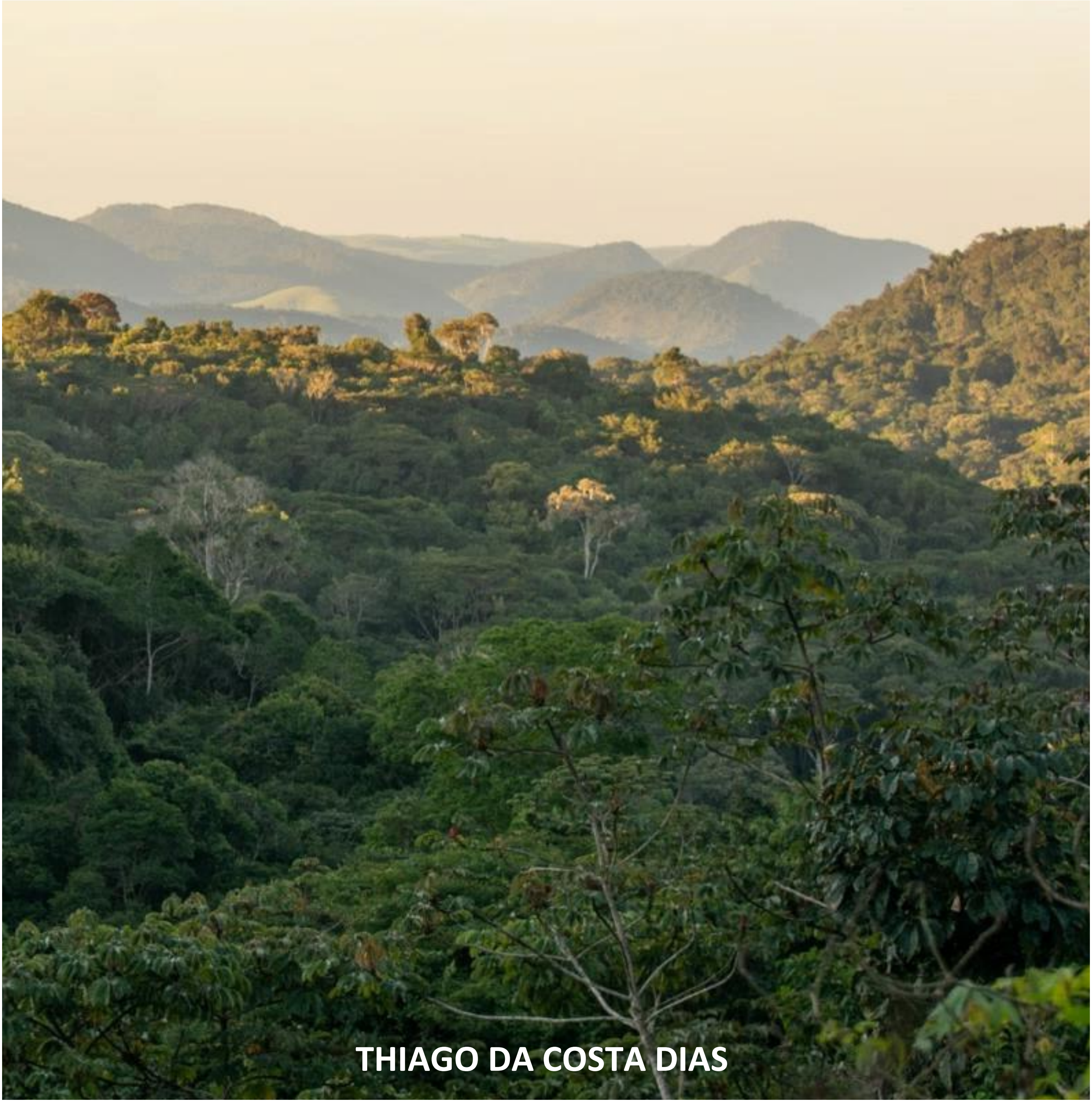
DINÂMICA ESPAÇO-TEMPORAL DA COBERTURA DE MATA ATLÂNTICA NO CENTRO DE ENDEMISMO PERNAMBUCO E USO DO HABITAT PELA AVIFAUNA AMEAÇADA DA REGIÃO



THIAGO DA COSTA DIAS

UNIVERSIDADE FEDERAL DE SÃO CARLOS
CENTRO DE CIÊNCIAS BIOLÓGICAS E DA SAÚDE
PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA E RECURSOS NATURAIS

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São Carlos – SP

2023

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Tese apresentada ao Programa de Pós-Graduação em Ecologia e Recursos Naturais (PPGERN) da Universidade Federal de São Carlos, para obtenção do título de Doutor em Ciências.

Área de concentração: Ecologia e Recursos Naturais

Orientador: Prof. Dr. Mercival Roberto Francisco

São Carlos – SP

2023

UNIVERSIDADE FEDERAL DE SÃO CARLOS

Centro de Ciências Biológicas e da Saúde
Programa de Pós-Graduação em Ecologia e Recursos Naturais

Folha de Aprovação

Defesa de Tese de Doutorado do candidato Thiago da Costa Dias, realizada em 30/06/2023.

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O Relatório de Defesa assinado pelos membros da Comissão Julgadora encontra-se arquivado junto ao Programa de Pós-Graduação em Ecologia e Recursos Naturais.

Aos meus pais Rosângela e Marcos, meus avós Ana e Cézar,

à minha irmã Thaís e minha companheira Brena,

pelo amor, incentivo e confiança,

***com carinho, dedico*.**

AGRADECIMENTOS

Ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) pela bolsa de doutorado concedida (Processo #141084/2019–7).

À Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) pelo apoio financeiro ao Projeto Temático ARCA do CEP (Processo # 2017/23548–2).

À Universidade Federal de São Carlos (UFSCar) e ao Programa de Pós-Graduação em Ecologia e Recursos Naturais (PPGERN).

Ao Laboratório de Ornitologia, do Departamento de Ciências Ambientais no Centro de Ciências e Tecnologias para Sustentabilidade da UFSCar – Sorocaba.

Ao Instituto de Preservação da Mata Atlântica (IPMA) pelo apoio logístico e acolhimento durante meus primeiros anos em Maceió/AL, principalmente nas figuras de Rosa, Ju e Fernando Pinto.

À CRAX e ao Criadouro Guaratuba, nas figuras de Roberto Azeredo, James Simpson e Marcos Wasilewsky, pela grande dedicação a conservação dos cracídeos brasileiros.

À Promotoria de Justiça do Meio Ambiente do Ministério Público de Alagoas (MPAL) pelo apoio durante os primeiros anos de meu doutorado, na figura do Promotor de Justiça Alberto Fonseca.

À Alexandra Elbakyan pelos importantes serviços prestados com a criação do Sci-hub, difundindo o conhecimento científico a todos que o querem acessar.

À Dra. Zlatka Pironkova, pela gentileza de enviar os scripts de Google Earth Engine utilizados inicialmente para a produção do Capítulo I desta tese.

À toda equipe do Projeto ARCA do CEP, pela amizade. À Luís Fábio Silveira, pela confiança e pelos valiosos ensinamentos, também por ser tão solicito e pelo grande serviço prestado a conservação das aves brasileiras. À Marina Elisa e Luiza Prado, pelo carinho e pelas risadas durante o período que passamos juntos subindo e descendo as grotas da RPPN Mata do Cedro, em Alagoas.

Aos queridos amigos de Araras/SP (República MST), Ribeirão Preto/SP e Maceió/AL, pelo apoio e amor.

Ao amigo Marcos J. M. Dubeux, por gentilmente ceder algumas das fotos utilizadas na composição deste trabalho.

Ao meu orientador Prof. Dr. Mercival Roberto Francisco, pela sabedoria, paciência, incentivo, apoio, e pelos conselhos. Que possamos levar a amizade e parceria para o resto da vida, Mercival. Obrigado!

À minha família: pais, avós, irmã, cunhado, tios e tias, primos e primas. Todos vocês foram e são fundamentais na minha vida e o amor que sinto por cada um é enorme e incondicional. Embora a saudade por estar distante seja grande, saibam que todos os dias vocês estão presentes no meu pensamento. Obrigado, obrigado e obrigado, amo vocês!

À minha companheira Brena e nossa família cheia de gatos, obrigado por compartilharem a vida comigo durante os últimos anos e pelo apoio, incentivo e amor. Por estarem comigo superando as dificuldades que a vida traz e pelo caminho durante esse processo. Por me ajudarem a manter a saúde mental, ou parte dela, durante o isolamento social da pandemia, quanto éramos só nós fechados em casa. Eu amo vocês!

"When one tugs at a single thing in nature, he finds it attached to the rest of the world."

John Muir

RESUMO

A Mata Atlântica é um dos *hotspots* da biodiversidade mais importantes do mundo, abrigando uma grande riqueza de espécies e sendo considerada palco para alguns dos maiores desafios para a conservação na atualidade. Uma pequena parcela do bioma localizada no nordeste brasileiro, conhecida como Centro de Endemismo de Pernambuco (CEP), se destaca por abrigar uma grande concentração de espécies ameaçadas e de distribuição restrita. Os ecossistemas insubstituíveis do CEP foram, e continuam sendo severamente afetados pela perda, fragmentação e degradação da vegetação florestal nativa da região. Atualmente, sua cobertura florestal encontra-se, em grande parte, defaunada, e muitas das relações ecológicas importantes para a manutenção da biodiversidade se perderam. Por conta disso, é fundamental promover ações de manejo e conservação de espécies e habitats no CEP, buscando reduzir os riscos de futuras perdas de espécies, já esperados para a região. Investigar o histórico de mudanças e o estado atual dos habitats florestais do CEP, além de caracterizar o uso do espaço e distribuição da fauna ameaçada da região, pode guiar os esforços de conservação e auxiliar a tomada de decisão voltada ao manejo da paisagem local. Sendo assim, o presente trabalho objetivou caracterizar a dinâmica espaço-temporal da cobertura florestal do CEP ao longo dos últimos 35 anos (1985-2020) por meio da (i) avaliação das tendências de acumulação/perda de biomassa nos remanescentes de vegetação nativa e (ii) da identificação de mudanças na configuração espacial e distribuição dos habitats florestais da região. Ainda, buscou-se (iii) revelar a distribuição, riqueza, recursos/habitats fundamentais e áreas de alta relevância ecológica para a avifauna endêmica e ameaçada do CEP, buscando, enfim, propor a criação de corredores ecológicos como ferramenta para a conservação da biodiversidade. A situação da cobertura florestal do CEP é alarmante e, embora tenham sido identificados acúmulo de biomassa (*greening*) e melhoria de métricas relacionadas a qualidade dos habitats durante as últimas décadas, fatores como o tamanho reduzido dos fragmentos, efeitos de borda severos e a substituição de vegetação madura por vegetação secundária ainda afetam as florestas da região. A persistência das populações de aves endêmicas e ameaçadas no CEP pode depender de estratégias de conservação energéticas, visando o manejo da paisagem em larga escala, e, aqui, propõe-se a criação do *Arco de Restauração do Centro de Endemismo de Pernambuco* (ARC-CEP), capaz de conectar fragmentos de alta relevância ecológica através de iniciativas de restauração florestal. Essa estratégia, juntamente com outras ações de conservação em andamento no CEP (e.g., criação de unidades de conservação), pode garantir melhorias cruciais para prevenir futuras extinções globais esperadas para a região, aumentando o fluxo gênico e de organismos, promovendo a recolonização de habitats e garantindo a adaptabilidade de populações frente às mudanças climáticas.

Palavras-chave: paisagens modificadas pelo homem, ecologia da paisagem, modelagem de distribuição de espécies, áreas prioritárias para conservação.

ABSTRACT

The Atlantic Forest is one of the world's most important biodiversity hotspots, harboring a high species richness and serving as the stage for some of the largest conservation challenges nowadays. A small portion of this biome located in northeastern Brazil, known as the Pernambuco Endemism Center (PEC), stands out for hosting a high concentration of threatened and restricted-distribution species. The irreplaceable ecosystems of the PEC have been continuously affected by deforestation, fragmentation, degradation, and defaunation, resulting in the loss of many crucial ecological relationships that maintain biodiversity. It is essential to promote management and conservation actions for species and habitats in the PEC to prevent anticipated species losses in the region. Across the PEC, investigating historical changes and the current state of forest habitats, and characterizing space use and distribution by its threatened wildlife may guide conservation efforts and assist decision-making focused on landscape management. Therefore, this study aimed to characterize the spatiotemporal dynamics of the forest cover in the PEC over the past 35 years (1985-2020) by (i) assessing trends in biomass accumulation/loss in remnants of native vegetation and (ii) identifying changes in the spatial configuration and distribution of forest habitats in the region. The study additionally intends to (iii) reveal the distribution, richness, key resources/habitats, and areas of high ecological relevance for the endemic and threatened avifauna of the PEC, ultimately proposing the creation of ecological corridors as a tool for biodiversity conservation. The condition of the PEC's forest cover is alarming, and although biomass accumulation (greening) and improvements in metrics related to habitat quality were identified over the last decades, factors such as the reduced size of the fragments, severe edge effects, and the replacement of mature by secondary vegetation are current threats for the local biodiversity. The persistence of endemic and threatened birds in the PEC may rely on energetic and large-scale conservation strategies and landscape management, and here we propose the creation of the *Pernambuco Endemism Center Restoration Arc* (PEC-ARC), which may be able to connect fragments with high ecological relevance through forest restoration initiatives. Together with the ongoing conservation actions that became increasingly important to the PEC over the last years, this strategy may provide critical improvements in habitat quality over the region, increase gene flow and organismal movement, promote habitat recolonization, and ensure population adaptability to climate change, which may ultimately reduce the risks of future global extinctions expected for the region.

Keywords: human-modified landscapes, landscape ecology, species distribution modeling, conservation priority areas.

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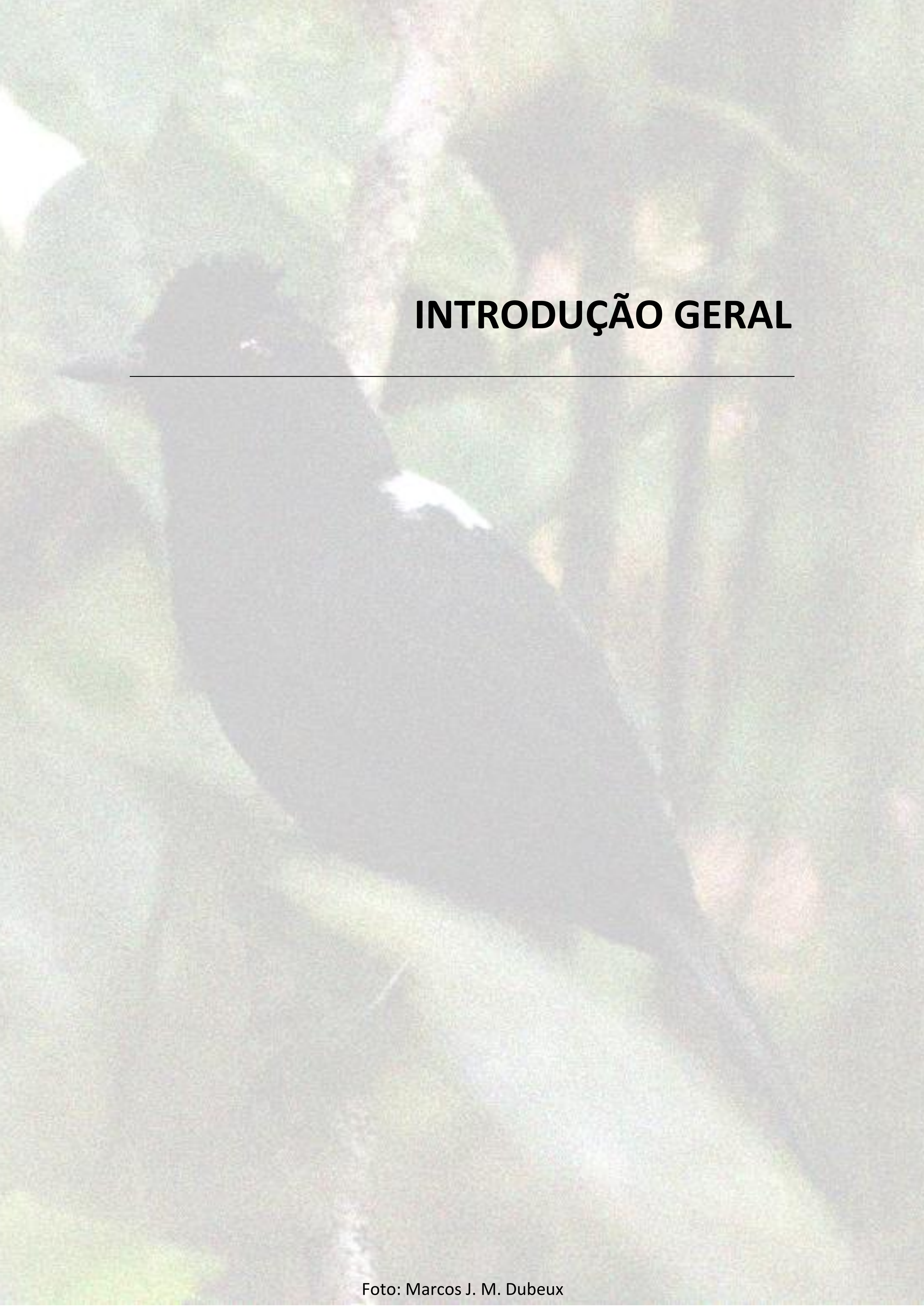


INTRODUÇÃO GERAL

Foto: Marcos J. M. Dubeux

INTRODUÇÃO GERAL

A Mata Atlântica, que originalmente ocupava cerca de 150 milhões de hectares (Muylaert *et al*., 2018), distribuídos principalmente em território brasileiro, destaca-se como um dos biomas mais ricos em biodiversidade e enfrenta aqueles que estão entre os maiores desafios para conservação global (Lima *et al*., 2020). As atividades econômicas desenvolvidas dentro de seus limites atualmente contribuem com aproximadamente 70% do produto interno bruto (PIB) nacional e representam dois terços da economia industrial brasileira (Joly, Metzger e Tabarelli, 2014; Martinelli e Moraes, 2013; Scarano e Ceotto, 2015). Esse cenário de desenvolvimento econômico esteve, historicamente, associado a substituição de grandes porções de vegetação florestal nativa por plantios agrícolas e pastagens destinadas à criação de gado, principais atividades desenvolvidas no bioma até hoje (Laurance, 2009; Zachos e Habel, 2011).

Os impactos mais significativos das atividades humanas nos ecossistemas da Mata Atlântica datam do final do século XV, com a chegada dos colonizadores europeus ao Brasil. Entre as principais atividades que contribuíram para a degradação ambiental no bioma, encontram-se (i) a expansão agrícola, impulsionada principalmente pelo ciclo do café e pela destinação de terras ao plantio de cana-de-açúcar para atender às demandas de produção de açúcar e álcool, (ii) a pecuária, com foco na criação de bovinos, e (iii) a industrialização, que resultou na derrubada e queima de uma parcela expressiva das florestas da região para o aquecimento de caldeiras até a meados do século XX (Almeida e Souza, 2023; Solórzano, Brasil e Oliveira, 2021). Em pouco mais de 500 anos, cerca de 84 a 88,6% da cobertura florestal do bioma foi removida (Ribeiro *et al*., 2009; Solórzano, Brasil e Oliveira, 2021), e uma porção considerável dos remanescentes de vegetação nativa encontra-se degradada (e.g., por meio do rejuvenescimento florestal, Rosa *et al*., 2021). Na década de 2000, cerca de 80% da cobertura florestal da Mata Atlântica encontrava-se distribuída em fragmentos menores que 50 ha, em sua maioria isolados e sob forte influência de efeitos de borda (Ribeiro *et al*., 2009). Além disso, somente 9% do bioma encontrava-se protegido por unidades de conservação (UCs) naquela época, representando apenas 1% de sua cobertura florestal original (Ribeiro *et al*., 2009).

Apesar do intenso histórico de desmatamento e degradação no passado (Ribeiro *et al*., 2009, 2011; Rosa *et al*., 2021; Solórzano, Brasil e Oliveira, 2021), a Mata Atlântica continua abrigando alguns dos ecossistemas mais ricos do planeta, sendo reconhecida como um *hotspot* da biodiversidade e apresentando um número significativo de táxons endêmicos (Rezende *et al*., 2018; Ribeiro *et al*., 2011). O bioma é casa para mais de 20.000 espécies (6.000 endêmicas), apresentando cerca de 2.645 vertebrados terrestres, dos quais 954 são endêmicos (1.025 aves – 215 endêmicas; 719 anfíbios – 504 endêmicos; 517 répteis – 126 endêmicos; 384 mamíferos – 109 endêmicos) (Figueiredo *et al*., 2021). Uma parcela considerável dessa diversidade encontra-se contemplada em listas de espécies ameaçadas nacionais (ICMBio, 2018a; MMA, 2022) e internacionais (IUCN, 2022), tornando a Mata Atlântica o bioma com maior número total e proporcional de táxons listados sob risco de extinção no Brasil (ICMBio, 2018a). A crise da biodiversidade na Mata Atlântica pode ser atribuída, pelo menos em parte, às reduções drásticas na abundância de espécies e às extinções locais que ocorreram no bioma durante as últimas décadas, resultando em ecossistemas simplificados, com relações ecológicas comprometidas, e comprometendo o provimento de serviços ecossistêmicos (Galetti *et al*., 2021). Em casos recentes mais extremos, espécies chegaram a ser completamente extintas, enquanto outras desapareceram na natureza e só sobrevivem graças a programas de conservação *ex situ* (ICMBio, 2018a, b).

A região biogeográfica da Mata Atlântica conhecida como Centro de Endemismo Pernambuco (CEP) e localizada ao norte do Rio São Francisco, se destaca como um *hotspot* localizado dentro de outro *hotspot*, por abrigar um elevado número de espécies endêmicas e ameaçadas (Tabarelli, Siqueira-Filho e Santos, 2006). Estendendo-se originalmente por cerca de 4,4 milhões de hectares nos estados de Alagoas, Pernambuco, Paraíba e Rio Grande do Norte (Ribeiro *et al*., 2009), o CEP está inserido em um contexto de isolamento geográfico que proporcionou o cenário ideal para a ação de processos de especiação que geraram uma biodiversidade única (Bocalini *et al*., 2021; Lins-e-Silva, Ferreira e Roda, 2021). A região abriga cerca de 486 táxons de aves, sendo 171 dependentes de ambientes florestais e 50 ameaçados (Araujo *et al*., 2023), e foi cenário para as extinções modernas de aves no Brasil, com os desaparecimentos do limpa-folha-do-nordeste *Philydor novaesi*, do gritador-do-nordeste *Cichlocolaptes mazarbarnetti*, e do caburé-de-pernambuco *Glaucidium mooreorum* (Develey e Phalan, 2021). O mutum-de-alagoas (*Pauxi mitu*), maior ave frugívora do CEP, foi declarado extinto na natureza no final dos anos 1970, sendo salvo graças à ação de criadouros conservacionistas e da parceria entre órgão públicos e privados, que auxiliaram a espécie a superar um gargalo genético extremo e proporcionaram a reintrodução de seis indivíduos no estado de Alagoas em 2019 (Francisco *et al*., 2021). São notáveis os indícios de defaunação nos ecossistemas do CEP (e.g., Garbino *et al*., 2018; Pontes *et al*., 2016; Pontes, Beltrão e Santos, 2019), gerados, principalmente, pelo intenso desmatamento e degradação da vegetação nativa da região no passado, que foram responsáveis por reduzir a cobertura florestal original em cerca de 87% (Lins-e-Silva, Ferreira e Roda, 2021; Ribeiro *et al*., 2009).

Ao menos quatro grandes ondas de desmatamento atingiram bruscamente os ecossistemas florestais do CEP desde a chegada dos colonizadores europeus no século XV (Lins-e-Silva, Ferreira e Roda, 2021). A região foi intensamente visitada pelos portugueses durante os primeiros anos do século XVI para extração de pau-brasil *Paubrasilia echinata* (Almeida e Souza, 2023). No entanto, essa atividade foi rapidamente substituída pela produção açúcar, que se tornou a principal atividade econômica da região até os dias de hoje (Lins-e-Silva, Ferreira e Roda, 2021). A partir de 1516, com o início do ciclo da cana-de-açúcar, uma parcela significativa da vegetação florestal costeira do CEP localizada nos vales planos situados próximos aos rios, foi convertida em plantios de cana-de-açúcar, representando a primeira onda de desmatamento na região (Almeida e Souza, 2023; Lins-e-Silva, Ferreira e Roda, 2021). No século XIX, as florestas das encostas com solos argilosos também foram removidas (segunda onda) e, com o avanço das técnicas agrícolas no século XX, os planaltos de origem sedimentar com solos drenados e menos férteis foram, por fim, ocupados (terceira onda) (Almeida e Souza, 2023; Lins-e-Silva, Ferreira e Roda, 2021). A quarta e última grande onda de desmatamento teve início em 1975 com a implementação do Programa Nacional do Álcool (Proálcool), responsável pela conversão de uma parcela relevante da já reduzida cobertura florestal (Lins-e-Silva, Ferreira e Roda, 2021). Além do desmatamento, a indústria sucroalcooleira contribuiu com a degradação em larga escala dos remanescentes florestais do CEP através da aplicação de defensivos agrícolas nocivos ao meio ambiente, da queima das plantações antes do início da colheita, e da remoção de árvores de grande porte para o aquecimento de caldeiras nas usinas (Almeida e Souza, 2023; Lins-e-Silva, Ferreira e Roda, 2021; Solórzano, Brasil e Oliveira, 2021).

Atualmente, as paisagens do CEP são caracterizadas por mosaicos de cultivos agrícolas, pastagens e pequenos fragmentos isolados de vegetação nativa, localizados, principalmente, nas áreas íngremes e nos topos dos morros (Lins-e-Silva, Ferreira e Roda, 2021; Ribeiro *et al.*, 2009). Assim como em outras paisagens modificadas pela ação antrópica, os padrões de riqueza e abundância de espécies do CEP devem estar intimamente relacionados ao tamanho dos remanescentes florestais na região (Martensen, Pimentel e Metzger, 2008). Nesses contextos, o tamanho reduzido das florestas pode (i) aumentar a susceptibilidade de populações à eventos estocásticos genéticos e demográficos (Uezu e Metzger, 2011), (ii) reduzir a heterogeneidade dos habitats, (iii) a disponibilidade de recursos, e (iv) o sucesso reprodutivo de indivíduos (Fahrig, 2001; Tews *et al.*, 2004; Zanette, Doyle e Trémont, 2000). Vertebrados especialistas de nicho e/ou estritamente florestais também podem ser prejudicados por conta da dominância de habitats influenciados pelos efeitos de borda, já que os mesmos só atingem picos de abundância a cerca de 200 – 400 m das bordas florestais (Hansbauer *et al.*, 2008; Pfeifer *et al.*, 2017), ambientes, estes, que muitas vezes não estão sequer disponíveis em paisagens alteradas (Banks-Leite, Ewers e Metzger, 2010).

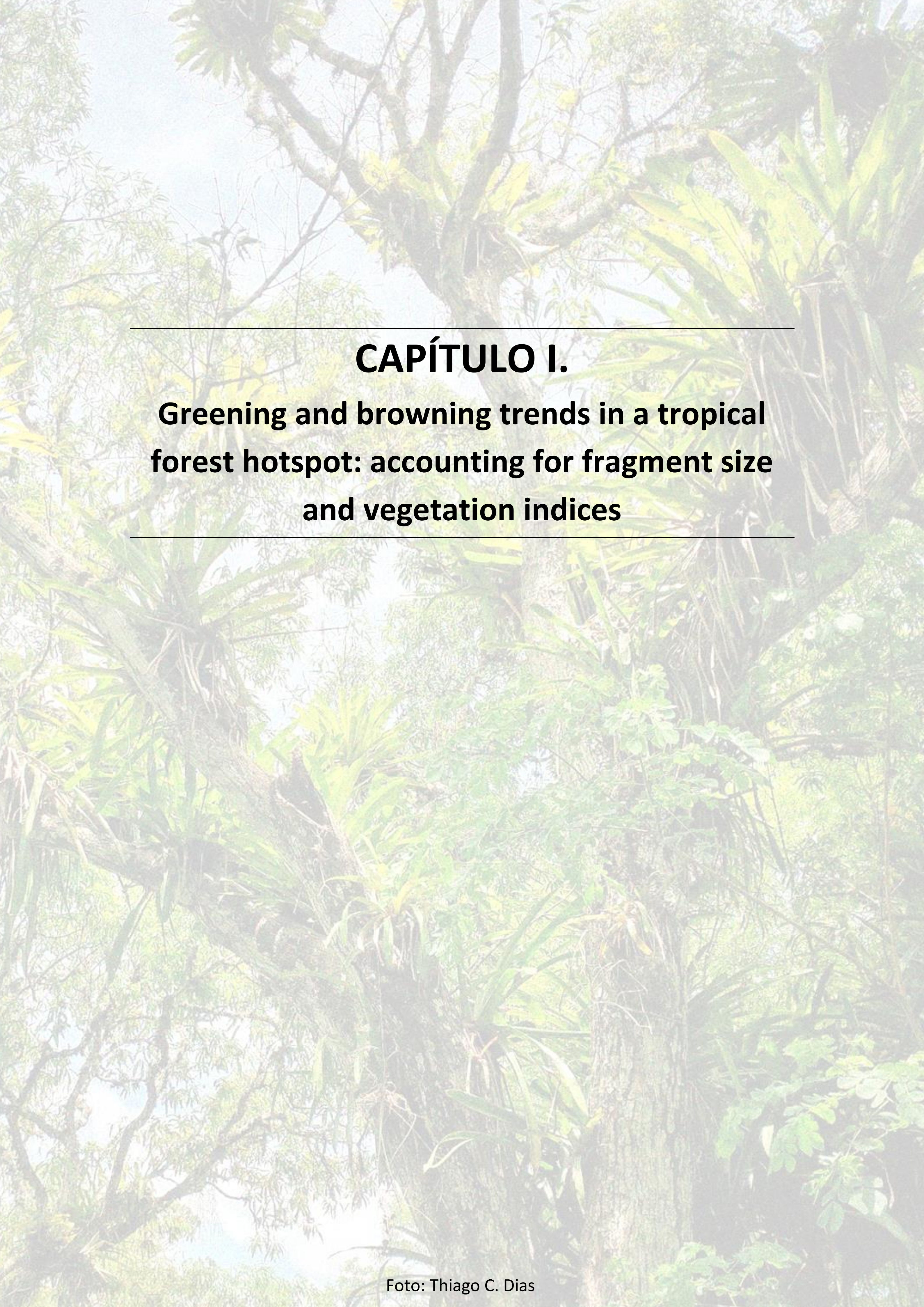
A maturidade (ou idade) das florestas também pode influenciar os padrões de distribuição e riqueza de espécies na paisagem (Barlow *et al.*, 2007; Gibson *et al.*, 2011; Rosa *et al.*, 2021). Mesmo que florestas secundárias sejam capazes de manter uma parcela significativa da comunidade biológica na Mata Atlântica, os processos relacionados ao rejuvenescimento da cobertura florestal impactam negativamente a biodiversidade e podem comprometer a persistência de espécies a longo prazo (Metzger *et al.*, 2009; Rosa *et al.*, 2021). Além desses fatores, a fragmentação de habitats florestais pode influenciar as relações estabelecidas entre espécies e seus ambientes nas paisagens da Mata Atlântica, influenciando o movimento de organismos, a mortalidade de indivíduos e, consequentemente, a demografia, genética e os riscos de extinções de populações (Crooks *et al.*, 2017; Debinski e Holt, 2000; Keyghobadi, 2007; Reed, 2004). Os efeitos do isolamento de habitats em populações silvestres podem variar de acordo com o tipo, qualidade e permeabilidade da matriz (Watling *et al.*, 2011): por exemplo, plantios de cana-de-açúcar podem exercer impactos mais negativos para uma parcela da biodiversidade do que áreas convertidas em pastagens e silvicultura (e.g., aves: Coelho *et al.*, 2016; mamíferos: Beca *et al.*, 2017, Feijó *et al.*, 2023; anfíbios: D’Anunciação *et al.*, 2013; borboletas: Brito *et al.*, 2021).

A situação dos ecossistemas do CEP é extremamente preocupante devido à alta degradação de sua cobertura florestal e às graves ameaças enfrentadas por uma parcela significativa da fauna local. Infelizmente, grande parte das espécies endêmicas e ameaçadas do CEP não estão incluídas em programas de conservação *ex situ*, o que poderia ter prevenido ao menos parte das extinções que ocorreram na região (Francisco *et al*., 2021). Essa situação intensifica ainda mais a necessidade de avaliar e proteger os remanescentes dos habitats florestais da região para a manutenção da biodiversidade local. Apenas 1% da cobertura florestal do CEP é protegida por unidades de conservação públicas (Ribeiro *et al*., 2009), e, mesmo com as iniciativas de criação de Reservas Privadas do Patrimônio Natural (RPPNs) durante as últimas três décadas (Carvalho *et al*., 2021), grande parte das florestas permanecem desprotegidas. Como os recursos financeiros investidos em conservação são limitados, é essencial identificar áreas de maior relevância ecológica no CEP para o maior número possível de espécies, especialmente se forem ameaçadas e/ou endêmicas (Buchanan, Donald e Butchart, 2011; Myers *et al*., 2000). Essas áreas podem ser designadas para a criação de novas unidades de conservação públicas e privadas, direcionar as ações de fiscalização e pesquisa científica, bem como impulsionar a identificação de áreas para a implementação de iniciativas de restauração ecológica (Menon *et al*., 2001).

Embora seja fundamental garantir a criação de unidades de conservação em áreas de grande relevância ecológica no CEP, essa medida provavelmente não é suficiente para assegurar a persistência de populações e espécies ameaçadas na região, prevenindo, assim, os riscos de futuras extinções globais (Pereira *et al*., 2014; Pereira, Araújo e Azevedo-Júnior, 2016). Nesse contexto, ações de conservação e manejo mais energéticas, como a restauração florestal em larga escala, torna-se essencial, pois apresentam o potencial para impactar diretamente a quantidade e qualidade de habitats nas paisagens da região. Apesar dos esforços dos programas de restauração florestal liderados pelo setor sucroalcooleiro no CEP, os resultados obtidos nas últimas décadas indicam melhorias limitadas na qualidade da cobertura florestal (Santos-Costa *et al*., 2016). Isso se deve, em parte, às práticas de restauração florestal inadequadas empregadas e à capacidade limitada de regeneração natural na área, ressaltando a importância de identificar estratégias para aprimorar os futuros programas de restauração florestal na região (Santos-Costa *et al*., 2016). Nesse contexto, uma alternativa é direcionar os esforços de restauração para aumentar a conectividade entre os remanescentes de vegetação florestal com alta importância ecológica para a biodiversidade endêmica e/ou ameaçada da região.

A implementação de corredores ecológicos pode promover a melhoria das condições para o movimento de organismos, aumentando as taxas de dispersão, promovendo o fluxo gênico, a recolonização de habitats e a adaptabilidade de espécies e populações às mudanças climáticas (Dover, 2014; Keeley *et al*., 2018; Kettle e Haines, 2006; Seidensticker *et al*., 2010; Serneels e Lambin, 2001; Zhang *et al*., 2007). Além disso, corredores ecológicos apresentam potencial para auxiliar a manutenção de funções e processos ecológicos, como o transporte/ciclo de nutrientes e a regeneração natural de espécies vegetais, atuando também na prevenção de fluxos indesejados como a erosão causada pela passagem d'água em paisagens acidentadas (Degteva *et al*., 2015; Doyle *et al*., 2000; Ladonina *et al*., 2001). Embora sejam reconhecidos como uma importante estratégia e ferramenta para a conservação da biodiversidade, os corredores ecológicos são frequentemente criados em regiões com baixo potencial para o desenvolvimento econômico, sem levar em consideração a importância do contexto ambiental local para a biodiversidade (Hilty *et al*., 2019). Essa realidade destaca a importância de levar em conta as respostas de espécies-alvo aos recursos/habitats disponíveis na paisagem para a implementar corredores ecológicos, visando principalmente aumentar sua efetividade no manejo e conservação da biodiversidade (Hilty *et al*., 2019).

O CEP se destaca como palco para alguns dos maiores desafios para conservação da biodiversidade no mundo, devido à situação de seus fragilizados ecossistemas florestais, à grande concentração de paisagens insubstituíveis e à alta diversidade de espécies endêmicas e ameaçadas na região (Donald *et al*., 2019; Pontes *et al*., 2016; Ribeiro *et al*., 2009; Vale *et al*., 2018). Com base nessa perspectiva, o objetivo deste trabalho foi (i) avaliar as tendências de acúmulo/perda de biomassa nos remanescentes de vegetação nativa do CEP, bem como sua causa e as possíveis variações de acordo com o tamanho dos fragmentos florestais analisados; (ii) identificar as mudanças na distribuição e configuração espacial das florestas do CEP entre 1985 e 2020, e avaliar o estado atual da cobertura de Mata Atlântica na região; e (iii) investigar as relações ecológicas estabelecidas entre a avifauna endêmica e ameaçada do CEP e seus habitats, identificando recursos fundamentais para a sua ocorrência, padrões de distribuição e riqueza, e fragmentos florestais prioritários para sua conservação. Como resultado, propõe-se a criação do *Arco de Restauração do Centro de Endemismo Pernambuco* (ARC-CEP), que visa designar áreas para o estabelecimento de corredores ecológicos capazes de reconectar áreas de alta relevância ecológica na região. Os produtos deste trabalho promovem uma avaliação compreensiva da situação dos habitats florestais do CEP e da avifauna endêmica e ameaçada associada a eles, contribuindo com a proposição de estratégias de conservação e o manejo da biodiversidade visando a redução dos riscos de extinção de espécies na Mata Atlântica do nordeste brasileiro.



CAPÍTULO I.

Greening and browning trends in a tropical forest hotspot: accounting for fragment size and vegetation indices

Foto: Thiago C. Dias

Greening and browning trends in a tropical forest hotspot: accounting for fragment size and vegetation indices

Abstract

Greening is the increase in vegetation biomass linked to raises in CO_2 emissions, nitrogen deposition, climate warming, and changes in land cover. Because greening implies land carbon storage, it can contribute to buffering climate changes. While tropical forests are responsible for an important amount of global greening, these environments have been increasingly fragmented, and fragments are thought to lose biomass over time. However, the interferences of forest fragmentation in greening and browning (decrease in vegetation biomass) balance have been an overlooked aspect of greening studies. Furthermore, the saturation of the vegetation indices often used for biomass assessment has been an important challenge for greening studies in dense tropical forests. Here we used Google Earth Engine to address greening and browning trends over the last 35 years for fragments of different sizes from a tropical hotspot, the Atlantic Forest of northeastern Brazil, and we contrasted the results obtained from two vegetation indexes, the traditional NDVI, and the recently developed kNDVI. Despite the highly advanced fragmentation level, greening predominated over browning independently of fragment size (< 10 ha, 10 – 100 ha, 100 – 1000 ha, and > 1000 ha), occurring more frequently but with lower intensity in the larger patches. Although these tendencies did not change with the use of different vegetation indexes, kNDVI proved to be more efficient to detect browning, to identify the different classes of intensity in both greening and browning, and for capturing the extreme greening and browning levels, confirming its lower saturation in relation to NDVI. Our results contradicted the prediction of a continuous unidirectional trend of biomass loss in highly fragmented habitats and revealed that although tropical forest fragments may retain less biomass than continuous forest tracts they may act as carbon sinks, and this can be another important reason for their conservation.

Keywords: remote sensing, global warming, carbon storage, biomass storage, forest fragmentation.

1. Introduction

Tropical forests play an important role in Earth's carbon and energy cycles, retaining over 40% of the global terrestrial carbon and accounting for more than 50% of the global primary productivity (Beer *et al*., 2010; Grace, 2004; Ngo *et al*., 2013; Pan *et al*., 2011). Despite their well-known functions in climate regulation and biological diversity maintenance (Joseph, Murthy e Thomas, 2011), tropical forests have suffered severe losses and fragmentation in the recent decades (Achard *et al*., 2002, 2014; Taubert *et al*., 2018), with the global average annual deforestation rate reaching at least 0.5% since the 1990s (Achard *et al*., 2014). On the other hand, vegetation in the tropics has undergone greening over the past few decades, except for some savannas and arid regions (Piao *et al*., 2020; Zhu *et al*., 2016), contributing to about 25% of global increases in leaf area since 2000 (Chen *et al*., 2019). Greening has been hypothesized to be a vegetation response to anthropogenic activities that have resulted in increased CO_2 levels in the atmosphere, increased nitrogen deposition, climate warming, and changes in land use and land cover (Zhu e Liu, 2015). Because the greening of vegetation is directly related to increases in land carbon storage, this phenomenon contributes to buffering both local and global climate changes (Bonan, 2008; Piao *et al*., 2020; Sitch *et al*., 2015).

Greening occurrence has mostly been observed at the landscape level throughout the tropics (e.g., Haro-Carrión, Waylen e Southworth, 2021; Nzabarinda *et al*., 2021), but refinements about greening/browning tendencies across specific vegetation classes are still overlooked, and one such knowledge gap regards to the potential contribution of forest fragments of different sizes to this process. Many of the tropical forest biomes have become highly fragmented, in such a way that the average fragment sizes dropped to no more than 17 ha in the Americas and 13 ha in Asia and Australia (Taubert *et al*., 2018). While the tropical vegetation is expected to experience greening mainly due to the increases in global carbon emissions (Zhu *et al*., 2016), forest fragments are known to lose biomass and carbon due to border effects and to the loss of important interactions, e.g., the extinction of large seed disperser animals (Islam, Deb e Rahman, 2017; Lima *et al*., 2020; Ma *et al*., 2017; Paula, Costa e Tabarelli, 2011; Shen *et al*., 2021; Silva-Júnior *et al*., 2020). Losses of biomass in forest fragments have been primarily reported through comparisons between continuous forests and remnants of different sizes (Lima *et al*., 2020; Shen *et al*., 2021; Silva-Júnior *et al*., 2020), and a few studies have demonstrated that forest fragments keep losing biomass over time (Shen *et al*., 2021; Silva-Júnior *et al*., 2020). Simulation analyses for small Atlantic Forest fragments (4 ha), for instance, suggested that biomass loss can persist over 100 years (Paula, Groeneveld e Huth, 2015). If the border effect is ceased, biomass levels are restored in about 150 years, but the more intense carbon losses are expected for the first five years after fragmentation (Paula, Groeneveld e Huth, 2015).

Since vegetation indices commonly used to assess greening and browning trends, such as NDVI, are also closely associated with the amounts of aboveground biomass and carbon storage (Li *et al*., 2021; Zhu e Liu, 2015), the empirical evidence for biomass loss in forest fragments could indicate that greening would not be expected to occur in these areas. However, temporal studies are still incipient, and little is known about whether, in the longer term, fragments could also potentially contribute to the greening process, e.g., by reabsorbing at least part of the carbon lost during the fragmentation process, or if the browning tendencies would persist over time and predominate in these areas even when direct disturbances (e.g., logging) are ceased. Elucidating this question is important because if overall tendencies for greening occur even in the highly fragmented ecosystems, carbon absorption would be another important reason for the conservation of their forest fragments.

Vegetation indices derived from remote sensing techniques, and the availability of temporal series of satellite imagery have permitted to infer about greening and browning tendencies over large regions within a tractable amount of time (Piao *et al*., 2020; Zhu *et al*., 2016). Even so, the saturation of commonly used remote sensing-derived vegetation indices when applied to dense vegetation, and the contamination of satellite data with clouds and aerosol, still are important difficulties for addressing greening trends in tropical forests (Piao *et al*., 2020; Samanta *et al*., 2010). These challenges can be overcome by (i) applying masking functions to detect and eliminate pixels contaminated by clouds, shadows, and haze (Wei *et al*., 2017; Zhu e Woodcock, 2012), and (ii) utilizing vegetation indices that better account for saturation over dense vegetation, like the recently developed kNDVI (Camps-Valls *et al*., 2021).

In this work, we analyzed the spatiotemporal trends of greening and browning in tropical forest fragments of different sizes from a biodiversity hotspot, the Atlantic Forest of northeastern Brazil, for which the last wave of deforestation occurred between 1970 and 1980 (Lins-e-Silva, Ferreira e Roda, 2021). We used Google Earth Engine

(Gorelick *et al*., 2017) to assess Landsat data from 1985 to 2020. We accounted for the saturation problem contrasting the results from two vegetation indices: the widely used NDVI (Normalized Difference Vegetation Index), and kNDVI (Camps-Valls *et al*., 2021). By applying Mann-Kendall trend tests and deriving Theil-Sen slopes in R environment (R Core Team, 2020), we addressed browning and greening in forest fragments < 10 ha, 10 – 100 ha, 100 – 1,000 ha, and > 1,000 ha. We provide evidence that, in a tropical region where intense fragmentation occurred more than 30 years ago, greening predominated over browning in all of the classes of fragment sizes, with the higher greening intensities evidenced in the small to medium-sized fragments (100 – 1,000 ha). It contradicted the predominant idea of a unidirectional pattern of biomass loss over time in tropical forest fragments, and to our knowledge, this is the first work evidencing that tropical forests fragments of different sizes can be important drivers of the vegetation greening phenomenon across the tropics.

2. Methods

2.1. Study Area

Our investigations were conducted at the Pernambuco Endemism Center (hereafter, PEC), an Atlantic Forest biogeographical region located north of the São Francisco River in Brazil, which comprises the states of Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte (Tabarelli, Siqueira-Filho e Santos, 2006) (Figure 1). The PEC has a tropical climate, with annual rainfall ranging from 750 to 1500 mm on average, and rains falling primarily during the autumn and winter (Tabarelli, Siqueira-Filho e Santos, 2006). According to IBGE (2018), open/ombrophilous forests and semideciduous stationary forests are the most common phythophysiognomies in the PEC, with ecological tension zones between savannah and stationary forests also occurring. The PEC accommodates a high number of endemic and distribution-restricted species (Silveira, Olmos e Long, 2003; Uchoa-Neto e Tabarelli, 2002), being the most threatened region of the entire Brazilian Atlantic Forest (Tabarelli e Santos, 2004).

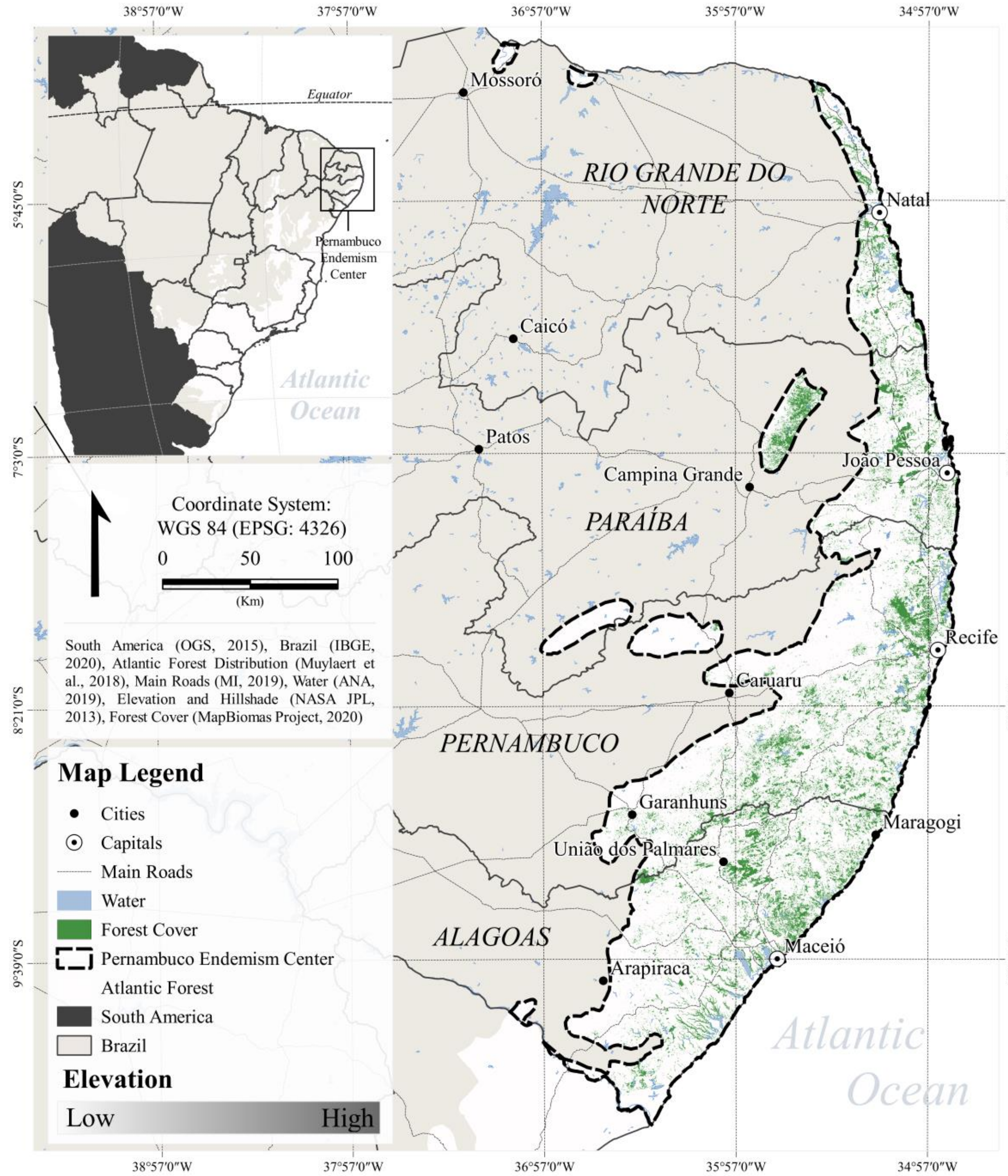


Figure 1. Geographic distribution of land use and land cover in the Pernambuco Endemism Center across the northeastern Brazilian states of Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte. Map created in QGIS (QGIS Development Team, 2021).

The PEC ecosystems have been historically degraded by human activities since the European arrival in 1500 (Ranta *et al*., 1998). Initially, logging of Brazilwood *Paubrasilia echinata* was the primary cause of degradation, but this activity was quickly replaced by forest clearing for sugar cane cultivation (Ranta *et al*., 1998). During the 1970 and 1980s, the sugar cane industry was largely responsible for a rapid and catastrophic reduction in natural vegetation, owing to the federal plan known as "Pró-Alcool", which encouraged the cultivation of sugar cane for ethanol fuel production

(Nemésio e Santos-Júnior, 2014). Nowadays, the landscape of PEC is mainly composed of very small forest fragments surrounded by an agro-pastoral matrix (Tabarelli, Siqueira-Filho e Santos, 2006). Not surprisingly, many taxa have disappeared from the PEC in recent decades, including medium and large mammals (Garbino *et al*., 2018), and its largest endemic forest-dwelling frugivorous bird, the Alagoas-curassow (*Pauxi mitu*), which was declared extinct in the wild in 1979 (Francisco *et al*., 2021).

2.2. Datasets

2.2.1. Forest Cover

We assessed the 2020 land cover layer from MapBiomas Project – Collection 6 (MapBiomas, 2022) in Google Earth Engine, and we used the class 'forest formation' as the indicative of the current forest cover of the Pernambuco Endemism Center. The MapBiomas project is a multi-institutional initiative to provide annual land use and land cover data at 30-m spatial resolution since 1985 for Brazil and other countries around the world (http://mapbiomas.org). All forest patches from the MapBiomas layer composed of less than 6 pixels (approximately 0.54 ha) were removed using Rook's case for pixel adjacency (Lloyd, 2010), since FAO's Global Forest Resource Assessment (FAO, 2020) defines the minimum forest size as 0.5 ha. We then calculated the area of forest patches (ha) through '*bfastSpatial'* package (Dutrieux e DeVries, 2014) in R (R Core Team, 2009) and classified the forest fragments as very small (< 10 ha), small (10 – 100 ha), medium (100 – 1,000 ha), and large (> 1,000 ha).

2.2.2. Satellite Imagery

We obtained satellite imagery of the PEC from 1985 to 2020 using Google Earth Engine. We collected surface reflectance products from Landsat-5, Landsat-7, and Landsat-8, and we filtered the collections to remove scenes with more than 80% cloud cover, using the *'CLOUD_COVER'* parameter in metadata. Google Earth Engine delivers atmospherically corrected Landsat surface reflectance products following the Landsat product guide (USGS, 2020a, b). The PEC bounds were defined by the integrative distribution of Atlantic Forest (Muylaert *et al*., 2018) in the states of Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte, and we used it to crop all Landsat scenes. Landsat-8 products were not used for time-series analyses since they appear to pull up the greenness indices even after applying the cross-sensor linear transformation in Roy *et al*. (2016) (results not shown).

Pixels containing clouds, water, saturated values, haze, and aerosol interference were removed from the satellite scenes using the masking functions described in Pironkova, Whaley e Lan (2018), in accordance with the Landsat product guide (USGS, 2020a, 2020b), since these interferences may cause errors in trend detection (Braaten, Cohen e Yang, 2015; Chen *et al*., 2015). We used the following equations to produce NDVI (equation 1) and kNDVI (equations 2 and 3) layers from the Landsat scenes:

$$NDVI = \left(\frac{NIR-red}{NIR+red}\right) \text{ (1)}$$

$$kNDVI = tahn\left(\left(\frac{NIR-red}{2\sigma}\right)^{2}\right) \text{ (2)}$$

$$kNDVI = tahn(NDVI^{2}) \text{ (3)}$$

NDVI was calculated following equation 1 between the Near Infrared (NIR) and red bands (Rouse *et al*., 1974; Tucker, 1979). kNDVI was computed using the simplified equation 3 by setting the length-scale parameter in equation 2 to $\sigma = 0.5$(NIR + red) as suggested by Camps-Valls *et al*. (2021). All ecophysiological explanations for averaging the value of σ can be found in sections S1 and S2 of Data Supplement in Camps-Valls *et al*. (2021). kNDVI addresses the challenges of dealing with saturation in dense vegetation (Camps-Valls *et al*., 2021), being more resilient to bias, complex phenological cycles, and also more robust when dealing with noise and instability across spatiotemporal scales (Camps-Valls *et al*., 2021). This recently developed index also allows more accurate measures of terrestrial carbon source/sink dynamics, performing better than the well-established indices NDVI and NIRv in monitoring key parameters like leaf area index, gross primary productivity, and sun-induced chlorophyll fluorescence (Camps-Valls *et al*., 2021).

2.2.3. Assessment of Greening and Browning Trends

In this study, NDVI and kNDVI were used as indicators of forest greenness (Pettorelli *et al*., 2011). From 1985 to 2020, we calculated annual maximum-values of NDVI and kNDVI using Landsat-5 and Landsat-7 products. Yearly maximum composites were used because temporal aggregation is a promising strategy for reducing data volume in time-series data without losing accuracy (Phan, Kuch e Lehnert, 2020). All areas previously classified as non-forest were removed from further analyses. Using the *'rkt'* package (Marchetto e Marchetto, 2015) in R environment (R Core Team, 2009), we adapted the time series analysis script from Pironkova, Whaley e Lan (2018) to calculate Mann-Kendall rank correlations and Theil-Sen's slope estimators and detect gradual changes in vegetation greenness that were consistent in direction (Pironkova, Whaley e Lan, 2018).

The non-parametric Mann-Kendall trend test determines if a regular time series shows a monotonic (upward or downward) trend, assuming a null hypothesis that no trend is present, and the alternative hypothesis that states for the presence of positive or negative trend (Fassnacht *et al*., 2019). Mann-Kendall tests do not require normal distribution, can be computed even with missing data, and extreme values do not affect its results (Pironkova, Whaley e Lan, 2018). Mann-Kendall requires data to be independent, and authors have argued that the effect of serial autocorrelation for long-term time series can be ignored (Erasmi *et al*., 2014; Pironkova, Whaley e Lan, 2018; Yue e Wang, 2002). Following Pironkova, Whaley e Lan (2018), we assumed that autocorrelation and seasonality were not an issue, since we used a 35-year time series of annual median composites.

From both NDVI and kNDVI indices, we derived layers representing the Mann-Kendall tau with an associated p-value, and the Theil-Sen's slope (Pironkova, Whaley e Lan, 2018). The Mann-Kendall tau coefficient ranges from -1 to 1, with negative values indicating a decrease in vegetation greenness, and positive indicating increasing temporal trends (Pironkova, Whaley e Lan, 2018). In areas where the Mann-Kendall test indicates a significant monotonic trend that looks linear, the non-parametric Theil-Sen's slope was used as an indicator of intensity in greening or browning (Pironkova, Whaley e Lan, 2018). The Theil-Sen slope raster was then classified based on the classical standards of NDVI changes in Li *et al*. (2015); (Table 1).

Table 1. Standards of NDVI from Li et al. (2015).

NDVI classical standard	**Range**
Serious Browning	Theil-Sen slope < −0.0090
Moderate Browning	−0.0090 ≤ Theil-Sen slope < −0.0045
Slight Browning	−0.0045 ≤ Theil-Sen slope < −0.0009

Unchanged	$-0.0009 \leq$ Theil-Sen slope < 0.0009
Slight greening	$0.0009 \leq$ Theil-Sen slope < 0.0045
Moderate greening	$0.0045 \leq$ Theil-Sen slope < 0.0090
Obvious greening	$0.0090 \geq$ Theil-Sen slope

3. Results

A total of 53,862 forest fragments were assessed over the PEC, ranging in size from 0.54 to 14,642.55 ha ($\bar{x}$ = 10.71 ± 129). When considering the total current forest cover of the PEC, classes of fragment sizes occupied relatively similar proportions (very small forest fragments < 10 ha: 17.15%; small forest fragments 10 – 100 ha: 27.66%; medium fragments 100 – 1,000 ha: 28.53%; large fragments > 1,000 ha: 26.66%). We found evidence of consistent greening over the total forest cover of the PEC when considering mean annual NDVI and kNDVI values (1985 to 2020) (Figure 2). Among fragment classes, significant increases were also found for small (NDVI), medium (NDVI and kNDVI), and large fragments (NDVI and kNDVI) (Figure 2).

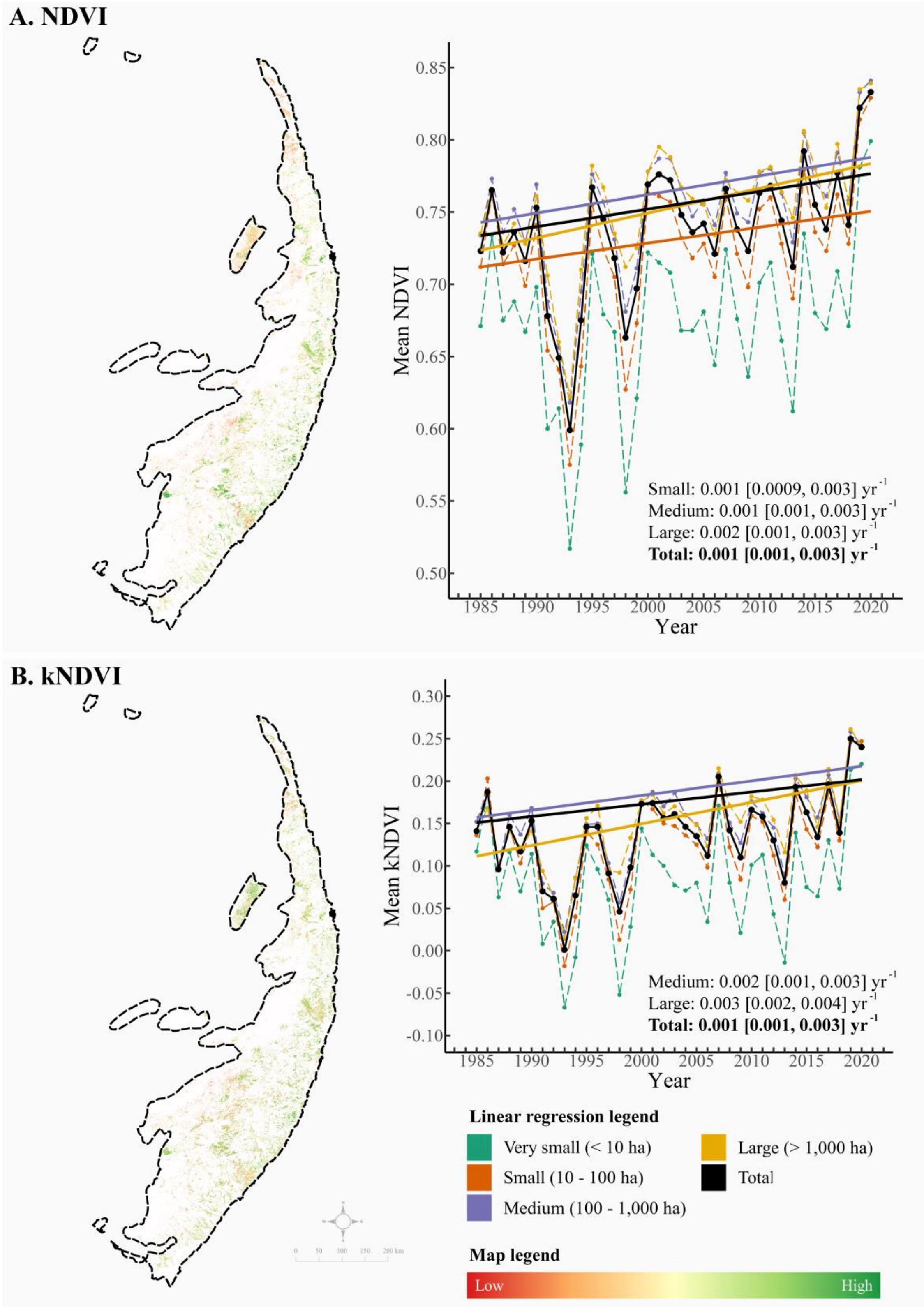


Figure 2. Spatial variation and temporal trends of annual averaged maximum NDVI and kNDVI values for forests across the Pernambuco Endemism Center, from 1985 to 2020. Only significant (Mann-Kendall p-value ≤ 0.05) annual rates of increase and prediction lines (Theil-Sen) are presented in the time-series graphs.

For NDVI, significant trends (p-value ≤ 0.05) in Mann-Kendall were observed in 269,492 ha, while significant trends were found to occur in 162,510 ha when using kNDVI. Positive trends were identified in 99% (266,797 ha) of the significantly changed pixels using NDVI, whereas 93% (151,134 ha) of significant positive trends were identified when using kNDVI.

Theil-Sen slope (related to the intensity of greening/browning) revealed that the forest fragments of the PEC had been through an overall slight-to-moderate significant greening over the last 35 years according to NDVI, and moderate-to-obvious according to kNDVI (Figure 3). For NDVI, significant slight greening occurred in 68.19% of the PEC fragments, moderate greening was seen in 26.33%, and obvious greening only occurred in 4.60% (Figure 3). For kNDVI, significant slight greening occurred in fewer areas of the forest vegetation (7.70%), while moderate (50.22%) and obvious greening (35.27%) were greater (Figure 3). According to NDVI-derived Theil-Sen slope, only 0.82% of the forest fragments of the PEC presented any type of browning (summing serious, moderate, and slight browning), and browning was more intense and occurred more frequently when using kNDVI, with slight (0.64%), moderate (3.39%), and serious (2.78%) browning occurring in larger areas (Figure 3).

Our findings confirm the existence of spatial variation in greening intensity over different sizes of forests (Figure 3). The percentage of the forest cover experiencing browning slightly decreased when increasing fragment size (Figure 3). Additionally, using NDVI it was possible to observe an increase in slight-to-moderate greening when increasing fragment size, with larger fragments also experiencing less obvious greening (Figure 3).

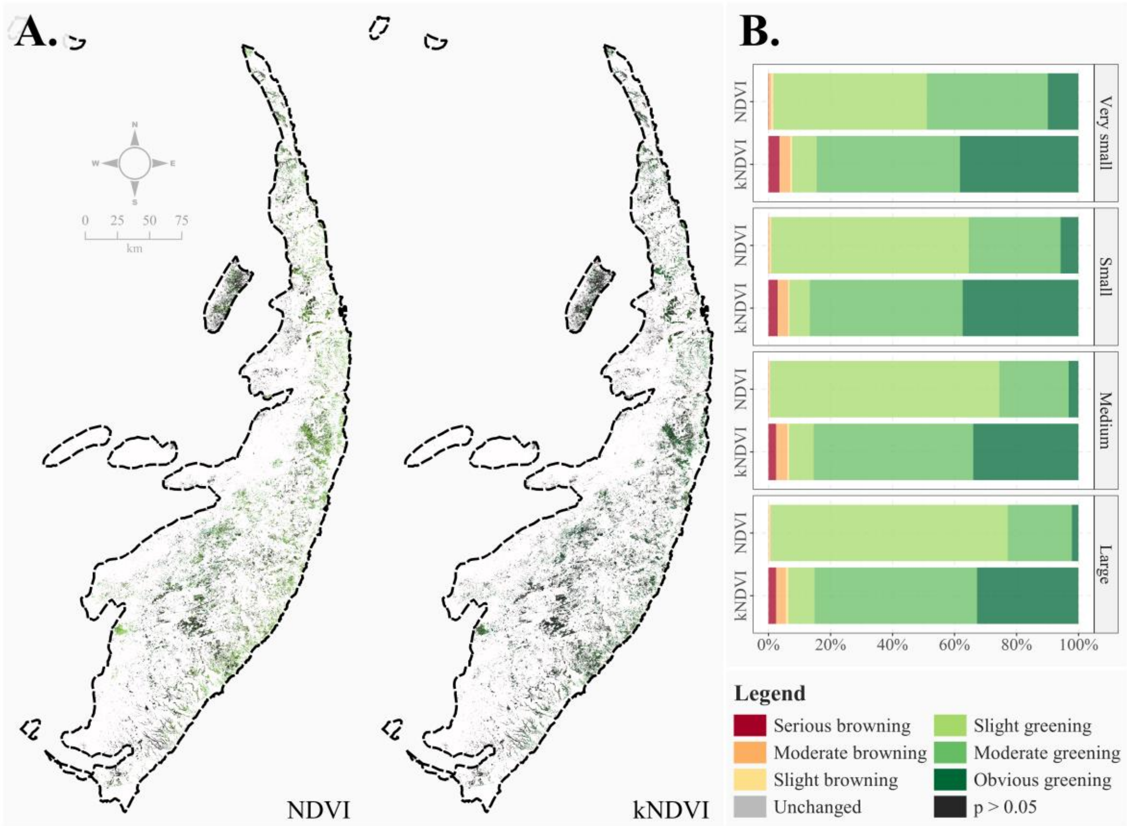


Figure 3. Greening and browning trends over the Pernambuco Endemism Center forests from 1985 to 2020. The figure display (A) the spatially explicit significant trends of greening and browning occurrences according to NDVI and kNDVI, and (B) the percentage of each intensity category distributed along very small (< 10 ha), small (10 – 100 ha), medium (100 – 1,000 ha), and large (> 1,000 ha) fragments.

4. Discussion

Our main finding was that the Atlantic Forest of the PEC presented a general tendency for greening over the last 35 years, despite its highly advanced fragmentation level (Tabarelli e Santos, 2004). Even in the smaller fragments (< 10 ha), greening outpaced browning tendencies. Although greening predominance over browning slightly increased with fragment size, greening intensity followed an opposite pattern, being lower in the larger patches.

Even with the similarities between the overall greening and browning tendencies derived from NDVI and kNDVI, the latter proved to be more efficient in detecting different classes of both greening and browning intensities, being more sensitive to variations. kNDVI seemed to perform better in capturing extreme intensities of greening and browning, which may confirm its lower saturation in relation to NDVI (Camps-Valls *et al.*, 2021). Although we have not assessed biomass levels of the study areas by traditional methods for comparative purposes, our results are among the first to confirm the greater efficiency of kNDVI for remote sensing studies on tropical forests (see also Camps-Valls *et al*., 2021). As kNDVI revealed more browning than NDVI, we suggest this index can provide more realistic scenarios of degradation levels for tropical forests.

In the PEC, logging activities could have played an important role in the observed greening patterns. In this region, emergent trees account for 59% of the aboveground biomass, and an overall 50% decrease in carbon retention was detected in forest fragments and forest borders, mainly as a consequence of emergent trees removal (Paula, Costa e Tabarelli, 2011). In addition, only about 8% of the PEC is composed of old-growth forests with full capacity of carbon storage (Paula, Costa e Tabarelli, 2011). Together, these may suggest that besides fragmentation, the forest fragments of the PEC were affected by intense logging activities. Although addressing the reasons why logging activities were so intense in the PEC forests is beyond the scope of this manuscript, it is known that the sugar cane industry was an important timber consumer in the past. The production of sugar and ethanol has long been among the main economic activities in the states of northeastern Brazil (Ranta *et al*., 1998), and during the decades of 1970 and 1980, timber was the fuel used to activate the boilers of these industries. Over the last 20 years, however, the use of sugar cane bagasse eliminated the need for timber as a source of energy, which contributed to cease at least one of the important timber demands (Bordonal *et al*., 2018). Then, our findings are consistent with a scenario in which increased greening tendencies observed for small and mid-sized fragments may reflect the recuperation of the emergent trees in areas that suffered from intense logging. The larger fragments with more than 1,000 ha, that showed less intense trends of both greening and browning, must be represented by protected areas that hold the majority of the remaining old-growth forests of the PEC. In these more mature environments, less variation in biomass across the years is expected because gains derived from tree recruitment are equivalent to the losses caused by tree deaths (Dai *et al*., 2013).

The slightly higher frequency and intensity of browning in the smaller fragments, where border ratios are increased, was somewhat expected. In the Brazilian Atlantic Forest, border habitats may not provide good conditions for emergent trees recuperation, and they were found to have only one-third of the emergent species when compared to the forest interior (Oliveira, Grillo e Tabarelli, 2004). In addition, borders are also more susceptible to lower humidity, higher air temperatures, and strong winds than the forest interiors (Magnago *et al*., 2015), which may lead to higher tree mortality (Silva, Pereira e Barros, 2014).

The variation in greening/browning tendencies found for the fragments of different sizes of the PEC contradicted the prediction of a continuous unidirectional trend of biomass loss in highly fragmented habitats (Paula, Costa e Tabarelli, 2011). Although fragments may retain less biomass than continuous forest tracts (Islam, Deb e Rahman, 2017; Lima *et al*., 2020; Ma *et al*., 2017; Paula, Costa e Tabarelli, 2011; Shen *et al*., 2021; Silva-Júnior *et al*., 2020), we demonstrated that even small to mid-sized fragments of forests may contribute to the phenomenon of biomass gain over time, which suggests that they may act as carbon sinks under specific conditions, being this another important reason for their conservation. These findings could be likely explained by the historical exploitation of the PEC region, especially the intensive logging followed by the reduction of this type of activity. This condition is certainly not exclusive from the PEC, as forest fragmentation is followed by logging in many parts of the world, and carbon retention may be an overlooked environmental service provided by tropical forests fragments.

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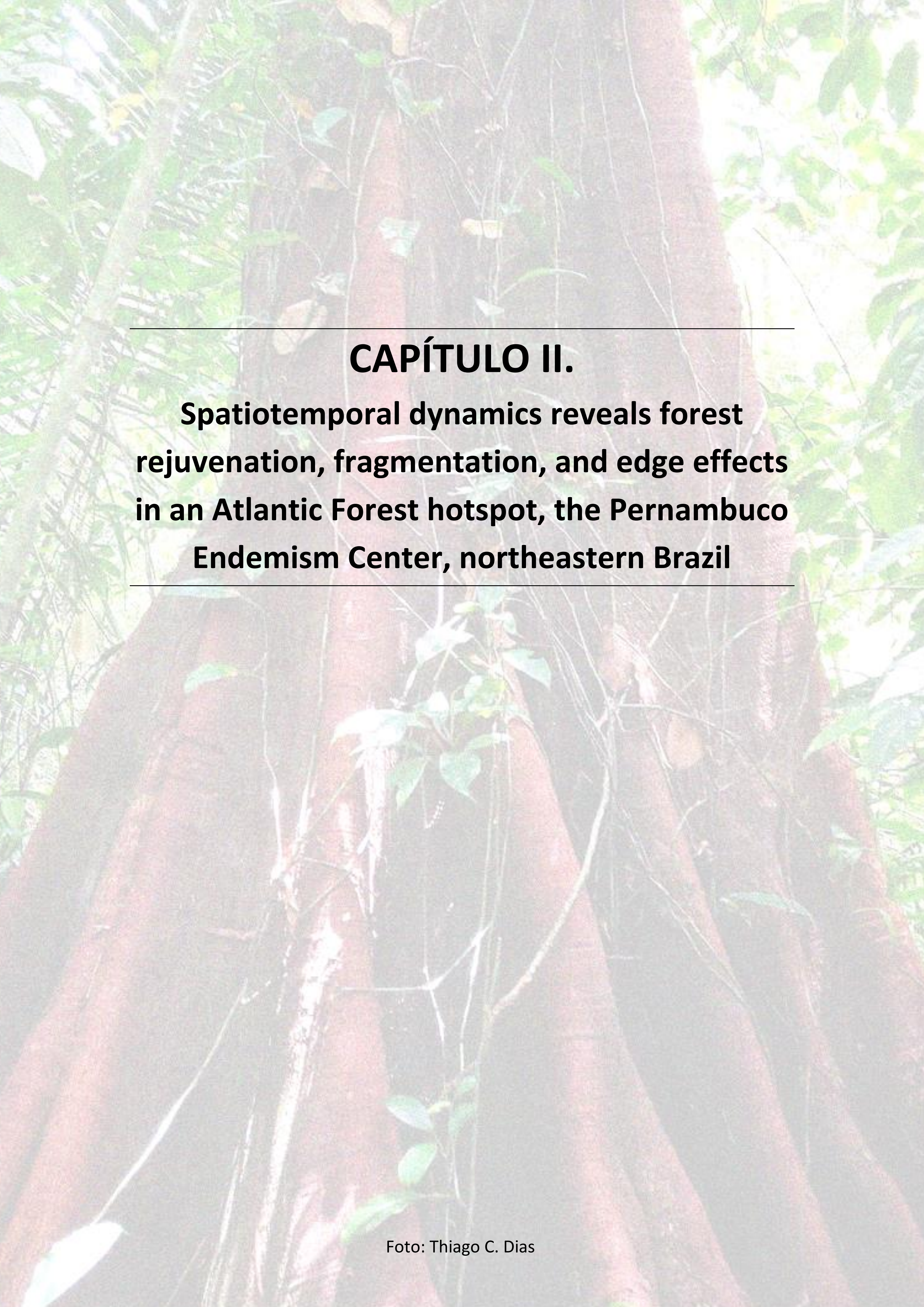


CAPÍTULO II.

Spatiotemporal dynamics reveals forest rejuvenation, fragmentation, and edge effects in an Atlantic Forest hotspot, the Pernambuco Endemism Center, northeastern Brazil

Foto: Thiago C. Dias

Spatiotemporal dynamics reveals forest rejuvenation, fragmentation, and edge effects in an Atlantic Forest hotspot, the Pernambuco Endemism Center, northeastern Brazil

Abstract

In human-modified landscapes, assessing the spatial patterns and distribution of forest fragments is important for conservation planning, and detailed studies are urgently needed in tropical forests. The Atlantic Forest is one of the world's most important biodiversity hotspots, jeopardized not only by the direct and indirect influences of fragmentation, but also by forest rejuvenation. The Pernambuco Endemism Center (PEC) is located northern from the São Francisco River, in northeastern Brazil, and it is the most degraded of the Atlantic Forest regions. However, little is known about the current status and temporal dynamics of its forest fragments. Here, we provide historical and contemporary overviews on the amount, distribution, and spatial configuration of the PEC's Atlantic Forest cover. About 90% of the fragments were very small (< 10 ha), and the average fragment size was about 11 ha. The amount of older forest cores in large fragments (> 1000 ha) summed 62,058 ha in 2017, representing only 12% of the remaining forest cover. Furthermore, we found a forest rejuvenation process that was 2.5 times higher than that of the whole Atlantic Forest. These findings suggest that the amount of forest cover alone may not be predictive of biodiversity conservation and that the protection of the PEC older forests is urgently needed. To assist conservation managers, we developed an open-access Google Earth Engine application that may contribute to conservation planning.

Keywords: connectivity, landscape metrics, protected area, neotropical region, landscape ecology, forest rejuvenation.

1. Introduction

Tropical forests harbor more than half of all known species and are among the most endangered ecosystems on Earth (Hoang e Kanemoto, 2021; Roberts, Hamilton e Piperno, 2021), with deforestation rates reaching around 5.5 Mha/yr^{-1} (Keenan *et al.*, 2015). For this reason, large forested tracts have become increasingly rare in tropical forest hotspots, where conservation managers are presented with the challenge of preserving biodiversity in small and isolated fragments (Costa-Araújo *et al.*, 2021; Edwards *et al.*, 2019; Hansen *et al.*, 2023). Then, assessing the spatial patterns and distribution of the fragments in highly degraded habitats is important for conservation planning because they can predict the extinction risks of biodiversity components (Crooks *et al.*, 2017; Regolin *et al.*, 2017), and because they can indicate the best remnants for the creation of protected areas (Mohammadi *et al.*, 2021, Zhang *et al.*, 2013). Furthermore, in dynamic environments forests can regenerate, and the replacement of old forests by secondary younger habitats has been recently proved to be a secretive temporal effect that can masquerade the loss of original habitats and can jeopardize species and ecosystem services (Rosa *et al.*, 2021).

The Brazilian Atlantic Forest is one of the world's most important biodiversity hotspots, which has been through a history of intense degradation since the European settlement more than 500 years ago (Metzger e Sodhi, 2009; Mittermeier *et al.*, 2011; Ranta *et al.*, 1998). Currently, only about 11.26% of its original 150 Mha remains, almost entirely (80%) in fragments smaller than 50 ha (Ribeiro *et al.*, 2009). Despite the continuous deforestation process, it was recently revealed that the area covered by native vegetation was relatively constant during the last 30 years (around 28 Mha) due to a hidden process of substitution of old forests by areas of secondary vegetation, with losses of older habitats ranging from 220,000 to 80,000 ha/year^{-1} from 2000 to 2015 (Rosa *et al.*, 2021). The Pernambuco Endemism Center (hereafter PEC) formerly comprised a 4.4 Mha area located north of the São Francisco River (Lins-e-Silva, Ferreira e Roda, 2021; Tabarelli & Roda, 2005), in northeastern Brazil, but today it is the most degraded of the Atlantic Forest regions (Ribeiro *et al.*, 2009), the reason why it has been considered a hotspot within a hotspot (Pontes *et al.*, 2016). Estimates pointed out that only about 320,000 to 360,000 ha of native forests were present in the PEC between 2001 and 2007, with dramatic levels of fragmentation and edge effects (Pontes *et al.*, 2016; Ribeiro *et al.*, 2009). However, previous studies did not capture the temporal dynamics of the PEC's forest cover over the last decades, and there is a lack of recent information on the status of the forest remnants.

Here, we provide an updated descriptive assessment of the spatial patterns and distribution of PEC's Atlantic Forest cover, and we reveal for the first time its temporal dynamics. We used Google Earth Engine (GEE) (Gorelick *et al*., 2017) to process annual land use and land cover layers from MapBiomas Project (MapBiomas, 2022) dating from 1985 to 2020, and we calculated metrics related to: forest cover area, age, number of fragments, mean and larger fragment sizes, core and edge areas, deforestation and forest regeneration rates. We predicted that the forest rejuvenation dynamic reported for the whole Atlantic Forest (Rosa *et al*., 2021) could be even more remarkable in the PEC because differently from southern Atlantic Forest regions, large and well-preserved forest tracts no longer exist northern from the São Francisco River. In this study, we incorporate forest quality parameters not previously considered by conservation managers, and we developed an open-access Google Earth Engine application that may potentially assist in conservation planning in this important biodiversity hotspot (https://dias93thiago.users.earthengine.app/view/forests-of-the-pec).

2. Methods

2.1. Description of the study Area

The Pernambuco Endemism Center (PEC) is a biogeographic zone of the Brazilian Atlantic Forest located in northeastern Brazil (Figure 4). Human interferences were responsible for the intense degradation of its forest formations since the 16th century, and the highest levels of fragmentation and deforestation occurred during the 1970s, mainly due to the activities of the sugar cane industry (Nemésio e Santos-Júnior, 2014). This intensive degradation reduced the forest cover to no more than 11.5% of its original size, mostly unprotected (protected areas account for about 1% of the forest cover) (Ribeiro *et al*., 2009). The PEC is located in a portion of the tropical zone where the predominant climate is Köppen's As (tropical with a dry season), and smaller portions of the climate are Köppen's Af (tropical without a dry season) are also found. Annual rainfall ranges from 1900 – 2200 mm in the coastal regions and 700 – 1000 mm in the western border, with annual mean temperature varying from 24 to 26º C (Alvares *et al*., 2013). The PEC went through four major waves of deforestation, the first three occurred between the sixteenth and eighteenth centuries, and the last started after 1975, during the establishment of the Proálcool Program (Brazilian Alcohol Program) (Lins-e-Silva, Ferreira e Roda, 2021). The PEC is home to the highest number of globally threatened species in the Americas (Pereira *et al*., 2014; Silveira, Olmos e Long, 2003; Stattersfield, 1998; Wege e Long, 1995). Large mammals are currently extinct in the PEC (e.g., puma *Puma concolor*, jaguar *Panthera onca*, white-lipped peccary *Tapirus terrestris*, giant ant-eater *Myrmecophaga tridactyla*, gray brocket *Mazama gouazoubira)*, and at least half of its medium-sized mammals have disappeared over the last 500 years (Garbino *et al*., 2018; Pontes *et al*., 2016; Pontes, Beltrão e Santos, 2019). It was also at the PEC that the modern Brazilian bird extinctions were registered (Butchart *et al*., 2018; ICMBio, 2018; Pereira *et al*., 2014).

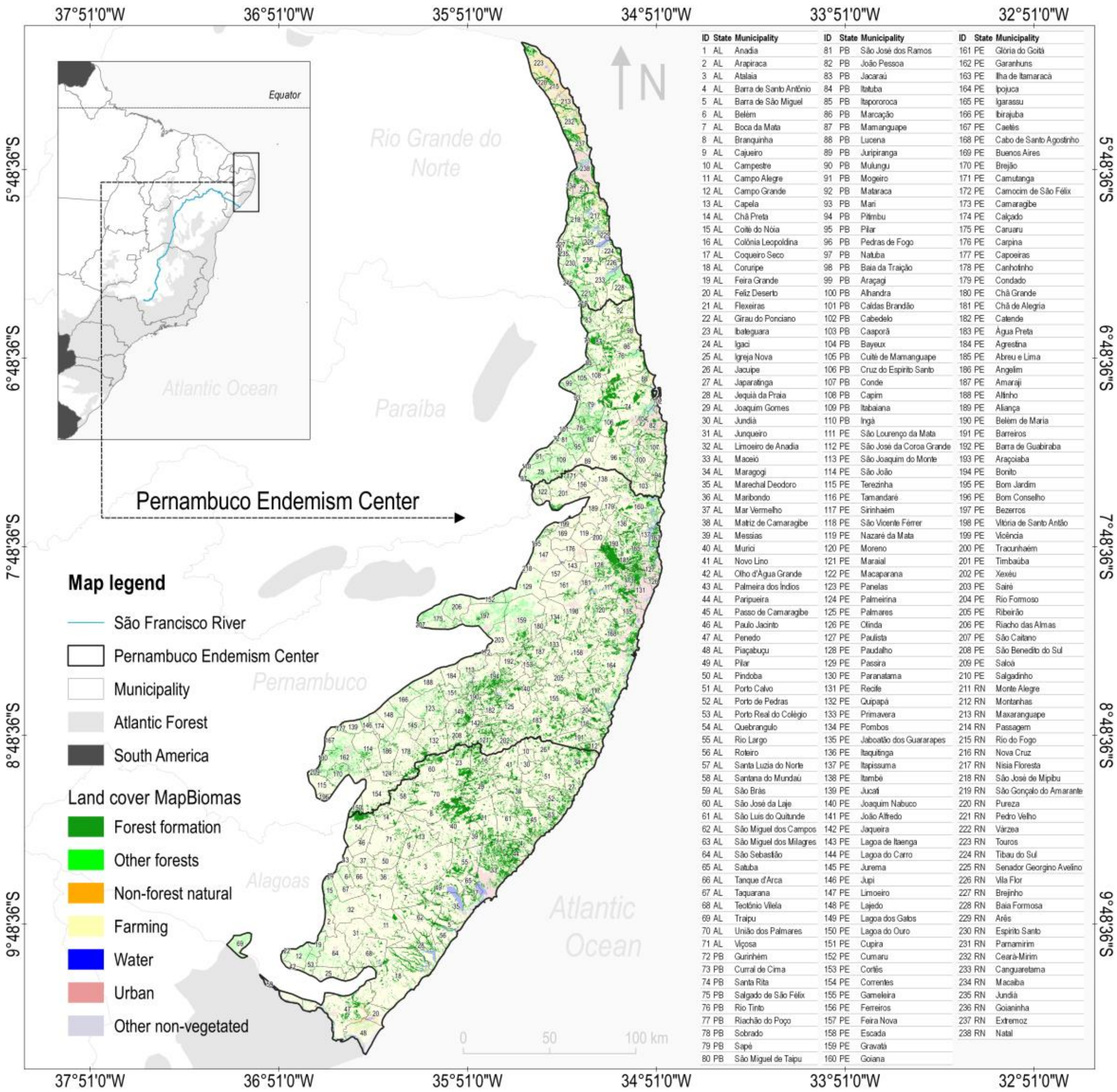


Figure 4. Location of the Pernambuco Endemism Center (PEC) in the Brazilian Atlantic Forest of northeastern Brazil. The 2020 land use and land cover layer from MapBiomas Project was adapted to show relevant aggregations of land cover classes. The class "Forest formation" from annual layers

represents a proxy of the PEC forest cover. The table on the right shows the identification (ID) and name of its municipalities.

2.2. Dataset

We used GEE to assess data from the sixth collection of the MapBiomas Project, a collaborative initiative that provides annual (1985-2020) land use and land cover information at 30 m spatial resolution for Brazil using Landsat imagery, representing the longest time series data for Brazil (MapBiomas, 2022). In GEE, we simplified the MapBiomas layers to retain only areas classified as forest formations (in such a way that all other land cover classes were removed from further analyses), representing proxies of the Brazilian Atlantic Forest cover of the PEC. All data from MapBiomas were processed with methods that take into account and correct interferences from clouds or atmospheric haze, and several spatial and temporal post-classification filters were applied to ensure data quality (MapBiomas, 2022). The Collection 6 Level 2 land use and land cover classes of the Atlantic Forest biome have a global accuracy of 85.5%, allocation disagreement of 8.3%, and area disagreement of 6.2% (MapBiomas, 2022). For the 'forest formation' class in Atlantic Forest biome (used in this study), overall accuracy ranged from 85.6% to 87.89% between 1985 e 2018 (MapBiomas, 2022). A stratified sample design that took the probabilities of sample weight adjustment into account was used to validate the MapBiomas data using more than 12,000 points, which were examined by three analysts (MapBiomas, 2022). Following the minimum forest size (0.5 ha) established by FAO's Global Forest Resource Assessment (FAO, 2020), we removed all fragments with less than six pixels (0.54 ha) using Rook's case for pixel adjacency (Lloyd, 2010). We assigned unique identifications to forest fragments and we calculated their areas using the *'bfastSpatial'* package (Dutrieux e DeVries, 2014) in R (R Core Team, 2009).

2.3. Forest cover, number of fragments, average, and largest fragment sizes

In GEE, we evaluated temporal changes in the forest cover extent and configuration by calculating the overall forest area and the areas of fragments < 10 ha (very small), 10 – 100 ha (small), 100 – 1,000 ha (medium), and > 1,000 ha (large). We choose to separate fragments according to their sizes for comparative purposes following the most recent study that investigated the PEC's forest cover (Pontes *et al.*, 2016). We also calculated the total number of fragments, and the number of fragments according to the abovementioned size classes. For forest area and number of fragments, we identified linear trends over time by applying a bottom-up breakpoint analysis using segmented package (Muggeo, 2008) in R. After selecting the number and location of breakpoints using Bayesian Information Criterion (BIC), this analysis subdivides a time series into phases with distinct trends and slopes (Taddeo e Dronova, 2020). We determined the average fragment size by dividing the total forest cover area by the number of fragments, and we inferred the size of PEC's largest fragment. To assess the current (2020) distribution of forests for each municipality of the PEC, we generated layers representing the forest cover area (total) and the number of fragments (very small, small, medium, and large fragments). We chose to calculate metrics for each municipality to facilitate the interpretation of our results by state government environmental agencies and policy makers. To capture processes that may operate in different spatial scales, we developed a tool in the GEE application *Forests of the PEC* which permits regions of interest to be defined by users. We additionally identified the remaining (2020) largest fragments of the PEC (fragments larger than 5,000 ha) and we generated information on their core and edge areas, as well as the areas composed by older and younger forests (see sections below).

2.4. Deforestation, forest regeneration, and identification of older and younger forests

We assessed the current (2017) amount and the distribution of older (> 35 years) and younger (< 35 years) forests of the PEC in GEE. We used as proxies of the older forests the pixels classified as forests in 1985 with no event of deforestation registered until 2017 (see methodology for deforestation classification below). Pixels classified as forests in 2017 that did not match these conditions were classified as younger forests. We generated layers containing the overall current distribution of older and younger forests, and their current distributions per municipality. To measure deforestation and forest regeneration, we implemented a moving window-based temporal filter in GEE (Nanni *et al*., 2019; Rosa *et al*., 2021).

Year-specific deforestation events were assumed when a given pixel was classified as forest for the two previous years (t – 2, t – 1) and as non-forest in the current (t) and subsequent year (t + 1) (Fig S1) (Rosa *et al*., 2021). We classified year-specific forest regeneration events when pixels were classified as non-forest for the two previous years (t – 2, t – 1), and then as forest in the current year (t) and in the next three subsequent years (t + 1, t + 2, t + 3) (Fig S2). Moreover, we investigated deforestation events across a range of fragment sizes (Fig S3). Using the annual deforestation layers, we extracted and averaged the fragment size during the two previous years (t – 2, t – 1) for each deforestation pixel. We then classified the resulting pixels of deforestation into deforestation of very small, small, medium, and large fragments (Rosa *et al*., 2021).

We discriminated deforestation of older forests by calculating the year of the first deforestation event in pixels classified as forests in 1985. We only classified the first deforestation event of a given 1985 forest pixel as deforestation of older forests. For each year, we remapped the values of deforestation from one to the value corresponding to its year of occurrence. After that, for each pixel, we extracted the minimum value (corresponding to the first event of deforestation) and masked the new classified images to remove all pixels not classified as forests in 1985 (Fig S4). We classified all the other deforestation events that did not matched the abovementioned conditions as deforestation of younger forests. We addressed deforestation rates of older forests only after 2000 because at least part of deforestation that occurred in the first years of our study time may stand as deforestation of younger forests that grew just before 1985 (Rosa *et al*., 2021). To evaluate the participation of each municipality in forest loss and gain rates across the PEC, we additionally mapped their accumulations from 1987 to 2017.

2.5. Core and edge areas

We calculated the Euclidean distance between the forest edge and its interior in GEE to assess changes in the amount of forest cores and edges for the PEC forests. We defined a conservative threshold of 50 m from the forest edge as the area with the higher influence of border effects and we considered all forests within this distance as edges (Melo, Dirzo e Tabarelli, 2006; Ranta *et al*., 1998). Using the core and edge layers, we calculated the total core and total edge area, as well as the proportions of forests covered by edges and core areas per year.

3. Results

3.1. Forest cover, number of fragments, average, and largest fragment sizes

During the last decades, nearly 5% of the PEC forest cover was lost (571,661 ha in 1985 and 539,877 ha in 2020), and the most drastic reduction occurred before the 1990s (Figure 5A). The amount of forests we detected in 2020 represents 12.3% of the original PEC's forest cover. Very small fragments (< 10 ha) represented around 25% (144,108 ha) of the forest cover in 1985 and 17% (94,091 ha) in 2020 (Table S1). For forest areas, the first breakpoint was detected between 1988 and 1991 for total and all other classes of fragment size (Figure 5A), where higher rates of decrease were identified (Table S3). Decreases in the forest extent were generally found to occur at a lower rate during the 1990s, followed by increases in the forest amount after the 2000s (Table S3).

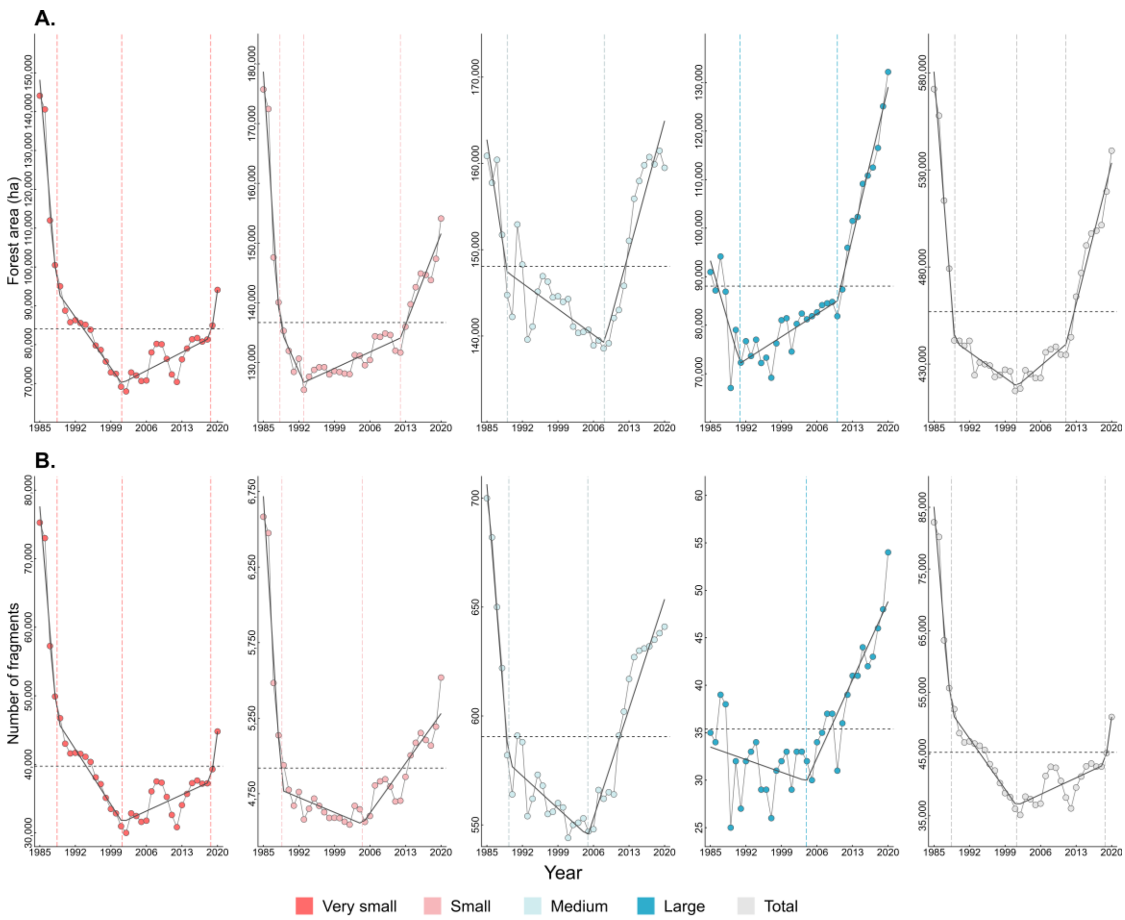


Figure 5. Historical changes in the forest cover of the Pernambuco Endemism Center. Section A displays changes in the total forest cover area (total and according to fragment size). Section B shows changes in the number of fragments (very small, small, medium, large, and total) from 1985 to 2020. Dotted horizontal lines represent the historical means and dotted vertical lines represent breakpoints. Bold black lines represent linear trends.

Almost all of the PEC fragments (roughly 87.44%) were classified as very small on average during the last decades, and only about 0.08% of the fragments were larger than 1,000 ha. Decreases in the number of fragments were found to be more pronounced during the 1980s, and the PEC experienced a period of lower decreasing rates during 1990 (Table S3). After the 2000s, increases in the number of fragments were found for all fragment classes and total, with generally high rates of increase for medium and large fragments (Table S3).

Only five municipalities of the PEC currently (2020) maintain more than 10,000 ha of native forests: Coruripe/AL, Maceió/AL, Murici/AL, Igarassu/PE, and Santa Rita/PB (Figure 6A). Fragments with increased sizes were generally confined to municipalities closer to the coast (eastern PEC) (Figure 6B). Furthermore, only the municipalities of Maceió and Coruripe in the state of Alagoas (AL) harbored more than five fragments larger than 1,000 ha each in 2020 (Figure 6B).

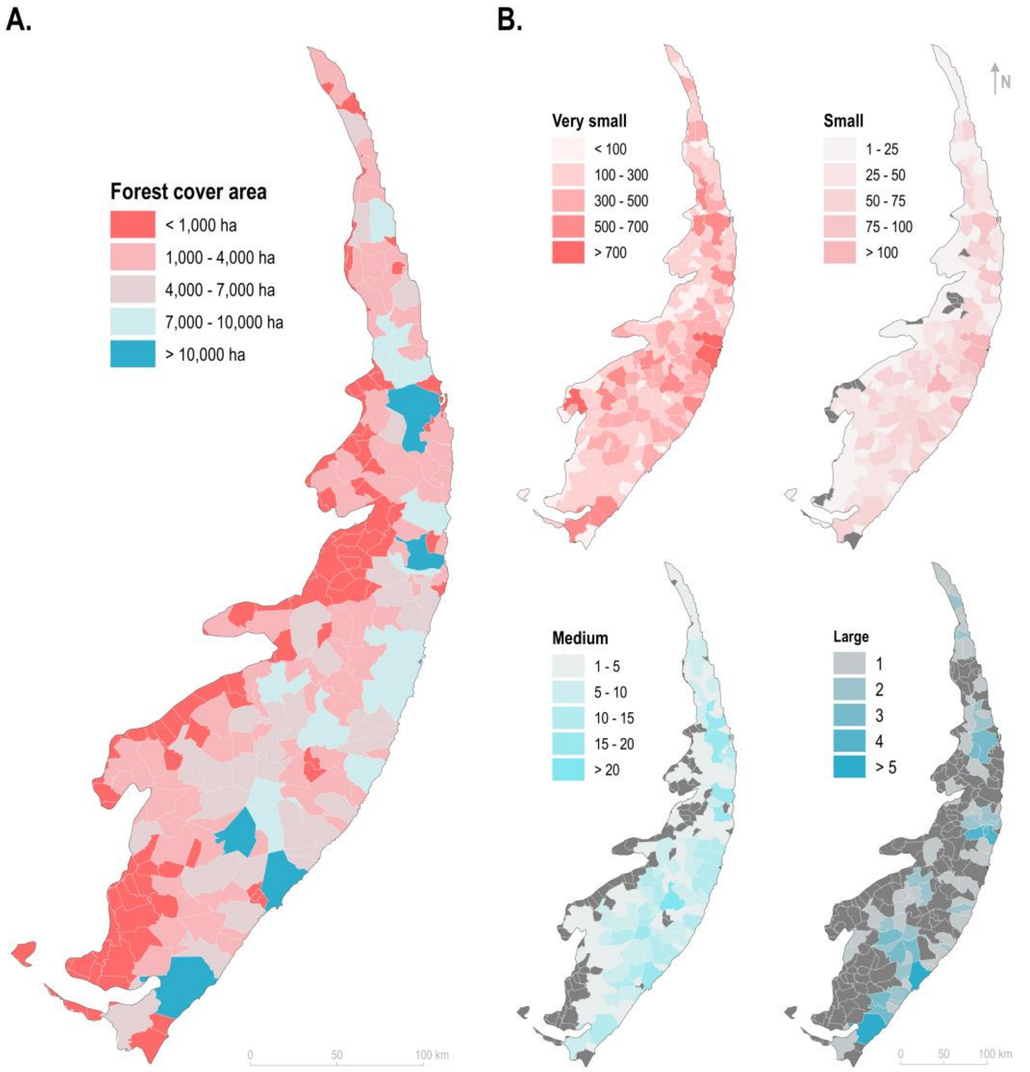
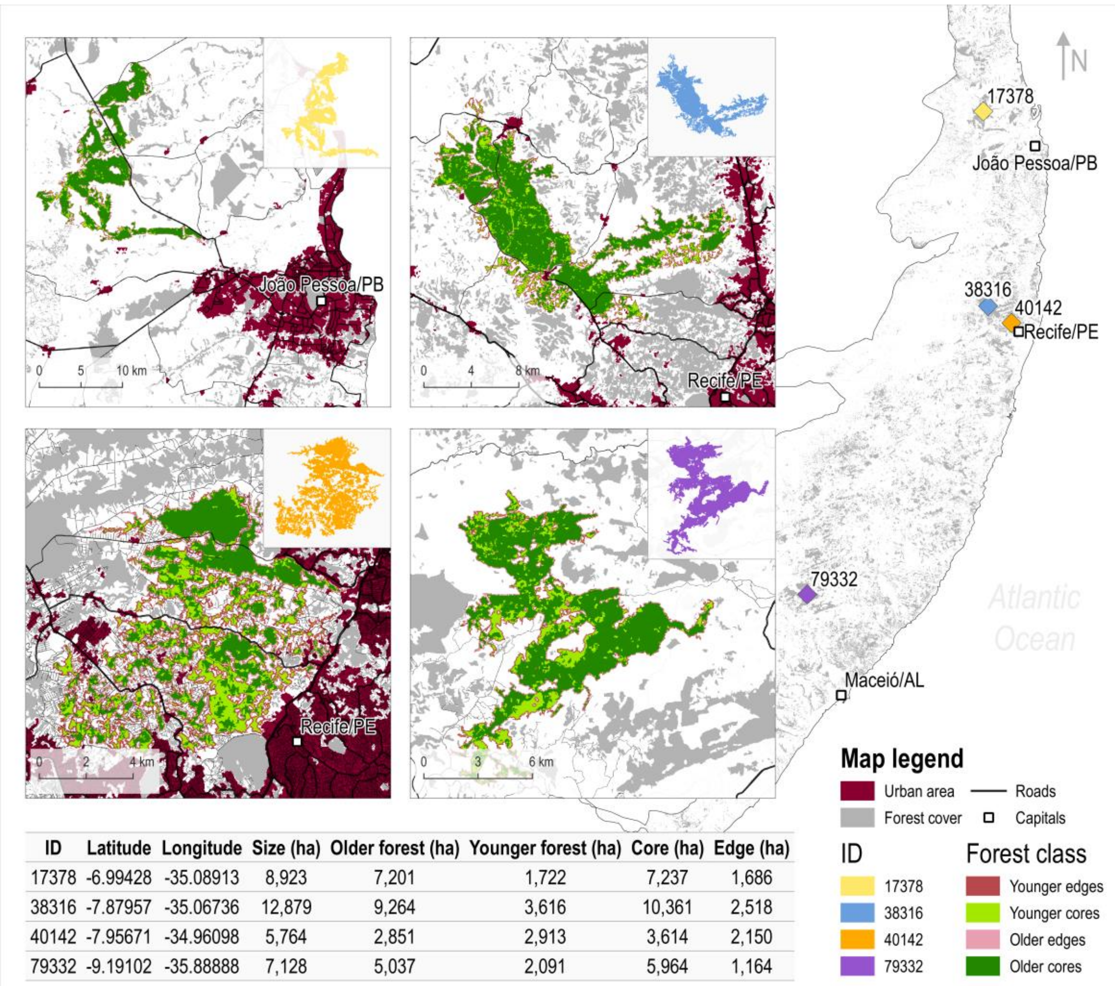


Figure 6. Current distribution of the forest cover and number of fragments of the Pernambuco Endemism Center according to its municipalities. Current status of the (A) total forest cover and (B) the numbers of fragments according to their sizes: very small (< 10 ha), small (10 – 100 ha), medium (100 – 1,000 ha), and large (> 1,000 ha), for each municipality of the Pernambuco Endemism Center. Fragments located in borders between municipalities were accounted for each of them. The identification of the municipalities is provided in the Figure 4.

The average size of the PEC's fragments was roughly 10.37 ha over the last decades and a significant increase was observed over time (0.11 ha/yr^{-1}, $R^2 = 0.68$; p-value < 0.001). The average size of the PEC's largest fragment over time was around 11,812 ha, and in 2020 the largest fragment was bigger than 14,000 ha for the first time since 1986. We identified four forest fragments larger than 5,000 ha in 2017, located in the states of Alagoas (ID 79332), Pernambuco (IDs 38316, 40142), and Paraíba (ID 17378) (Figure 7). The largest fragment identified in 2017 was ID 388316, located in Pernambuco state, with 12,897 ha (Figure 7). All fragments except ID 40142 were primarily composed by older forests that grew before 1985 (ID 79332: 71%; ID 40142: 49%; ID 38316: 72%; ID 17378: 81%) (Figure 7). In addition, ID 40142 also presented the lowest percentage of core area cover (63%). However, except for ID 79332, all fragments larger than 5,000 ha were located nearby roads and state capitals (Figure 7).



ID	Latitude	Longitude	Size (ha)	Older forest (ha)	Younger forest (ha)	Core (ha)	Edge (ha)
17378	-6.99428	-35.08913	8,923	7,201	1,722	7,237	1,686
38316	-7.87957	-35.06736	12,879	9,264	3,616	10,361	2,518
40142	-7.95671	-34.96098	5,764	2,851	2,913	3,614	2,150
79332	-9.19102	-35.88888	7,128	5,037	2,091	5,964	1,164

Figure 7. Largest forest fragments of the Pernambuco Endemism Center. Identification of the fragments larger than 5,000 ha in the year of 2017 over Pernambuco Endemism Center.

3.2. Identification of older and younger forests

We identified three municipalities in Alagoas state (Coruripe, Maceió, and Murici), three in Pernambuco (Água Preta, Abreu e Lima, and Igarassu), and two in Paraíba (Santa Rita and Rio Tinto) with more than 5,000 ha of older forests. In summary, we detected a current (2017) cover of 237,708 ha of older forests and 260,984 ha of younger forests (Figure S5).

3.3. Deforestation and forest regeneration

We identified the accumulated loss of more than 670,000 ha of forests in the PEC over the last decades (Figure 8A). The average annual deforestation rate was around 21,648 ha/yr^{-1}, and the highest losses were observed before the 1990s (1987: 95,198 ha; 1988: 55,486 ha; 1989: 51,595 ha) (Figure 8A). After the 2000s, deforestation rates were mainly below the average annual deforestation rate (Figure 8A). The deforestation rate of older forests was around 1,903 ha/yr^{-1} since 2000 and of younger forests was roughly 11,159 ha/yr^{-1} since 1987 (Figure 8A). Deforestation was more common in very small fragments; however, we detected evidence of losses of 20,138 ha in large fragments from 1987 to 1989 (Figure 8B).

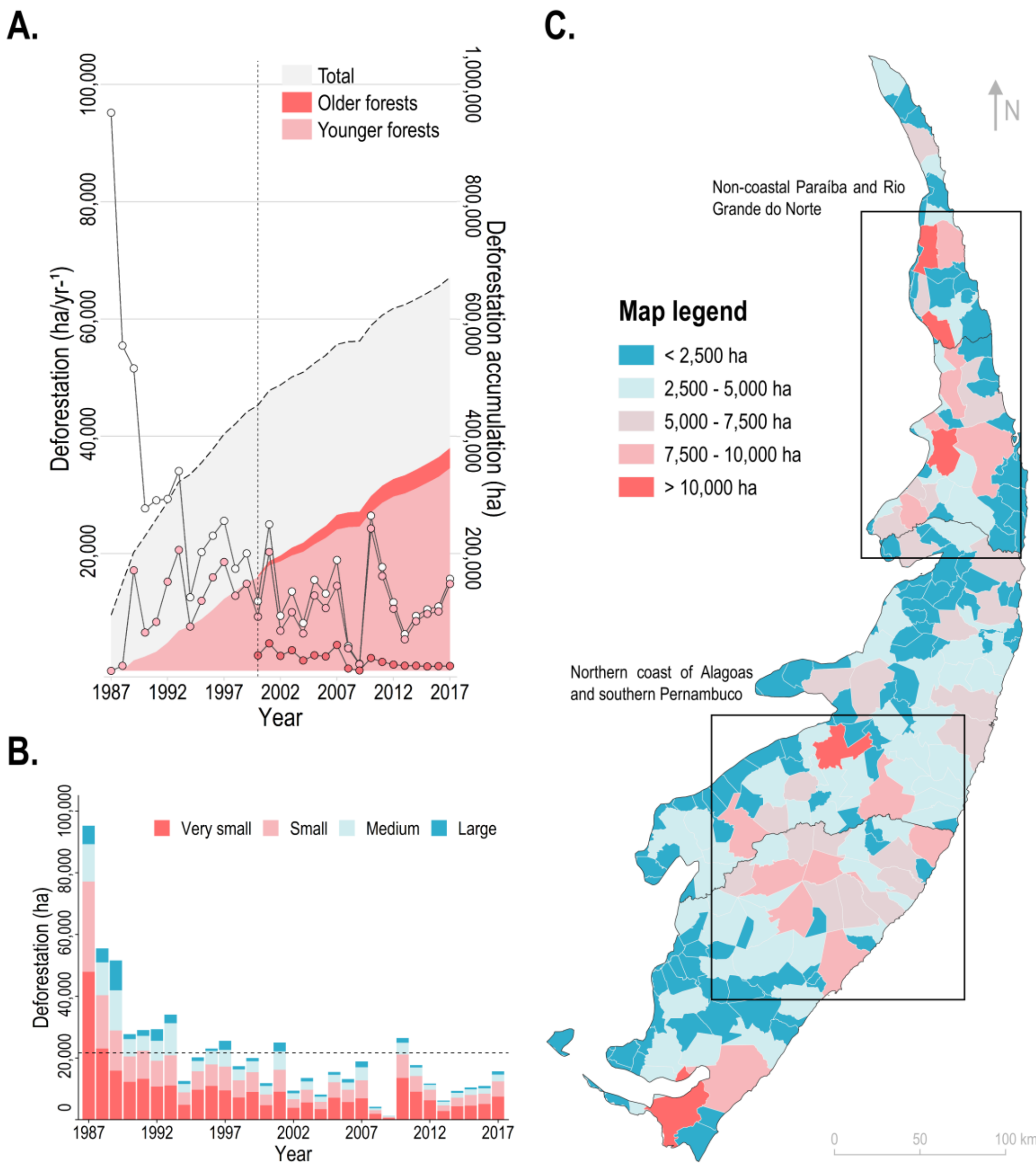


Figure 8. Forest losses over the last decades in the Pernambuco Endemism Center. Section A shows an overview of the annual deforestation rates (total, older, and younger forest losses) and the deforestation accumulation from 1987 to 2017. Section B display the losses in very small (< 10 ha), small (10 – 100 ha), medium (100 – 1,000 ha), and large (> 1,000 ha) fragments. The dotted horizontal line is the average annual deforestation rate. Section C shows an overview of the deforestation accumulation for each municipality of the PEC, from 1987 to 2017. The municipalities' identification is provided in Figure 4.

Five municipalities (Penedo/AL, Bonito/PE, Sapé/PB, Pedro Velho/RN, and São José de Mipibu/RN) lost over 10,000 ha of forests since the late 1980s (Figure 8C). Deforestation was largely concentrated in the municipalities near the borders between northern Alagoas and southern Pernambuco, and in a latitudinal gradient extending from the non-coastal PEC regions of Paraíba to middle Rio Grande do Norte (Figure 8C).

Over the last few decades, the PEC experienced the accumulation of 443,324 ha of forest regeneration, with an average annual rate of 14,301 ha/yr^{-1} (Figure 9A). In general, higher reforestation rates were detected during the first years of our time-lapse (Figure 9A). The municipalities of Maceió/AL, Bonito/PE and Cabo de Santo Agostinho/PE accumulated the highest forest regeneration rates since 1987 (Figure 9B).

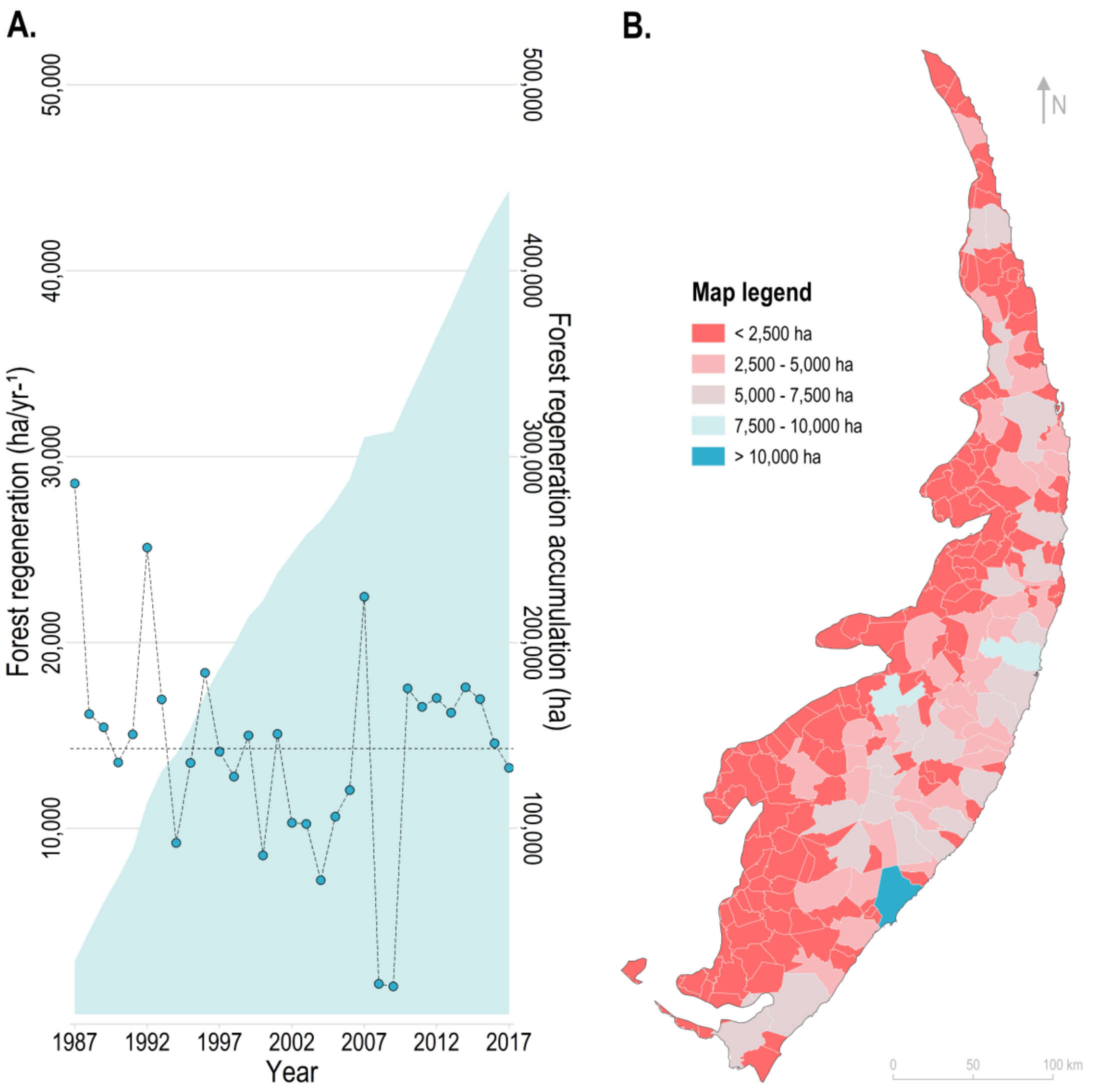


Figure 9. Forest regeneration over the last decades in the Pernambuco Endemism Center. Section A displays annual forest regeneration rates and the accumulation of forest gain over time. The dotted horizontal line represents the average annual forest regeneration rate. Section B shows the spatial

distribution of forest regeneration accumulation across the municipalities of the PEC. The municipalities' identification is provided in Figure 4.

3.4. Core and edge areas

On average, more than half of the PEC forest cover (53.6% ± 3.2%) was located within the first 50 m from the edge, with mean core and edge areas being around 211,615 ha and 245,314 ha, respectively. We found about 10% of increase in the proportion of core areas over our study period. Currently, the total forest cover represented by core and edge areas are 255,228 ha and 284,649 ha, respectively (Figure 10).

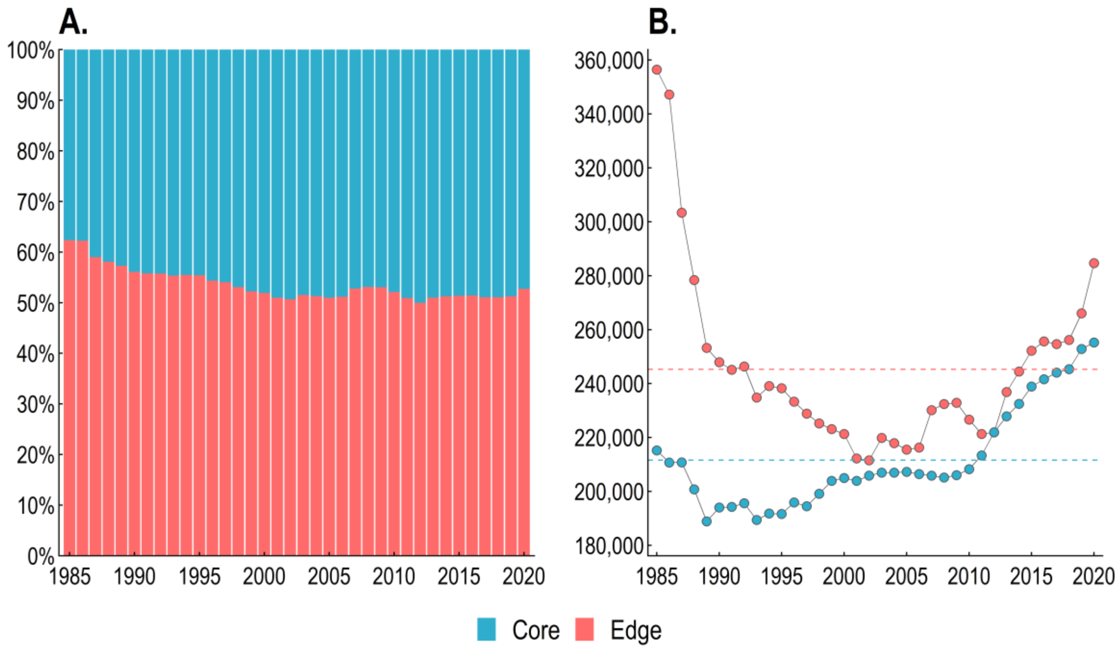


Figure 10. Changes in core and edge area over the forests of the Pernambuco Endemism Center from 1985 to 2020. Section A displays the variation in the percentage of forests composed of cores and edges over time. Section B shows changes in the area (ha) of cores and edges. The bluish and reddish horizontal dotted lines in Section B represent the average annual areas of cores and edges, respectively.

3.5. Forest quality

The amount of older forest cores in large fragments, which may represent the PEC's higher-quality habitats, was only about 62,058 ha in 2017, representing 12% of the total forest cover in that year (Table 2 and Figure S6).

Table 2. Area of the Atlantic Forest cover over the Pernambuco Endemism Center according to quality.

	Very small	Small	Medium	Large

Older forest cores	2,501 ha	33,692 ha	67,848 ha	62,058 ha
Younger forest cores	2,902 ha	21,79 ha	29,737 ha	18,775 ha
Older forest edges	11,319 ha	25,729 ha	21,284 ha	11,137 ha
Younger forest edges	47,805 ha	51,369 ha	34,601 ha	16,438 ha

Forest Area of older and younger forests distributed into cores and edges in very small (< 10 ha), small (10 – 100 ha), medium (100 – 1,000 ha), and large (> 1,000 ha) fragments of the Pernambuco Endemism Center in 2017.

4. Discussion

Our main finding is that a large portion of the PEC forests is threatened not only by fragmentation and edge effects but also by forest rejuvenation, with older forest cores in large fragments representing only 12% (62,058 ha) of the remaining (2017) forest cover. Temporal analyses revealed an overall reduction of around 5% in the total forest cover from 1985 to 2020, and the highest deforestation rates were found between 1985 and early 2000s. At least 87% of the 4.4 Mha of the original PEC forest cover was devastated before 1985, suggesting that most of its fragments may have been isolated for many decades or centuries. Although we observed a tendency for forest cover recuperation in the last two decades, it was insufficient to compensate for the losses that occurred in the decades of 1980 and 1990. Our estimate of the total remaining forest cover of the PEC was higher than previously reported, i.e., in 1990-1995 (256,581 ha) (MMA, 2000), 2005 (360,455 ha) (Ribeiro *et al.*, 2009), and 2001-2007 (322,372 ha) (Pontes *et al*., 2016). We suggest that it has occurred due to: i) the recuperation of part of the forests during the last decade, ii) differences in the data spatial resolution, iii) differences in the minimum size of fragments considered as forests, and iv) the use of more conservative methods for forest cover classification in the abovementioned studies. The situation observed in the PEC may also extend to other tropical forests in human-modified landscapes, and our results suggest the need for further investigations in tropical regions to characterize the degradation of these biodiverse ecosystems around the globe.

We observed a positive balance between forest regeneration and deforestation and a decrease in forest fragmentation in the last decade. This tendency may be related to the PEC's ongoing initiatives of forest restoration, linked to the Atlantic Forest Restoration Pact (Lins-e-Silva, Ferreira e Roda, 2021) and/or changes in practices of the sugar-cane industry in face of the increasing need for producing “environmentally correct” products since the 1990s (Tabarelli & Roda, 2005). However, this should not obscure the dramatic conservation status of the PEC forests. As expected, the drastic deforestation of the decades of 1980 and 1990, and the tendency of forest regeneration registered during the last decade, resulted in a process of forest rejuvenation about 2.5 times higher than that estimated for the whole Brazilian Atlantic Forest (Rosa *et al*., 2021). Despite the importance of secondary forests in maintaining a fraction of the original biological diversity in certain regions (Chazdon *et al*., 2009; Dent e Wright, 2009; Metzger *et al*., 2009), younger forests may not maintain high-quality habitats, and their ecological communities can be altered (Bihn *et al*., 2008; Pinho *et al*., 2018; Santos *et al*., 2008). In the PEC, areas that have been through restoration programs, for instance, were only a third as dense as older forest remnants and maintained considerably different tree communities, with only half of the original vegetal species richness (Santos-Costa *et al*., 2016).

It is also of great concern that the PEC forests are currently mainly distributed (roughly 90%) into very small fragments (< 10 ha), and that the average fragment size is only about 11 ha. This scenario is more pessimistic than that previously reports that informed that 73.3% of the PEC fragments were smaller than 10 ha (Pontes *et al*., 2016). Our findings were also more alarming than the previous estimates for the entire Brazilian Atlantic Forest, in which 80% of fragments were smaller than 50 ha (Ribeiro *et al*., 2009). The mean fragment size of the PEC was also smaller than the overall values observed for tropical forests (17 ha for the Americas and 13 ha for Asia and Australia) (Taubert *et al*., 2018).

Nowadays, only about 12% (62,058 ha) of the PEC forest cover is composed of higher-quality habitats (i.e., older forest cores in fragments larger than 1,000 ha). It is worth noting, however, that we considered as older, the forests present in 1985 not removed until 2017, meaning that we have not discriminated between the areas targeted to selective logging and those that could have regenerated just before 1985. Then, the amount of primary areas is certainly smaller than our estimate. This may be the reason why old-growth forests with full capacity of carbon storage represent only 8% of the total forest cover of the PEC (Dias *et al*., 2022; Paula, Costa e Tabarelli, 2011). Furthermore, we only evaluated edges effects within the first 50 m from the borders. However, forest-dwelling and niche specialized tropical species tend to be highly sensitive to edge effects, which can extend up to 400 m into the interior of tropical forests (Hansbauer *et al*., 2008; Laurance, 2008; Laurance *et al*., 2007; Lopes *et al*., 2009; Murcia, 1995; Pfeifer *et al*., 2017).

The scenario of intense forest rejuvenation and fragmentation highlights the importance of maintaining the last older core areas in larger fragments of the PEC to preserve taxa dependent on older forests to thrive and to serve as sources of biodiversity for the regenerating areas. We suggest that ensuring effective protection of these larger blocks of older forest cores, and increasing connectivity between these higher-quality habitats and their surrounding forests must be top priorities for the conservation of the PEC forest-dependent biodiversity. The increase in metrics related to habitat quality over the last decades may indicate a slight recovery of the native forest cover in the region, but forest rejuvenation, fragmentation, and edge effects are still undergoing threats to the PEC. Our results evidenced that forest cover information alone may provide a false scenario about the conservation status of the Brazilian Atlantic Forest. By addressing the temporal component and investigating the spatial characteristics of the fragments, we provide a more realistic scenario of the PEC's forest cover and more precise information for conservation practitioners and decision-makers.

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CAPÍTULO III.

Endemic and threatened birds as surrogates for identifying conservation priority areas and designing ecological corridors in America's most endangered habitat

Foto: Thiago C. Dias

Endemic and threatened birds as surrogates for identifying conservation priority areas and designing ecological corridors in America's most endangered habitat

Abstract

Investigating multi-taxa macroecological patterns could reveal key information on habitat requirements, distribution, and richness of the endangered species in biodiversity hotspots, therefore providing critical insights for spatial conservation and landscape management, and ultimately prevent species extinctions. The Pernambuco Endemism Center (PEC) is a biogeographic region of the Brazilian Atlantic Forest known to harbor the most threatened habitats of the Americas and a considerable number of bird extinctions. Here, we modeled the distribution of 30 endemic and endangered birds to reveal key habitats/resources for their survival, identify conservation priority areas, and design ecological corridors over the PEC. We found variation in responses of taxa for distinct landscape characteristics (between organisms and when grouping taxa by conservation status) and that environmental variables related to forest quality (e.g., distance to large fragments, distance to the forest edge, percentage of tree cover, percentage of older forests) were important predictors of habitat suitability for the regional endangered avifauna. Additionally, we revealed areas and forest fragments of high ecological importance for the PEC's threatened birds, and we propose the creation of the *Pernambuco Endemism Center Restoration Arc* (PEC-ARC) that may maximize the investments in conservation and guarantee the connectivity of crucial areas for long-term species survival.

Keywords: threatened species, biodiversity conservation, habitat selection, human-modified landscapes, Pernambuco Center of Endemism.

1. Introduction

Biodiversity has been lost at unprecedented rates because of anthropogenic activities. In the global scenario of intense degradation, tropical forests are of special concern (Hoang e Kanemoto, 2021; Roberts, Hamilton e Piperno, 2021) because they keep more than half of the world's known species, and average deforestation rates have been approximately 0.5% of the total area per year (Achard *et al*., 2002; Hoang e Kanemoto, 2021; Roberts, Hamilton e Piperno, 2021). In the face of the limited monetary resources to invest in conservation, identifying priority areas for conservation has been the most plausible way to preserve as much biodiversity as possible (Buchanan, Donald e Butchart, 2011; Myers *et al*., 2000). To achieve this purpose, different approaches have been proposed, often based on species diversity, beta diversity, levels of endemism, and on the presence of rare, threatened, or flag species (Mirzaei *et al*., 2017; Myers *et al*., 2000). Not rarely, however, reserve networks are simply delimited opportunistically in areas not suitable for agriculture (Politi *et al*., 2021), and in these cases, it is often not known whether they really represent the most ecologically relevant areas for the biodiversity of the target region (Prieto-Torres, Nori e Rojas-Soto, 2018).

In megadiverse habitats such as tropical forests, preserving all biodiversity in a target priority area is virtually impossible (Politi *et al*., 2021). Then, a reliable approach is delimiting areas for conservation based on the distribution of threatened taxa (Mirzaei *et al*., 2017; Politi *et al*., 2021). Because individual species can present specific habitat requirements, uncovering areas where the potential distributions of multiple endangered taxa overlap can optimize biodiversity conservation (Mirzaei *et al*., 2017; Politi *et al*., 2021). It means that adequate delimitations of effective conservation areas strongly rely on the knowledge of species distributions, but precise information is scarce for many taxa, especially for those inhabiting megadiverse tropical regions (Botero-Delgadillo *et al*., 2022; Carvalho *et al*., 2017; Dias-Silva *et al*., 2021; Politi *et al*., 2021). However, in the last decades, species distribution models (SDMs) have provided a tractable way to overcome this limitation (Botero-Delgadillo *et al*., 2022; de Carvalho *et al*., 2017; Dias-Silva *et al*., 2021; Guillera-Arroita *et al*., 2015; Guisan e Thuiller, 2005). These models mostly use climate, topographic, land-use, and vegetation characteristics data from points of confirmed occurrence of the taxa to estimate key habitat requirements, suitable areas, and their potential geographical distribution (He *et al*., 2015), being a paramount tool for conservation planning (Botero-Delgadillo *et al*., 2022; Carvalho *et al*., 2017; Dias-Silva *et al*., 2021).

When the regions under consideration are drastically disturbed and fragmented, the joint effect of connectivity also must be incorporated in conservation planning, as each independent area may not guarantee the long-term persistence of isolated populations and taxa with larger territorial requirements (Miranda *et al*., 2021; Fajardo *et al*., 2014; Prugh *et al*., 2008). Wildlife corridors contribute to organismal dispersal, promoting habitat recolonization and increasing gene flow, therefore reducing the risks of extinction due to demographic and genetic effects (Gregory e Beier, 2014; Kormann *et al*., 2016). For this reason, when natural corridors are not available, designing protected area networks that facilitate future habitat restoration and reconnections is advised (Santos *et al*., 2020; Santos *et al*., 2018). Because of the monetary costs for the creation and maintenance of corridors, their implementation must be planned using the accurate methods (LaPoint *et al*., 2013).

Many global initiatives to delimit key conservation areas have been proposed based on the occurrence of endemic and/or endangered organisms, such as the hotspots (Myers *et al*., 2000), or the IBAs (Important Bird Areas) for birds (Donald *et al*., 2019). For instance, Buchanan, Donald e Butchart (2011) used distribution information of forest-dependent birds to develop global maps of priority areas for conservation by attributing impact scores to 5 km cells of forested areas (Buchanan, Donald e Butchart, 2011). These scores were determined by the number of species occurring in a target cell (species with limited distribution affecting more) and by the potential impact of the cell loss on the conservation status of the world's forest-dwelling birds (Buchanan, Donald e Butchart, 2011). With this approach, they identified the Atlantic Forest as one of the ecoregions with the highest scores, also highlighting the importance of its northeastern portion (named Pernambuco coastal forests by the authors), ranked among the top 10 regions of special conservation concern for birds on Earth (Buchanan, Donald e Butchart, 2011).

Within the Atlantic Forest, the Pernambuco Endemism Center (PEC) is a biogeographic region in northeastern Brazil classified as a hotspot within a hotspot (Buchanan, Donald e Butchart, 2011; Lima *et al*., 2022; Prado *et al*., 2022a, b). The PEC was home to the modern global bird extinctions in Brazil (ICMBio, 2018; Pereira *et al*., 2014), and undocumented bird extinctions are somehow expected since new species have been recently described and promptly recommended to be listed as threatened (e.g., Alagoas Black-throated Trogon *Trogon muriciensis*) (Dickens *et al*., 2021). Currently, only about 12% of its original 44,000 km² has remained (Dias, Silveira e Francisco, 2023), and only a small portion is protected (Ribeiro *et al*., 2009). Of the total forest cover, more than 75% are distributed in fragments smaller than 10 km², roughly 90% of the fragments have less than 0.1 km², and about 12% of the remaining forests are higher-quality habitats (i.e., older forest cores in fragments larger than 10 km²) (Dias, Silveira e Francisco, 2023).

The dramatic level of fragmentation of the PEC's forests (Dias, Silveira e Francisco, 2023; Ribeiro *et al*., 2009) suggests that the persistence of its forest-dependent avifauna will not rely only on the identification and protection of key conservation areas (e.g., Pereira *et al*., 2014, 2016). Indeed, more energetic conservation actions such as large-scale forest restoration and ecological corridor planning are urgently needed. This region has been considered within the Atlantic Forest hotspot and the Pernambuco coastal forests are placed among the highest-ranked conservation priority areas in the world (Buchanan, Donald e Butchart, 2011; Myers *et al*., 2000). Additionally, one of the PEC's conservation unities (Murici Ecological Station) has been recognized as an IBA by Birdlife International due to the presence of critically endangered taxa. However, the identification of key conservation areas and the systematic planning of reserve networks based on accurate methods and criteria were never performed for the PEC.

Here, we reveal novel insights for spatial conservation planning over the PEC based on its endemic and endangered avifauna, demonstrating the usefulness of ensemble SDMs for identifying the habitat requirements, distribution, and richness of its birds. The products from SDMs were used to calculate the area of suitable landscapes and forests for each bird taxa, as well as the area of suitable habitats located within protected areas. We lastly used spatially-explicit proxies of the probability of occurrence for each taxon from the SDMs together with landscape information to identify conservation priority areas and plan reserve networks capable of increasing landscape connectivity through forest restoration initiatives. The outcomes of our study could potentially make a significant contribution to conservation efforts over the PEC and guide landscape management for preventing future biodiversity losses.

2. Methods

2.1. Study area

The PEC is a biogeographic region of the northeastern Brazilian Atlantic Forest, located north of the São Francisco River. Four major waves of deforestation were responsible for the removal of almost 90% of the PEC Atlantic Forest cover during the last centuries (Dias, Silveira e Francisco, 2023; Lins-e-Silva, Ferreira e Rodal, 2021). The remaining forests are currently threatened by fragmentation (roughly 90% of the fragments are smaller than 0.1 km²), edge effects (more than 50% of the forests are within the first 50 m from the border), and rejuvenation (only half of the forests are older than 35 years) (Dias, Silveira e Francisco, 2023). Alarmingly, estimates pointed out that roughly 12% of the remaining forests of the PEC are represented by higher quality habitats (i.e., older forest cores in large fragments) (Dias, Silveira e Francisco, 2023), and that only 8% of the forests show full capacity of carbon storage (Paula, Costa e Tabarelli, 2011; Dias *et al*., 2022).

We generate a 0.5-degree buffer around the entire Atlantic Forest coverage north from the São Francisco River to define our study area (Muylaert *et al*., 2018). We choose to include the "Brejos de Altitude" in our region of interest, a set of altitudinal forests (Pereira *et al*., 2020), due to the imminent importance of these enclaves to endangered and endemic birds of the PEC (Oliveira-Silva *et al*., 2021), taking into account potential regions of high ecological importance nearby the PEC borders (Lima *et al*., 2023).

2.2. Occurrence dataset

We downloaded occurrence data for 34 endangered bird taxa occurring in the PEC, all forest dependents (Table S4). All birds except *Conopophaga cearae* are endemic to the PEC. Taxa occurrence data were downloaded from the specimens housed at Museu de Zoologia da Universidade de São Paulo (MZUSP), the Global Biodiversity Information Facility – GBIF (https://www.gbif.org), ATLANTIC BIRDS dataset (Hasui *et al*., 2018), and from the Brazilian Biodiversity Extinction Risk Assessment System – SALVE (ICMBio, 2022). GBIF represents the largest and most widely used biodiversity dataset of species occurrence in the world (Luo *et al*., 2021). ATLANTIC BIRDS is the most complete dataset on Brazilian Atlantic Forest birds' occurrences, which compiled unpublished reports and published data from museum collections, literature, and other online data sources (Hasui *et al*., 2018). The SALVE system is a consolidated database developed by the Chico Mendes Institute for Biodiversity Conservation – ICMBio to facilitate the process of extinction risk assessment of Brazilian species (ICMBio, 2022). Taxa were searched by their scientific names and protonyms, and in the case of subspecies, we also searched for the full-species name. We assessed and downloaded GBIF data using the *'rgbif'* package (Chamberlain *et al*., 2017) in R environment (R Core Team, 2009), ATLANTIC BIRDS dataset via Supplementary Material of Hasui *et al*. (2018), and SALVE data from https://sicae.sisicmbio.icmbio.gov.br/.

Using the *'CoordinateCleaner'* package (Zizka *et al*., 2019) in R, we applied the automated cleaning framework to filter our mixed dataset (Zizka *et al*., 2019, 2020). We first removed occurrences with no coordinates, within marine areas, coordinate-country mismatches, occurrences assigned to political units' centroids (country, state, and municipality), outlier coordinates, and coordinates assigned to research institutions. We also removed data with low coordinate precision (larger than 1 km due to the spatial resolution of the environmental variables used for SDMs), individual counts smaller than one and larger than 99, and data collected before 1945 (we only kept data after the end of the Second World War due to the common imprecision of old records). We choose not to remove presence data with missing information on coordinate precision, individual count, and year of record. Occurrences outside our study area and in non-vegetated areas (according to the 2020 land use and land cover layer from MapBiomas) (MapBiomas, 2022) were also removed. Lastly, for each taxon, spatial duplicates were removed, and coordinates within 1 km from each other were deleted prioritizing the most recent occurrence in a 1 km buffer to minimize spatial autocorrelation. After this process, organisms with less than five occurrences were removed from further analysis, which resulted in a list of 30 from the 34 original taxa.

2.3. Environmental variables

We used Google Earth Engine (Gorelick *et al*., 2017) to assess and generate 31 environmental variables representative of the PEC's terrain, climate, forest cover, biomass, human impacts, and water bodies (Table S5). For variables related to the PEC forest cover, we first assessed and downloaded the 2020 MapBiomas land use and land cover layer (MapBiomas, 2022) using Google Earth Engine and used the '*bfastspatial*' package (Dutrieux e DeVries, 2014) in R to calculate fragment size and to assign them individual identification numbers. All layers were rescaled to 1 km spatial resolution and we assessed correlation using Pearson's correlation test and removed variables with r > 0.7 (Oliveira-Silva *et al*., 2022; Ramírez-Albores *et al*., 2021) (Figure S7). Multicolinearity was then assessed using the Variation Inflation Factor (VIF), and we continuously removed less important variables (based on their ecological relevance) until all variables showed VIF < 5 (Colyn *et al*., 2020; Ranjitkar *et al*., 2014; Rogerson, 2001) (Table S6). After this procedure, 17 variables were kept for modeling species distribution: distEdge, distLargeForests, distMediumForests, distProtArea, distRoads, distWater, elevation, gHM, maxEVI, minEVI, mTPI, percAgropastoral, percOldForest, precSeason, slope, tempRange, and treeCover (see Appendix S7 for the full description of the variables).

2.4. Species distribution modeling

Due to the great availability of algorithms used for modeling species distribution and the variation in their predictive performance across species, regions, and applications, authors have suggested that combining predictions from different models (ensemble modeling) may be useful and produce more reliable results (Hao *et al*., 2019). We modeled endemic and endangered bird taxa distribution using the *'biomod2'* package (Thuiller *et al*., 2016) in R to build ensembles of SDMs. We built models using five widely-used algorithms (generalized linear models – GLM, generalized boosted models – GBM, classification tree analysis – CTA, artificial neural networks – ANN, and maximum entropy – MAXENT), chosen due its advantages in terms of optimizing models with a high predictive performance while reducing computation time (Breiner *et al*., 2018). For each taxon, we created three random sets of pseudo-absences with 10,000 background points, generated with a minimum point-to-point distance of 1 km (Almasieh, Mohammadi e Alvandi, 2022; Barbet-Massin *et al*., 2012; Scherrer, Christe e Guisan, 2019). Occurrences and background points were equally down-weighted by setting the prevalence parameter to 0.5 (Scherrer, Christe e Guisan, 2019). We ran 100 replications using 80% of data for calibration and 20% for evaluation (random sets of calibration and evaluation points were used in each replication), totalizing 1,500 models for each taxon (3 sets of pseudo-absences x 5 algorithms x 100 replications). These models were individually evaluated based on the True Statistic Skill (TSS) and the Receiver Operating-Characteristic (ROC).

The final ensemble models were built by calculating the proportionally weighted sum of probabilities (weights were attributed proportionally to the value of the evaluation score TSS) across predictions of models with TSS > 0.8 (Leta *et al*., 2019). From the ensemble models, we extracted the (i) variables' importance, (ii) response curves for the environmental variables, (iii) habitat suitability layers, (iv) binary layers representatives of the taxa distribution, (v) area of the suitable landscape, suitable forests using the MapBiomas land use and land cover layer (MapBiomas, 2022), and distribution within protected areas using the World Database on Protected Areas – WDPA (UNEP-WCMC e IUCN, 2023), and (vi) layers on the endemic and/or endangered birds' alpha diversity (α-diversity), generated by summing all binary occurrence layers. When convenient, results were aggregated by taxa conservation status into Data Deficient (DD), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR) (ICMBio, 2018; MMA, 2022).

2.5. Conservation Priority Areas (CPAs)

We used Zonation 5 v1.0 (Moilanen *et al*., 2022) to identify Conservation Priority Areas (CPAs) through a hierarchical-driven approach. This software implements an analysis that first assumes that all cells over the landscape must be prioritized for conservation and then it removes pixels gradually based on the least overall loss for biodiversity subject to what remains in the environment (Jalkanen, Toivonen e Moilanen, 2020; Nori *et al*., 2016). We performed the identification of CPAs based on the Core Area Zonation rule for pixel removal (CAZ1), which assigns higher values to areas where highly-weighted taxa occur (Moilanen *et al*., 2022).

We included the habitat suitability layers in Zonation by first assigning zero to all non-occurrence pixels (below the individual TSS threshold) based on the binary occurrence layers from the ensemble modeling. Those layers were then weighted according to the taxon conservation status (Data deficient [DD] = 1, Vulnerable [VU] = 2, Endangered [EN] = 3, and Critically Endangered [CR] = 4) (Lehtomäki *et al*., 2019; Ramírez-Albores *et al*., 2021; Taylor *et al*., 2017). We also included the Global Human Modification (gHM) layer (Kennedy *et al*., 2019) as a proxy of the landscape ecological condition, penalizing pixels in regions of higher human influence (Lehtomäki *et al*., 2019; Nori *et al*., 2016) since they may represent areas of low conservation concern for the PEC's avifauna, as well as built-up areas.

Finally, we merged the World Database on Protected Areas – WDPA (UNEP-WCMC e IUCN, 2023) to a buffer of 1 km around the coordinates of each federal and state private reserve of natural heritage (RPPNs) in the PEC (for IDs of protected areas, see Table S7). Protected areas were then included as a hierarchical mask in our analysis, forcing Zonation to take into account the pre-existence of protected areas and then include non-protected cells of ecological importance to generate the CPAs (Ramírez-Albores *et al*., 2021).

2.6. Corridor planning

We used the Linkage Pathways Tool from the Linkage Mapper Toolbox in ArcGIS (McRae e Kavanagh, 2011) for proposing ecological corridors to connect forest fragments of high conservation value for the PEC's endemic and endangered avifauna. This tool generates the least-cost pathways between pre-determined areas by taking into account the surface resistance to animal movement/dispersal (Gallo e Greene, 2018). For the definition of the areas to be connected, we first used the 2020 land use and land cover layer from MapBiomas (MapBiomas, 2022) to select Atlantic Forest fragments larger than 1111 pixels (approximately 1 km²), since the larger fragments may present higher species richness (Giraudo *et al*., 2008). For each of these fragments, we extracted the mean value derived from the Zonation rank map and removed all fragments with values lower than 0.95. The final Conservation Priority Fragments (CPFs) layer was composed of fragments larger than 1 km² with an average conservation priority value > 95%.

After the identification of CPFs, we generated a resistance surface layer for corridor modeling by considering landscape features and the responses of bird taxa to the PEC environment. We used five layers representative of landscape features, which were rescaled to range from 0 (non-resistance) to 1 (maximum resistance). The first layer represents the Atlantic Forest fragments from the 2020 MapBiomas land use and land cover (MapBiomas, 2022) (zero resistance = forest, one resistance = non-forest). The second was the rescaled inverse of the tree canopy coverage (Sexton *et al*., 2013) (higher resistances for lower tree cover). We also calculated the Euclidean distance to Atlantic Forest fragments and assigned higher resistances to areas further from forest patches. To prioritize corridors that would ensure the restoration of the existing legal debt of the PEC's Atlantic Forest, we generated a layer with resistance values set to zero in riparian areas of permanent preservation (APPs) without forests, and to one the areas outside or within APPs but already filled with forests (Rezende *et al*., 2018). We lastly added a proxy of barriers (water bodies from the National Water and Sanitation Agency – ANA, and roads from Brazil's National Transport Infrastructure Department - DNIT) to taxa movement across the PEC (resistance in barriers set to one, and in all other features of the landscape set to zero). The final landscape resistance layer was obtained by calculating the mean of the five abovementioned layers.

Posterior to calculating landscape resistance, we generated resistance layers according to taxa responses to the environment by applying the following equation to habitat suitability layers (hs) derived from the ensemble SDMs (Tobgay e Mahavik, 2020):

$$\left(\left(hs - max(hs)\right) * -1\right) + \min(hs)$$

Habitat-suitability models were known to produce better results in generating resistance surfaces when compared, for example, to experts' opinions (Milanesi *et al*., 2017). All bird taxa resistance layers were then averaged. Lastly, landscape resistance and taxa resistance layers were summed and divided by two to obtain the final resistance layer, which was included in the Linkage Pathways Tool for corridor planning. We lastly calculated the cost-weighted distance/corridor length (CWD/CL) ratio as a proxy of the adversity for bird taxa to disperse and landscape resistance to forest restoration through the proposed corridors (Proctor *et al*., 2015).

3. Results

Ensemble models showed higher accuracy than other single algorithms in predicting bird taxa and habitat relationships over the PEC (Table S8), with TSS accuracies (using testing data) ranging from 0.85 to 1 (Table S8). The variables distance to large fragments, distance to the forest edge, and percentage of tree cover were on average the most important in predicting endangered and endemic bird distribution across the PEC ($\bar{x} = 0.55$, $\bar{x} = 0.08$, and $\bar{x} = 0.08$, respectively). We additionally detected variation in variable importance according to taxa conservation status, with distance to large fragments, percentage of older forests, and percentage of agropastoral matrix disproportionally affecting Critically Endangered taxa (Figure 11).

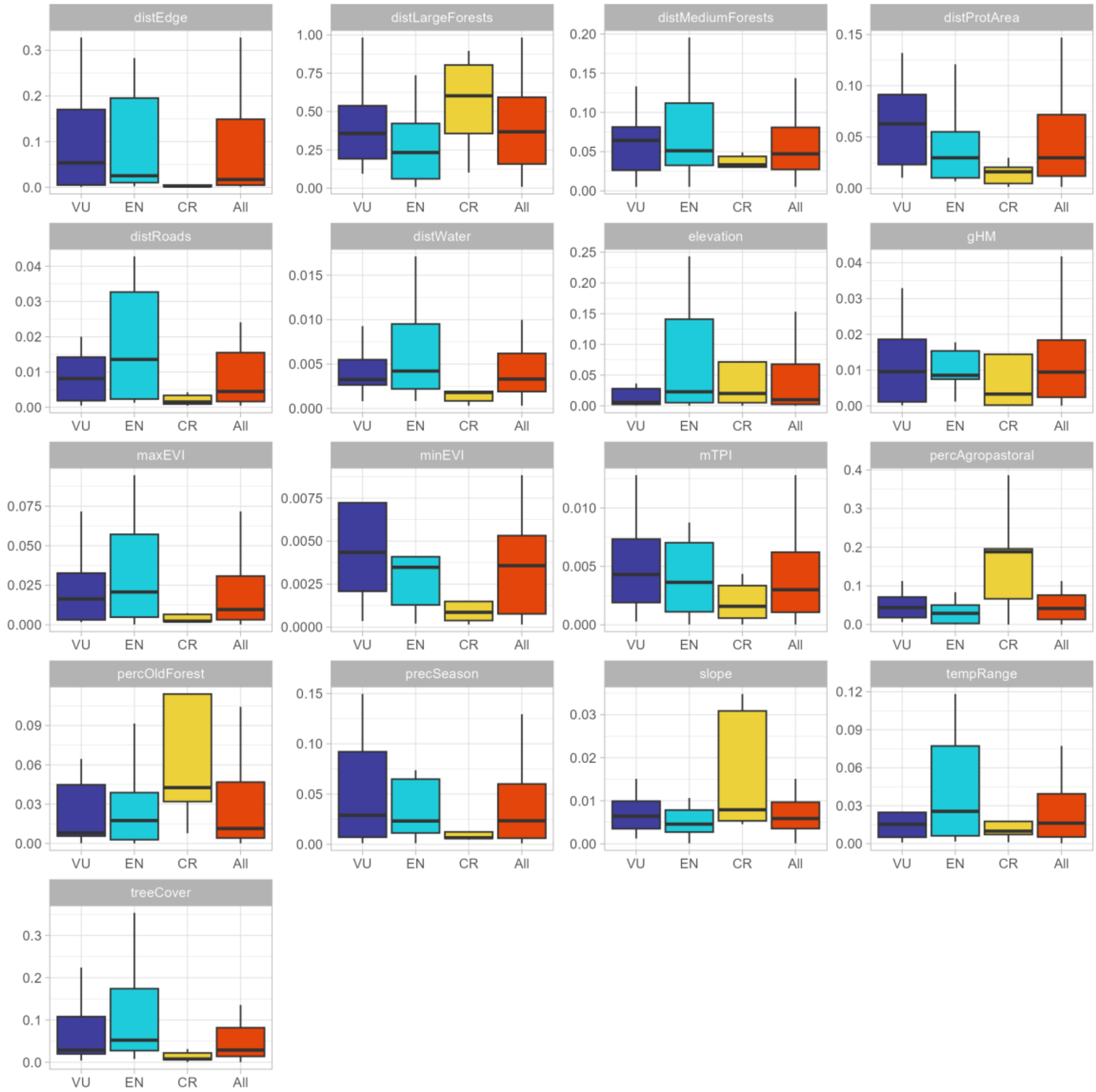

Figure 11. Total and cross-conservation status variable importance for the assemblage of endangered and endemic birds of the Pernambuco Endemism Center (PEC). Critically Endangered = CR, Endangered = EN, and Vulnerable = VU. Results for Data Deficient (DD) taxa were not shown since this group was only represented by *Hemithraupis flavicollis melanoxantha*.

We found consistent tendencies of habitat selection for the overall bird assemblage of the PEC and cross-conservation status (Figure 12). Higher suitability was found inside and nearby large fragments, with higher percentages of tree cover and small variations in temperature across the year, mostly steep and away from roads (Figure 12). However, Critically Endangered taxa showed higher preferences for landscapes with larger concentrations of older forests (Figure 12).

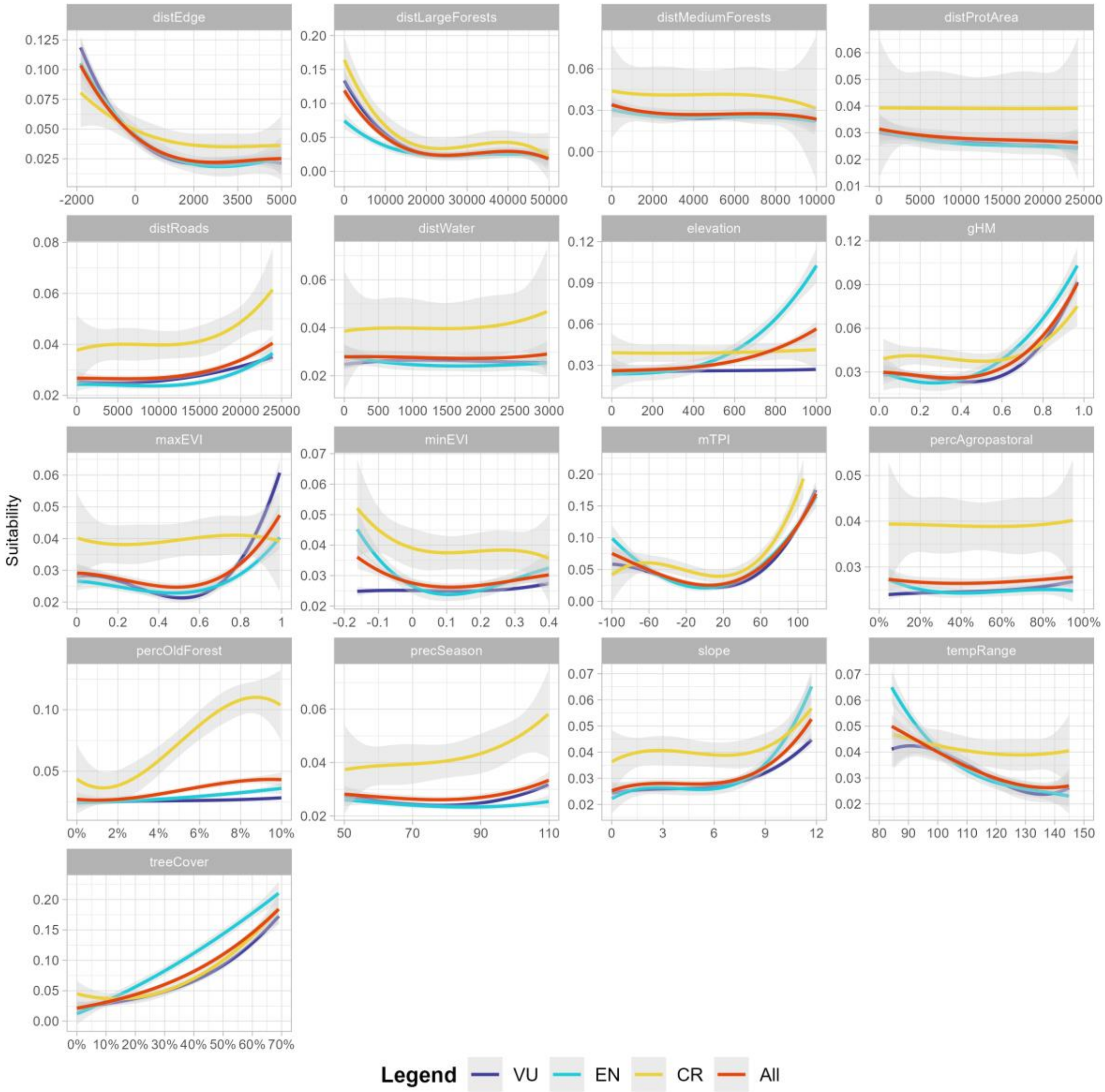

Figure 12. Overall and grouped by conservation status response curves of endangered and endemic bird taxa of the Pernambuco Endemism Center (PEC) in the northeastern portion of the Brazilian Atlantic Forest for 17 environmental variables. Critically Endangered = CR, Endangered = EN, and Vulnerable = VU. Results for Data Deficient (DD) taxa were not shown since this group was only represented by *Hemithraupis flavicollis melanoxantha*.

Consistent patterns on the remaining area of landscape and forests suitable for taxa persistence were found to exist over distinct threat categories. Our results demonstrated that highly threatened taxa were more likely to have reduced landscape and forests available over the PEC. On average, the avifauna had 10,556 km² of suitable landscape (protected = 403 km², unprotected = 10,153 km²), composed by 2,855 km² of suitable forests (protected = 170 km², unprotected = 2,685 km²). The average suitable landscape available for Critically Endangered (CR) taxa was therefore much smaller (remaining = 4,853 km², protected = 186 km², unprotected = 4,667 km²), with roughly 1,360 km² of forests (protected = 102 km², unprotected = 1258 km²) fitting their habitat requirements. The taxa found to have less available habitat were *Iodopleura pipra leucopygia* (suitable landscape = 42 km², suitable forests = 37 km²) and *Megascops alagoensis* (suitable landscape = 76 km², suitable forests = 61 km²) (Table 3). Generally, all birds have relatively small areas of suitable forests protected (Table 3).

Table 3. Remaining habitat (km²) for 30 endemic and endangered birds of the Pernambuco Endemism Center (PEC), in the northeastern portion of the Brazilian Atlantic Forest.

Taxa	Suit. Land.	Suit. For.	Suit. Land. Prot.	Suit. For. Prot.	Suit. Land. Unprot.	Suit. For. Unprot.	Cons. status
Automolus lammi	3,738	1,617	192	126	3,546	1,491	EN
Caryothraustes brasiliensis (NE pop.)	2,403	901	75	52	2,328	849	VU
Cercomacroides laeta sabinoi	3,855	1,812	199	137	3,656	1,674	VU
Conopophaga cearae	4,965	2,046	210	128	4,755	1,918	EN
Conopophaga melanops nigrifrons	10,337	3,009	497	199	9,840	2,811	VU
Dendrocincla taunayi	494	368	81	69	413	298	EN
Hemithraupis flavicollis melanoxantha	1,463	672	116	78	1,347	594	DD
Hemitriccus griseipectus naumburgae	8,063	2,807	476	219	7,587	2,588	VU
Hemitriccus mirandae	1,794	538	119	66	1,675	472	EN
Iodopleura pipra leucopygia	42	37	31	29	11	8.7	EN
Leptodon forbesi	10,447	3,208	450	198	9,997	3,010	EN
Megascops alagoensis	76	61	17	15	59	46	CR
Momotus momota marcgravianus	2,420	1,236	186	118	2,234	1,119	EN
Myrmoderus ruficauda soror	3,140	1,286	211	134	2,929	1,152	EN
Myrmotherula snowi	744	314	114	84	630	230	CR
Penelope superciliaris alagoensis	10,028	3,284	302	152	9,726	3,132	CR
Phylloscartes ceciliae	2,742	820	123	93	2,619	727	CR
Picumnus pernambucensis	17,501	5,049	791	293	16,710	4,756	VU
Platyrinchus mystaceus niveigularis	24,771	5,753	744	286	24,027	5,467	VU
Pyriglena pernambucensis	16,906	4,394	482	191	16,424	4,203	VU
Schiffornis turdina intermedia	22,944	4,943	769	231	22,175	4,712	VU
Synallaxis infuscata	19,604	4,542	462	196	19,142	4,346	EN
Tangara cyanocephala cearensis	16,409	4,312	393	192	16,016	4,120	VU
Tangara fastuosa	19,582	5,005	786	281	18,796	4,723	VU
Terenura sicki	10,675	2,320	375	166	10,300	2,154	CR
Thalurania watertonii	21,415	5,251	764	274	20,651	4,977	EN
Thamnophilus aethiops distans	14,607	3,961	334	189	14,273	3,772	EN
Thamnophilus caerulescens pernambucensis	24,004	5,182	778	264	23,226	4,918	VU
Xenops minutus alagoanus	23,207	5,508	1,097	312	22,110	5,197	VU
Xiphorhynchus atlanticus	18,307	5,399	923	316	17,384	5,084	VU

Legend: Suit. = Suitable, Land. = Landscape, For. = Forest, Prot. = Protected, Unprot. = Unprotected, Cons. = Conservation.

The highest alpha-diversity areas for endangered and endemic birds of the PEC were found to be concentrated in isolated patches, mostly close to the eastern continental border where Atlantic Forest fragments are concentrated (Figure 13). Areas of higher alpha-diversity of Critically Endangered taxa were found between the states of Alagoas and Pernambuco, specifically close to the Murici Ecological Station, RPPN Vila d'Água, RPPN Boa Sorte, Pedra Talhada Biological Reserve, RPPN Pedra d'Antas, and RPPN Frei Caneca (Figure 13).

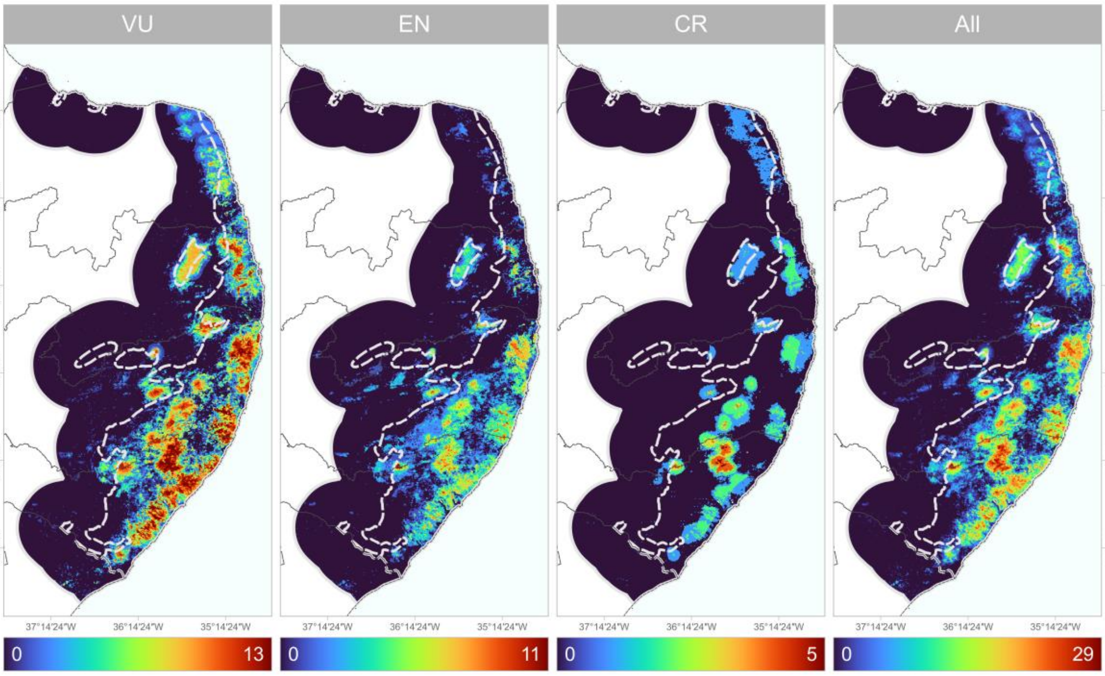

Figure 13. Spatially-explicit patterns of endemic and/or endangered bird taxa alpha diversity (α-diversity) over the Pernambuco Endemism Center (PEC), in the northeastern portion of the Brazilian Atlantic Forest.

We identified that the larger CPAs were distributed along Alagoas and Pernambuco states, but some small portions of high conservation value were also found for Paraíba and Rio Grande do Norte (Figure 14). The portion close to and north of the Murici Ecological Station was the largest conglomerate of high conservation priority found for the entire PEC (Figure 14). Within the CPAs, it was also possible to identify 262 forest patches that were classified as CPFs (> 10 km², conservation priority rank > 0.95) (Figure 14). The CPFs with the highest rank (> 0.99) were mostly located within protected areas, but several fragments with high conservation values (0.95 – 0.99) were located outside protected areas (Figure 14). We propose the creation of 638 ecological corridors between the 262 CPFs, ranging in length from 42 m to about 200 km ($\overline{x}$ = 9.62 km). The CWD/CL ratio ranged from 0.33 to 0.74 ($\overline{x}$ = 0.54). In general, corridors with a high CWD/CL ratio were found for the connection between CPFs close to each other, especially for those close to the Murici Ecological Station and its northern portions (Figure 14).

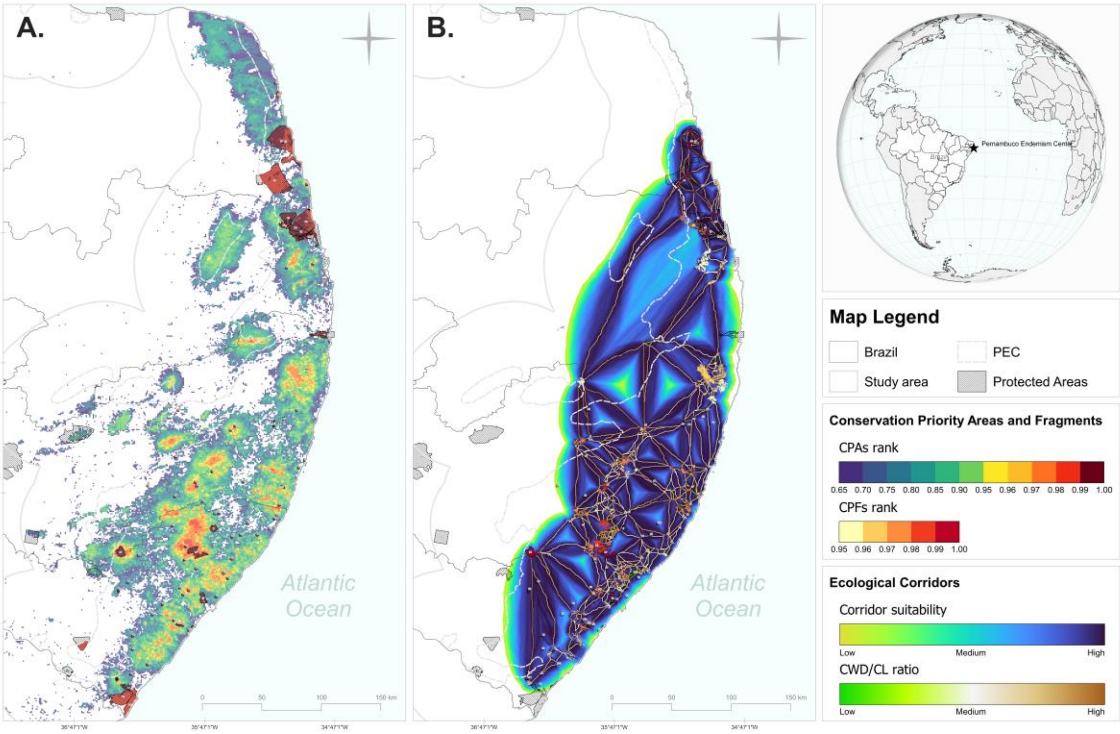

Figure 14. Spatial distribution of (A) Conservation Priority Areas (CPAs), (B) Conservation Priority Fragments (CPFs), and ecological corridors proposed for endangered and endemic bird taxa of the Pernambuco Endemism Center (PEC). For the IDs of protected areas, see Table S7.

Six complexes with conglomerates of CPFs were identified, within which we detected corridors with low CWD/CL ratios (Maceió, Murici, Serra Grande, Pedra Talhada, Pedra D'Antas, and Saltinho) (Figure 15). On a broader spatial scale, we unrevealed an arc-shaped area suitable for future restoration actions to increase connectivity that involved five out of the six complexes, which we named *Pernambuco Endemism Center Restoration Arc* (PEC-ARC) (Figure 15).

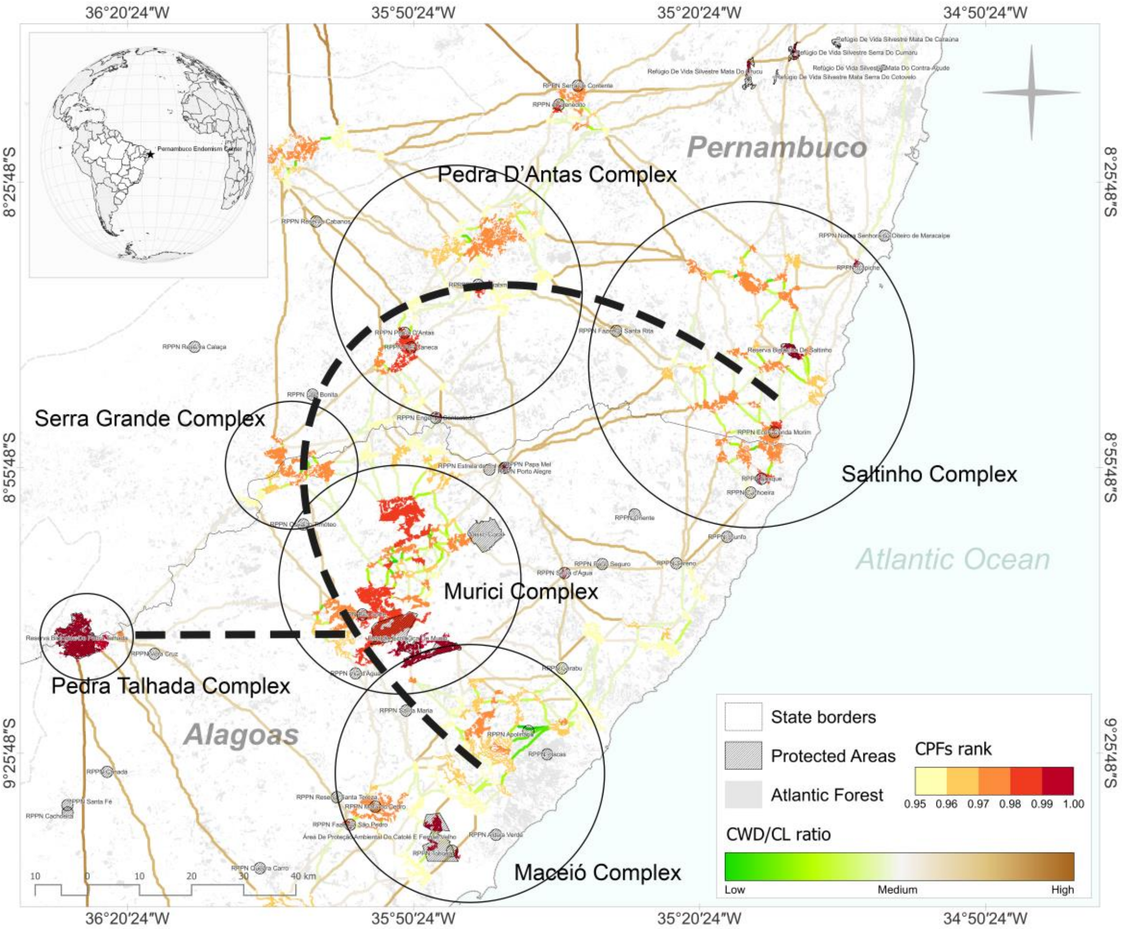

Figure 15. Identification of the *Pernambuco Endemism Center Restoration Arc* (PEC-ARC) with six complexes of Conservation Priority Fragments (CPFs) and corridors with relatively low CWD/CL ratios. Five complexes (Maceió, Murici, Serra Grande, Pedra D'Antas, and Saltinho) show an arc-shaped distribution along northeastern Alagoas and southern Pernambuco states. The connection between Pedra Talhada and Murici complexes is highlighted due to the large forest patches and high conservation importance over these regions. For the IDs of protected areas, see Table S7.

4. Discussion

Ensemble modeling showed overall high accuracy in predicting endangered and endemic bird taxa distribution across the PEC, a region where a catastrophic wave of bird extinctions is expected to occur unless urgent conservation actions are developed. Landscape features related to forest quality (e.g., distance to edge, percentage of tree cover, and distance to large fragments) were important predictors of habitat suitability for the PEC birds. Higher occupancy probability was generally related to large forest fragments with increased tree cover. Critically Endangered taxa showed relatively higher preferences for areas where older forests were more abundant. It was also possible to identify key areas for bird conservation over the PEC and to propose ecological corridors for reducing the effects of habitat fragmentation, therefore increasing organismal movement and gene flow. We highlight the importance of the Murici Ecological Station, Pedra Talhada Biological Reserve (Pereira, Araújo e Azevedo-Júnior, 2016) and its adjacent areas as bird-diverse regions of top conservation priority, and highlight the importance of protecting key habitats while increasing connectivity inside the six complexes of CPFs and between them through the implementation of large-scale forest restoration programs over the *Pernambuco Endemism Center Restoration Arc* (PEC-ARC).

Forest characteristics had a large impact in predicting avifauna distribution throughout the PEC, which was somehow expected since the endemic and endangered bird taxa of the region are mostly forest-dependent (Lima *et al*., 2022; Pereira *et al*., 2014; Silveira, Olmos e Long, 2003). However, with our analyses, we revealed the forest attributes with a higher impact on bird distribution, with an overall higher selection for forest cores in large fragments with a higher percentage of tree cover. Large fragments and older forests disproportionally affected the presence of Critically Endangered taxa over the PEC, and their persistence in the future may rely on the protection of large forest remnants mostly composed of older vegetation. This may be challenging since older forest cores in large fragments represent only 12% of the current PEC forest cover, and they are severely fragmented (Dias, Silveira e Francisco, 2023).

Most of the suitable landscapes and forests available for the PEC birds are currently unprotected, and we found that taxa listed under higher threat categories have less suitable areas. The birds with lower availability of suitable landscapes and forests may also be prioritized in conservation planning, since they may be more susceptible to extinction due to the restricted distribution of suitable habitats (Chen, Chuanwu *et al*., 2019; Garcia-R e Marco, 2020; Vale *et al*., 2018). Our findings reinforce the importance of ensuring legal protection of high-quality habitats for birds, and, since the majority of the PEC's forests are currently not in public lands (Lins-e-Silva, Ferreira e Rodal, 2021), encouraging the creation of Private Reserves of Natural Heritage may be of urgently needed in the region, especially in areas with suitable forests for Critically Endangered taxa and/or high bird diversity.

Despite being an important conservation action for the PEC, habitat protection alone may be insufficient to prevent future losses of Atlantic Forest birds (Pizo e Tonetti, 2020). For forest-dependent birds, active and passive ecological restoration may be a fundamental instrument for increasing landscape connectivity, therefore improving organismal movement, recolonization, and gene flow (Gregory e Beier, 2014; Kormann *et al*., 2016). Considering the response of birds and landscape features, we identified the *Pernambuco Endemism Center Restoration Arc* (PEC-ARC) where active management aiming at increasing forest connectivity may be especially useful to prevent future global extinctions of the PEC endangered avifauna. The municipalities over this area were among the ones with the highest accumulated deforestation over the last 35 years (Dias, Silveira e Francisco, 2023), which may have somewhat contributed as a major threat to most of the PEC birds. We also highlight the importance of connecting Murici Ecological Station and Pedra Talhada Biological Reserve, two of the most bird-diverse regions of the PEC (Pereira *et al*., 2014).

Since ecological restoration is a tool that may be able to reduce extinction rates (Newmark *et al*., 2017), we propose (i) the creation of local restoration programs inside each complex of CPFs (Maceió, Murici, Serra Grande, Pedra D'Antas, Saltinho, and Pedra Talhada), starting with the corridors with low CWD/CL ratio connecting CPFs with higher conservation value, (ii) considering the connection between complexes to increase gene flow and bird movement over a large spatial scale. According to the Atlantic Forest Restoration Pact (AFRP), there is a goal for restoring around 10,000 km² of forests in the northeastern section of the Atlantic Forest (Calmon *et al*., 2011), and the decrease in sugarcane planted area (main agricultural land cover over the region) indicates the availability of land for restoration (Lins-e-Silva, Ferreira e Roda, 2021). However, initiatives carried out by sugarcane producers over the last two decades sometimes presented poor outcomes (Santos-Costa *et al*., 2016).

We highlight that considering the responses of threatened wildlife and landscape features in the creation of ecological corridors through active and passive forest restoration would increase the conservation outcomes related to threatened species' survival and ecosystem services over the PEC. Increasing the connectivity of conservation priority fragments through the creation of ecological corridors may be a top-conservation goal over the PEC, facilitating gene flow, organismal movement, climate adaptation, and the recolonization of habitat patches, which depends on reliable maps capable of guiding conservation efforts (Beier *et al*., 2011). Increasing surveillance of top-scored habitats (i.e., older forest cores in large fragments with high tree cover) may also be able to increase the protection of endangered bird populations. With our study, we identified possible strategies to improve conservation actions over the Pernambuco Endemism Center and for its endangered avifauna, which may guide conservation practitioners and prevent future extinctions.

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CONSIDERAÇÕES FINAIS

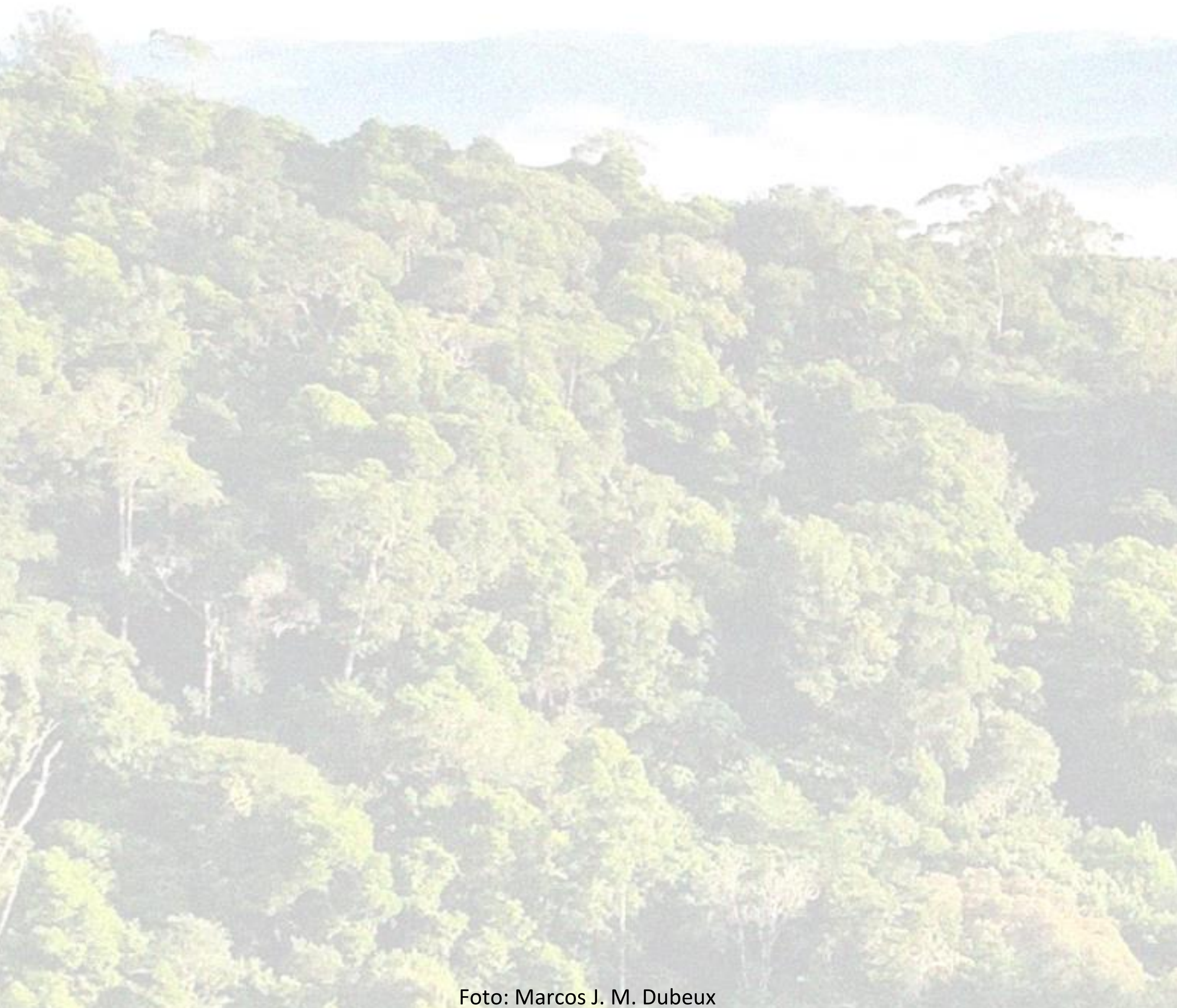

Foto: Marcos J. M. Dubeux

CONSIDERAÇÕES FINAIS

Através deste trabalho, foi possível apresentar uma avaliação abrangente da dinâmica espaço-temporal dos remanescentes de Mata Atlântica no Centro de Endemismo Pernambuco (CEP), além de avaliar relações estabelecidas entre a avifauna endêmica ameaçada e seus habitats para identificar recursos fundamentais à sua ocorrência e delimitar áreas prioritárias para conservação na região. Ainda, aqui propõe-se a criação de corredores ecológicos e do *Arco de Restauração do Centro de Endemismo Pernambuco* – ARC-CEP através de iniciativas de restauração ecológica em larga escala buscando aumentar a conectividade entre fragmentos de alta relevância ecológica e promover maior fluxo de indivíduos entre os remanescentes de habitat nessa importante região do Brasil. De maneira geral, os resultados obtidos apontam para uma condição preocupante dos ecossistemas do CEP. Embora tenham sido registrados acúmulo de biomassa e melhoria de métricas relacionadas à qualidade das florestas da região durante as últimas décadas, fatores como a dominância de fragmentos de tamanho reduzido, a fragmentação de habitats, os efeitos de borda e o rejuvenescimento da vegetação representam ameaças atuais à biodiversidade do CEP.

No Capítulo I, foi demonstrado que o fenômeno conhecido como *greening*, relacionado à tendência de acúmulo de biomassa na vegetação ao longo do tempo e ao consequente aumento nos estoques de carbono acima do solo de determinada área (Piao *et al*., 2020; Zhu *et al*., 2016), predominou nos remanescentes florestais do CEP, independentemente de seus tamanhos. No entanto, observou-se uma menor variação na biomassa (tanto em termos de aumento – *greening*, quando de diminuição – *browning*) em fragmentos maiores, o que pode indicar que o tamanho dos remanescentes florestais pode afetar a variação da biomassa ao longo do tempo. Na região, esses processos estão provavelmente relacionados à recuperação de áreas de vegetação secundária e ao possível ressurgimento de árvores emergentes que foram quase totalmente removidas no passado para o aquecimento de caldeiras nas usinas de açúcar. O processo de acúmulo de biomassa observado para a cobertura florestal do CEP pode contradizer a tendência de perda de biomassa esperada para ambientes altamente fragmentados. Embora fragmentos possam reter menor quantidade de carbono quando comparados a grandes áreas de floresta contínua, o fato de atuarem como sumidouros de carbono pode ser outro importante motivo para sua conservação.

No Capítulo II, a dinâmica de distribuição e configuração espacial dos fragmentos florestais do CEP foi acessada entre 1985 e 2020. Os resultados revelaram que, embora tenham sido identificadas melhorias na qualidade da cobertura florestal da região (e.g., aumento no tamanho médio de fragmento, aumento na área de núcleos florestais, redução nas taxas de desmatamento), ameaças como o tamanho reduzido dos fragmentos (quase 90% é menor que 10 ha), efeitos de borda severos (53.6% das florestas estão a até 50 m da borda), e o rejuvenescimento da vegetação (ao menos metade da vegetação tem menos de 35 anos) ainda ameaçam os habitats florestais do CEP. Consequentemente, apenas 12% da já reduzida cobertura florestal da região é possivelmente composta por habitats de maior qualidade (i.e., núcleos florestais mais antigos em grandes fragmentos). Essas características permitem classificar o CEP como uma das áreas mais degradadas da Mata Atlântica, em conformidade com o encontrado por Ribeiro *et al*. (2009), e inferir sobre as razões, possivelmente relacionadas à degradação ambiental, que levaram espécies da região à extinção (Pereira *et al*., 2014; Silveira, Olmos e Long, 2003; Stattersfield, 1998; Wege e Long, 1995). Utilizando o Google Earth Engine, foi possível desenvolver o aplicativo online (web e mobile) aberto *Forests of the PEC*, onde usuários poderão acessar dados atuais e históricos relacionados à dinâmica de distribuição, configuração espacial e outras características dos remanescentes florestais da região (https://dias93thiago.users.earthengine.app/view/forests-of-the-pec) (Figura 16).

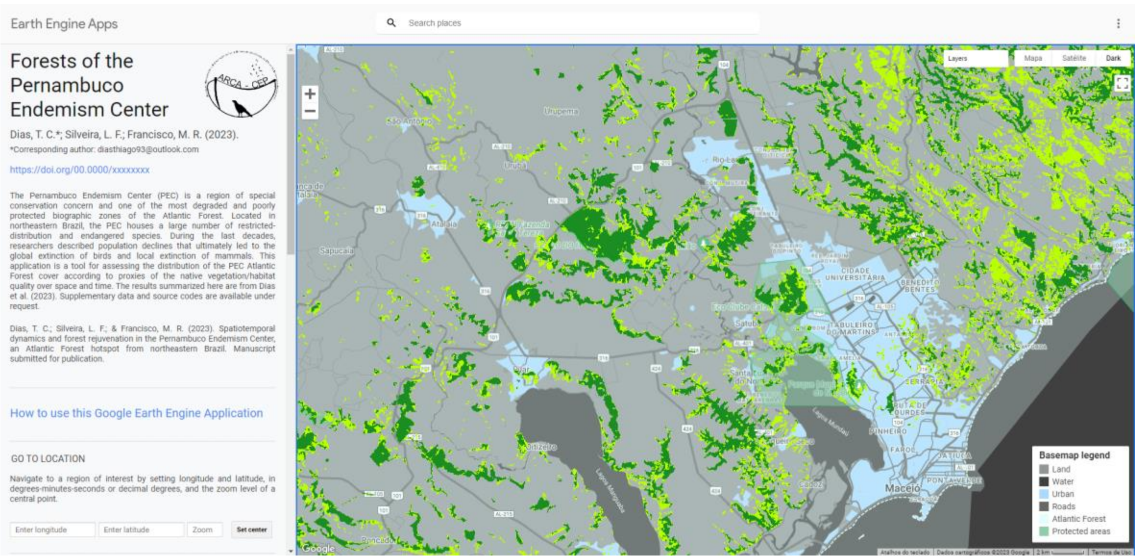

Figura 16. Visão geral do aplicativo *Forests of the Pernambuco Endemism Center*, compilando os principais resultados do Capítulo II deste trabalho, onde é possível observa a distribuição de florestas jovens (< 35 anos, verde-limão) e mais velhas (> 35 anos, verde-escuro), próximo a região metropolitana de Maceió/AL.

O Capítulo III deixa evidente o fato de grande parte das aves endêmicas e ameaçadas do CEP apresentarem distribuição restrita, limitada a poucas paisagens e florestas da região (e.g., existem apenas 37 km² de florestas apropriadas para a ocorrência de *Iodopleura pipra leucopygia* no mundo, e 61 km² para *Megascops alagoensis*). Além disso, foi possível observar que a distribuição de espécies criticamente ameaçadas (CR) foi mais afetada pela presença de grandes fragmentos (> 10 km²) e de florestas antigas (> 35 anos), características encontradas em apenas alguns dos remanescentes do CEP, como as unidades de conservação Estação Ecológica de Murici e Reserva Biológica de Pedra Talhada, que foram destacadas como extremamente importantes para a avifauna local por outros autores (Pereira, Araújo e Azevedo-Júnior, 2016). Outros remanescentes florestais de alta relevância ecológica para as aves do CEP foram identificados, nas quais ações de proteção e fiscalização devem ser reforçadas. Alguns desses fragmentos, distribuídos em seis complexos relativamente próximos contendo fragmentos florestais importantes para a biodiversidade local, se localizam entre o norte de Alagoas e o sul do Pernambuco. Para promover a conservação nesses complexos, sugere-se o início imediato de discussões buscando viabilizar ações que assegurem o aumento da conectividade entre os fragmentos ali localizados. Mais importante ainda é promover a conexão entre os seis complexos identificados, através da implementação de projetos de restauração florestal em larga escala e da criação do *Arco de Restauração do Centro de Endemismo Pernambuco* (ARC-CEP). Essas medidas apresentam grande potencial para aumentar a qualidade dos ambientes florestais da região e prevenir futuras perdas de espécies na região.

É incontestável a preocupante situação dos habitats florestais e da avifauna do Centro de Endemismo Pernambuco (CEP). No entanto, é importante ressaltar que existem ações voltadas ao manejo da paisagem e à conservação da biodiversidade que ainda podem ser implementadas na região, além dos esforços já realizados para a manutenção da fauna e flora ameaçadas do CEP. Embora iniciativas de restauração florestal em larga escala possam envolver altos custos de implantação e manutenção, aqui, declara-se que as mesmas podem ser fundamentais para promover a proteção da fauna e da flora no CEP. Uma vez que as áreas de alta relevância ecológica identificadas contém uma parcela significativa da biodiversidade ameaçada da região, garantir o aumento da conectividade entre elas e áreas adjacentes pode reduzir os efeitos relacionados ao isolamento populacional e garantir a promoção de relações ecológicas perdidas nos ecossistemas da região.

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APÊNDICES

Foto: Marcos J. M. Dubeux

APÊNDICES

1. Capítulo II

1.1. Appendix S1. Classification of deforestation and forest regeneration events.

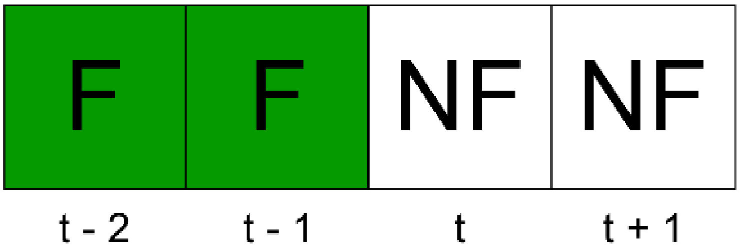

Figure S1. Moving window temporal filter for classifying deforestation.

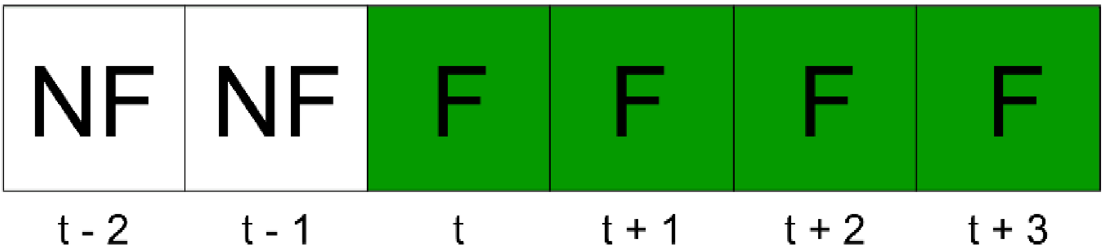

Figure S2. Moving window temporal filter for classifying forest regeneration.

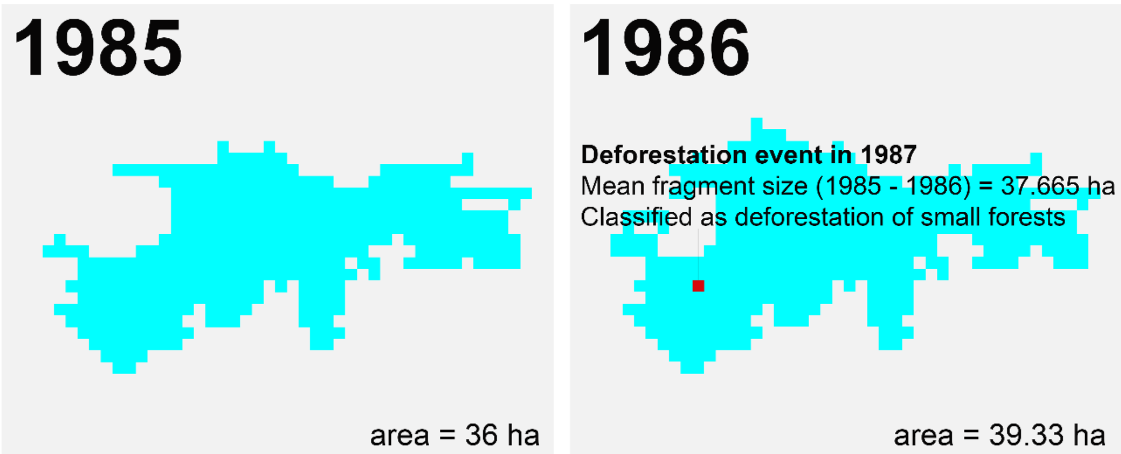

Figure S3. Scheme of the methods for the classification of deforestation according to fragment size.

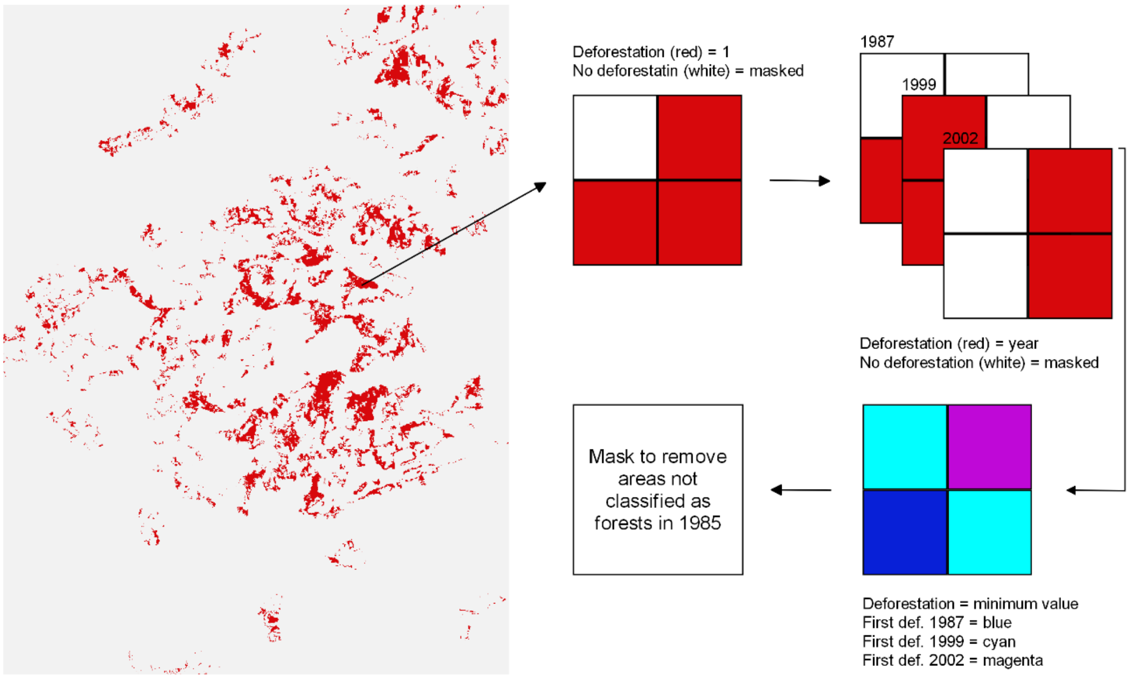

Figure S4. Scheme for the classification of older forests deforestation.

1.2. Appendix S2. Class-level metrics, deforestation, and forest regeneration for the Atlantic Forest cover over the Pernambuco Endemism Center.

Table S1. Landscape metrics of forests over the Pernambuco Endemism Center. Class-level metrics related to forest cover area (total and by four classes of fragment size), number of fragments (total and by four classes of fragment size), largest fragment area, mean fragment area, core and edge areas. Values presented in hectares for area-related metrics.

Year	FA - VS	FA – S	FA – M	FA - L	FA - T	NF - VS	NF - S	NF - M	NF - L	NF - T	LFA	MFA	CORE	EDGE
1985	144,108	175,729	160,874	90,951	571,661	75,263	6,583	700	35	82,581	15,355	7	215,229	356,432
1986	140,579	172,447	157,753	87,156	557,935	72,999	6,475	682	34	80,190	15,355	7	210,715	347,220
1987	111,996	147,593	160,419	94,162	514,169	57,267	5,483	650	39	63,439	13,098	8	210,774	303,395
1988	100,484	140,074	151,727	86,908	479,193	49,903	5,137	622	38	55,700	12,455	9	200,795	278,398
1989	95,032	135,296	144,753	67,068	442,149	46,733	4,939	582	25	52,279	12,656	8	188,889	253,260
1990	88,754	131,961	142,221	79,029	441,965	43,014	4,776	564	32	48,386	12,423	9	194,059	247,906
1991	85,762	128,443	152,925	72,285	439,414	41,594	4,671	591	27	46,883	12,932	9	194,274	245,139
1992	86,307	130,659	148,281	76,707	441,953	41,680	4,762	588	32	47,062	11,393	9	195,616	246,337
1993	85,561	125,436	139,587	73,652	424,235	41,535	4,580	554	33	46,702	11,616	9	189,416	234,820
1994	85,125	127,626	141,094	77,019	430,865	41,100	4,651	562	34	46,347	11,514	9	191,801	239,063
1995	83,832	128,777	145,140	72,215	429,964	40,349	4,718	573	29	45,669	11,564	9	191,676	238,289
1996	79,778	129,216	146,931	73,308	429,232	38,108	4,670	568	29	43,375	9,297	10	195,927	233,305
1997	78,639	129,225	146,298	69,173	423,335	37,118	4,628	555	26	42,327	9,370	10	194,503	228,832
1998	75,656	128,008	144,479	76,248	424,391	35,117	4,590	556	31	40,294	9,624	11	199,147	225,244
1999	72,846	128,590	144,609	81,034	427,078	33,493	4,591	560	32	38,676	10,650	11	203,958	223,120
2000	72,485	128,418	143,952	81,441	426,296	32,854	4,589	558	33	38,034	10,688	11	204,969	221,326
2001	69,162	128,153	144,288	74,559	416,161	30,975	4,565	544	29	36,113	11,076	12	203,943	212,219
2002	67,955	128,055	141,094	80,267	417,370	30,005	4,546	550	33	35,134	11,731	12	205,849	211,521
2003	72,822	131,255	140,351	82,407	426,834	32,850	4,670	551	33	38,104	11,780	11	206,979	219,856
2004	72,054	131,144	140,471	81,224	424,893	32,469	4,647	553	32	37,701	11,824	11	206,986	217,906
2005	70,615	129,561	140,707	81,869	422,751	31,615	4,564	547	30	36,756	12,083	12	207,256	215,495
2006	70,768	130,421	138,912	82,658	422,760	31,788	4,603	548	34	36,973	11,817	11	206,462	216,298
2007	77,998	134,397	139,492	84,137	436,023	36,058	4,805	566	35	41,464	8,628	11	205,854	230,170

2008	80,199	134,291	138,568	84,514	437,572	37,510	4,832	562	37	42,941	8,614	10	205,173	232,399
2009	80,097	134,866	139,160	84,792	438,916	37,330	4,846	565	37	42,778	8,626	10	206,055	232,861
2010	76,324	134,608	142,088	81,850	434,870	35,257	4,798	564	31	40,650	11,354	11	208,249	226,621
2011	72,318	131,982	143,012	87,369	434,682	32,626	4,699	591	36	37,952	11,612	11	213,374	221,308
2012	70,378	131,666	145,809	95,955	443,808	30,842	4,704	602	39	36,187	11,876	12	221,923	221,885
2013	76,196	136,001	151,035	101,490	464,722	34,061	4,862	617	41	39,581	12,295	12	227,841	236,881
2014	78,998	139,749	155,905	102,308	476,959	35,692	5,004	627	41	41,364	12,480	12	232,503	244,456
2015	81,381	142,614	157,958	109,124	491,078	37,258	5,087	630	44	43,019	12,569	11	238,909	252,169
2016	81,713	144,903	159,790	110,816	497,222	37,640	5,152	631	42	43,465	12,668	11	241,600	255,621
2017	80,791	144,677	160,737	112,488	498,692	37,183	5,106	632	43	42,964	12,879	12	244,036	254,657
2018	81,329	143,797	159,906	116,523	501,555	37,232	5,069	635	46	42,982	12,842	12	245,376	256,179
2019	84,941	147,361	161,459	125,098	518,859	39,289	5,194	638	48	45,169	13,845	11	252,808	266,051
2020	94,091	154,113	159,495	132,179	539,877	44,803	5,519	641	54	51,017	14,643	11	255,228	284,649

FA: forest area; NF: number of fragments; LFA: largest fragment area; MFA: mean fragment area; CORE: core area; EDGE: edge area; VS: very small fragments (< 10 ha); S: small fragments (10 – 100 ha); M: medium fragments (100 – 1,000 ha); L: large fragments (> 1,000 ha); T: total.

Table S2. Deforestation and forest regeneration over the Pernambuco Endemism Center. Deforestation was classified according to fragment size (in deforestation of very small, small, medium, and large fragments) and forest age (in deforestation of older and younger forests). Values presented in hectares.

Year	DEF - VS	DEF - S	DEF - M	DEF - L	DEF - O	DEF - Y	DEF - T	FREG - T
1987	47,878	29,254	12,128	5,937	–	0	95,198	28,564
1988	23,043	17,323	10,583	4,537	–	852	55,486	16,154
1989	15,880	13,076	12,976	9,664	–	17,157	51,595	15,442
1990	12,292	8,166	5,663	1,596	–	6,531	27,717	13,553
1991	13,281	9,084	4,817	1,901	–	8,364	29,083	15,059
1992	10,743	8,371	6,453	3,749	–	15,211	29,315	25,113
1993	11,072	9,767	10,471	2,770	–	20,632	34,080	16,941
1994	4,848	3,997	2,770	924	–	7,570	12,539	9,223
1995	9,689	6,034	3,321	1,208	–	11,955	20,252	13,526
1996	10,934	7,012	4,324	791	–	15,960	23,060	18,369

1997	9,524	7,733	5,410	2,922	–	18,573	25,589	14,137
1998	7,218	5,563	3,522	1,106	–	12,809	17,409	12,789
1999	8,968	6,431	3,595	1,056	–	14,860	20,050	15,005
2000	4,685	3,464	2,817	931	2,658	9,239	11,897	8,550
2001	9,090	7,069	5,997	2,834	4,704	20,286	24,990	15,082
2002	3,851	2,827	1,921	798	2,556	6,842	9,398	10,307
2003	5,590	4,138	2,719	1,096	3,526	10,017	13,543	10,249
2004	3,439	2,398	1,664	658	1,771	6,388	8,159	7,221
2005	7,156	4,997	2,406	965	2,678	12,846	15,524	10,636
2006	5,744	3,940	2,417	1,089	2,482	10,708	13,190	12,063
2007	6,947	5,829	4,240	1,888	4,409	14,495	18,905	22,468
2008	1,892	1,178	629	534	391	3,842	4,233	1,642
2009	601	339	178	90	70	1,138	1,208	1,503
2010	13,561	7,536	3,851	1,525	2,201	24,273	26,474	17,534
2011	9,040	5,110	2,791	771	1,541	16,171	17,712	16,550
2012	6,317	3,352	1,605	420	1,080	10,614	11,694	17,021
2013	2,800	1,869	1,200	393	881	5,381	6,262	16,226
2014	4,343	2,816	1,596	616	884	8,488	9,371	17,592
2015	4,579	3,480	1,755	675	753	9,736	10,489	16,958
2016	5,164	3,256	1,751	799	826	10,143	10,969	14,586
2017	7,519	4,876	2,266	1,032	846	14,847	15,693	13,260

DEF: deforestation; FREG: forest regeneration; VS: very small fragments (< 10 ha); S: small fragments (10 – 100 ha); M: medium fragments (100 – 1,000 ha); L: large fragments (> 1,000 ha); O: older forests; Y: younger forests; T: total.

1.3. Appendix S3. Breakpoint analysis and linear trends for forest cover area and number of fragments in the Atlantic Forest cover over the Pernambuco Endemism Center from 1985 to 2020.

Table S3. Breakpoints and linear trends of forest cover area and number of fragments of the Pernambuco Endemism Center. Forests were classified according to fragment size (in very small, small, medium, and large fragments), and metrics were calculated separately for all of them and total. Values for areas presented in hectares.

Metric	Initial year	Breakpoint year	Estimated slope	t-value	R^2
FA - VS	1985	1988	-15,946 ± 1,476.3	-10.801	0.96998
FA - VS	1988	2001	-1,864.7 ± 244.69	-7.6207	0.96998
FA - VS	2001	2019	673.17 ± 163.42	4.1191	0.96998
FA - VS	2019	2020	9,150 ± 4,668.3	1.96	0.96998
FA - S	1985	1988	-13,137 ± 1,086.7	-12.089	0.96454
FA - S	1988	1993	-1,931.4 ± 1,086.7	-1.7774	0.96454
FA - S	1993	2012	391.06 ± 101.78	3.8424	0.96454
FA - S	2012	2020	2,184.3 ± 313.7	6.9631	0.96454
FA - M	1985	1989	-3,826.8 ± 972.6	-3.9346	0.871686
FA - M	1989	2008	-427.25 ± 128.82	-3.3166	0.871686
FA - M	2008	2020	2,165.2 ± 257.2	8.4184	0.871686
FA - L	1985	1991	-3,634.7 ± 929.31	-3.9112	0.949254
FA - L	1991	2010	671.46 ± 150.75	4.454	0.949254
FA - L	2010	2020	4,404.3 ± 428.01	10.29	0.949254
FA - T	1985	1989	-33,803 ± 1,892.7	-17.859	0.984042
FA - T	1989	2001	-1,880.3 ± 500.51	-3.7568	0.984042
FA - T	2001	2011	2,232.7 ± 772.7	2.8895	0.984042
FA - T	2011	2020	10,385 ± 658.96	15.759	0.984042
NF - VS	1985	1988	-9,181.2 ± 883.64	-10.39	0.96998
NF - VS	1988	2001	-1,149.8 ± 146.46	-7.8506	0.96998
NF - VS	2001	2019	340.62 ± 97.821	3.4821	0.96998
NF - VS	2019	2020	5,514 ± 2,794.3	1.9733	0.96998
NF - S	1985	1989	-533 ± 51.946	-10.261	0.947493
NF - S	1989	2004	-14.072 ± 6.2994	-2.2339	0.947493
NF - S	2004	2020	47.115 ± 6.2994	7.4792	0.947493
NF - M	1985	1989	-29.6 ± 3.0585	-9.6778	0.953366
NF - M	1989	2005	-2.1321 ± 0.57801	-3.6888	0.953366
NF - M	2005	2020	7.1824 ± 0.52454	13.693	0.953366
NF - L	1985	2004	-0.18947 ± 0.13248	-1.4303	0.775609
NF - L	2004	2020	1.1765 ± 0.15658	7.5134	0.775609
NF - T	1985	1988	-9,739.4 ± 921.02	-10.575	0.970093
NF - T	1988	2001	-1,173.7 ± 152.66	-7.6883	0.970093
NF - T	2001	2019	383.05 ± 101.96	3.7569	0.970093
NF - T	2019	2020	5,848 ± 2,912.5	2.0079	0.970093

FA: forest area; NF: number of fragments; VS: very small fragments (< 10 ha); S: small fragments (10 – 100 ha); M: medium fragments (100 – 1,000 ha); L: large fragments (> 1,000 ha); T: total.

1.4. Appendix S4. The current distribution of older and younger forests across the Pernambuco Endemism Center.

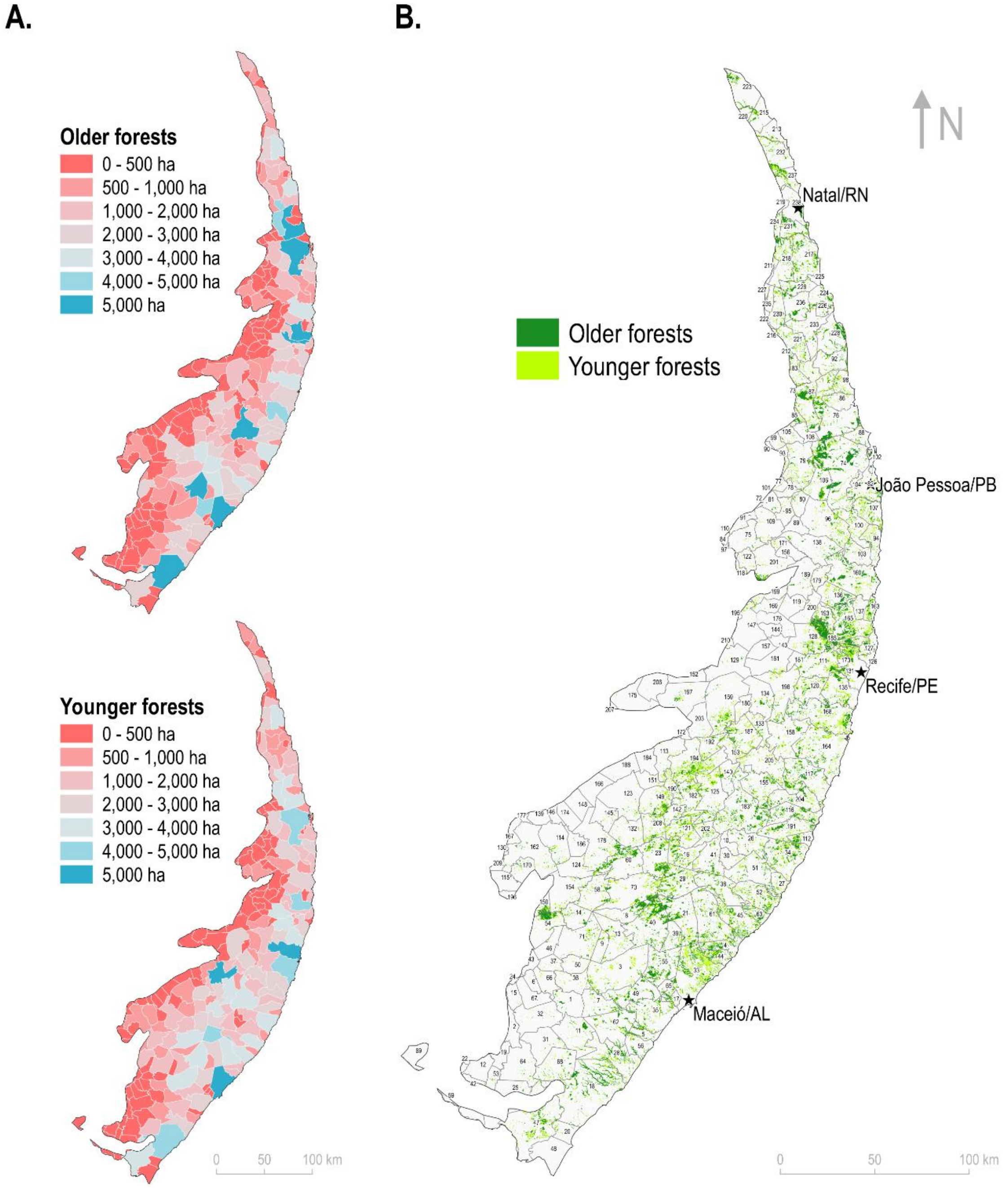

Figure S5. Older and younger forests of the Pernambuco Endemism Center. The current distribution of older and younger forests according to (A) the municipalities of the PEC, and (B) the spatial distribution and configuration of older and younger forests.

1.5. Appendix S5. Forest quality according to forest age, size, and edge effects

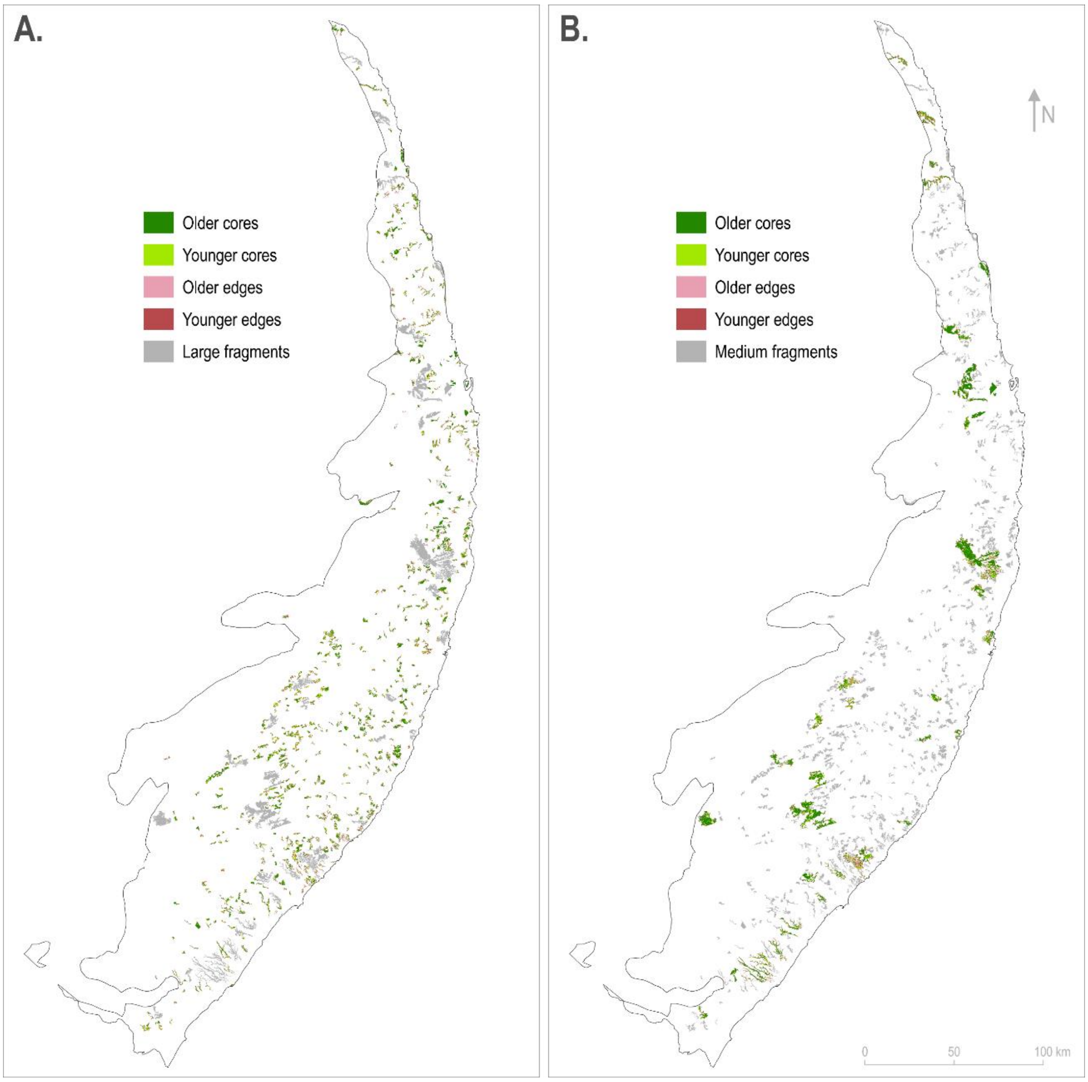

Figure S6. Quality of the Atlantic Forest cover over the Pernambuco Endemism Center. Current (2017) classification of forests according to age and edge effects for (A) large (> 1,000 ha), and (B) medium (100 – 1,000 ha) fragments over the Pernambuco Endemism Center.

2. Capítulo III

2.1. Appendix S6. Endangered and endemic bird taxa from the Pernambuco Endemism Center.

Table S4. Bird taxa from the Pernambuco Endemism Center (PEC) assessed during our study. The taxa in bold represents species removed from the analysis due to the low number of occurrence points.

ID	Scientific name	Distribution	Cons. status		Occ. points
			IUCN	ICMBio, MMA	
1	*Automolus lammi*	PEC	EN	EN	39
2	*Caryothraustes brasiliensis* (NE pop.)	PEC	-	VU	14
3	*Cercomacroides laeta sabinoi*	PEC	-	VU	30
4	*Conopophaga cearae*	AF	NT	EN	26
5	*Conopophaga melanops nigrifrons*	PEC	-	VU	26
6	*Dendrocincla taunayi*	PEC	-	EN	9
7	*Hemithraupis flavicollis melanoxantha*	PEC	-	DD	16
8	*Hemitriccus griseipectus naumburgae*	PEC	-	VU	58
9	*Hemitriccus mirandae*	PEC	VU	EN	13
10	*Iodopleura pipra leucopygia*	PEC	-	EN	6
11	*Leptodon forbesi*	PEC	EN	EN	57
12	*Megascops alagoensis*	PEC	-	CR**	7
13	*Momotus momota marcgravianus*	PEC	-	EN	12
14	*Myrmoderus ruficauda soror*	PEC	-	EN*	41
15	*Myrmotherula snowi*	PEC	CR	CR	16
16	***Odontophorus capueira plumbeicollis***	**PEC**	**-**	**CR**	**3**
17	*Penelope superciliaris alagoensis*	PEC	-	CR	16
18	***Phaethornis margarettae camargoi***	**PEC**	**-**	**EN**	**3**
19	*Phylloscartes ceciliae*	PEC	CR	CR	42
20	*Picumnus pernambucensis*	PEC	-	VU	38
21	*Platyrinchus mystaceus niveigularis*	PEC	LC	VU	27
22	*Pyriglena pernambucensis*	PEC	-	VU	22
23	*Schiffornis turdina intermedia*	PEC	-	VU	18
24	***Sclerurus caudacutus caligineus***	**PEC**	**-**	**CR**	**4**
25	*Synallaxis infuscata*	PEC	EN	EN	89
26	*Tangara cyanocephala cearensis*	PEC	-	VU	16

27	*Tangara fastuosa*	PEC	VU	VU	63
28	*Terenura sicki*	PEC	CR	CR	41
29	*Thalurania watertonii*	PEC	EN	EN	40
30	*Thamnophilus aethiops distans*	PEC	-	EN	20
31	*Thamnophilus caerulescens pernambucensis*	PEC	-	VU	24
32	***Trogon muriciensis***	**PEC**	**-**	**CR*****	**1**
33	*Xenops minutus alagoanus*	PEC	LC	VU	51
34	*Xiphorhynchus atlanticus*	PEC	-	VU	45

Distribution from specimens housed at MZUSP, Roda, Pereira e Albano (2011), Marrara (2020), and Dantas *et al*. (2021). Distribution: PEC = PEC-endemic, AF = Atlantic Forest-endemic

*Risk assessed at higher taxonomic levels

**Conservation status suggested by Dantas *et al*. (2021)

***Conservation status suggested by Dickens *et al*. (2021)

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2.2. Appendix S7. Environmental variables representing the Pernambuco Endemism Center habitats.

Table S5. Environmental variables used for species distribution modeling.

Group	Included	Variable	Dataset Provider	Description
Terrain	Yes	elevation	NASA / USGS / JPL-Caltech	Digital elevation data.
	Yes	slope	NASA / USGS / JPL-Caltech	Represents the steepness of the ground surface.
	Yes	mTPI	Conservation Science Partners	Multi-Scale Topographic Position Index, calculated using elevation subtracted by the mean elevation within a neighborhood.
	No	topoDiversity	Conservation Science Partners	Topographic diversity represents the variety of temperature and moisture conditions.
Climate	No	tempMean	University of California, Berkeley	WorldClim V1 Bioclim, annual mean temperature.
	No	tempSeason	University of California, Berkeley	WorldClim V1 Bioclim, annual temperature seasonality.
	No	tempMax	University of California, Berkeley	WorldClim V1 Bioclim, maximum temperature in the hottest month.
	No	tempMin	University of California, Berkeley	WorldClim V1 Bioclim, minimum temperature in the coldest month.
	Yes	tempRange	University of California, Berkeley	WorldClim V1 Bioclim, annual temperature range.
	No	precAnnual	University of California, Berkeley	WorldClim V1 Bioclim, accumulated annual precipitation.
	No	precWet	University of California, Berkeley	WorldClim V1 Bioclim, precipitation in the wettest month.
	No	precDry	University of California, Berkeley	WorldClim V1 Bioclim, precipitation in the driest month.
	Yes	precSeason	University of California, Berkeley	WorldClim V1 Bioclim, annual precipitation seasonality.
Human	Yes	gHM	Conservation Science Partners	Global Human Modification dataset, cumulative measure of human modification.
	Yes	distProtArea	UN Environment World Conservation Monitoring Centre (UNEP-WCMC) / Protected Planet	Euclidean distance to protected areas generated using the World Database on Protected Areas.
	Yes	distRoads	Brazil's national transport infrastructure department (DNIT)	Euclidean distance to roads generated using federal and state road data from DNIT.
	Yes	percAgropastoral	MapBiomas Collection 6.0	Percentage of the agropastoral matrix in a 1-km radius buffer.

Forest	No	percOtherForests	MapBiomas Collection 6.0	Percentage of non-Atlantic Forest in a 1-km radius buffer.
	Yes	distLargeForests	MapBiomas Collection 6.0	Euclidean distance to > 10 km² Atlantic Forest fragments.
	Yes	distMediumForests	MapBiomas Collection 6.0	Euclidean distance to 1 – 10 km² Atlantic Forest fragments.
	No	distSmallForests	MapBiomas Collection 6.0	Euclidean distance to < 1 km² Atlantic Forest fragments.
	No	nFrag	MapBiomas Collection 6.0	Number of Atlantic Forest fragments in a 1-km radius buffer.
	Yes	distEdge	MapBiomas Collection 6.0	Euclidean distance to Atlantic Forest borders. Negative values represent distances from the border to the forest core. Positive values represent distances away from the forest borders into the matrix.
	Yes	treeCover	NASA LP DAAC at the USGS EROS Center	The percentage of a pixel covered by trees.
	Yes	percOldForest	MapBiomas Collection 6.0	Percentage of older (> 35 years) Atlantic Forest in a 1-km radius buffer.
	No	percYoungForest	MapBiomas Collection 6.0	Percentage of younger (< 35 years) Atlantic Forest in a 1-km radius buffer.
Biomass	No	meanEVI	NASA LP DAAC at the USGS EROS Center	1-km mean EVI (2018-01-01 - 2022-12-31).
	Yes	minEVI	NASA LP DAAC at the USGS EROS Center	1-km minimum EVI (2018-01-01 - 2022-12-31).
	Yes	maxEVI	NASA LP DAAC at the USGS EROS Center	1-km maximum EVI (2018-01-01 - 2022-12-31).
	No	diffEVI	NASA LP DAAC at the USGS EROS Center	Difference between maximum EVI and minimum EVI.
Other	Yes	distWater	Brazil's National Water and Sanitation Agency	Euclidean distance to watercourses and water bodies.

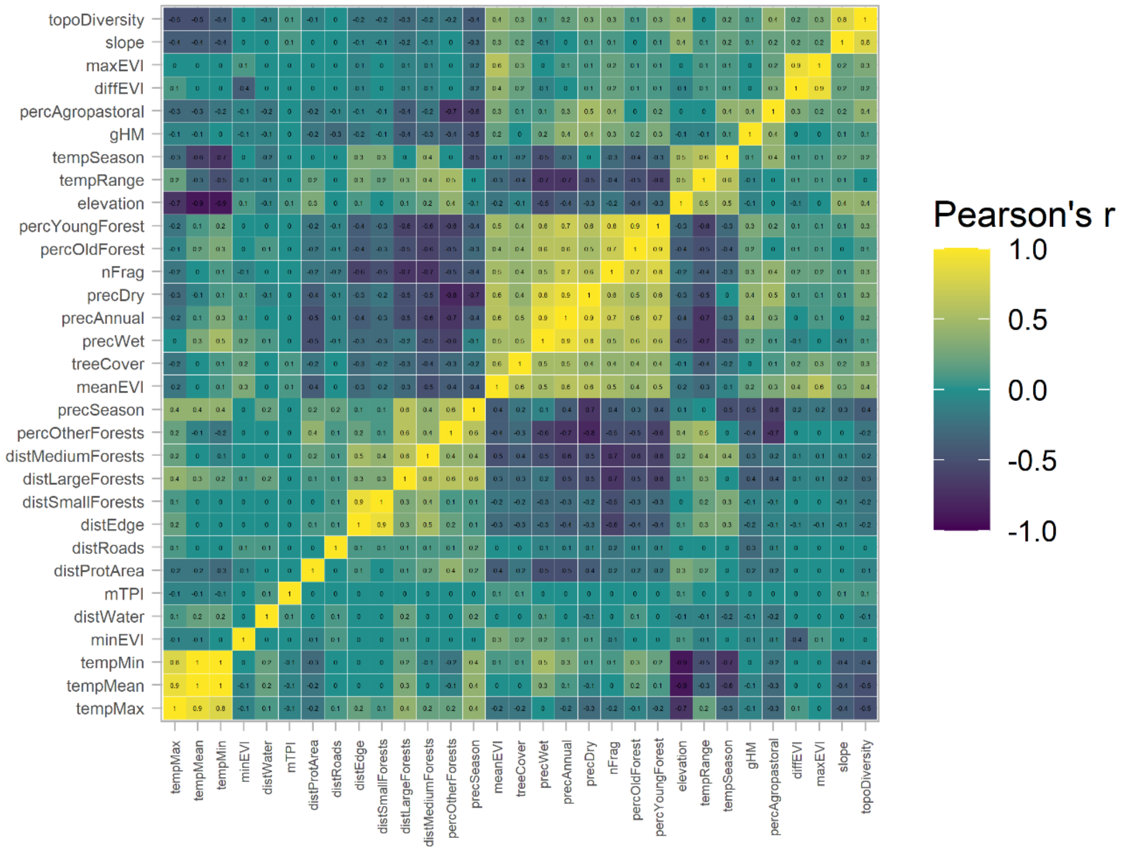

Figure S7. Correlation matrix showing Pearson's r for the 31 pre-defined environmental variables.

Table S6. Variation Inflation Factor (VIF) for the remaining 17 environmental variables with Pearson's < 0.7. For VIF, the remaining variables were continuously removed until none showed VIF > 5.

Variables	VIF	Variables	VIF
distEdge	1.395206	minEVI	1.171803
distLargeForests	2.827853	mTPI	1.063299
distMediumForests	2.01613	percAgropastoral	1.908332
distProtArea	1.459872	percOldForest	2.447882
distRoads	1.158977	precSeason	3.289526
distWater	1.161358	slope	1.382391
elevation	1.994298	tempRange	1.960882
gHM	1.773882	treeCover	1.824317
maxEVI	1.365392		

2.3. Appendix S8. List of the protected areas of the Pernambuco Endemism Center

Table S7. List of protected areas.

ID	Name	Protection category	Longitude	Latitude	Source
1	Xukuru	Indigenous Area	-36.76935	-8.32459	UNEP-WCMC & IUCN (2023)
2	Kapinawá	Indigenous Area	-37.34713	-8.61663	UNEP-WCMC & IUCN (2023)
3	Fulni-ô	Indigenous Reserve	-37.11164	-9.11217	UNEP-WCMC & IUCN (2023)
4	Xukuru-Kariri	Indigenous Area	-36.62485	-9.38914	UNEP-WCMC & IUCN (2023)
5	Wassu-Cocal	Indigenous Area	-35.71439	-9.04695	UNEP-WCMC & IUCN (2023)
6	Caiçara/Ilha de São Pedro	Indigenous Area	-37.38737	-9.81895	UNEP-WCMC & IUCN (2023)
7	Tingui Botó	Indigenous Reserve	-36.72738	-9.91975	UNEP-WCMC & IUCN (2023)
8	Kariri-Xocó	Indigenous Area	-36.83398	-10.14106	UNEP-WCMC & IUCN (2023)
9	Acaú-Goiana	Extractive Reserve	-34.86146	-7.55648	UNEP-WCMC & IUCN (2023)
10	Barra do Rio Camaratuba	Area of Relevant Ecological Interest	-34.97663	-6.59774	UNEP-WCMC & IUCN (2023)
11	Jenipabu	Environmental Protection Area	-35.21417	-5.71171	UNEP-WCMC & IUCN (2023)
12	Bonfim/Guaraíra	Environmental Protection Area	-35.1735	-6.08299	UNEP-WCMC & IUCN (2023)
13	Ponta do Tubarão	Sustainable Development Reserve	-36.46454	-5.08996	UNEP-WCMC & IUCN (2023)
14	Piquiri-Una	Environmental Protection Area	-35.24754	-6.37212	UNEP-WCMC & IUCN (2023)
15	Catolé e Fernão Velho	Environmental Protection Area	-35.79759	-9.58277	UNEP-WCMC & IUCN (2023)
16	Marituba do Peixe	Environmental Protection Area	-36.40917	-10.33709	UNEP-WCMC & IUCN (2023)
17	Kariri-Xocó	Indigenous Area	-36.83559	-10.14026	UNEP-WCMC & IUCN (2023)
18	Potiguara de Monte-Mor	Indigenous Area	-35.05487	-6.77675	UNEP-WCMC & IUCN (2023)
19	Potiguara	Indigenous Area	-35.14128	-6.66069	UNEP-WCMC & IUCN (2023)
20	Furna Feia	National Park	-37.51106	-5.05432	UNEP-WCMC & IUCN (2023)
21	Mata do Urucu	Wildlife Refuge	-35.25372	-8.24272	UNEP-WCMC & IUCN (2023)
22	Mata da Usina São José	Wildlife Refuge	-35.00174	-7.8355	UNEP-WCMC & IUCN (2023)
23	Mata de Caraúna	Wildlife Refuge	-35.10097	-8.18649	UNEP-WCMC & IUCN (2023)
24	Mata do Contra-Açude	Wildlife Refuge	-35.02191	-8.23046	UNEP-WCMC & IUCN (2023)
25	Serra do Cumaru	Wildlife Refuge	-35.17534	-8.20428	UNEP-WCMC & IUCN (2023)
26	Mata Serra do Cotovelo	Wildlife Refuge	-35.20679	-8.24632	UNEP-WCMC & IUCN (2023)
27	Saltinho	Biological Reserve	-35.18163	-8.72424	UNEP-WCMC & IUCN (2023)
28	Manguezais da Foz do Rio Mamanguape	Area of Relevant Ecological Interest	-34.98884	-6.79503	UNEP-WCMC & IUCN (2023)
29	Piaçabuçu	Environmental Protection Area	-36.3567	-10.40067	UNEP-WCMC & IUCN (2023)

30	Santa Isabel	Biological Reserve	-36.70948	-10.6394	UNEP-WCMC & IUCN (2023)
31	Pedra Talhada	Biological Reserve	-36.428	-9.22843	UNEP-WCMC & IUCN (2023)
32	Guaribas	Biological Reserve	-35.15736	-6.71969	UNEP-WCMC & IUCN (2023)
33	Potiguara	Indigenous Area	-35.00317	-6.68897	UNEP-WCMC & IUCN (2023)
34	Jacaré de São Domingos	Indigenous Area	-35.08442	-6.73588	UNEP-WCMC & IUCN (2023)
35	Barra do Rio Mamanguape	Environmental Protection Area	-34.96876	-6.79588	UNEP-WCMC & IUCN (2023)
36	Murici	Ecological Station	-35.85004	-9.2288	UNEP-WCMC & IUCN (2023)
37	Catimbau	National Park	-37.34719	-8.50381	UNEP-WCMC & IUCN (2023)
38	Nísia Floresta	National Forest	-35.18228	-6.08155	UNEP-WCMC & IUCN (2023)
39	Açu	National Forest	-36.94732	-5.57751	UNEP-WCMC & IUCN (2023)
40	Restinga de Cabedelo	National Forest	-34.85655	-7.06405	UNEP-WCMC & IUCN (2023)
41	Bicho Homem	Private Reserve of Natural Heritage	-35.72713	-8.61010	Carvalho *et al*. (2021)
42	Jussaral	Private Reserve of Natural Heritage	-35.72713	-8.61010	Carvalho *et al*. (2021)
43	Benedito	Private Reserve of Natural Heritage	-35.58576	-8.29462	Carvalho *et al*. (2021)
44	Engenho Contestado	Private Reserve of Natural Heritage	-35.80112	-8.84286	Carvalho *et al*. (2021)
45	EcoFazenda Morim	Private Reserve of Natural Heritage	-35.20933	-8.86817	Carvalho *et al*. (2021)
46	Fazenda Santa Rita	Private Reserve of Natural Heritage	-35.48577	-8.69061	Carvalho *et al*. (2021)
47	Fazenda Tabatinga	Private Reserve of Natural Heritage	-34.82401	-7.60474	Carvalho *et al*. (2021)
48	Laje Bonita	Private Reserve of Natural Heritage	-36.01678	-8.80221	Carvalho *et al*. (2021)
49	Pedra d'Antas	Private Reserve of Natural Heritage	-35.85588	-8.69391	Carvalho *et al*. (2021)
50	Serro Azul	Private Reserve of Natural Heritage	-35.98936	-8.13992	Carvalho *et al*. (2021)
51	Trapiche	Private Reserve of Natural Heritage	-35.06278	-8.58014	Carvalho *et al*. (2021)
52	Reserva Gulandim	Private Reserve of Natural Heritage	-36.34000	-9.97700	Carvalho *et al*. (2021)
53	Reserva Santa Tereza	Private Reserve of Natural Heritage	-35.97400	-9.50700	Carvalho *et al*. (2021)
54	Fazenda São Pedro	Private Reserve of Natural Heritage	-35.95100	-9.55500	Carvalho *et al*. (2021)
55	Fazenda Rosa do Sol	Private Reserve of Natural Heritage	-35.90500	-9.83200	Carvalho *et al*. (2021)
56	Fazenda Pereira	Private Reserve of Natural Heritage	-36.36130	-10.25020	Carvalho *et al*. (2021)
57	Lula Lobo	Private Reserve of Natural Heritage	-36.35080	-10.29100	Carvalho *et al*. (2021)
58	Vera Cruz	Private Reserve of Natural Heritage	-36.29300	-9.25600	Carvalho *et al*. (2021)
59	Engenho Gargaú	Private Reserve of Natural Heritage	-34.95413	-7.01558	Carvalho *et al*. (2021)
60	Fazenda Pacatuba	Private Reserve of Natural Heritage	-35.15641	-7.04635	Carvalho *et al*. (2021)
61	Reserva Calaça	Private Reserve of Natural Heritage	-36.22294	-8.71872	Carvalho *et al*. (2021)
62	Serra do Contente	Private Reserve of Natural Heritage	-35.55289	-8.26137	Carvalho *et al*. (2021)

63	Nossa Senhora do Oiteiro de Maracaípe	Private Reserve of Natural Heritage	-35.01678	-8.52391	Carvalho *et al*. (2021)
64	Frei Caneca	Private Reserve of Natural Heritage	-35.84439	-8.71929	Carvalho *et al*. (2021)
65	Reserva Cabanos	Private Reserve of Natural Heritage	-36.01042	-8.49913	Carvalho *et al*. (2021)
66	Fazenda Santa Beatriz do Carnijó	Private Reserve of Natural Heritage	-35.07890	-8.14150	Carvalho *et al*. (2021)
67	Mata Estrela	Private Reserve of Natural Heritage	-35.00043	-6.40460	Carvalho *et al*. (2021)
68	Dunas Douradas	Private Reserve of Natural Heritage	-35.23917	-5.62564	Carvalho *et al*. (2021)
69	Mata da Bela	Private Reserve of Natural Heritage	-35.11431	-6.42253	Carvalho *et al*. (2021)
70	Triunfo	Private Reserve of Natural Heritage	-35.29175	-9.05136	Carvalho *et al*. (2021)
71	Tobogã	Private Reserve of Natural Heritage	-35.77266	-9.60078	Carvalho *et al*. (2021)
72	Santa Fé	Private Reserve of Natural Heritage	-36.44521	-9.52089	Carvalho *et al*. (2021)
73	Placas	Private Reserve of Natural Heritage	-35.60659	-9.43190	Carvalho *et al*. (2021)
74	Cachoeira	Private Reserve of Natural Heritage	-36.44492	-9.53388	Carvalho *et al*. (2021)
75	Cachoeira	Private Reserve of Natural Heritage	-35.25073	-8.97370	Carvalho *et al*. (2021)
76	Bosque	Private Reserve of Natural Heritage	-35.23164	-8.94939	Carvalho *et al*. (2021)
77	Aldeia Verde	Private Reserve of Natural Heritage	-35.69592	-9.57279	Carvalho *et al*. (2021)
78	Planalto	Private Reserve of Natural Heritage	-36.35151	-10.16927	Carvalho *et al*. (2021)
79	Madeiras	Private Reserve of Natural Heritage	-36.33726	-9.87378	Carvalho *et al*. (2021)
80	Estrela do Sul	Private Reserve of Natural Heritage	-35.70765	-8.93338	Carvalho *et al*. (2021)
81	Porto Alegre	Private Reserve of Natural Heritage	-35.68117	-8.93055	Carvalho *et al*. (2021)
82	Papa Mel	Private Reserve of Natural Heritage	-35.67948	-8.93047	Carvalho *et al*. (2021)
83	Porto Seguro	Private Reserve of Natural Heritage	-35.51017	-9.09886	Carvalho *et al*. (2021)
84	Canadá	Private Reserve of Natural Heritage	-36.37585	-9.46256	Carvalho *et al*. (2021)
85	Vila d'Água	Private Reserve of Natural Heritage	-35.94150	-9.29038	Carvalho *et al*. (2021)
86	Boa Sorte	Private Reserve of Natural Heritage	-35.92943	-9.18714	Carvalho *et al*. (2021)
87	Osvaldo Timóteo	Private Reserve of Natural Heritage	-36.03271	-9.02953	Carvalho *et al*. (2021)
88	Santa Maria	Private Reserve of Natural Heritage	-35.85299	-9.35532	Carvalho *et al*. (2021)
89	Mata do Cedro	Private Reserve of Natural Heritage	-35.90690	-9.52350	Carvalho *et al*. (2021)
90	Serra d'Água	Private Reserve of Natural Heritage	-35.57598	-9.11430	Carvalho *et al*. (2021)
91	Garabu	Private Reserve of Natural Heritage	-35.58037	-9.28120	Carvalho *et al*. (2021)
92	Saint Michel 1	Private Reserve of Natural Heritage	-35.87679	-9.80366	Carvalho *et al*. (2021)
93	Santa Cristina	Private Reserve of Natural Heritage	-35.95204	-9.79145	Carvalho *et al*. (2021)
94	Sereno	Private Reserve of Natural Heritage	-35.38060	-9.09754	Carvalho *et al*. (2021)
95	Quebra Carro	Private Reserve of Natural Heritage	-36.10873	-9.63123	Carvalho *et al*. (2021)

96	Saint Michel 2	Private Reserve of Natural Heritage	-35.86372	-9.79874	Carvalho *et al*. (2021)
97	Baixa Grande	Private Reserve of Natural Heritage	-36.18787	-9.70980	Carvalho *et al*. (2021)
98	Conceição Lyra I	Private Reserve of Natural Heritage	-36.45797	-10.20955	Carvalho *et al*. (2021)
99	Saint Michel 3	Private Reserve of Natural Heritage	-35.86501	-9.79936	Carvalho *et al*. (2021)
100	Conceição Lyra IV	Private Reserve of Natural Heritage	-36.45947	-10.19935	Carvalho *et al*. (2021)
101	Salvador Lyra	Private Reserve of Natural Heritage	-36.02396	-9.75347	Carvalho *et al*. (2021)
102	Boca do Rio	Private Reserve of Natural Heritage	-35.98500	-9.78628	Carvalho *et al*. (2021)
103	Riacho Seco	Private Reserve of Natural Heritage	-36.22481	-10.09272	Carvalho *et al*. (2021)
104	Conceição Lyra II	Private Reserve of Natural Heritage	-36.45263	-10.19971	Carvalho *et al*. (2021)
105	Oriente	Private Reserve of Natural Heritage	-35.45344	-9.01184	Carvalho *et al*. (2021)
106	Conceição Lyra III	Private Reserve of Natural Heritage	-36.44832	-10.16385	Carvalho *et al*. (2021)
107	Pindoba	Private Reserve of Natural Heritage	-35.99463	-9.78298	Carvalho *et al*. (2021)
108	Apolinário	Private Reserve of Natural Heritage	-35.63923	-9.39100	Carvalho *et al*. (2021)
109	Olho d'Água	Private Reserve of Natural Heritage	-35.97399	-9.78930	Carvalho *et al*. (2021)

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2.4. Appendix S9. Cross-taxa evaluation of the ensemble distribution models.

Table S8. Performance evaluation for GLM, GBM, CTA, ANN, MAXENT, and Ensemble (EM) based on True Skill Statistic (TSS) for 30 bird taxa of the Pernambuco Endemism Center (PEC), in northeastern Brazilian Atlantic Forest.

Taxa	GLM Mean TSS	GBM Mean TSS	CTA Mean TSS	ANN Mean TSS	MAXENT Mean TSS	EM Weighted Mean TSS
Automolus lammi	0.79	0.84	0.67	0.68	0.60	0.97
Caryothraustes brasiliensis (NE pop.)	0.65	0.66	0.66	0.56	0.83	0.98
Cercomacroides laeta sabinoi	0.74	0.85	0.71	0.62	0.82	0.97
Conopophaga cearae	0.66	0.70	0.49	0.55	0.56	0.96
Conopophaga melanops nigrifrons	0.69	0.72	0.53	0.59	0.74	0.91
Dendrocincla taunayi	0.38	0.84	0.74	0.45	0.82	1.00
Hemithraupis flavicollis melanoxantha	0.59	0.85	0.72	0.67	0.93	0.99
Hemitriccus griseipectus naumburgae	0.80	0.84	0.66	0.72	0.84	0.92
Hemitriccus mirandae	0.40	0.73	0.63	0.34	0.85	0.98
Iodopleura pipra leucopygia	0.29	0.71	0.27	0.28	0.81	1.00
Leptodon forbesi	0.78	0.82	0.68	0.57	0.75	0.92
Megascops alagoensis	0.70	0.78	0.61	0.59	0.75	1.00
Momotus momota marcgravianus	0.52	0.67	0.68	0.51	0.89	0.98
Myrmoderus ruficauda soror	0.79	0.83	0.69	0.62	0.75	0.98
Myrmotherula snowi	0.70	0.89	0.84	0.66	0.94	0.99
Penelope superciliaris alagoensis	0.63	0.62	0.36	0.37	0.63	0.92
Phylloscartes ceciliae	0.84	0.88	0.79	0.66	0.85	0.98
Picumnus pernambucensis	0.77	0.83	0.72	0.58	0.74	0.97
Platyrinchus mystaceus niveigularis	0.77	0.79	0.48	0.48	0.79	0.92
Pyriglena pernambucensis	0.70	0.83	0.77	0.64	0.85	0.91
Schiffornis turdina intermedia	0.76	0.78	0.75	0.63	0.87	0.91
Synallaxis infuscata	0.75	0.76	0.63	0.56	0.48	0.86
Tangara cyanocephala cearensis	0.43	0.83	0.54	0.44	0.87	0.90

Tangara fastuosa	0.79	0.81	0.67	0.52	0.79	0.87
Terenura sicki	0.84	0.88	0.84	0.68	0.73	0.94
Thalurania watertonii	0.79	0.80	0.67	0.58	0.81	0.84
Thamnophilus aethiops distans	0.79	0.81	0.60	0.47	0.79	0.98
Thamnophilus caerulescens pernambucensis	0.70	0.72	0.51	0.49	0.77	0.97
Xenops minutus alagoanus	0.73	0.80	0.59	0.64	0.77	0.80
Xiphorhynchus atlanticus	0.81	0.85	0.69	0.66	0.70	0.91

Table S9. Ensemble models evaluation based on Receiver Operating-Characteristic (ROC) and True Skill Statistic (TSS) for 30 bird taxa of the Pernambuco Endemism Center (PEC), in northeastern Brazilian Atlantic Forest.

Taxa	ROC Test. data	ROC Cut.	ROC Sens.	ROC Spec.	TSS Test. data	TSS Cut.	TSS Sens.	TSS Spec.
Automolus lammi	1	439.5	100	96.97	0.97	439	100	96.96
Caryothraustes brasiliensis (NE pop.)	1	538.5	100	98.03	0.98	531	100	97.91
Cercomacroides laeta sabinoi	1	336.5	100	97.13	0.97	330	100	97
Conopophaga cearae	0.99	493.5	100	96.09	0.96	490	100	95.97
Conopophaga melanops nigrifrons	0.99	382.5	100	91.68	0.91	376	100	91.41
Dendrocincla taunayi	1	471.5	100	99.66	1	470	100	99.63
Hemithraupis flavicollis melanoxantha	1	453.5	100	98.84	0.99	449	100	98.79
Hemitriccus griseipectus naumburgae	0.99	327.5	98.3	93.38	0.92	326	98.28	93.33
Hemitriccus mirandae	1	494.5	100	98.51	0.98	487	100	98.44
Iodopleura pipra leucopygia	1	690.5	100	99.97	1	690	100	99.97
Leptodon forbesi	0.99	323.5	100	91.6	0.92	319	100	91.45
Megascops alagoensis	1	682.5	100	99.97	1	683	100	99.97
Momotus momota marcgravianus	1	351.5	100	98.12	0.98	345	100	98.02
Myrmoderus ruficauda soror	1	520.5	100	97.7	0.98	513	100	97.57
Myrmotherula snowi	1	581	100	99.4	0.99	574	100	99.37
Penelope superciliaris alagoensis	0.99	469.5	100	91.73	0.92	467	100	91.49

Phylloscartes ceciliae	1	399.5	100	97.87	0.98	393	100	97.83
Picumnus pernambucensis	0.99	287.5	100	96.46	0.96	282	100	96.22
Platyrinchus mystaceus niveigularis	0.98	212.5	100	92.98	0.93	209	100	92.49
Pyriglena pernambucensis	0.98	184.5	95.5	95.98	0.91	184	95.46	95.88
Schiffornis turdina intermedia	0.95	211.5	100	91.41	0.91	209	100	91.04
Synallaxis infuscata	0.96	288.5	94.4	90.52	0.85	285	94.38	90.12
Tangara cyanocephala cearensis	0.98	167.5	100	95.63	0.96	166	100	95.54
Tangara fastuosa	0.97	198.5	98.4	87.67	0.86	194	98.41	87.09
Terenura sicki	0.98	238.5	97.6	96.47	0.94	233	97.56	96.25
Thalurania watertonii	0.95	182.5	100	87.84	0.88	182	100	87.78
Thamnophilus aethiops distans	0.99	303.5	100	98.16	0.98	302	100	98.07
Thamnophilus caerulescens pernambucensis	0.98	263.5	100	95.02	0.95	263	100	94.93
Xenops minutus alagoanus	0.94	185.5	100	83.19	0.83	183	100	82.84
Xiphorhynchus atlanticus	0.98	167.5	100	92.4	0.92	166	100	92.21

Foto: Marcos J. M. Dubeux