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

EFEITOS DO CLIMA E DA PAISAGEM NOS PADRÕES DE DISTRIBUIÇÃO E DE RIQUEZA DE FELINOS DA MATA ATLÂNTICA

PAULA DANYELLE RIBEIRO DE SOUZA

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PAULA DANYELLE RIBEIRO DE SOUZA

Tese apresentada ao Programa de Pós-Graduação em Ecologia e Recursos Naturais da Universidade Federal de São Carlos, como parte dos requisitos para obtenção do título de Doutora em Ciências na área de concentração em Ecologia e Recursos Naturais

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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 da candidata Paula Danyelle Ribeiro de Souza, realizada em 08/11/2024.

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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.

Dedico à minha mãe Neide, ao meu esposo Fernando e à minha filha Lara.

AGRADECIMENTOS

Agradeço à Universidade Federal de São Carlos e ao Centro de Ciências Biológicas e da Saúde pelo acolhimento institucional. À Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), pela bolsa concedida (processo #88887.519051/2020-00), que foi crucial para viabilizar minha conclusão no doutorado. Ao Programa de Pós-Graduação em Ecologia e Recursos Naturais, pela oportunidade de desenvolver minhas pesquisas ao longo de toda a pós-graduação, do mestrado ao doutorado. Ao Programa de Apoio à Pós-Graduação (PROAP) pelo auxílio financeiro que possibilitou minha participação no XI Congresso Brasileiro de Mastozoologia. A Salatiel e Maurício, a dupla dinâmica de orientadores. Eles não apenas guiaram minha trajetória acadêmica desde o mestrado, mas também aceitaram o desafio de orientar uma aluna que mora em Santa Catarina, estuda em São Paulo e integra dois laboratórios ao mesmo tempo. Essa orientação foi além do meio acadêmico, refletindo humanidade e altruísmo. A Miltinho por todo acolhimento, disponibilidade e por ser um ótimo facilitador e gestor de equipes. À Júlia Oshima por ser um anjo na minha jornada de doutorado e de ecologia espacial, sua contribuição foi além do profissional. A Maurício Vancine pelas parcerias nos trabalhos e por ser uma fonte de ensinamentos. Ao LAMAq (Laboratório de Mamíferos Aquáticos) pelo apoio físico que por muitas vezes utilizei para trabalhar. Às minhas colegas do LAMAq, Bruna e Maria Eduarda, pela parceria de campo e risadas. À Bab e Luana pelo apoio em campo, nos manuscritos e pela amizade muito enriquecedora que levarei para toda vida. Sou eternamente grata à minha mãe pelo seu incentivo e apoio constante, por seu amor imensurável, e por ser meu principal exemplo de superação e força. Meu profundo agradecimento ao meu esposo e companheiro Fernando que esteve sempre disposto a me ajudar, incentiva-me todos os dias e segura minha mão nesta caminhada. E, agradeço à minha pequena Lara que ainda não nasceu, mas que já é minha fonte de força e determinação.

“*Fazer ciência é procurar por padrões repetidos*.”

- MacArthur

RESUMO

Duas forças que mais afetam a biodiversidade, são as mudanças climáticas globais (*Global Climate Change* - GCC) e a mudança no uso e cobertura da terra (*Land use* e *Land cover Change* - LULC). Para compreendermos melhor os impactos das GCCs e da LULC sobre a biodiversidade, é fundamental analisar como esses fatores interagem com os ecossistemas terrestres, incluindo o bioma Mata Atlântica. Neste contexto, os principais objetivos desta tese foram: 1) avaliar como o clima e a paisagem influenciam, atualmente, os padrões de distribuição e de riqueza das espécies *Leopardus emiliae*, *L. guttulus*, *L. wiedii*, *Herpailurus yagouaroundi*, *L. pardalis, Puma concolor* e *Panthera onca* na Mata Atlântica; 2) investigar o quanto essa distribuição está protegida por Unidades de Conservação de Proteção Integral (UCPIs); e 3) entender como os padrões de riqueza taxonômica de felinos silvestres responderão as GCCs e a LULC na Mata Atlântica até 2050. Para alcançar os objetivos um e dois, foram utilizados Modelos de Distribuição de Espécies para estimar áreas adequadas, tanto para o cenário atual como para o ano de 2050, para distribuição de cada espécie e para a riqueza taxonômica de felinos. Os modelos foram feitos com variáveis climáticas e de paisagem, utilizando diferentes algoritmos. Todos os dados de ocorrência das espécies foram obtidos de *data papers*, outros artigos científicos, coleções científicas e bancos de dados. Os resultados indicaram que apenas 30% da Mata Atlântica são atualmente adequados para riqueza de felinos, com áreas de baixa riqueza de espécies localizadas no nordeste do Brasil e na Argentina. Apenas 9% dessas áreas adequadas são cobertas por UCPIs, evidenciando uma grande lacuna na conservação de felinos. Espécies como *L. emiliae* (1,37%) e *P. onca* (1,97%) são as menos protegidas. As projeções para 2050 indicaram que a perda de habitat adequado será de ~87%, devido à combinação das GCCs a da LULC. Adicionalmente, cerca de 61% das áreas analisadas da Mata Atlântica têm baixa permeabilidade para a riqueza de felinos atualmente. Os resultados desta tese destacam a necessidade urgente de ações de conservação na Mata Atlântica, incluindo implementação, manutenção e a expansão de UCPIs, a restauração da paisagem e o aumento da conectividade entre as áreas adequadas. Essas medidas poderão mitigar os impactos negativos das GCCs e da LULC na riqueza de felinos na Mata Atlântica.

Palavras-chave: Conservação; habitats adequados; modelo de distribuição de espécies; perda de habitat; riqueza de felinos

ABSTRACT

Two of the most significant forces affecting biodiversity worldwide are Global Climate Change (GCC) and Land Use and Land Cover Change (LULC). To better understand the impacts of GCC and LULC on biodiversity, it is crucial to analyze how these factors interact with terrestrial ecosystems, including the Atlantic Forest biome. In this context, the main objectives of this thesis were: (1) to evaluate how climate and landscape currently influence the distribution and richness patterns of the species *Leopardus emiliae*, *L. guttulus*, *L. wiedii*, *Herpailurus yagouaroundi*, *L. pardalis*, *Puma concolor*, and *Panthera onca* in the Atlantic Forest; (2) to investigate the extent to which this distribution is protected by Strict Protection Conservation Units (SPCUs); and (3) to understand how the taxonomic richness patterns of wild felines will respond to GCC and LULC in the Atlantic Forest by 2050. To achieve the first and second objectives, species distribution modeling were used to estimate suitable areas for both the current scenario and the year 2050, for the distribution of each species and for the taxonomic richness of felines. The models were created using climatic and landscape variables, employing different algorithms. All species occurrence data were obtained from data papers, other scientific articles, scientific collections, and databases. The results indicated that only 30% of the Atlantic Forest is currently suitable for feline richness, with areas of low species richness located in northeastern Brazil and Argentina. Only 9% of these suitable areas are covered by FPAs, highlighting a significant gap in feline conservation. Species such as *L. emiliae* (1.37%) and *P. onca* (1.97%) are the least protected. Projections for 2050 indicated that the loss of suitable habitat will be more pronounced under the pessimistic scenario (~87%) due to the combination of GCC and LULC. Additionally, about 61% of the analyzed areas in the Atlantic Forest have low permeability for feline richness. The results of this thesis underscore the urgent need for conservation actions in the Atlantic Forest, including the implementation, maintenance, and expansion of FPAs, landscape restoration, and increased connectivity between suitable areas. These measures could mitigate the negative impacts of GCC and LULC on feline richness in the Atlantic Forest.

Keywords: Cats richness; conservation; habitat loss; species distribution modeling; suitable habitats

SUMÁRIO

INTRODUÇÃO GERAL

Duas forças que mais afetam a biodiversidade no mundo todo são as mudanças climáticas globais (*Global Climate Change* - GCC) e as mudanças no uso e cobertura da terra (*Land-use* e *Land-cover Change* - LULC) (NEWBOLD, 2018; POWERS & JETZ, 2019). Historicamente, as atividades humanas intensas têm submetido a biodiversidade global a um estado de crise por meio da extensa conversão de ambientes naturais para uso humano (CEBALLOS et al., 2015; CHASE et al., 2020; DAVISON et al., 2021; MONASTERSKY, 2015). A perda, fragmentação e o aumento do isolamento do habitat devido ao uso da terra para urbanização, agricultura e pastoreio, são as maiores ameaças contemporâneas às espécies terrestres em todo o mundo (BANKS-LEITE; et al., 2020; FAHRIG, 2013; HADDAD et al., 2015; MAXWELL et al., 2016). Cerca de 14% das espécies foram perdidas para a LULC quando comparado aos habitats intocáveis globalmente (NEWBOLD et al., 2015) e cerca de 1.700 espécies devem se tornar ameaçadas até 2070 (POWERS & JETZ, 2019). Adicionalmente, as GCCs poderão induzir mudanças na distribuição das espécies, alterando a composição e a estrutura de habitats naturais (PREVEDELLO et al., 2019). Se não houver mitigação das GCCs, aproximadamente 35% dos animais do planeta provavelmente perderão mais de 50% de sua atual faixa climática até 2080. Sendo assim, muitas espécies da fauna, mesmo as comuns e generalistas, experimentarão a contração de áreas climaticamente adequadas (WARREN et al., 2013). Para compreendermos melhor o impacto das GCCs e da LULC sobre a biodiversidade é fundamental analisar como esses fatores interagem com os ecossistemas terrestres, incluindo o bioma/ecorregião Mata Atlântica.

Foram propostos diferentes limites territoriais para a Mata Atlântica, mas neste trabalho, adotamos o limite integrador apresentado por MUYLAERT et al., (2018) (*Figura 1*). Segundo esse estudo, 93% dos limites da Mata Atlântica estão em território brasileiro, estendendo-se principalmente pelo litoral. Mas também alcança o interior do continente e partes do Paraguai (5,3%) e Argentina (1,7%) (MUYLAERT et al., 2018). A Mata Atlântica apresenta um amplo gradiente longitudinal, latitudinal e atitudinal, variando de 0 a ~3.000 metros, e uma extensa diversidade climática conforme a classificação de Köppen-Geiger. Registra precipitações superiores a 1.000 mm^3/ano, com maiores índices nas regiões litorâneas e menores no interior do continente, acompanhadas de temperaturas amplamente variáveis (PEEL et al.,

2007). Além disso, o relevo e os tipos de solo dessa ecorregião variam bastante (EISENLOHR & OLIVEIRA-FILHO, 2015). Essas variações contribuem para tornar a Mata Atlântica uma ecorregião megadiversa e favoreceram a formação de diversos ecossistemas caracterizados por fitofisionomias distintas (CARNAVAL et al., 2009; SOBRAL-SOUZA et al., 2015; MARQUES & GRELLE, 2021; VELOSO et al., 1991). Esses ecossistemas incluem a floresta ombrófila densa, floresta ombrófila mista, floresta semidecídua, floresta decidual, pântanos, manguezais, campos rupestres, campos de altitude, florestas de araucária e ecótonos (SCARANO, 2002).

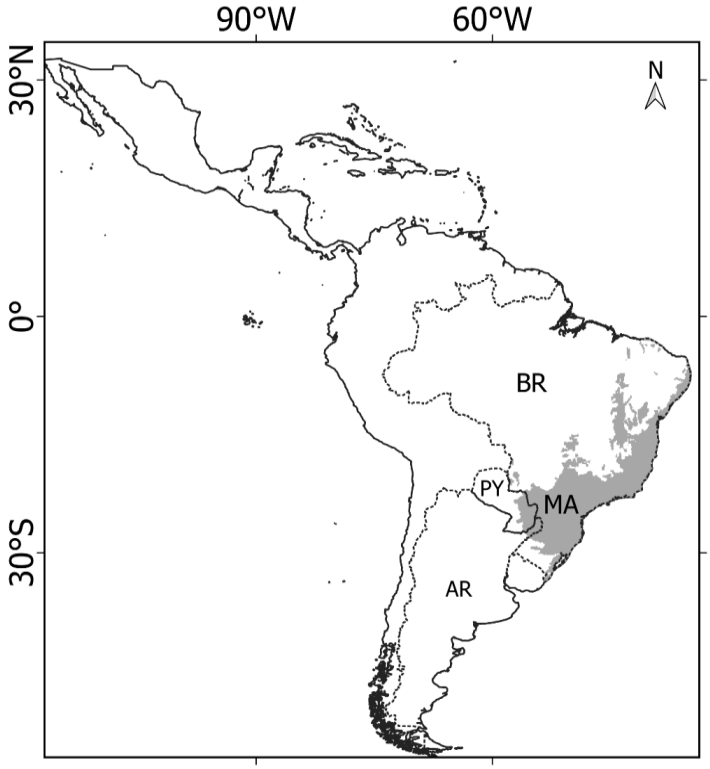

Figura 1. O limite integrador da Mata Atlântica (MA) abrangendo os países Brasil (BR), Paraguai (PY) e Argentina (AR).

A Mata Atlântica, reconhecida como um dos *hotspots* de biodiversidade mais ameaçados do mundo (MITTERMEIER et al., 2011; MYERS et al., 2000), tem apresentado um aumento líquido na cobertura florestal natural nas últimas duas décadas no Brasil (VANCINE et al., 2024). Esse aumento ocorreu provavelmente, após o estabelecimento de leis a partir de 1988 como a determinação da proteção de todos os biomas (artigo 225 da Constituição da República Federativa do Brasil de 1988), a criação de instituições de fiscalização, gestão e fomento, como por exemplo,

o Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), o Fundo Nacional do Meio Ambiente (FNMA) e o Ministério do Meio Ambiente e Mudança do Clima (MMA). Bem como, a criação do Sistema Nacional de Unidades de Conservação (SNUC), a Lei da MataAtlântica e o Novo Código Florestal. No entanto, apesar desse progresso, a pressão do desmatamento, que é mais intensa em determinadas regiões, ainda coloca a Mata Atlântica em um alto grau de ameaça (BICUDO et al., 2023). Aproximadamente 77% da vegetação natural desse bioma foi convertida para uso humano e mais de 97% de seus remanescentes têm menos de 50 ha (REZENDE et al., 2018; VANCINE et al., 2023). Sabe-se que as Áreas Protegidas representam a pedra angular nas estratégias de conservação da biodiversidade regional (LEWIS et al., 2019). Porém, a Mata Atlântica possui um grande déficit de Áreas Protegidas o que é insuficiente para conservação de muitas espécies (LEMES et al., 2014; LOURENÇO-DE-MORAES et al., 2019; RIBEIRO-SOUZA et al., 2022; RIBEIRO-SOUZA et al., 2024; OLIVEIRA et al., 2014). Esse déficit na proteção na Mata Atlântica é motivo de grande preocupação para a conservação de espécies que se encontram em algum grau de ameaça nesse mesmo bioma, como é o caso das espécies de predadores (CASO et al., 2013; MARINHO, 2015; TORTATO et al., 2018). Espécies de predadores têm experienciado extinções ou declínios em sua distribuição e abundância em muitas regiões, sendo considerados como um dos grupos mais ameaçados em todo o mundo por conta dos impactos antrópicos da LULC (CEBALLOS et al., 2015; VALENZUELA-GALVÁN et al., 2008).

De maneira geral, predadores de vários tamanhos desempenham um papel crucial na regulação dos ecossistemas (ESTES et al., 2011; HAIRSTON et al., 1960; RIPPLE et al., 2014; RITCHIE et al., 2012). Espécies que ocupam posições mais elevadas na cadeia trófica, como os predadores de topo, desempenham um controle *top-down* sobre espécies de presas (ESTES et al., 2011; TERBORGH, 1999). Assim, esses predadores podem influenciar as comunidades vegetais de maneira indireta, afetando o comportamento e a densidade das presas, levando à redução da herbivoria e ao crescimento da vegetação (HAIRSTON et al., 1960; RIPPLE & BESCHTA, 2012). Adicionalmente, felinos de maior porte são considerados espécies guarda-chuva quando se trata de definir áreas prioritárias para a conservação da biodiversidade (RAY et al., 2013). Na ausência ou declínio de grandes felinos, os mesopredadores (<15 kg) podem exercer o papel de predador de topo no ambiente, causando mudanças na cadeia alimentar (CROOKS & SOULÉ, 1999; PRUGH et al., 2009). Os

mesopredadores são predadores de importantes dispersores de sementes. Além disso, são extremamente importantes em ecossistemas insulares ou locais continentais com comunidades relativamente simples (ROEMER et al., 2009).

Na Mata Atlântica ocorrem naturalmente cinco espécies de pequenos felinos, potencialmente mesopredadores: *Leopardus emiliae, Leopardus guttulus, Leopardus wiedii*, *Herpailurus yagouaroundi* e *Leopardus pardalis* (NAGY-REIS et al., 2020; IUCN, 2022). A principal ameaça a essas espécies é a perda e fragmentação de seus habitats naturais, além da caça retaliatória devido à predação de aves domésticas (CASO et al., 2013; OLIVEIRA et al., 2008; MARINHO, 2015; SUNQUIST & SUNQUIEST, 2002; TORTATO et al., 2018). Quatro dessas cinco espécies estão distribuídas em todos os países dentro do limite integrador da Mata Atlântica, incluindo Brasil, Paraguai e Argentina, enquanto *Leopardus emiliae* é endêmica do Brasil.

Essa espécie, anteriormente considerada *Leopardus tigrinus* (SCHREBER, 1775), foi recentemente reconhecida como uma espécie plena (NASCIMENTO & FEIJÓ, 2017). *Leopardus emiliae* é a menor das sete espécies de felinos da Mata Atlântica, com uma média de 2,4 kg. (NASCIMENTO & FEIJÓ, 2017; OLIVEIRA & CASSARO, 2005). Adicionalmente, pode ser encontrada principalmente em áreas de várzea, mas também ocorre em savanas abertas e ambientes florestais (MARINHO, 2015). A área de vida de *L. emiliae* ainda é pouco conhecida, mas sabe-se que é menor que a área de vida de *L. tigrinus* (1 - 25 km²; OLIVEIRA et al., 2010). Desta maneira, o risco de extinção de *L. emiliae* é alto (NASCIMENTO & FEIJÓ, 2017) em comparação ao risco de extinção de *L. tigrinus* que é classificada como “vulnerável” pela IUCN (International Union for Conservation of Nature; PAYAN & DE OLIVEIRA, 2016) e “em perigo” no Brasil (MMA, 2022). *Leopardus guttulus* (HENSEL 1872) tem sua distribuição no Brasil, Argentina e Paraguai, com uma área de vida variando de 2 a 25 km² (OLIVEIRA et al., 2010). Seu habitat natural pode variar desde florestas até áreas abertas de savanas e vegetação de praia (CRUZ et al., 2019; GOULART et al., 2009; TORTATO & OLIVEIRA, 2005). Essa espécie é classificada como “vulnerável” pela IUCN (Oliveira et al., 2016) e no Brasil (MMA, 2022). A distribuição de *L. wiedii* (SCHINZ, 1821) se estende do México até a Argentina e Uruguai, com uma área de vida de 1 a 20 km² (OLIVEIRA et al., 2010). Ela está fortemente associada a habitats florestais e cobertura de árvores (CRUZ et al., 2019; GOULART et al., 2009; OLIVEIRA, 1998; REGOLIN et al., 2017). Atualmente, *L. wiedii* é considerada “quase ameaçada” pela IUCN, mas é “vulnerável” no Brasil (MMA, 2022), onde é amplamente

distribuída na Mata Atlântica. *Herpailurus yagouaroundi* (É. Geoffroy, 1803) possui uma ampla distribuição, desde o norte do México até a porção central da Argentina e sua área de vida chega até 100 km² (KONECNY, 1989). Essa espécie está presente em diversos tipos de habitats, incluindo áreas semi-áridas, restingas, pântanos, florestas de savana e florestas primárias (CRUZ et al., 2019; OLIVEIRA, 1994; ESPINOSA et al. 2018; NOWELL & JACKSON 1996; REGOLIN et al., 2017). *Herpailurus yagouaroundi* é classificado como “pouco preocupante” pela IUCN e “vulnerável” no Brasil (MMA, 2022). *Leopardus pardalis* tem uma ampla distribuição geográfica, estendendo-se do sul dos Estados Unidos até a Argentina e Uruguai, com uma área de vida de até 43 km². Tal espécie pode ser encontrada em uma variedade de habitats que compartilham uma característica em comum, uma cobertura vegetal bem estruturada (BIETTI et al., 2006; CRUZ et al., 2019; EMMONS, 1988; REGOLIN et al., 2017). De acordo com a IUCN, *L. pardalis* é classificado como 'pouco preocupante' (PAVIOLO et al., 2015), enquanto não consta como ameaçado no Brasil (MMA, 2022).

Além dos mesopredadores, existem duas espécies de grandes felinos na Mata Atlântica: *Puma concolor* e *Panthera onca* (NAGY-REIS et al., 2020; IUCN, 2022). *Puma concolor* (LINNAEUS, 1771) é o segundo maior felino das Américas e tem a maior extensão de ocorrência na região Neotropical em comparação a outras espécies de felinos (SUNQUIST & SUNQUIST, 2002). A área de vida varia consideravelmente ao longo de sua distribuição, de 32 a 1.031 km² (LINDZEY et al., 1987). Embora seja bastante associado à vegetação densa, indivíduos de *P. concolor* também podem habitar áreas abertas (ANGELIERI et al., 2016; LARUE & NIELSEN, 2011; LYRA-JORGE et al., 2010; MAZZOLLI et al., 2022; NOWELL & JACKSON, 1996; REGOLIN et al., 2017). É classificada como uma espécie 'quase ameaçada' pela IUCN (NIELSEN et al., 2015) e não ameaçado no Brasil (MMA, 2022). *Panthera onca* (LINNAEUS, 1758) é o maior felino das Américas, com distribuição que se estende dos Estados Unidos até a Argentina. As estimativas de área de vida de *P. onca* na Mata Atlântica variam entre 87 a 139 km² (CRAWSHAW et al., 2004; CULLEN et al., 2005). Seu habitat é tipicamente caracterizado por densa cobertura florestal (MORATO et al., 2016; PARDO et al., 2023; SANDERSON et al., 2002). *Panthera onca* é classificada como “quase ameaçada” pela IUCN (Quigley et al., 2017) e “vulnerável” no Brasil (MMA, 2022) (ver *Figura 2*). As principais ameaças a essas espécies de grandes felinos são a perda e fragmentação de seus habitats naturais,

caça retaliatória devido à predação de animais domésticos e os atropelamentos (ANGELIERI et al., 2016; BOGONI et al., 2022; CUYCKENS et al., 2017; NIELSEN et al., 2015; QUIGLEY et al., 2017).

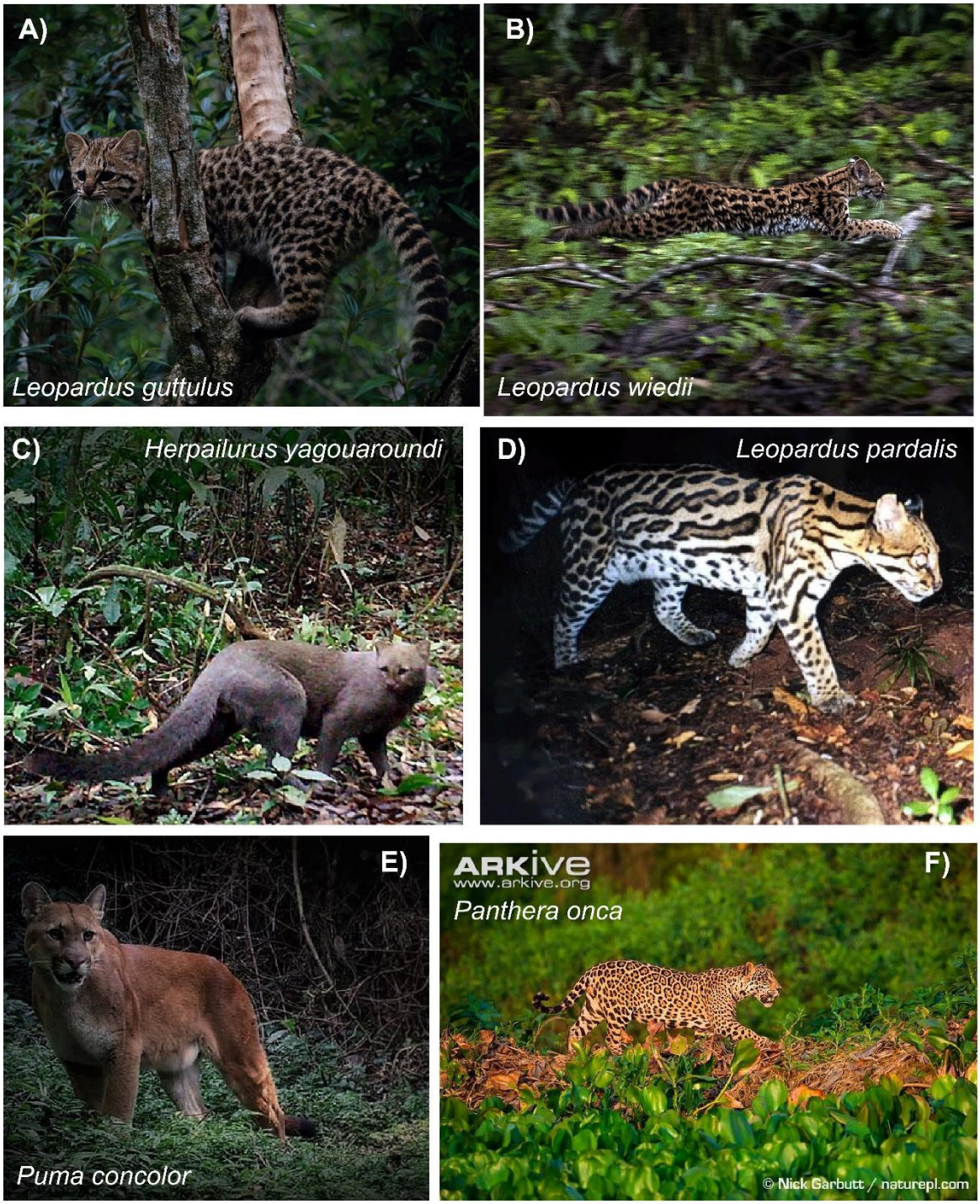

Figura 2. Espécies-alvo utilizadas nesta tese. A) *Leopardus guttulus*, foto: Junior Santos/Instituto Felinos do Aguaí; B) *Leopardus wiedii*, foto: Junior Santos/Reserva São Francisco; C) *Herpailurus yagouaroundi*, foto: Reserva São Francisco; D) *Leopardus pardalis*, foto: Reserva do Aguaí; E) *Puma concolor*, foto: Reserva São Francisco; e F) *Panthera onca*.

Compreender a distribuição geográfica, uso do habitat e como as alterações antrópicas afetam a distribuição dos felinos da Mata Atlântica é fundamental para conservação deles (WHITTAKER et al., 2005; WIENS et al., 2010). Por exemplo, o nicho ecológico de uma espécie pode passar por modificações ou permanecer conservado. Quando uma espécie mantém seu nicho diante de mudanças em seu habitat (e.g. GCCs e LULC), pode ocorrer o isolamento e extinção local e regional dessa espécie (WIENS, 2004). Entender e rastrear onde essas mudanças ocorrerão no futuro é fundamental para direcionar estratégias de conservação e mitigação que ajudem a preservar felinos da Mata Atlântica. Modelos de Distribuição de Espécies (MDEs) (ELITH & LEATHWICK, 2009) são comumente utilizados em ecologia e biogeografia (GUISAN & ZIMMERMANN, 2000; GUISAN & THUILLER, 2005; PETERSON, 2006). Os MDEs têm como objetivo principal criar representações no espaço geográfico, considerando às distribuições reais das espécies.

O uso de MDEs pode ser uma das principais ferramentas para planejar e orientar a conservação de felinos na Mata Atlântica. Alguns estudos quantificaram a importância de diferentes preditores ambientais na adequação do habitat para espécies de felinos (CRUZ et al., 2019; ESPINOSA et al., 2018; REGOLIN et at., 2017). No estudo de SARTOR et al. (2021) foi investigada a influência de variáveis ambientais (elevação, clima e paisagem) na dinâmica espacial de uma zona de hibridização de *L. guttulus* e *L. geoffroy*. No estado de São Paulo, Brasil, foram avaliados os efeitos da restauração de paisagens altamente fragmentadas e modificadas pelo homem, na adequação de habitat de *P. concolor* (ANGELIERI et al., 2016). No extremo sul da Mata Atlântica, foi avaliada a distribuição potencial de *L. pardalis* a partir de preditores climáticos e o quanto dessas áreas estão dentro de Áreas Protegidas (ARAÚJO et al., 2021). Na Argentina, pesquisadores investigaram os limites históricos de *P. onca* para estimar os efeitos das atividades humanas na distribuição dessa espécie (CUYCKENS et al., 2017). No Brasil, foram estimadas áreas adequadas para a última espécie (FERRAZ et al., 2012). Por fim, algumas pesquisas examinaram os efeitos da GCCs sobre a distribuição potencial de *L. tigrinus*, *L. guttulus* (Vale et al., 2015) e *L. pardalis* (LEHNEN & LOMBARDI, 2023).

A paisagem na Mata Atlântica tem passado por intensas mudanças (LULC), como a conversão de florestas, perda, fragmentação e isolamento de habitats, devido às atividades humanas. Esse processo associado à GCCs, poderá intensificar as ameaças à biodiversidade. Portanto, é fundamental compreender os efeitos da

conversão de habitat, principalmente das áreas florestais, e das GCCs sobre as espécies de felinos na Mata Atlântica. É importante ressaltar que a maior parte dos estudos sobre ecologia e conservação na Mata Atlântica, tem se concentrado em felídeos de maior porte, como *P. concolor* e *P. onca* (ANGELIERI et al., 2016; BOGONI et al., 2022; CRAWSHAW et al., 2004; CULLEN et al., 2005; CUYCKENS et al., 2017; LARUE & NIELSEN, 2011; LINDZEY et al., 1987; LYRA-JORGE et al., 2010; MAZZOLLI et al., 2022; MORATO et al., 2016; NIELSEN et al., 2015; NOWELL & JACKSON, 1996; PARDO et al., 2023; QUIGLEY et al., 2017; REGOLIN et al., 2017; SANDERSON et al., 2002; entre outros), enquanto as espécies de pequenos felinos têm sido pouco estudadas. Além disso, os estudos que utilizam MDEs com felinos, são escassos nesta ecorregião, e os poucos existentes geralmente consideram apenas variáveis climáticas ou de paisagem de forma isolada. No entanto, a combinação de variáveis de clima e paisagem em MDEs tem demonstrado melhor desempenho, especialmente quando se fazem projeções para cenários futuros (ESKILDSEN et al., 2013; REGOS et al., 2019). Adicionalmente, a inclusão da LULC em MDEs é essencial para projeções futuras, uma vez que a perda de habitat é um importante fator preditivo para a extinção de espécies (BETTS et al., 2017; THUILLER et al., 2004). Outra lacuna de conhecimento identificada durante a revisão desta pesquisa, é a falta de estudos que avaliem áreas adequadas e prioritárias para a conservação da riqueza de felinos na Mata Atlântica. Segundo a "*Insurance hypothesis*", a riqueza de espécies ao longo de suas distribuições desempenha um papel fundamental no funcionamento saudável dos ecossistemas (YACHI & LOREAU, 1999). Isso se aplica especialmente à riqueza de felinos, espécies fundamentais para o bom funcionamento dos ecossistemas (ESTES et al., 2011; HAIRSTON et al., 1960; RIPPLE et al., 2014; RITCHIE et al., 2012). Esses conhecimentos escassos são cruciais para embasar as decisões relacionadas à conservação dos felinos na Mata Atlântica.

Hipóteses

Capítulo II - *The future of the wild felines under climate and landscape changes in the Atlantic Forest*

Neste capítulo abordamos duas hipóteses: 1) A perda de áreas adequadas para a riqueza de felinos na Mata Atlântica será mais acentuada sob a influência das GCC e da LULC. Isso deve acontecer devido aos efeitos combinados dessas duas forças que mais afetam a biodiversidade no mundo todo; e 2) Supomos que haverá um aumento na quantidade de áreas com baixa permeabilidade no futuro em comparação com o cenário atual. A contínua pressão do desmatamento na Mata Atlântica nos leva a essa suposição.

Objetivos

Em um contexto de mudanças climáticas e de intensificação do uso e cobertura da terra na Mata Atlântica, nossos principais objetivos foram avaliar como as GCCs e a LULC afetam e afetarão os padrões de distribuição geográfica das espécies *Leopardus emiliae*, *L.* guttulus, *L. wiedii*, *Herpailurus yagouaroundi*, *L. pardalis, Puma concolor* e *Panthera onca*; e identificar áreas prioritárias com alta riqueza taxonômica.

Objetivos específicos

Capítulo I - *Under pressure: suitable areas for neotropical cats within an under protected biodiversity hotspot*

1. Modelar a distribuição potencial de sete espécies de felinos da Mata Atlântica utilizando variáveis climáticas e de paisagem;
2. Analisar as áreas adequadas com maior probabilidade de abrigar a maior riqueza taxonômica dessas espécies;
3. Quantificar a proporção destas áreas cobertas por Unidades de Conservação de Proteção Integral;

4. Propor estratégias prioritárias de conservação para os felinos da Mata Atlântica.

Capítulo II - *The future of the wild felines under climate and landscape changes in the Atlantic Forest*

1. Avaliar possíveis mudanças nos padrões de distribuição e riqueza de felinos diante da GCC e LULC.
2. Identificar a extensão e localização de áreas permeáveis e áreas de baixa permeabilidade no futuro (2050).

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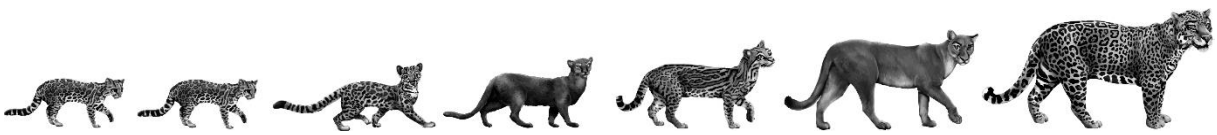
CAPÍTULO 1:
UNDER PRESSURE: SUITABLE AREAS FOR NEOTROPICAL CATS WITHIN AN UNDER PROTECTED BIODIVERSITY HOTSPOT

Publicado na revista *Remote Sensing Applications: Society and Environment*



Ilustrações: Pedro Busana.

Under pressure: suitable areas for Neotropical cats within an under protected biodiversity hotspot

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ABSTRACT

Understand which factors influence the distribution of feline species can contribute to better planning of conservation strategies in a biodiversity hotspot. We modeled the potential distribution of seven cat species occurring in the Atlantic Forest (AF). Here, we combined climatic and landscape perspectives to determine the most suitable areas considering the taxonomic richness of these cats. We also assessed the ability of fully protected areas (FPAS) to protect these cat species. The results indicated that only 30% of the AF remnants are suitable for all species. Areas with low species richness were located in Argentina and northeastern Brazil. For taxonomic richness, the Serra do Mar (45.89%) and the Araucaria (27.90%) sub-regions had the highest suitable areas, followed by the Interior sub-region (21.89%). The Brejos Nordestinos and Pernambuco sub-regions had less than 1% suitability. Considering taxonomic richness, only 9% of suitable areas are covered by FPAs. *Leopardus emiliae* (1.37%) and *Panthera onca* (1.97%) had the lowest values of suitable areas covered by FPAs. The other species of cats are also under low protection (*L. guttulus* = 5.38%, *L. wiedii* = 5.71%, *Herpailurus yagouaroundi* = 6.70%, *L. pardalis* = 3.85%, and *Puma concolor* = 4.94%). We reveal that a low percentage of suitable areas are currently fully protected. This study also provides important conservation measures to be implemented in different AF sub-regions. These findings may help in the planning, maintenance, and implementation of FPAs through restoration programs and the establishment of ecological corridors.

Keywords: Atlantic Forest, biodiversity conservation, habitat loss, species distribution model, species richness

INTRODUCTION

The Neotropics have a high degree of endemism and harbor the largest remnants of natural areas on the planet (Loyola et al., 2009), including some global biodiversity hotspots (Oliveira et al., 2016). Among these hotspots, the Atlantic Forest (hereafter AF) has been the focus of many studies due to its high species richness, endemism, and degree of threat (Mittermeier et al., 2011; Joly et al., 2014). Species extinction in the AF is directly related to forest loss, urban and agriculture expansion, climate change, and invasive species (Bellard et al., 2014; Estrada et al., 2017; Bello et al., 2021). Currently, the AF has about 26% of the original forest cover and highly isolated fragments (Rezende et al., 2018). Nevertheless, the AF harbors about 321 mammal species, including 89 endemic species (Graipel et al., 2017).

Human-caused environmental disturbances are the primary pressures responsible for the loss of species, ecological functions, and ecosystem services in the AF (Bogoni et al., 2018, 2022; Cruz et al., 2018; de Lima et al., 2020). These disturbances affect species richness, distribution and abundance, as well as interspecific interactions (Fahrig, 2003; Gutiérrez et al., 2019; Lewis et al., 2015). Moreover, biodiversity information remains scarce, outdated, or inaccurate for many regions in the AF, including protected areas (Oliveira et al., 2017). These issues make it difficult to efficiently assess the conservation status of species, particularly carnivorous mammals (Oliveira et al., 2016). Historically, carnivorous mammals have undergone extinctions or declines in distribution and abundance in many regions due to habitat loss, forest fragmentation, and illegal hunting (Valenzuela-Galván et al., 2008; Ceballos et al., 2015). Accordingly, there is great concern about the conservation status of neotropical felines, which are responsible for the maintenance of important ecological processes and ecosystem functions in tropical forests (Portela and Dirzo, 2020).

Neotropical wild cats (hereafter “cats”) are top predators, and by controlling prey populations, they influence vegetation structure, composition, and abundance, as well as ecological succession (Terborgh et al., 2001; Estes et al., 2011; Morgan et al., 2017). Furthermore, larger body mass felines (e.g., the puma and jaguar) are considered umbrella species in defining priority areas for biodiversity conservation (Jenkins et al., 2013; Ray et al., 2013). Seven species of Neotropical cats (Felidae) occur in the AF (Nagy-Reis et al., 2020; IUCN, 2022), all of which are experiencing

reductions in range and population size (IUCN, 2022). Most conservation studies conducted in the AF have focused on the jaguar (Panthera onca) and puma (*Puma concolor*), which are the largest cats (see Lyra-Jorge et al., 2010; Morato et al., 2016). Therefore, small, cryptic cats, such as the southern tiger cat (*Leopardus guttulus*), the margay (*Leopardus wiedii*), and the jaguarundi (*Herpailurus yagouaroundi*) remain poorly studied and lack information regarding their biology, ecology, and conservation (Macdonald et al., 2010; Nagy-Reis et al., 2017; IUCN, 2022).

According to the “insurance hypothesis”, species richness across their range is an important factor influencing the proper functioning of ecosystems (Yachi and Loreau, 1999). Therefore, conservation efforts should consider species richness to establish priority areas for conservation (Ceballos and Ehrlich, 2006). Most studies on the effects of habitat loss and forest fragmentation on species richness in the AF have been conducted at small (local or regional) scales. These results have been constantly used to infer large-scale impacts on biodiversity (Sobral-Souza et al., 2021). Recent publications of species occurrence databases make large-scale studies possible, thus contributing to fill these knowledge gaps. Species Distribution Modeling (SDM) has been widely used to predict the occurrence and areas of higher richness (Fuller et al., 2007; Santos et al., 2020; Sobral-Souza et al., 2021) and to identify priority areas for conservation (Brooks et al., 2006; Oshima et al., 2021; Mittermeier et al., 2005; Ribeiro-Souza et al., 2022). In general, SDM relates occurrence records with environmental variables to identify suitable areas that allow populations of a given species to persist (Elith and Leathwick, 2009).

Here, we model the potential distribution of seven cat species in the AF using climatic and landscape variables. We also analyze the suitable areas most likely to harbor the highest taxonomic richness of these species. Moreover, we quantified the proportion of these areas covered by fully protected areas (FPAs). Lastly, based on these data, we suggest strategies for the conservation of cats in the AF areas identified as priorities.

MATERIAL AND METHODS

Study area

Different territorial boundaries have been proposed for the AF, but in this work, we adopted the integrative boundary proposed by Muylaert et al. (2018) (Fig. 1). According to this boundary, the AF covers 90% of its territory in Brazil, extending mainly along the coast but also reaching the inland areas of the continent and parts of Paraguay and Argentina (Muylaert et al., 2018). The AF exhibits a broad longitudinal, latitudinal, and altitudinal gradient, ranging from 0 to ~3000 m, and extensive climatic diversity according to the Köppen-Geiger classification. It records precipitation exceeding 1000 mm^3/year, with higher indices in coastal regions and lower ones in the inland areas, accompanied by widely variable temperatures (Peel et al., 2007). Additionally, the topography and soil types of this ecoregion vary considerably (Eisenlohr and Oliveira-Filho, 2015). These variations have favored the formation of diverse ecosystems characterized by distinct phytophysiognomies (Carnaval et al., 2009; Sobral-Souza et al., 2021; Veloso et al., 1991). It is known that Protected Areas represent a cornerstone in regional biodiversity conservation strategies (Lewis et al., 2019). However, the AF has a significant deficit of Protected Areas, which is insufficient for the conservation of many species (Lemes et al., 2014; Lourenço-de-Moraes et al., 2019; Ribeiro-Souza et al., 2022; Soares-Filho et al., 2014).

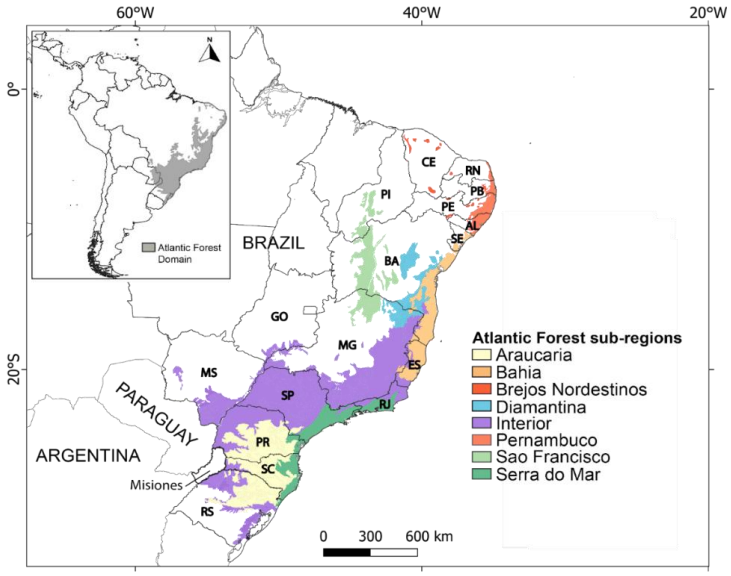

Fig. 1. Atlantic Forest sub-regions by Silva and Casteleti (2003). See also the province of Misiones in Argentina and the Brazilian states names: AL = Alagoas, BA = Bahia, CE = Ceará, ES = Espírito Santo, GO = Goiás MG = Minas Gerais, MS = Mato Grosso do Sul, PE = Pernambuco, PB = Paraíba, PI = Piauí, PR = Paraná, RJ = Rio de Janeiro, RN = Rio Grande do Norte, RS = Rio Grande do Sul, SC = Santa Catarina, SE = Sergipe and SP = São Paulo.

Selection of occurrence locations

We compiled 20,000 feline occurrence records for the entire Neotropical region. For this, we used the open databases Atlantic Mammals (Souza et al., 2019), Atlantic Camtraps (Lima et al., 2017) and Neotropical Carnivores (Nagy-Reis et al., 2020); data available in the literature (see Sartor et al., 2021; Nascimento and Feijó, 2017); and the virtual databases GBIF (www.gbif.org), SiBBr (www.sibbr.gov.br), PortalBio (portaldabiodiversidade.icmbio.gov.br) and speciesLink (specieslink.net). We only considered records obtained through camera traps, roadkill, radiotelemetry, active search, transects, and museum records. We only considered data collected from the year 2000 onwards and with precise geographic coordinates (better than 1 km precision). Next, we removed duplicate or overlapping occurrence records for each species. To minimize spatial autocorrelation, which could inflate model predictions (Araújo and Guisan, 2006; Veloz, 2009), we selected only one occurrence record within each 1 km2 pixel for the small cats (*H. yagouaroundi*, *Leopardus emiliae*, *L. guttulus*, *L. pardalis*, and *L. wiedii*) and 5 km2 pixels for the *P. onca* and *P. concolor*. The

occurrence records that did not meet our criteria were disregarded from this study. This selection was necessary because large felid species such as *P. concolor* and *P. onca* have larger home ranges than small felids (Crawshaw et al., 2004; Lindzey et al., 1987) and can have a scale of effect (Alegre et al., 2023; Zeller et al., 2014) that is greater than other small felids when we consider resource selection analysis. Therefore, large felids can cover long distances per day, and the same individual may be recorded in different camera traps. At the end of the data selection, we obtained 5284 cat occurrence records for the Neotropical region (see https://github.com/LEEClab/ms_ neotropical_cats_suitability). Within these occurrence records for the Neotropical region, the following were used in the climatic models: 23 for *L. emiliae*, 381 for *L. guttulus*, 693 for *L. wiedii*, 870 for *H. yagouaroundi*, 1,821 for *L. pardalis*, 1,779 for *P. concolor*, and 677 for *P. onca*. Within the expanded limit of the AF (Muylaert et al., 2018), we obtained 2263 records. To generate landscape models within the AF, we used 19 occurrence data for *L. emiliae*, 381 for *L. guttulus*, 244 for *L. wiedii*, 422 for *H. yagouaroundi*, 597 for *L. pardalis*, 464 for *P. concolor*, and 73 for *P. onca*. (Figure appendix B.1).

Climate, environmental and landscapes predictors

We obtained 19 bioclimatic variables from WorldClim v2.1 (www.worldclim.org). These variables were generated from interpolated data recorded between 1950 and 2000 (Hijmans et al., 2005). In addition to climatic variables, we also used topographic, landscape, and human influence variables. The topographic variables were the terrain ruggedness index (median and standard deviation of the terrain ruggedness index, Amatulli et al., 2018) and terrain slope (median and standard deviation of the slope, Amatulli et al., 2018). The landscape variables included the percentage of tree canopy cover (Hansen et al., 2013), habitat heterogeneity (coefficient of variation of Enhanced Vegetation Index data and Shannon index of Enhanced Vegetation Index data, Tuanmu and Jetz, 2015), and water frequency (Feng et al., 2016). The human influence variable was human density (population density per 1 km²; https://sedac.ciesin.columbia.edu/data/ collection/gpw-v4/documentation) and human footprint (Venter et al., 2016). We used the topographic, landscape, and human influence variables to compose our landscape model and the bioclimatic variables to compose the climatic model. All layers were at 30 arc sec resolution (~1 km at the

equator). To reduce the degree of uncertainty associated with the model results (Dormann et al., 2008), we tested all variables for multicollinearity using a variance inflation factor (VIF < 2.0; Dormann et al., 2013) (Table appendix A.1). Five variables were selected for the landscape models: terrain ruggedness, percentage of tree canopy cover, habitat heterogeneity, water frequency and human density. Four variables were selected for the climatic models: mean temperature of the wettest quarter (BIO8), mean temperature of the driest quarter (BIO9), precipitation of the wettest month (BIO13) and precipitation of the coldest quarter (BIO19) (Table 1).

Table 1. Values from Variance Inflation Factor (VIF). Variables used in the species distribution models (*).

Variable	**Abbreviation**	**VIF**
Coefficient of Variation of EVI data - heterogeneity	Habitat heterogeneity*	1.23
Water Frequency - Global Inland Water	Water Frequency*	1.02
Population density per 1km²	Human density*	1.21
Standard deviation terrain ruggedness index	Terrain ruggedness*	1.15
Percent of treecover from 2000	Tree cover*	1.27
Mean Temperature of Driest Quarter	BIO09*	1.61
Precipitation of Wettest Month	BIO13*	1.38
Precipitation of Coldest Quarter	BIO19*	1.77
Mean Diurnal Range	BIO02	1.82
Mean Temperature of Wettest Quarter	BIO08*	1.33
Isothermality	BIO03	1.90

Modeling procedures

We separately developed landscape and climate-based SDMs for each species. To include the full climatic niche of the species, the climatic models were generated for the entire Neotropical region following the delimitation proposed by Morrone (2014). Afterwards, they were clipped to fit the expanded limit of the AF in Brazil, Argentina, and Paraguay, as well as the landscape models (Muylaert et al., 2018). We used the ensemble forecasting approach to test different methodologies on a set of predictions (Araújo and New, 2007). To accomplish this, we employed three algorithms utilizing varying techniques: (i) machine learning method that estimates species distributions by finding the maximum entropy distribution, MaxEnt (Phillips et al., 2006); (ii) random forest, an artificial intelligence method that combines predictive regression tree predictors (Breiman, 2001); and (iii) multiple discriminant analysis (MDA) method, a classification based on multiple models (Hastie et al., 1994). We selected 1000 background points, 70% of occurrence data for training the algorithm and 30% for external testing, randomized 10 times to generate less biased models (k-folding technique, k = 2). In the end, we obtained 30 climatic and 30 landscape models for each species (10 × 3 algorithms). The efficiency of the models was evaluated using the True Skill Statistic (TSS) test (Allouche et al., 2006). The TSS test generates values between −1 and 1, with values closer to 1 indicating perfect agreement, and values of zero or less indicating a performance no better than random (Allouche et al., 2006). The area under the ROC curve (AUC; Hanley and McNeil, 1982) values were also presented as an additional assessment (Table 0.2). Models with AUC values > 0.90 are excellent; 0.80 - 0.90 are good; 0.70 - 0.80 are reasonable; 0.60 - 0.70 are poor, and 0.50 - 0.60 are failing (Araujo et al., 2005). All models were run using the “sdm” package (Naimi and Araújo, 2016) in the R environment. From the generated models, we estimated the suitable areas for each species from a maximum decision threshold that maximizes the sum of sensitivity and specificity (Max SSS) (Manel et al., 2001). This approach is one of the most recommended for measuring the performance of SDMs (Liu et al., 2005, 2013; Shabani et al., 2018). Following the maximization of the sum of sensitivity-specificity, the higher the sensitivity, the lower the false absence rate, and the higher the specificity, the lower the false presence rate. Thus, we selected areas with higher climate and landscape suitability as priorities for conservation. We

then constructed binary maps, in which 0 = areas with inadequate climate and landscape and 1 = areas with adequate climate and landscape.

EcoLand and cat species richness in the AF

To measure the area with climatic and landscape suitability for each species, we ran an EcoLand analysis (Sobral-Souza et al., 2021), in which we constructed a composite map and a comparative map of the results of the two models generated separately. For this, we created maps with four different habitat suitability classes per species using the following criteria: (i) high climatic and landscape suitability - areas (pixel) with values > 0.5 for both models, (ii) high climatic and low landscape suitability - areas with values > 0.5 for the climatic model and ≤ 0.5 for the landscape model, (iii) high landscape and low climatic suitability - areas with values > 0.5 for the landscape model and ≤ 0.5 for the climate model, and (iv) low climatic and landscape suitability - areas with values ≤ 0.5 for both models.

To elaborate the taxonomic richness maps along the AF, we summed the binary maps of the seven species separately for each suitability type (climate and landscape). Next, we summed and reclassified the two resulting maps (one of richness based on climate and another based on landscape), generating a map with the estimated number of species (richness) per pixel (Figure appendix B.2). In the richness scatterplot, the X-axis represents the richness predicted by the climate, and the Y-axis the richness predicted by the landscape. In the EcoLand scatterplot, we created four categories based on climate and landscape (Table 2).

Table 2. Species richness criteria for the EcoLand scatterplot categories.

Category	**Climate richness**	**Landscape richness**
Low climate and low landscape	< 4 species	< 4 species
Low climate and high landscape	< 4 species	≥ 4 species
High climate and low landscape	≥ 4 species	< 4 species
High climate and high landscape	≥ 4 species	≥ 4 species

We calculated the areas predicted by the final taxonomic richness maps in km², selecting only suitable areas for more than four species. We also calculated the areas using the final EcoLand maps, considering only areas with high climatic and landscape suitability for each species using QGIS. The calculations were then tabulated considering the total suitable area for taxonomic richness, values by AF sub-regions (Silva and Casteleti, 2003, Fig. 1), and FPAs. The following categories were included: Ia (Strict Nature Reserve), Ib (Wilderness Area), II (National Park), and III (Monument or natural feature) (IUCN, 2001). Data on protected areas were obtained from protectedPlanet (Juffe-Bignoli et al., 2014; https://www.protectedplanet.net/en).

RESULTS

Climate and landscape-based models

The potential species distribution models demonstrated performance with TSS ranging from 0.36 to 0.73 (climate) and 0.34 to 0.92 (landscape). Regarding our AUC results, we obtained models with reasonable performance for climate (AUC = 0.73) and landscape (AUC = 0.71) and good performance for climate (AUC = 0.82) and landscape (AUC = 0.89) (Table appendix A.2).

Species richness and protected areas

In the climatic models, areas with the highest richness indicated suitability for seven species, which were concentrated mainly in small patches within the Interior sub-region of southern Brazil. Areas with the second highest richness (six species) were observed in the Araucaria, Serra do Mar, and Interior sub-regions. The results predicted by the landscape also estimated suitable areas for up to seven species, especially in the Misiones region in Argentina and the Serra do Mar and Araucaria sub-regions in Brazil (Fig. 2).

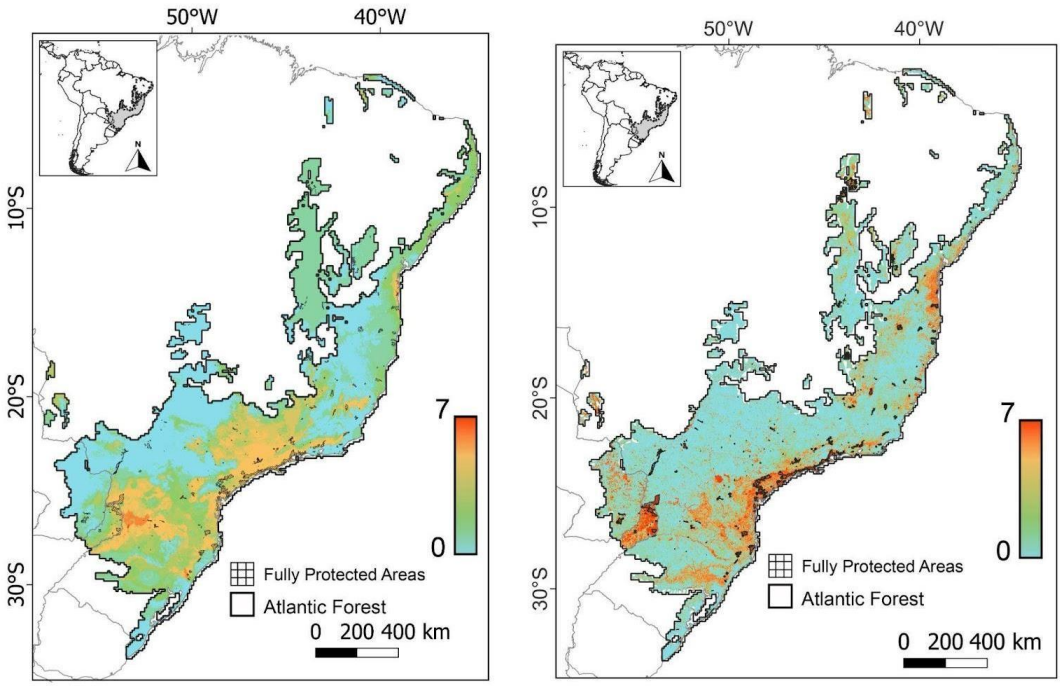

Fig. 2. Distribution of Neotropical cat richness in the Atlantic Forest according to climatic and landscape models.

The results considering species richness, classified by the EcoLand method, indicated that only 30% of the AF remnants are suitable for all analyzed species. For seven cat species, suitable areas were concentrated mainly in remnants within the Serra do Mar subregion (from southeastern to southern Brazil) and in some patches on the border of Brazil and Argentina. Areas with low species richness (1 - 3 species) were located in Argentina and southern and northeastern Brazil (Fig. 3). For the areas with higher taxonomic richness (> 4 species), the Serra do Mar (45.89%) and Araucaria (27.90%) sub-regions had the highest suitable areas. The Brejos Nordestinos and Pernambuco sub-regions had less than 1% suitability. Considering this higher taxonomic richness, only ~ 9% of suitable areas are covered by FPAs (*Table 3*). *Leopardus emiliae* (1.37%) and *P. onca* (1.97%) had the lowest values of suitable areas covered by FPAs. The other species are also under low protection (*L. guttulus* = 5.38%, *L. wiedii* = 5.71%, *H. yagouaroundi* = 6.70%, *L. pardalis* = 3.85%, and *P. concolor* = 4.94%; Table appendix A.3).

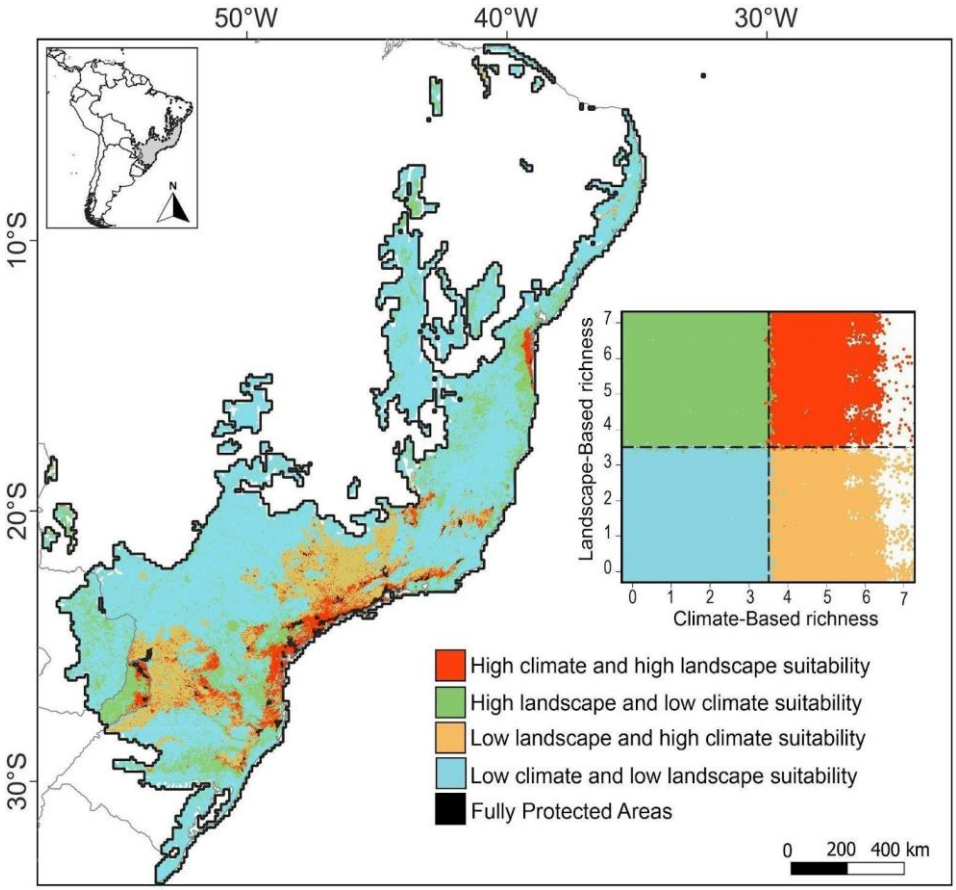

Fig. 3. Distribution of Neotropical cat richness in the Atlantic Forest according to the EcoLand model.

Table 3. Suitable areas and percentage predicted by the climate and landscape (EcoLand) for higher taxonomic richness (≥ 4 species) areas in the Atlantic Forest (AF). We present the total suitable areas for each AF sub-region and the total suitable areas covered by fully protected areas (FPAs).

Atlantic Forest sub-region	Total		FPAs	
	km²	%	km²	%
Climate	415,219	100.0	16,330	3.93
Landscape	351,159	100.0	11,383	3.24
EcoLand				
Araucaria	83,849	27.90	1,395	1.66
Bahia	10,647	3.54	204	1.92
Brejos Nordestinos	972	0.32	20	2.06
Serra do Mar	137,917	45.90	19,774	14.34
Pernambuco	1,547	0.51	37	2.39
Interior	65,632	21.80	6,819	10.39
Total	**300,564**	**100.0**	**28,249**	**9.40**

DISCUSSION

In this study, we present SDMs of suitable areas predicted by climate and landscape for seven cat species in the AF. Our results show that only ~30% of the AF remnants are suitable for cat species. Furthermore, over 90% of suitable areas are located outside FPAs and in small, isolated forest patches. These findings reinforce the impacts of habitat loss and fragmentation in the AF and high-light their negative effects on the conservation of wild cats in this ecoregion. Based on our findings, we classify regions with different suitability levels and suggest punctual and essential measures. Our results address several goals of the National Action Plan for the Conservation of Small Cats (NAP Small Cats) and the National Action Plan for the Conservation of Big Cats (NAP Big Cats). Above all, our results contribute to filling existing knowledge gaps in the AF by identifying potential habitats for forest-dependent cats based on data compiled at the biome level and related to climatic and landscape variables. Thus, we provide new information that is essential for decision-making regarding cat conservation.

Although higher resolution landscape data could provide a more detailed perspective of cat habitat suitability in our study, which can be considered a limitation of it, the ocurrence data currently available for modeling the distribution of cats in the AF is not yet systematized along the entire biome. Therefore, higher resolution occurrence data and frequent monitoring will also be necessary for more detailed predictions. To our knowledge, our predictions provide the best current overview of the status of suitable areas for neotropical cats in the AF considering the datasets based on presence-only data.

Climate and landscape based models

Camera traps are potentially more effective at night (Srbek-Araujo and Chiarello, 2005), and most felids are predominantly nocturnal (Graipel et al., 2019); however, the species *H. yagouaroundi*, is predominantly diurnal (Giordano 2016). Our study includes 870 records of this species. Previous studies indicate that *H. yagouaroundi* is a habitat generalist and is associated with open areas (Caso et al., 2015; Regolin et al., 2017), which may explain the lower performance of our landscape models. There are few records of the occurrence of *H. yagouaroundi* obtained using

camera traps in open areas, especially due to the risk of loss of such equipment (Magioli et al., 2022).

The wide geographic distribution may have influenced the lower TSS values for the climatic models of *H. yagouaroundi*, *L. pardalis*, *P. onca* and *P. concolor*. Since climatic variables influence the distribution of these species more strongly at first-order selection (Johnson, 1980), landscape variables are essential to predict suitable remnant areas at finer, second-order levels. Our results uncover climatically suitable areas for *L. emiliae* in the northern AF and *L. guttulus* in the southern AF (Figure appendix B.17 and Figure B.18, respectively). These findings further support the definition of the two valid species, *L. guttulus* and L. tigrinus (Nascimento, 2010; Trigo et al., 2013). The existence of large suitable fragments (in terms of climate and landscape) makes Serra do Mar a priority area for the protection of Brazilian endangered species, such as *L. guttulus* and *H. yagouaroundi*.

For *L. wiedii*, we detected (as predicted by the landscape models) large continuous fragments in the Serra do Mar potentially suitable for the species (Figure appendix B.19). In contrast, these same fragments have low climatic suitability for the species, making it necessary to monitor these areas under future climate change scenarios (Figure appendix B.5). For *L. guttulus*, our models suggest suitable areas more concentrated in the Serra do Mar and Araucaria (Figure appendix B.18). However, this species has already been recorded in altered areas, as long as there was adjacent native vegetation that allowed its movement across the landscape (Oliveira Santos et al., 2012). In this case, an important conservation action could be to focus on forest restoration to increase the functional connectivity between the forest fragments where the species still occur.

Although *P. concolor* occurs throughout most of South America and shows more generalist habitat selection, our models indicate that suitable areas are limited to the large continuous fragments in the Serra do Mar and small portions in the Araucaria and Interior sub-regions. The greater use of landscapes with forest cover was shown in another study carried out in the AF (Regolin et al., 2017). In the Interior sub-region in southeastern Brazil, there is high climatic suitability for the species, but fragments with high landscape and climatic suitability are smaller and far apart. In northeastern Brazil, the models for many regions indicate low climatic suitability, and the remaining fragments (Bahia, Brejos Nordestinos, and Pernambuco sub-regions) with landscape suitability occurring close to the coast (Figure appendix B.22).

Our model exhibits few suitable areas for *L. emiliae* predicted by climate and landscape (Figure appendix B.17), thus requiring greater attention for its conservation status. *Leopardus pardalis* is widely distributed throughout South America (except Chile), but our models indicate a considerable reduction of areas that are originally suitable. The areas with high climatic and landscape suitability for this species are located in the Serra do Mar, Araucaria, Bahia, and Interior sub-regions (Figure appendix B.21). Despite the reduction of originally suitable areas, our results show that *L. pardalis* is still the Neotropical cat with the largest suitable area (high climatic and landscape suitability; area = 305,000 km²) in the AF (Table appendix A.3), which reinforces its important role as a mesopredator in this ecoregion (Moreno et al., 2006; Silva-Pereira et al., 2011).

Finally, our models for *P. onca* indicate a suitable area (high climatic and landscape suitability) of only 6546 km2 (Figure appendix B.23). According to Paviolo et al. (2016), *P. onca* has lost about 85% of its habitat and has practically disappeared from northeastern, southeastern, and southern Brazil (Sanderson et al., 2002; Tôrres et al., 2008). In addition to the great loss of suitable forest habitats, the remaining areas are highly fragmented, reaching 93% loss of its connectivity, mainly in Brazil and Paraguay (Pardo et al., 2023).

Species richness and protected areas

Areas with high richness (> 4 species) and high climatic and landscape suitability are located in the AF's most continuous or most connected remnants. This is the case of the Serra do Mar, which is considered one of the most preserved sub-regions in the AF with a high fauna species richness (Carnaval et al., 2009; Silva and Casteleti, 2003) and a center of endemism for species of marsupials, primates, and rodents (Costa et al., 2000). Our findings reinforce the importance of the Serra do Mar sub-region, especially considering the ecological importance of cats and their degree of threat, mainly due to habitat loss and hunting (Bogoni et al., 2022; Valenzuela-Galván et al., 2008). Although this sub-region is the most covered by FPAs in the AF, the current protected area (~14% of the total area) may be insufficient to conserve its biodiversity. The expansion of FPAs in the Serra do Mar could enable the maintenance of suitable areas, thus achieving one of the goals for the conservation of *P. onca* and *P. concolor* (Brasil, 2018).

The suitable areas in the Araucaria, the second sub-region with the highest potential richness of cats, are very fragmented and poorly protected (~2% of FPAs). Some of the FPAs are located on the border of Brazil and Argentina, which may make the conservation of cat species beyond borders unfeasible. Therefore, both countries must cooperate to conserve this important region. The maintenance of *P. onca* populations in the southern Brazilian AF is probably accomplished by migrating individuals from the Misiones region, where a larger amount of suitable habitat is still available. Associated with measures to mitigate poaching and conflicts arising from the predation of domestic livestock (Mazzolli et al., 2002), the areas bordering Argentina can be recolonized by young dispersing individuals. In fact, this scenario has been identified in the Iguaçu National Park in recent decades. In the Bahia sub-region, we observed a continuous fragment with climatic and landscape suitability. This area is more isolated from the other suitable areas in the southern AF and is not covered by FPAs. Therefore, the persistence and dispersal of cats among these regions may be impaired, especially for small-sized forest species such as *L. guttulus* and *L. wiedii* (Cruz et al., 2019). The Interior sub-region, with only 7% of the original forest cover (Ribeiro et al., 2009), is dominated by areas of low potential climatic and landscape richness. The exceptions are areas near the Serra do Mar, where there is high climatic suitability between the states of São Paulo and Minas Gerais and some patches of remnant fragments near Diamantina and Bahia.

The Diamantina, Pernambuco, and São Francisco sub-regions have small, fragmented areas with high landscape suitability, low climatic suitability, and few FPAs. Moreover, these sub-regions are transition zones between biomes such as Caatinga and Cerrado, which also harbor Neotropical cat populations (Oliveira et al., 2016). The Brejos Nordestinos region has a relatively small area compared to other sub-regions and a naturally dispersed distribution (Ribeiro et al., 2009), presenting mostly areas of low climatic and landscape suitability, small remaining forest fragments, and few FPAs.

Implications for conservation and protected areas

Increased human pressure on biodiversity conservation has caused impacts such as changes in the activity pattern of mammals (Gaynor et al., 2018), roadkill (Abra et al., 2021), poisoning and slaughter (Lima et al., 2017), and poaching (Peres et al., 2016). Consequently, biodiversity loss has increased in areas where species still occur

(Galetti et al., 2017; Peres et al., 2016). Thus, strategies must be created to halt the loss of biodiversity by planning priority areas for conservation and creating new FPAs. Recent studies have addressed the prioritization of large-scale conservation areas, greatly contributing to the goals of biodiversity conservation and the understanding of their limitations. These studies suggest that, by expanding conservation efforts, part of the AF will hold great potential to increase biodiversity protection (Pouzols et al., 2014; Luby et al., 2022). In view of our results, we suggest some specific measures for the conservation of cats in the AF.

Areas with high climatic and low landscape suitability (Araucaria, Serra do Mar, and Interior) need restoration of natural forest cover to prevent loss of biodiversity in the AF. Moreover, creating functionally connected ecological corridors is necessary to increase the connectivity and species dispersal between fragments, especially in the Bahia and Interior sub-regions, thus increasing the persistence of forest species populations (Frankham, 1996). In the Araucaria sub-region, we observed large areas with climatic suitability for cat richness among fragments suitable for landscape. The restoration of the landscape and the creation of ecological corridors will enable the connection between patches in the Araucaria, according to priority conservation actions previously suggested (Brasil, 2018). Thus, there will be a large extension suitable for the climate and landscape near the Iguaçu National Park and the Araucárias National Park. The same is true for the Interior sub-region, especially in southeastern Brazil, where there is a large area (orange area, Fig. 3) near FPAs such as Campos do Jordão State Park, Itatiaia National Park, and Cantareira State Park. A recent study has shown the importance of small habitat patches for biodiversity (Riva and Fahrig, 2023). We consider that expanding the connection between small fragmented areas and protected areas is essential to enable the rescue effect and the recomposition of communities through the top-down effect promoted by cats in the AF (Elton, 1927; Gonzalez et al., 1998).

Many species may migrate in search of climatically suitable habitats under climate change scenarios (Singh, 2020), which will require the existence of other suitable landscapes to enable dispersals. Areas with low climatic and high landscape suitability, such as Misiones (Argentina), Araucaria, Bahia, and part of the Serra do Mar (Brazil), may become climatically suitable in the future. Therefore, additional studies on the effects of climate change on cat species in the AF are needed. Butti et al. (2022) showed that carnivores are undergoing the greatest habitat loss compared

to other mammalian orders. Areas with low climatic and high landscape suitability (green areas - Fig. 3) are located mainly in southern Brazil, close to FPAs. These areas are extremely important because they provide forest cover, primarily for widely distributed Neotropical cats, covering a wide climatic range (Macdonald et al., 2010).

Human-induced landscape changes compromise ecosystem stability and resilience due to reduced species richness and functional groups (Tscharntke et al., 2012). To avoid such problems and enable the persistence of wild cats, preserving areas that have both climate and landscape suitability in the AF is necessary. We consider the regions with high habitat suitability for more species as priorities for conservation. These conservation measures can inhibit the loss of suitable habitat, the main factor influencing the local extinction of about 75% of mammal species (Bogoni et al., 2022). New FPAs should be strategically created, considering the expansion of biodiversity protection and connectivity between existing FPAs.

Our results endorse the classification of the Serra do Mar sub-region as an extremely high-priority area for conservation (Brasil, 2018). Suitable habitats that are connected and protected by FPAs will reduce hunting pressure, one of the main drivers of the local extinction of cat species (Bogoni et al., 2022; Gallego-Zamorano et al., 2020), and will enable increased gene flow and effective population sizes (Fahrig, 2003). We also draw attention to the priority areas for conservation on the border between Brazil and Argentina, which have high suitability predicted by climate and landscape and harbor prey populations and potential areas for their distribution (Paviolo et al., 2018). The protection of habitats of threatened species (e.g., Ribeiro-Souza et al., 2022) contributes to the conservation of other species dependent on the same habitat, such as cats, which are a key group in an ecosystem. Studies conducted in the Americas have shown the importance of maintaining the connectivity among protected areas beyond national borders (Dudley et al., 2014; Thornton et al., 2020; Ribeiro-Souza et al., 2022). The Iguaçu National Park (between Brazil and Argentina), the Mesoamerican Biological Corridor (Hilty et al., 2012), and the transboundary conservation measures in of the Gran Chaco (https:// www.wwf.org.py/que_hacemos/proyectos/pacha/) are prime examples of this type of conservation.

CONCLUSIONS

We show for the first time how integrated landscape and climatic models can be used to estimate habitat suitability and important conservation areas for Neotropical cats in the AF. We reveal that only a low percentage of suitable areas are currently fully protected. This study also provides important conservation guidelines based on suitability models for specific sub-regions in the AF that could be used by stakeholders. These findings may help in planning the maintenance and implementation of FPAs through restoration programs and the establishment of ecological corridors in this decade. We also suggest that future conservation efforts could be focused not only on the conservation of cat richness suitable areas but also on new modeling approaches considering the presence and potential distribution of prey, improving functional connectivity, and considering possible future climate and landscape change scenarios to strengthen the knowledge about suitable areas in the AF.

Funding

This work was supported by Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - CAPES (process #88887.519051/2020-00), Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq (process #130769/2021-5; #442147/2020-1; #440145/2022-8; #402765/2021-4; #313016/2021-6 and #440145/2022-8; 420094/2023-7) and Fundação de Amparo à Pesquisa do Estado de São Paulo - FAPESP (processes #2013/50421-2; #2020/01779-5; #2021/06668-0; #2021/08322-3; #2021/08534-0; #2021/10195-0; #2021/10639-5; #2022/10760-1; #2014/23132-2 and #2021/02132-8). This study is also part of the Centro de Pesquisa em Dinâmica da Biodiversidade e Mudanças Climáticas, which is financed by the FAPESP.

Ethical statement

All authors declare that all ethical practices have been followed in relation to the development, writing, and publication of the article.

Author contribution

Conceptualization: Paula Ribeiro-Souza, Júlio Haji, Julia Oshima, Fernando Lima, Milton Ribeiro, Maurício Graipel, Barbara Lima-Silva and José Pires. Data curation: Paula Ribeiro-Souza and Júlio Haji. Formal analysis: Paula Ribeiro-Souza and Júlio Haji. Funding acquisition: Paula Ribeiro-Souza, Júlio Haji and Milton Ribeiro. Investigation: Paula Ribeiro-Souza. Methodology: Paula Ribeiro-Souza, Júlio Haji, Julia Oshima, Fernando Lima, Milton Ribeiro, Maurício Graipel, Barbara Lima-Silva and José Pires. Project administration: Paula Ribeiro-Souza and Júlio Haji. Resources: Paula Ribeiro-Souza, Júlio Haji, Maurício Graipel and Milton Ribeiro. Software: Paula Ribeiro-Souza. Supervision: Paula Ribeiro-Souza and Júlio Haji. Validation: Paula Ribeiro-Souza, Júlio Haji, Julia Oshima, Fernando Lima, Milton Ribeiro, Maurício Graipel, Barbara Lima-Silva and José Pires. Visualization: Paula Ribeiro-Souza, Júlio Haji, Julia Oshima, Fernando Lima, Milton Ribeiro, Maurício Graipel, Barbara Lima-Silva and José Pires. Writing – original draft: Paula Ribeiro-Souza and Júlio Haji. Writing – review & editing: Paula Ribeiro-Souza, Júlio Haji, Julia Oshima, Fernando Lima, Milton Ribeiro, Maurício Graipel, Barbara Lima-Silva and José Pires.

Data accessibility statement

The feline occurrence data used in the analyses and the richness and ecoland maps are available at the link: https:// datadryad.org/stash/share/7MpwfQWHDmImnFBhV_Czejjq-_QW4_5CRWv-fu51f6g; All variables used are third party data freely available online. Climate data are available on the Worldclim website (https://www.worldclim.org/data/worldclim21.html). The landscape variables are available on the following sites: Habitat heterogeneity (http://www.earthenv.org/texture), Water frequency (DOI: 10.1080/17538947.2015.1026420), Human density (http://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-densityrev10), Terrain ruggedness (http://www.earthenv.org/topography) and Tree cover (https://doi.org/10.1126/science.1244693).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We shared the link with the data in the revised version of the manuscript.

Acknowledgements

We thank all the researchers who contributed to the cat database we used for the analyses.

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Supporting information 1

for manuscript

"*Under pressure: suitable areas for Neotropical cats within an under-protected biodiversity hotspot*"

Table A.1. Values from Variance Inflation Factor (VIF). Variables used in the species distribution models (*).

Variable	Abbreviation	VIF
Coefficient of Variation of EVI data - heterogeneity	Habitat heterogeneity*	1.23
Water Frequency - Global Inland Water	Water Frequency*	1.02
Population density per 1km²	Human density*	1.21
Standard deviation terrain ruggedness index	Terrain ruggedness*	1.15
Percent of treecover from 2000	Tree cover*	1.27
Mean Temperature of Driest Quarter	BIO09*	1.61
Precipitation of Wettest Month	BIO13*	1.38
Precipitation of Coldest Quarter	BIO19*	1.77
Mean Diurnal Range	BIO02	1.82
Mean Temperature of Wettest Quarter	BIO08*	1.33
Isothermality	BIO03	1.90

Table A.2. Values of the area under the receiver-operating characteristic curve (AUC), the true skill statistic (TSS), COR (correlation of presence/pseudo absence) and deviance from the statistical quality of fit for tree methods used in the study.

Species	**Algorithm**	**AUC mean**	**COR**	**TSS mean**	**Deviance**
Landscape					
H. yagouaroundi	MDA	0.70	0.30	0.34	2.15
	MaxEnt	0.73	0.37	0.38	1.34
	Random Forest	0.72	0.36	0.37	1.07
Average		0.72		0.36	
L. emiliae	MDA	0.70	0.03	0.48	0.27
	MaxEnt	0.71	0.06	0.37	1.36
	Random Forest	0.72	0.04	0.38	0.20
Average		0.71		0.41	
L. guttulus	MDA	0.72	0.34	0.38	1.64
	MaxEnt	0.74	0.37	0.40	1.29
	Random Forest	0.74	0.38	0.38	1.04
Average		0.73		0.39	
L. pardalis	MDA	0.74	0.39	0.39	2.08
	MaxEnt	0.78	0.47	0.44	1.18
	Random Forest	0.76	0.45	0.42	1.10
Average		0.76		0.42	
L. wiedii	MDA	0.79	0.42	0.50	1.29
	MaxEnt	0.81	0.46	0.52	1.01
	Random Forest	0.79	0.43	0.50	0.81
Average		0.80		0.51	

	MDA	0.75	0.40	0.40	1.63
P. concolor	MaxEnt	0.79	0.47	0.45	1.17
	Random Forest	0.78	0.47	0.46	1.02
Average		0.77		0.44	
	MDA	0.83	0.37	0.67	0.75
P. onca	MaxEnt	0.90	0.54	0.74	0.49
	Random Forest	0.93	0.56	0.77	0.26
Average		0.89		0.73	
Climate					
	MDA	0.69	0.29	0.32	1.14
H. yagouaroundi	MaxEnt	0.72	0.34	0.38	1.35
	Random Forest	0.98	0.63	0.93	0.06
Average		0.80		0.54	
	MDA	0.78	0.21	0.55	0.31
L. emiliae	MaxEnt	0.83	0.22	0.62	0.55
	Random Forest	0.79	0.47	0.47	0.35
Average		0.80		0.55	
	MDA	0.76	0.42	0.44	1.05
L. guttulus	MaxEnt	0.83	0.50	0.55	1.02
	Random Forest	0.86	0.59	0.60	0.81
Average		0.82		0.53	
	MDA	0.65	0.26	0.26	1.31
L. pardalis	MaxEnt	0.72	0.37	0.36	1.31
	Random Forest	0.83	0.56	0.51	0.97
Average		0.73		0.38	

L. wiedii	MDA	0.75	0.30	0.42	0.93
	MaxEnt	0.77	0.37	0.43	1.15
	Random Forest	0.84	0.52	0.55	0.74
Average		0.79		0.47	
P. concolor	MDA	0.70	0.30	0.34	1.21
	MaxEnt	0.73	0.37	0.35	1.30
	Random Forest	0.80	0.52	0.49	0.97
Average		0.74		0.39	
P. onca	MDA	0.67	0.18	0.36	0.53
	MaxEnt	0.74	0.29	0.45	1.00
	Random Forest	0.84	0.53	0.62	0.38
Average		0.75		0.48	

Table A.3. Suitable areas, in km² and percentage (%) predicted by the high climate and high landscape for each species in the Atlantic Forest (AF). We present the total of suitable areas and those covered by Fully Protected Areas (FPAs).

Specie	**Suitable area**		
	Total (km²)	FPAs (km²)	**%**
L. emiliae	9.831	135	1,37
L. guttulus	230.301	12.386	5,38
L. wiedii	76.503	4.368	5,71
H. yagouaroundi	236.458	15.843	6,70
L. pardalis	304.804	11.737	3,85
P. concolor	216.871	10.715	4,94
P. onca	6.546	129	1,97

Supporting information 2

for manuscript

"*Under pressure: suita ble areas for Neotropical cats within an under-protected biodiversity hotspot*"

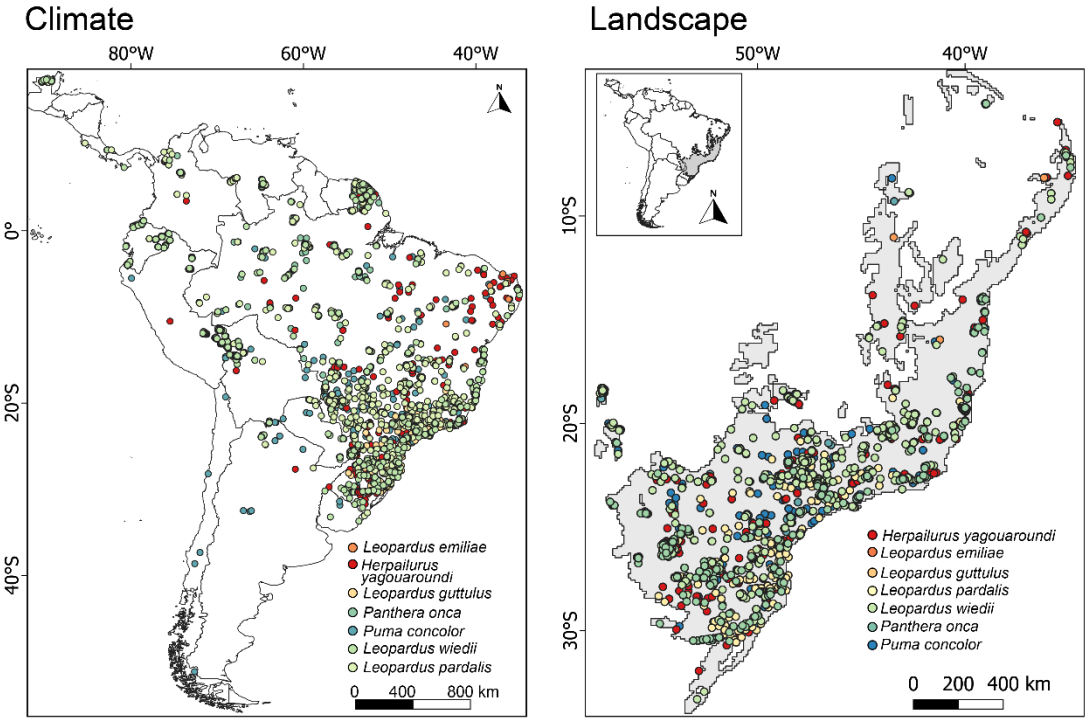


Figure B.1. Occurrence records used in climate and landscape models, respectively.

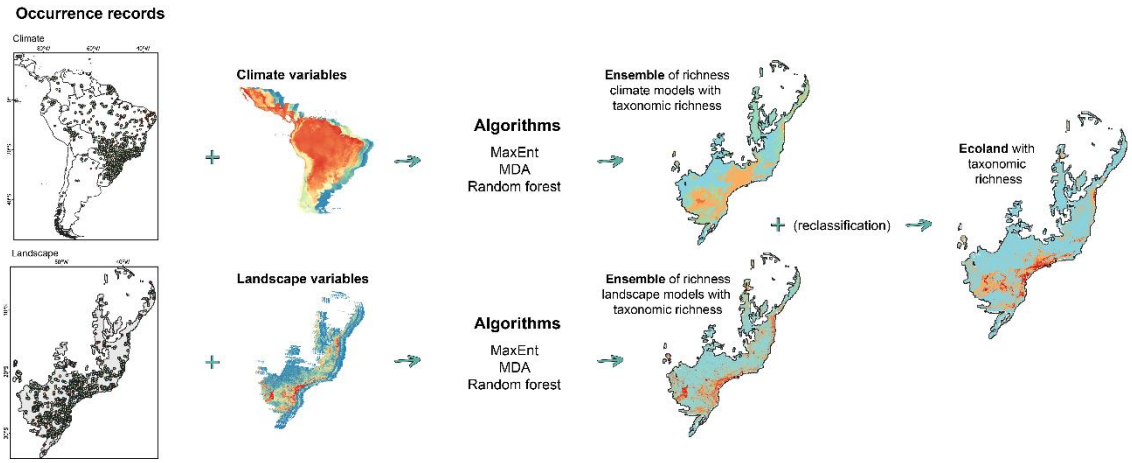


Figure B.2. Graphical abstract for species distribution modelling.

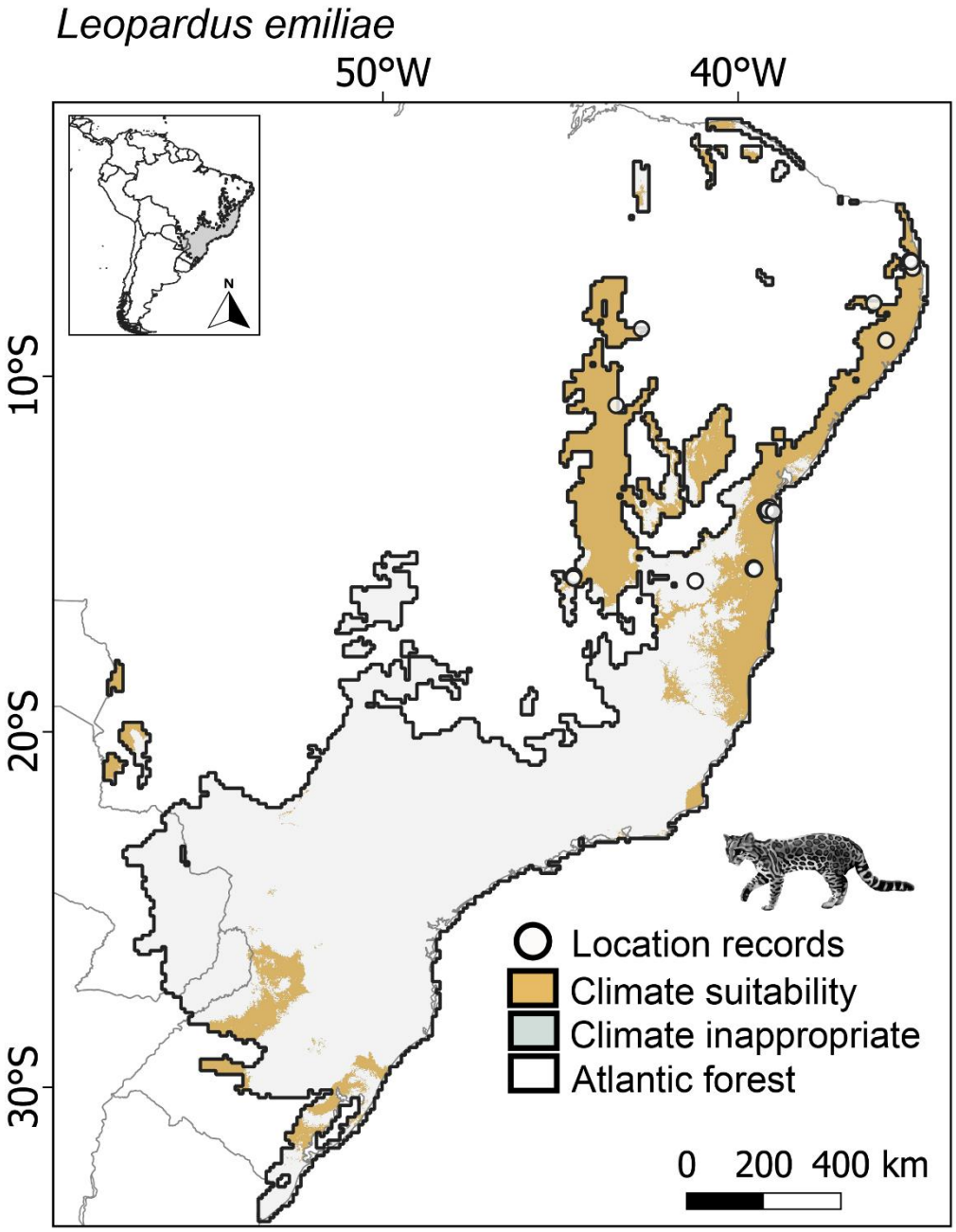


Figure B.3. *Leopardus emiliae* distribution in Atlantic Forest according to the climate model. Illustration by *L. emiliae*: Pedro Busana

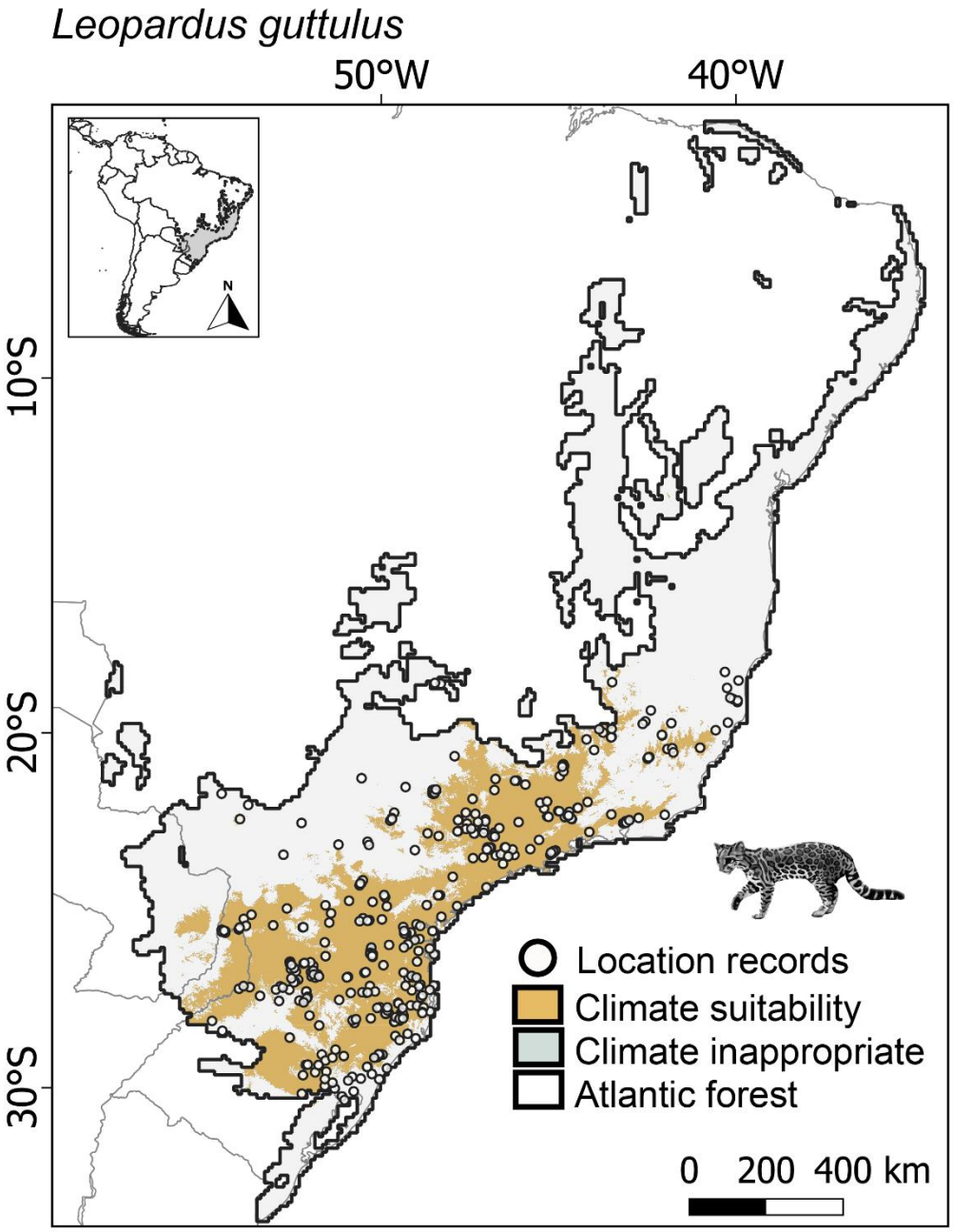


Figure B.4. *Leopardus guttulus* distribution in Atlantic Forest according to the climate model. Illustration by *L. guttulus*: Pedro Busana.

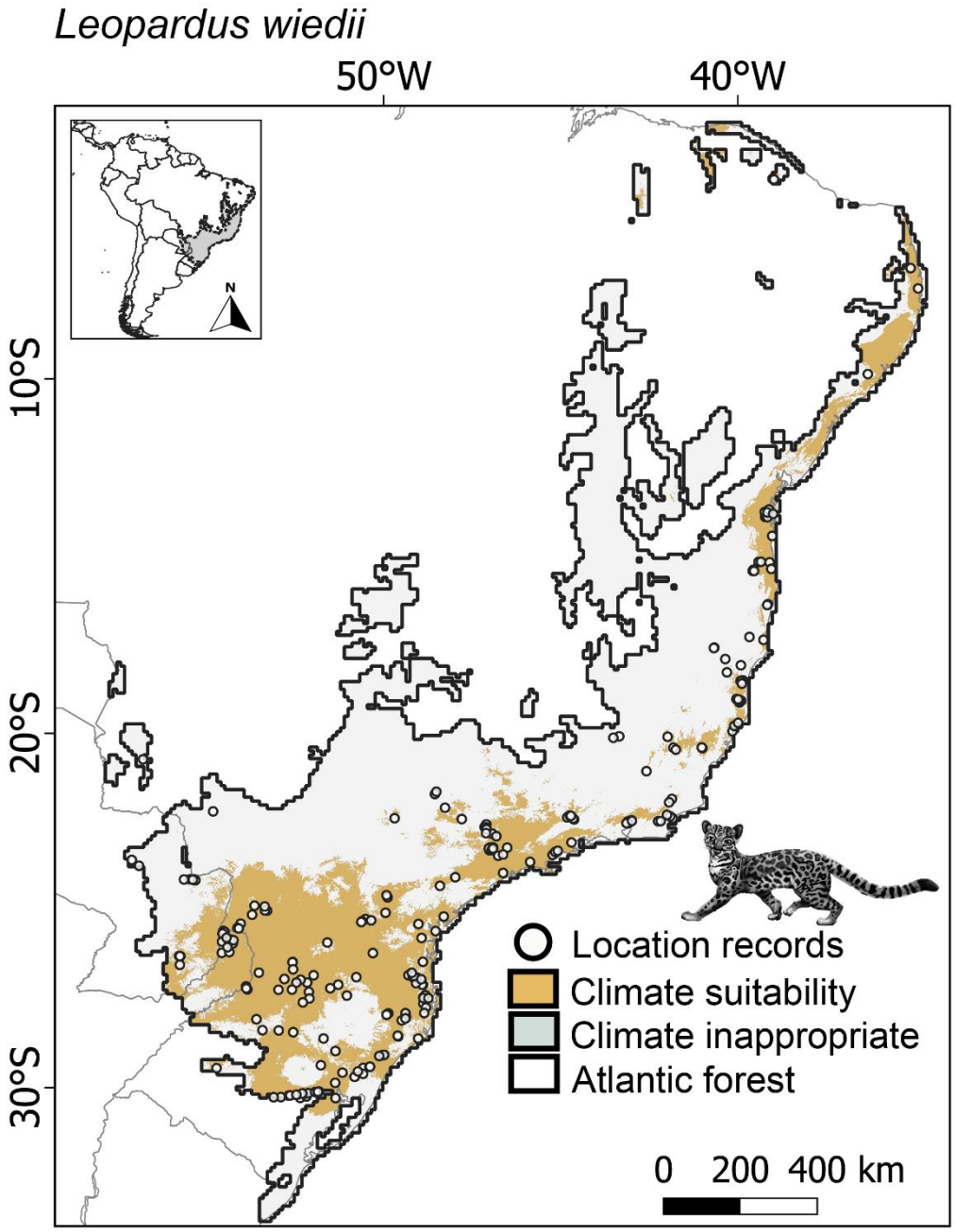


Figure B.5. *Leopardus wiedii* distribution in Atlantic Forest according to the climate model. Illustration by *L. wiedii*: Pedro Busana

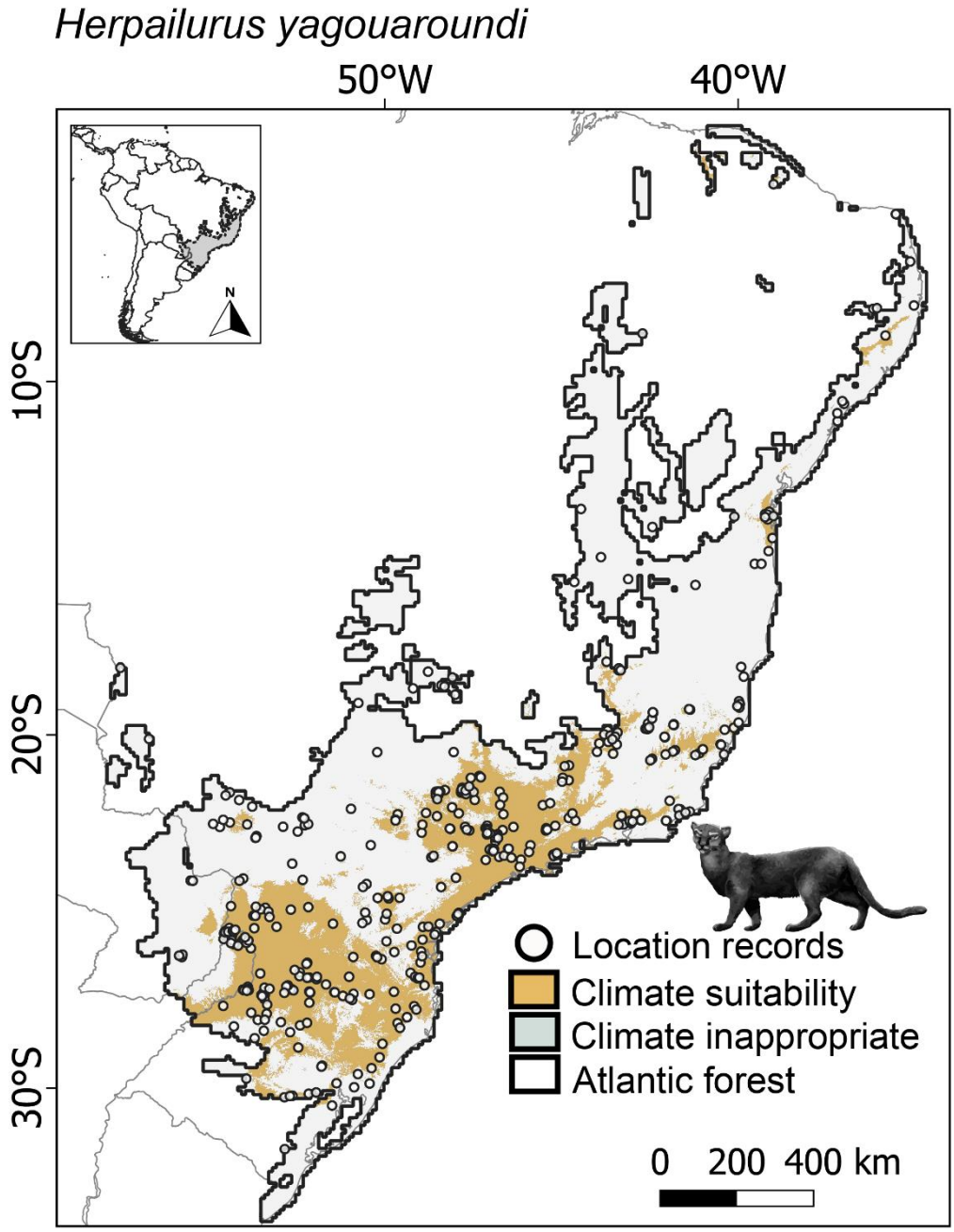


Figure B.6. *Herpailurus yagouraoundi* in Atlantic Forest according to the climate model. Illustration by *H. yagouraoundi*: Pedro Busana.

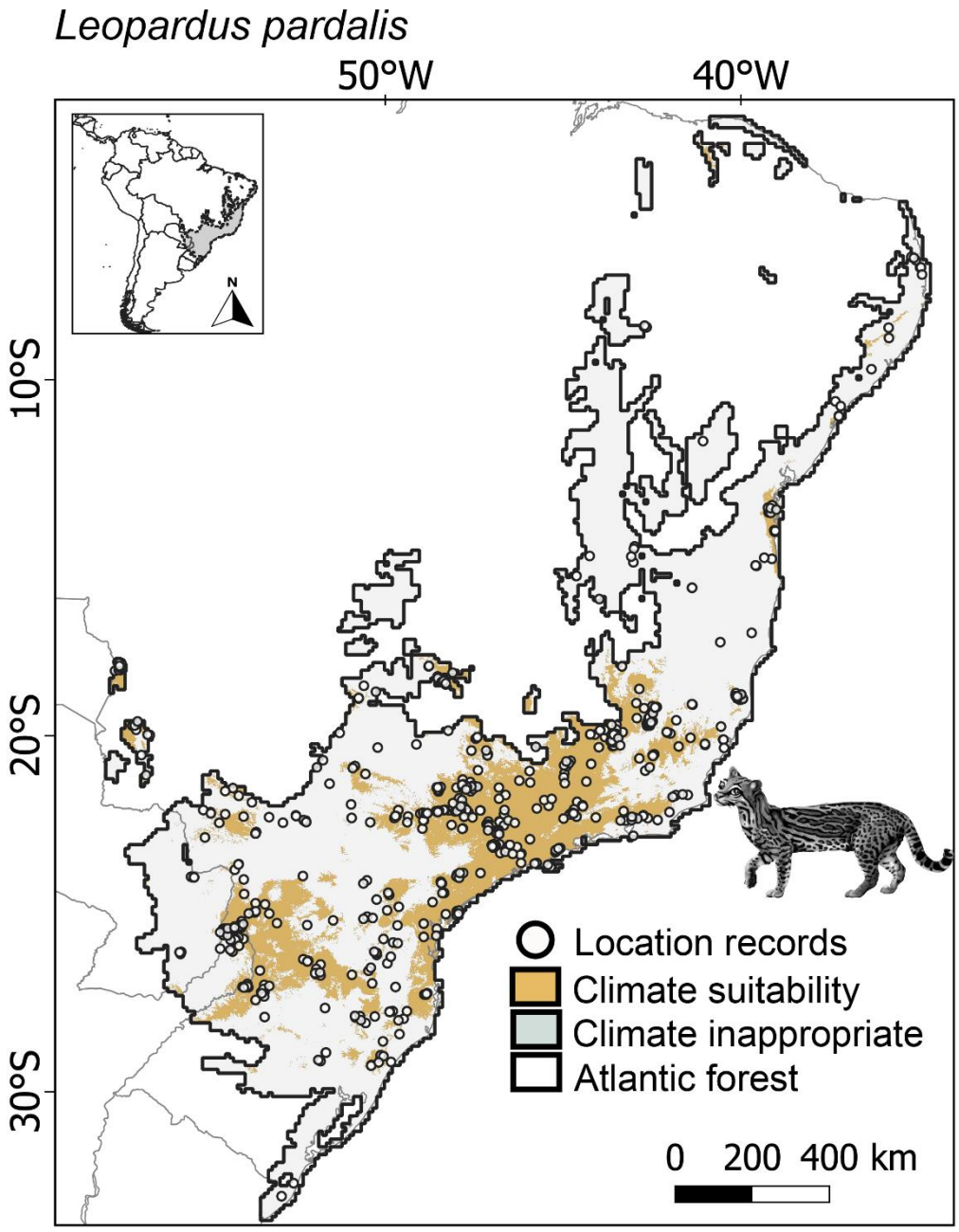


Figure B.7. *Leopardus pardalis* distribution in Atlantic Forest according to the climate model. Illustration by *L. pardalis*: Pedro Busana.

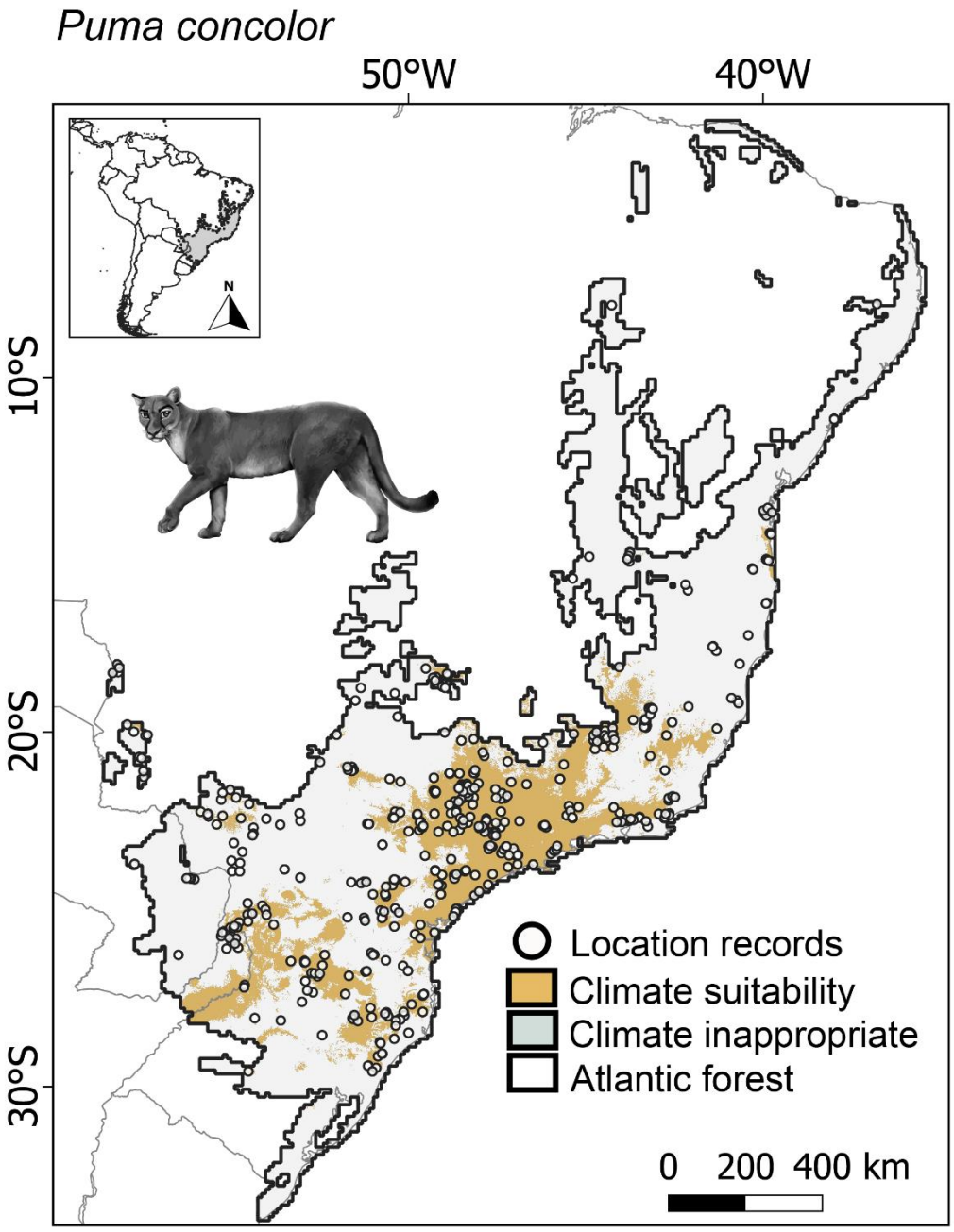


Figure B.8. *Puma concolor* distribution in Atlantic Forest according to the climate model. Illustration by *P. concolor*: Pedro Busana.

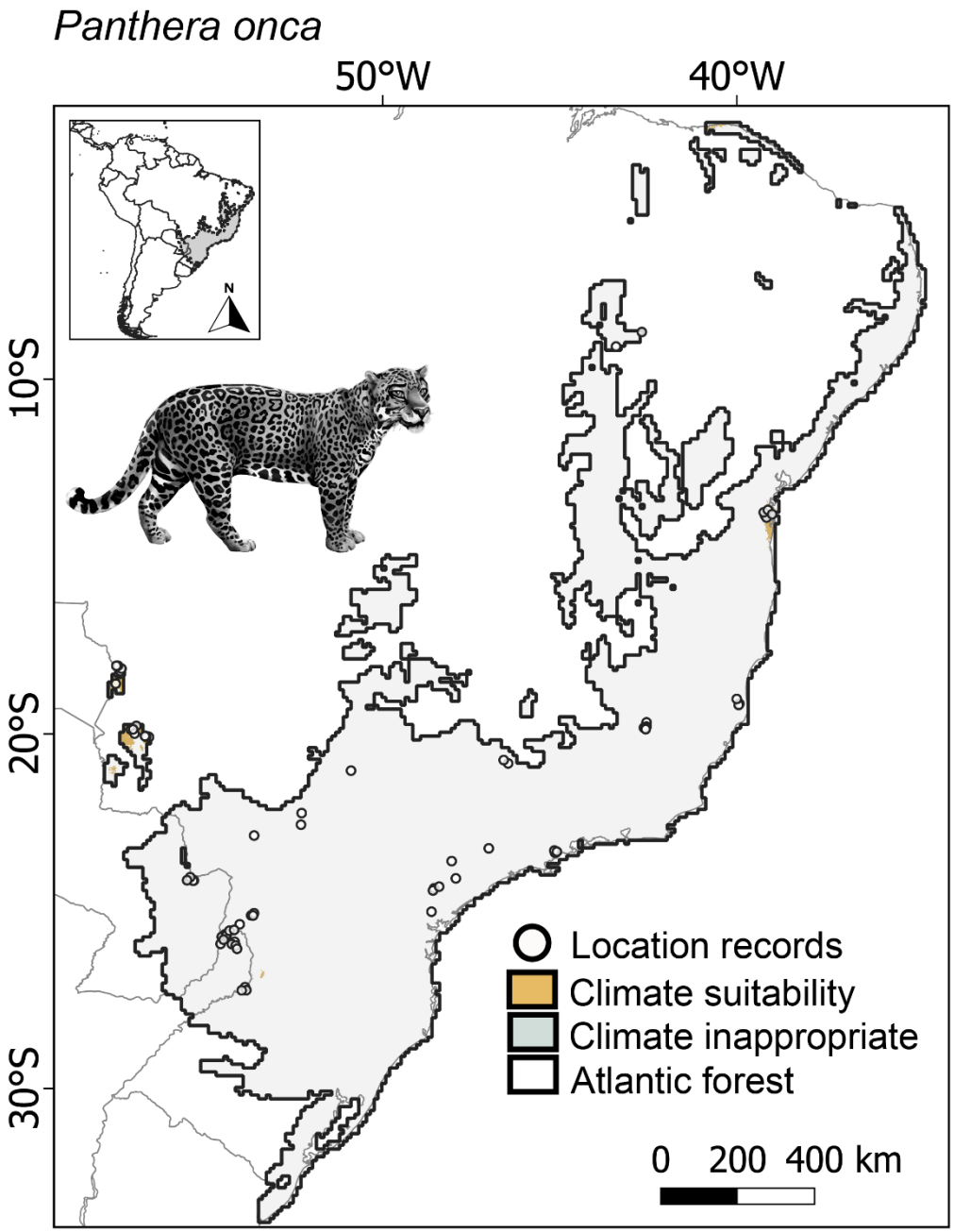


Figure B.9. *Panthera onca distribution* in Atlantic Forest according to the climate model. Illustration by *P. onca*: Pedro Busana.

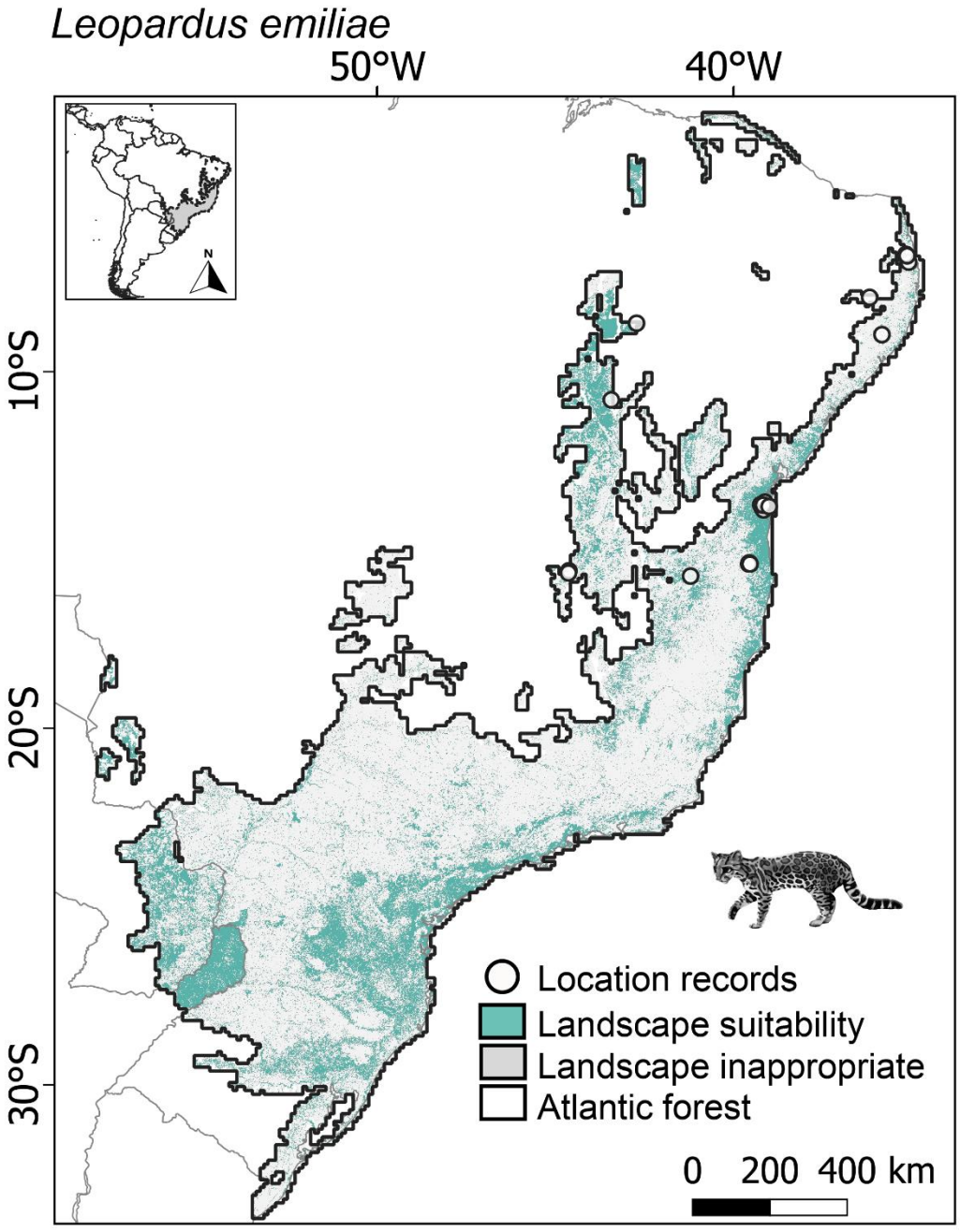


Figure B.10. *Leopardus emiliae* distribution in Atlantic Forest according to the landscape model. Illustration by *L. emiliae*: Pedro Busana.

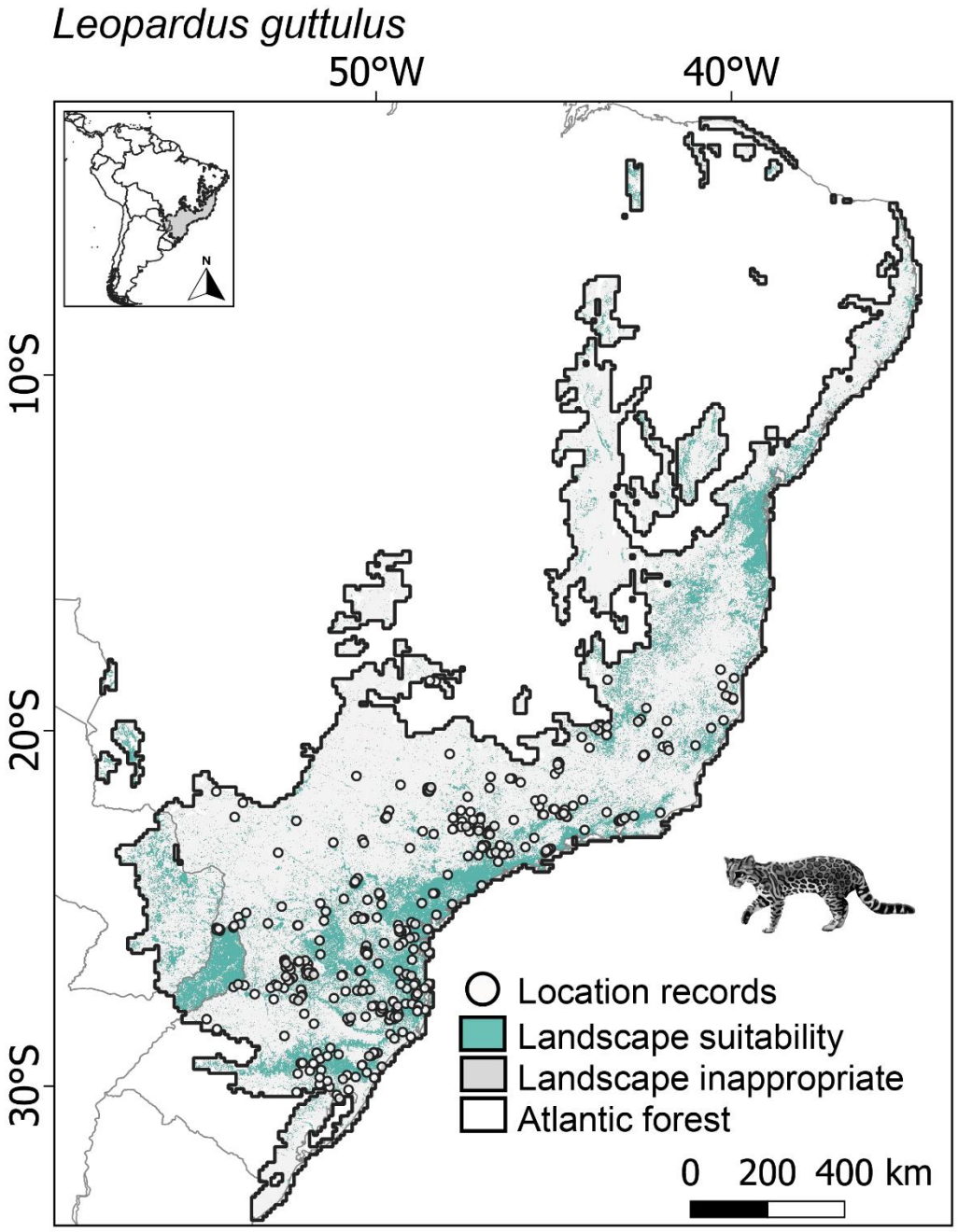


Figure B.11. *Leopardus guttulus* distribution in Atlantic Forest according to the landscape model. Illustration by *L. guttulus*: Pedro Busana.

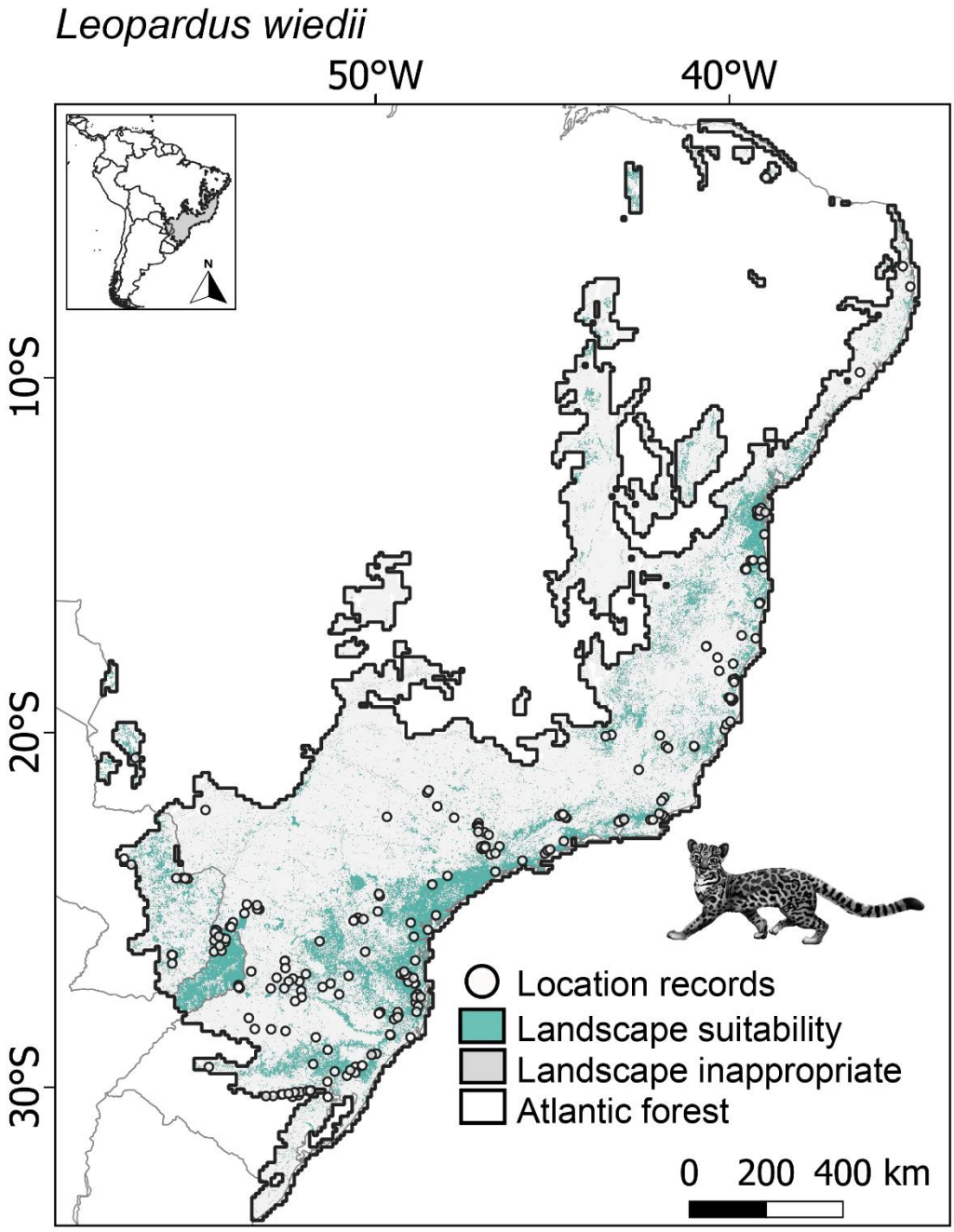


Figure B.12. *Leopardus wiedii* distribution in Atlantic Forest according to the landscape model. Illustration by *L. wiedii*: Pedro Busana.

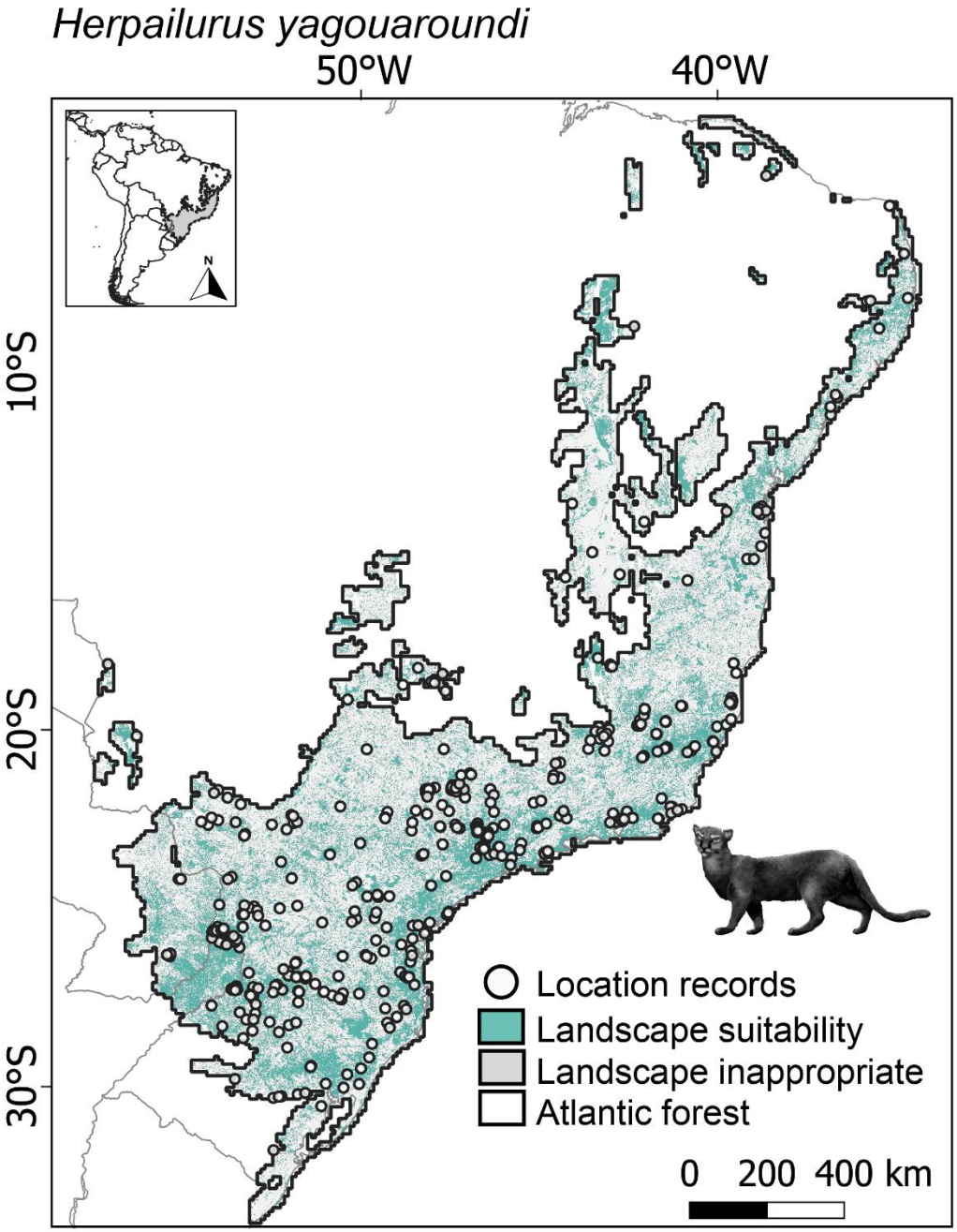


Figure B.13. *Herpailurus yagouaroundi* distribution in Atlantic Forest according to the landscape model. Illustration by *H. yagouaroundi*: Pedro Busana.

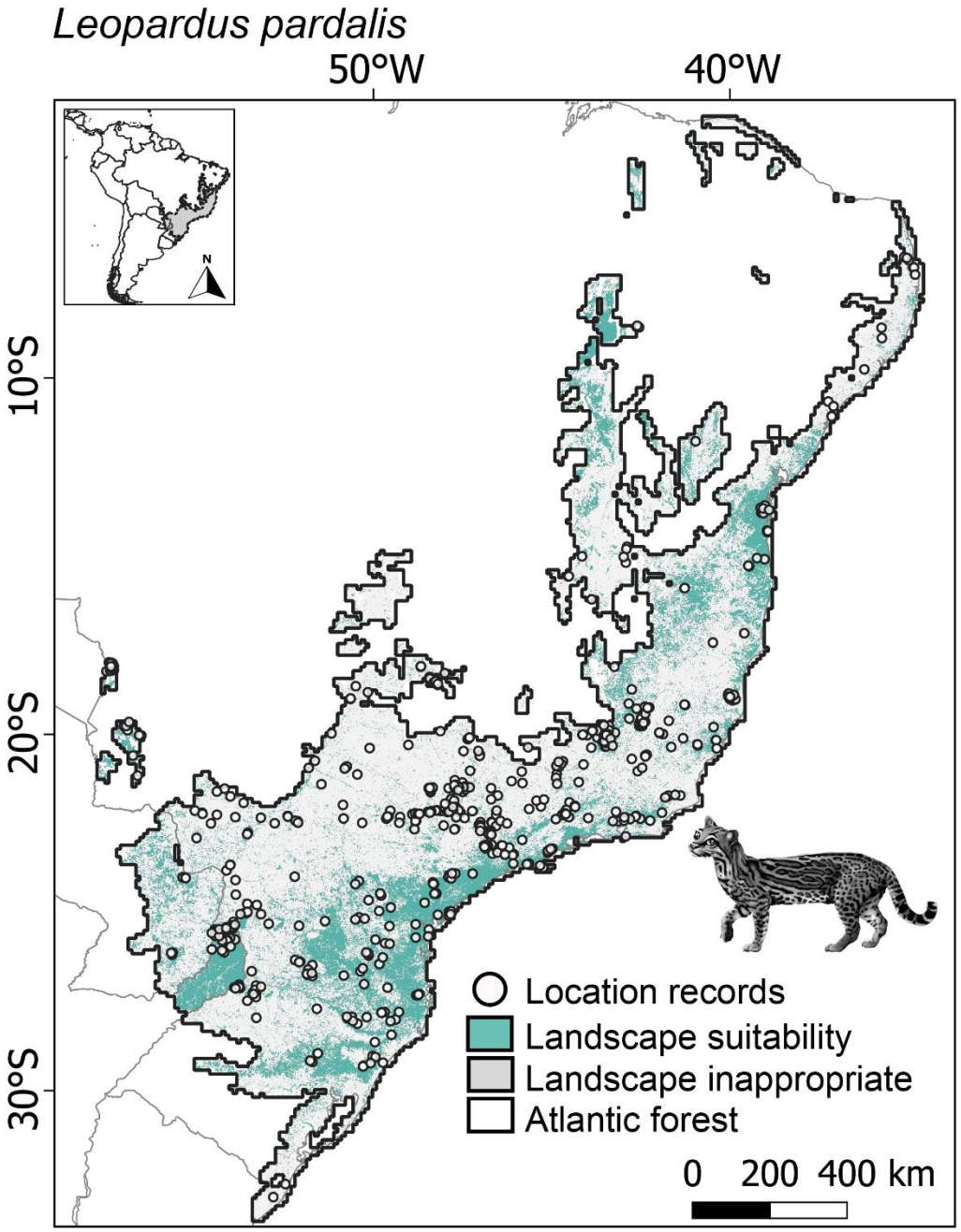


Figure B.14. *Leopardus pardalis* distribution in Atlantic Forest according to the landscape model. Illustration by *L. pardalis*: Pedro Busana.

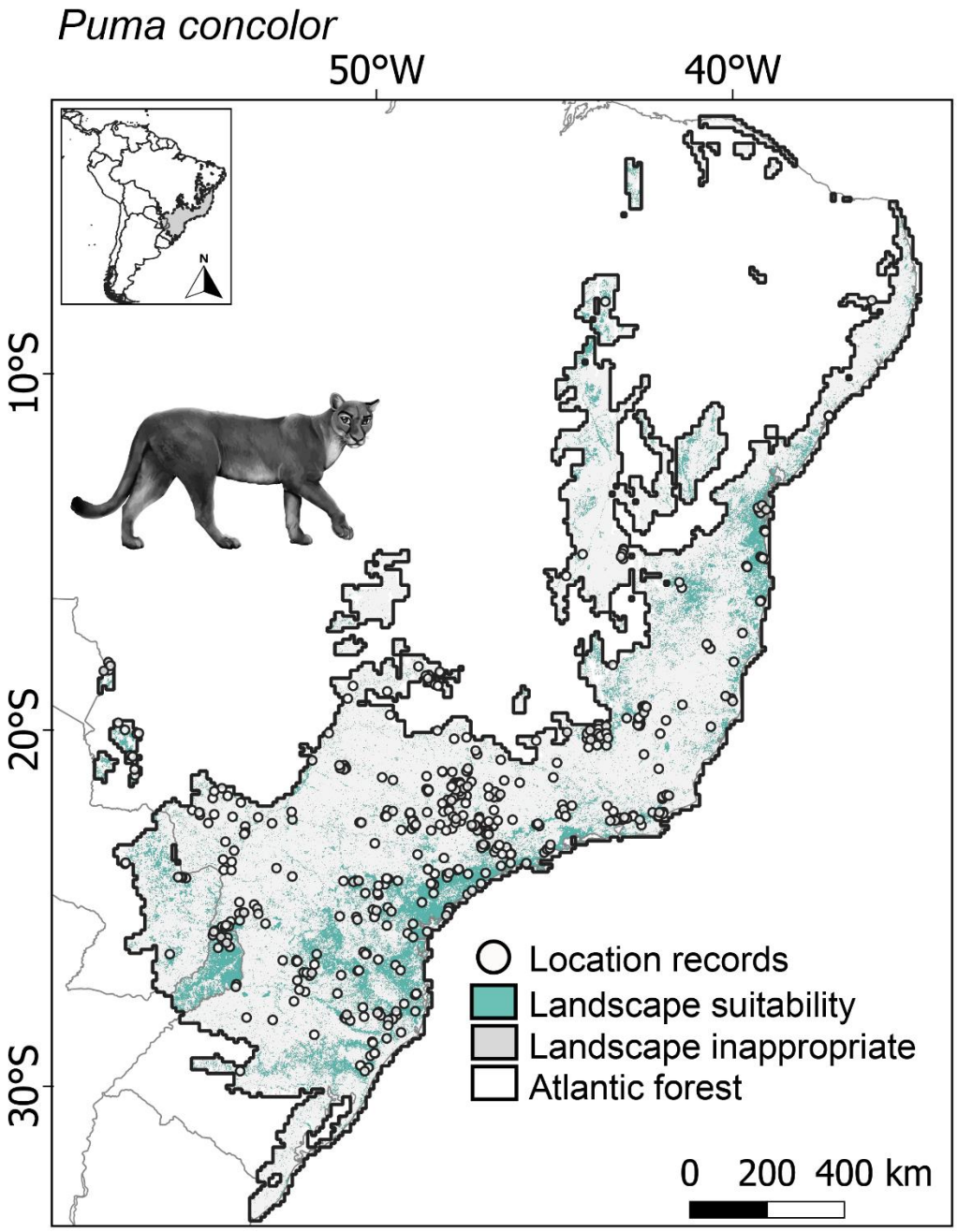


Figure B.15. *Puma concolor* distribution in Atlantic Forest according to the landscape model. Illustration by *P. concolor*: Pedro Busana.

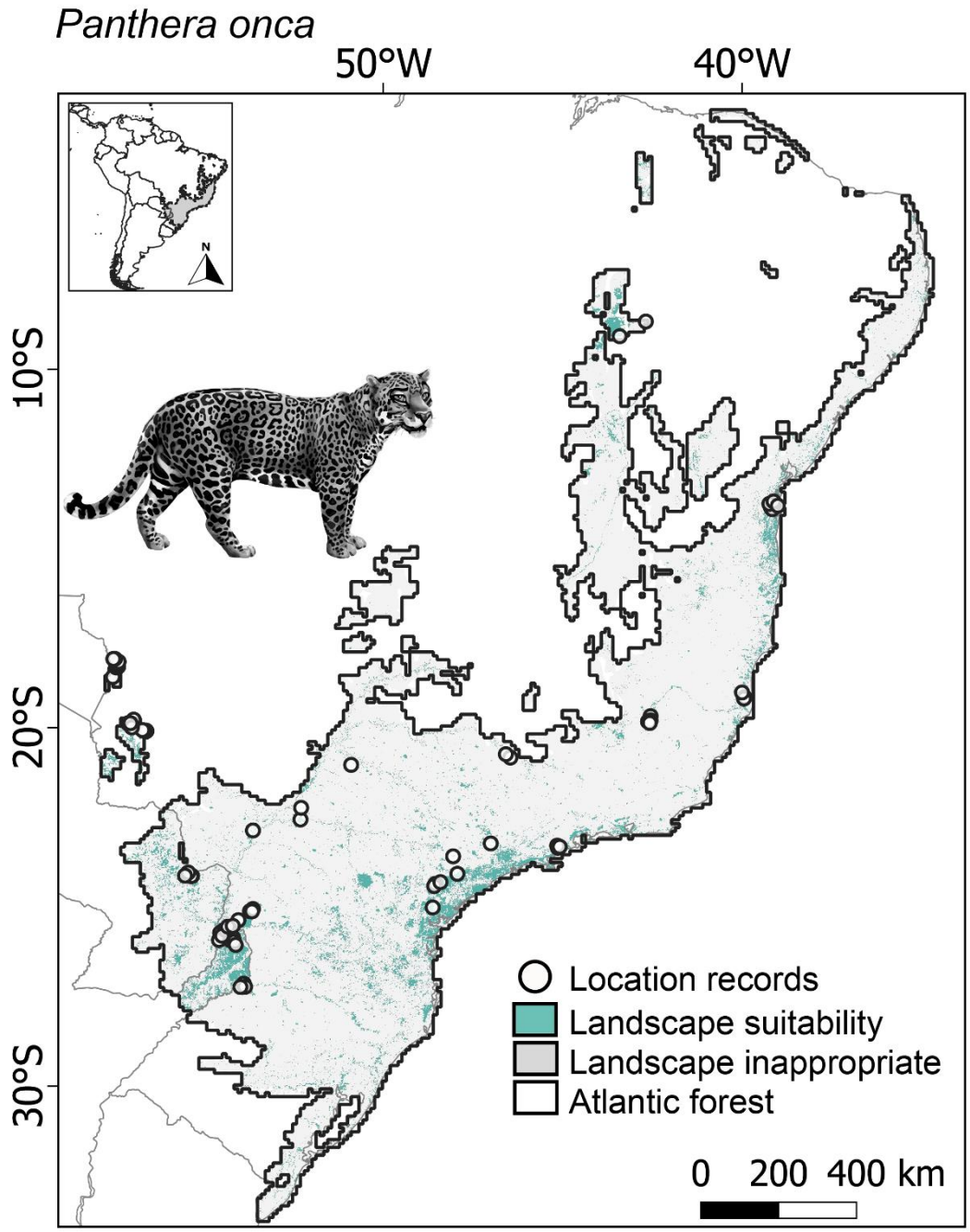


Figure B.16. *Panthera onca* distribution in Atlantic Forest according to the landscape model. Illustration by *P. onca*: Pedro Busana.

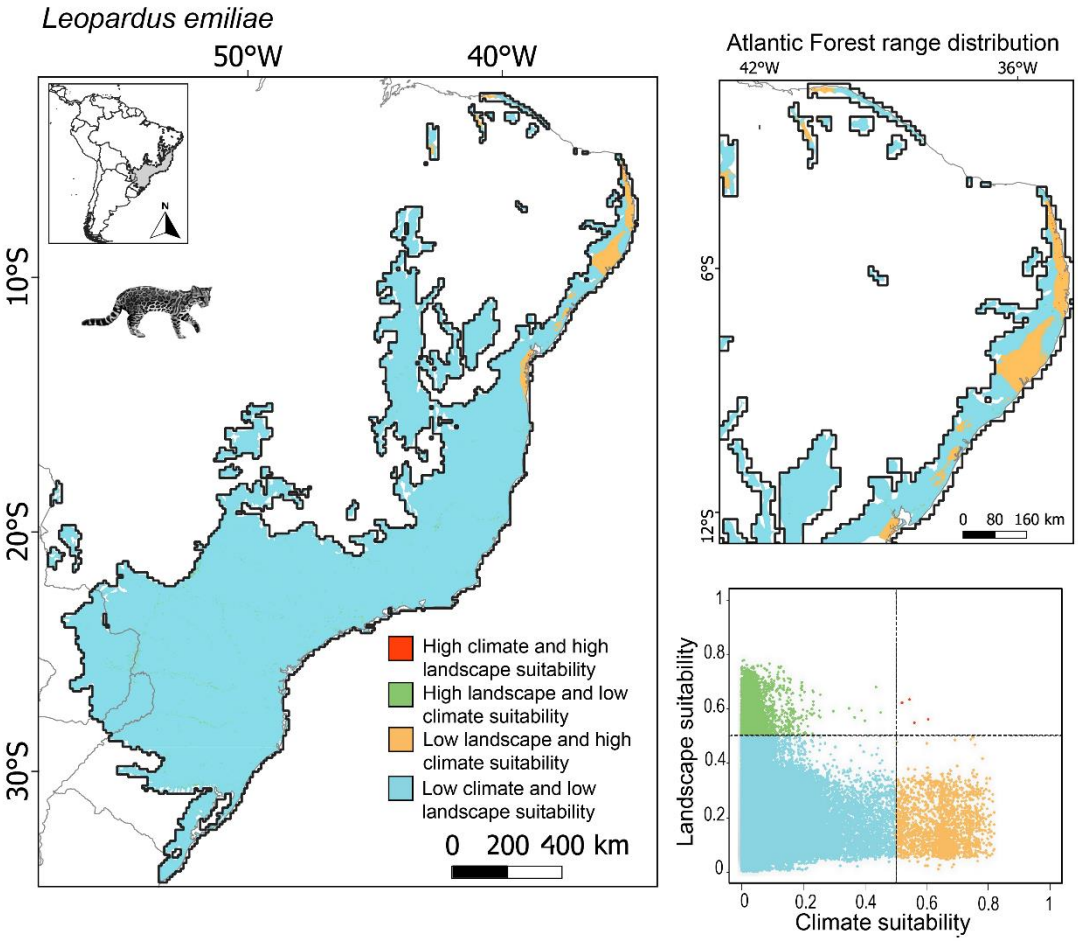


Figure B.17. *Leopardus emiliae* distribution in Atlantic Forest according to the EcoLand model. Illustration by *L. emiliae*: Pedro Busana.

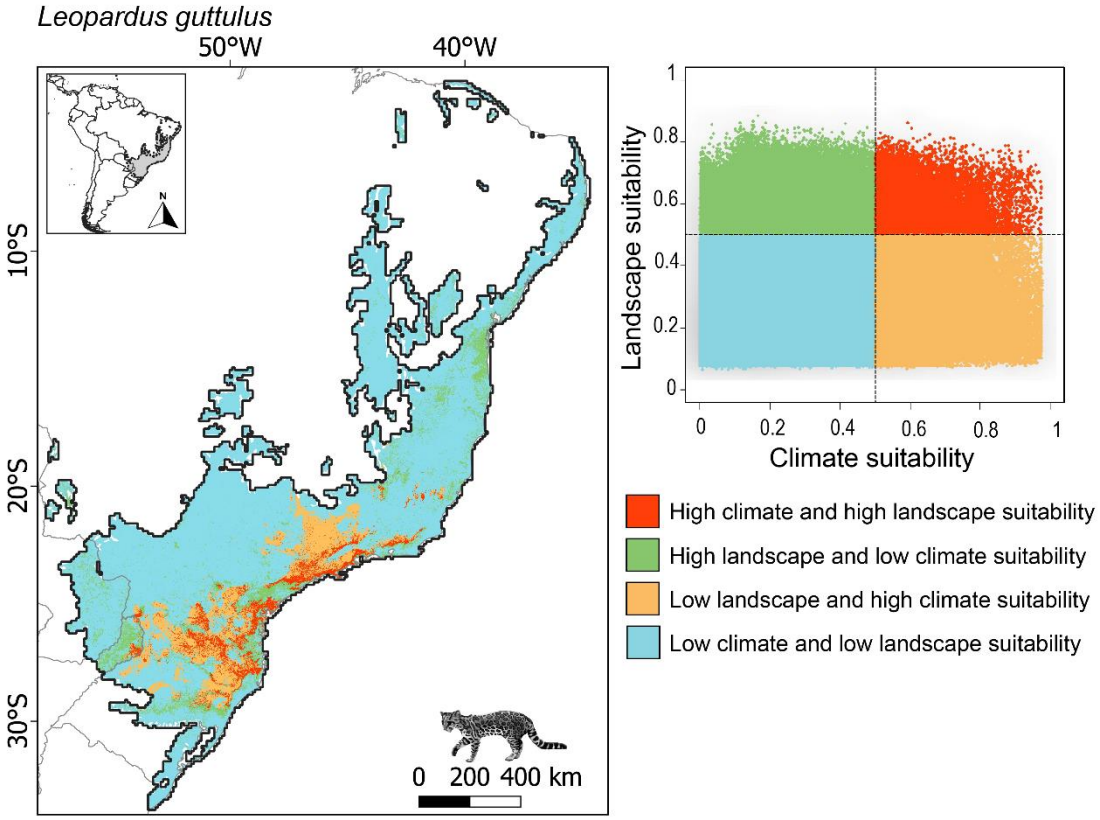


Figure B.18. *Leopardus guttulus* distribution in Atlantic Forest according to the EcoLand model. Illustration by *L. guttulus*: Pedro Busana.

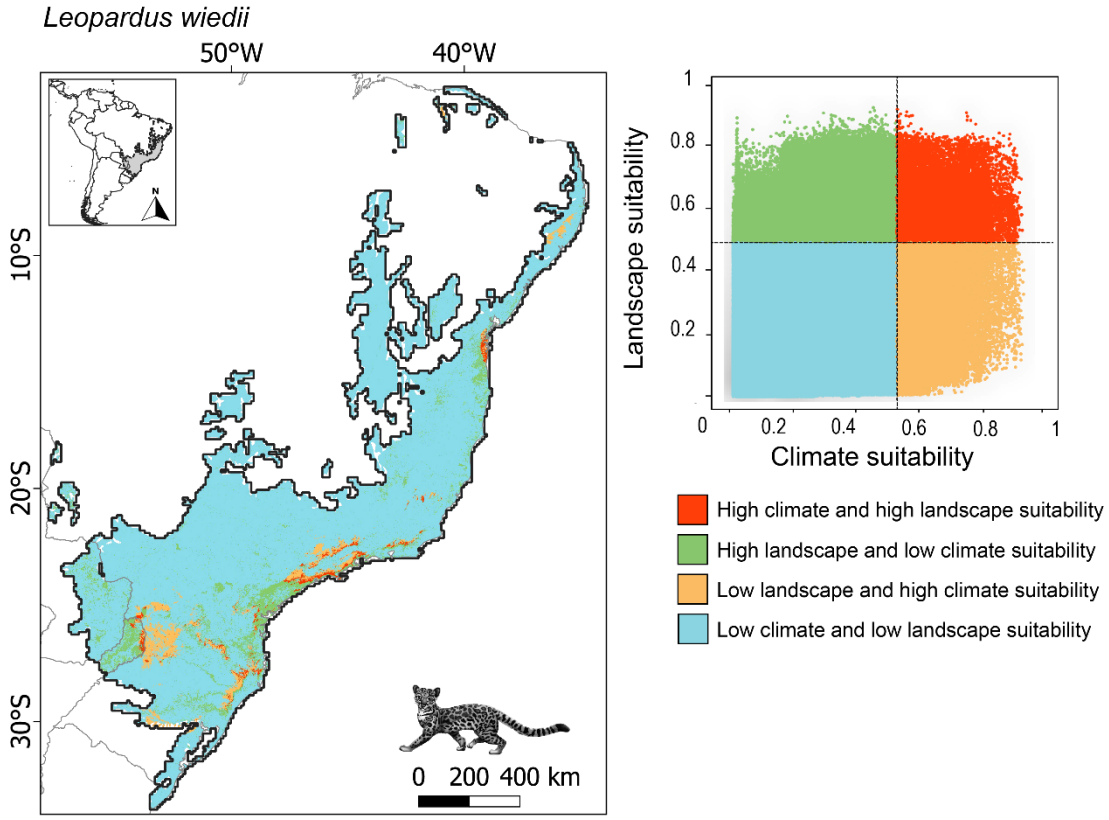


Figure B.19. *Leopardus wiedii* distribution in Atlantic Forest according to the EcoLand model. Illustration by *L. wiedii*: Pedro Busana.

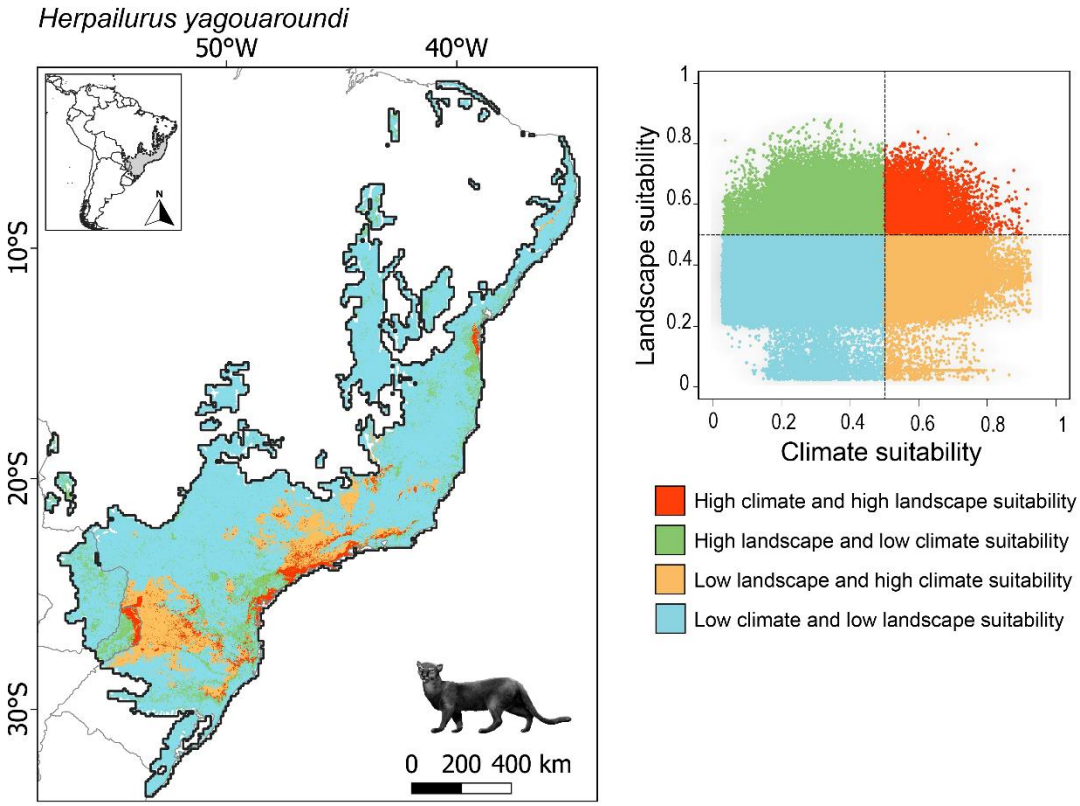


Figure B.20. *Herpailurus yagouaroundi* distribution in Atlantic Forest according to the EcoLand model. Illustration by *H. Herpailurus yagouaroundi*: Pedro Busana.

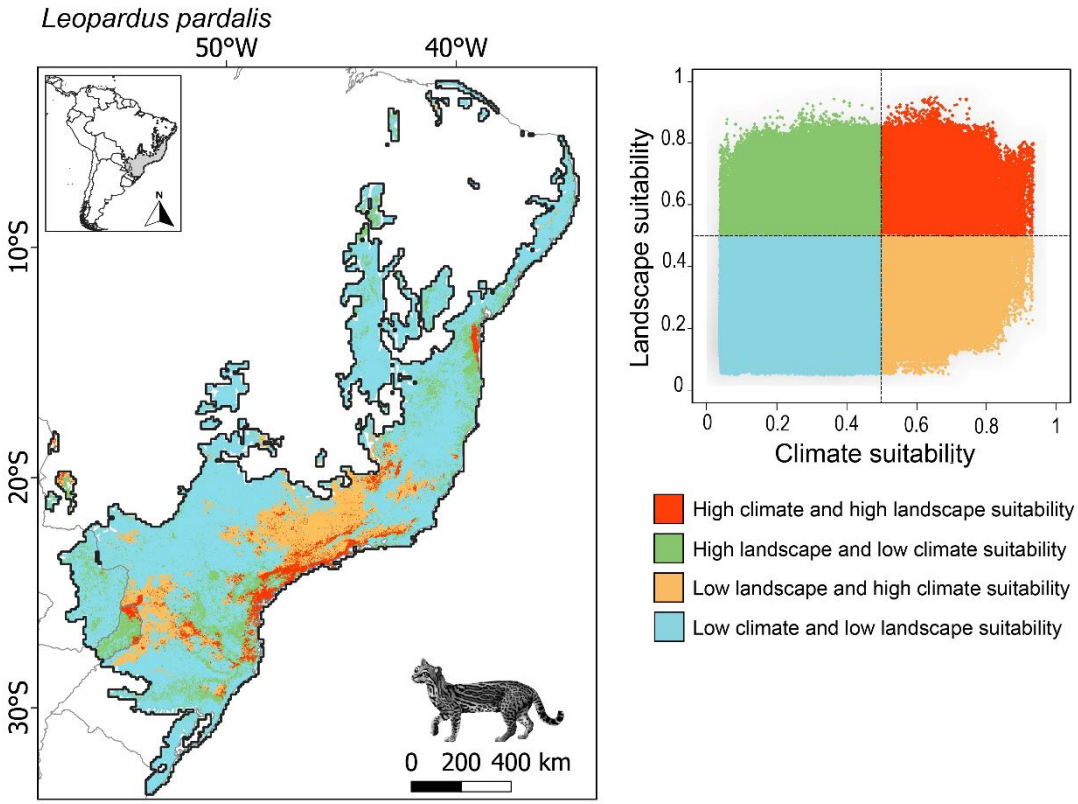


Figure B.21. *Leopardus pardalis* distribution in Atlantic Forest according to the EcoLand model. Illustration by *L. pardalis*: Pedro Busana.

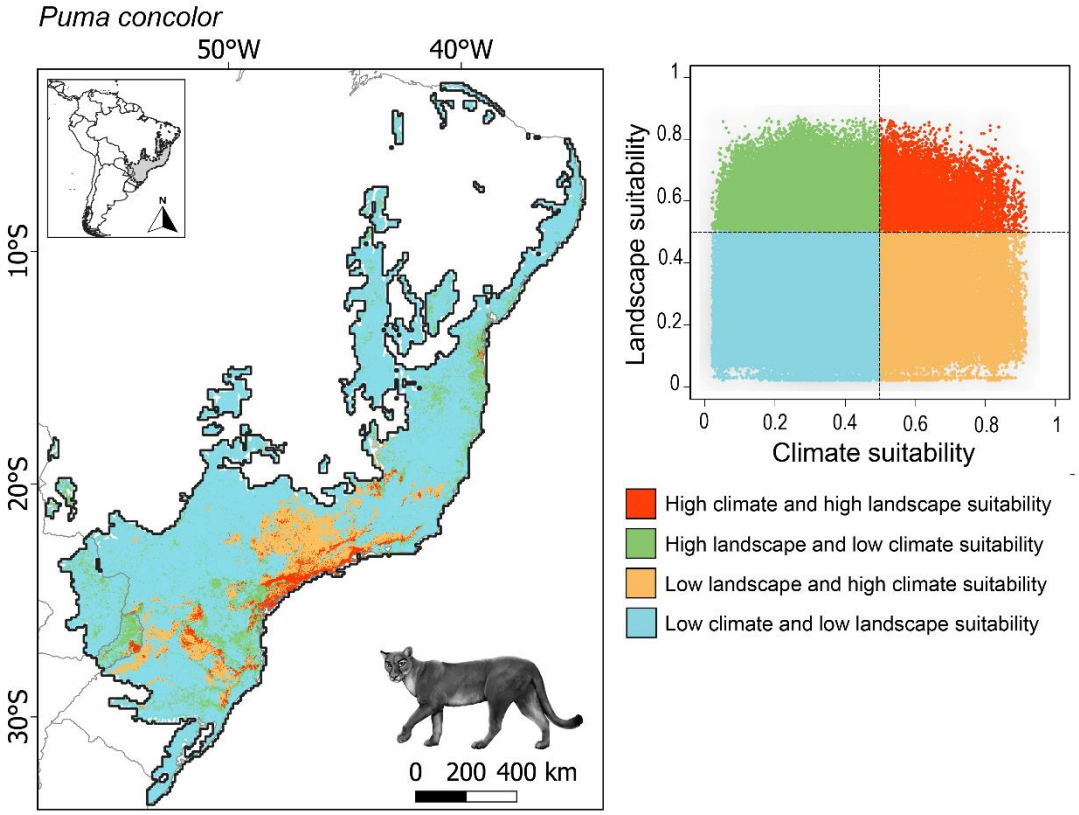


Figure B.22. *Puma concolor* distribution in Atlantic Forest according to the EcoLand model. Illustration by *P. concolor*: Pedro Busana.

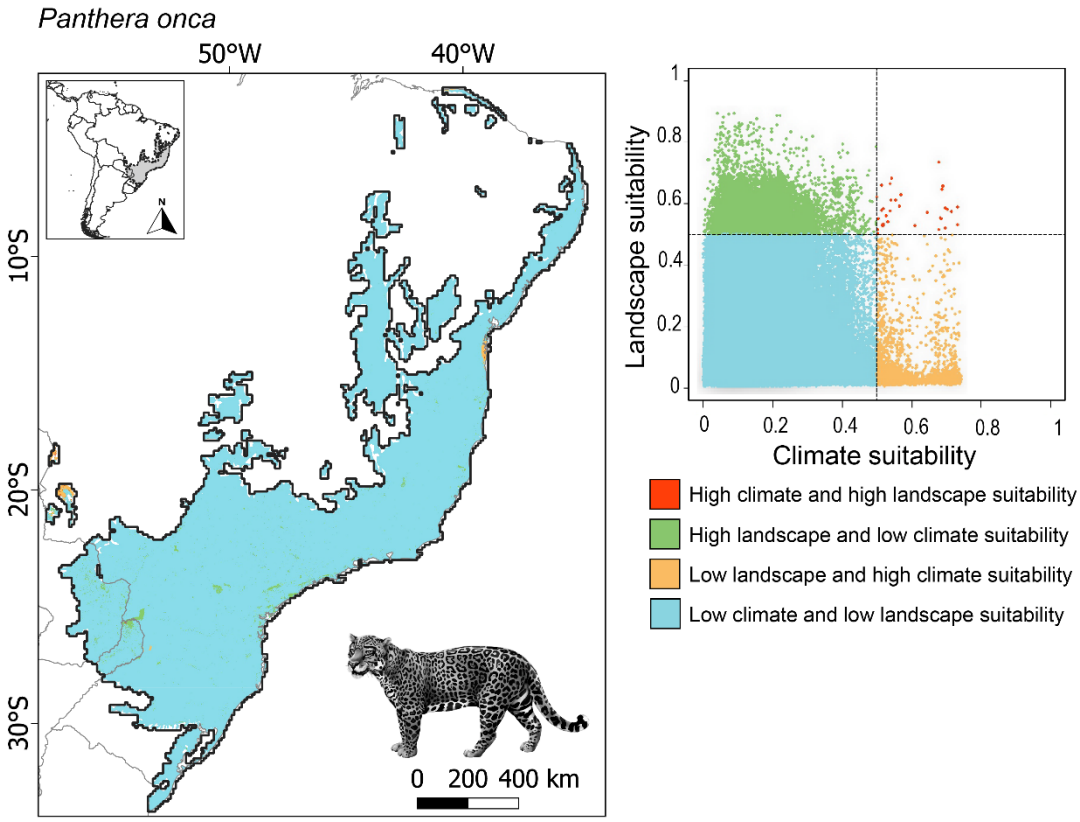


Figure B.23. *Panthera onca* distribution in Atlantic Forest according to the EcoLand model. Illustration by *P. onca*: Pedro Busana.

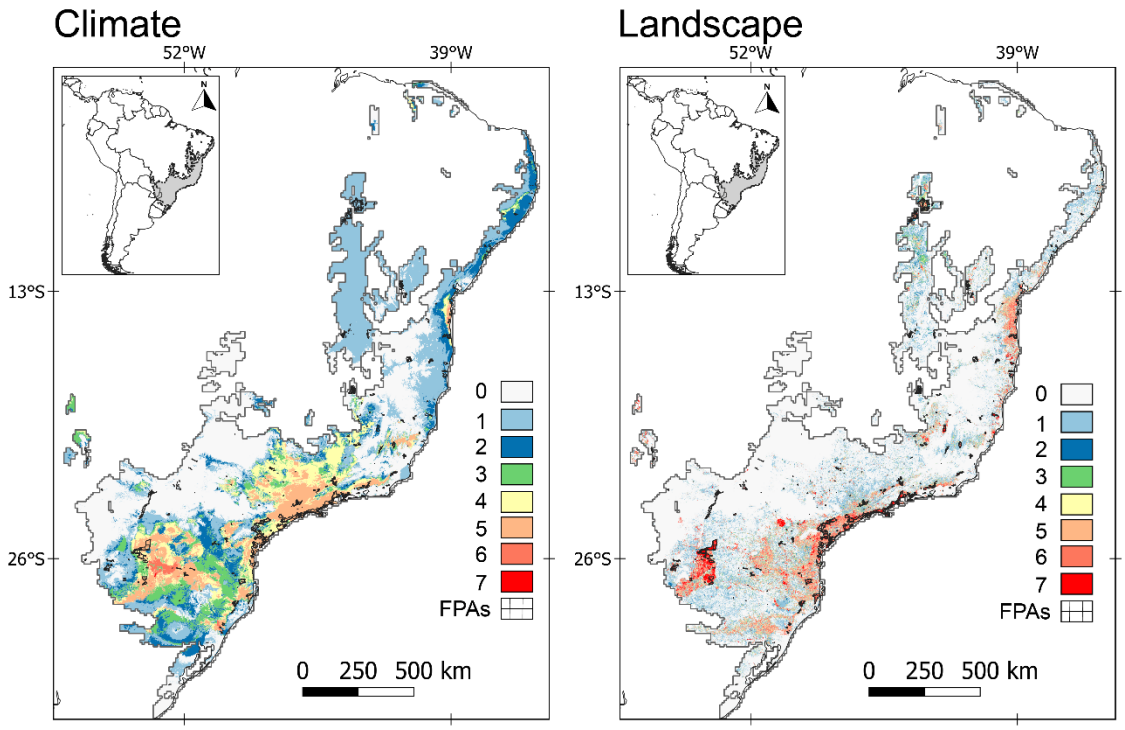
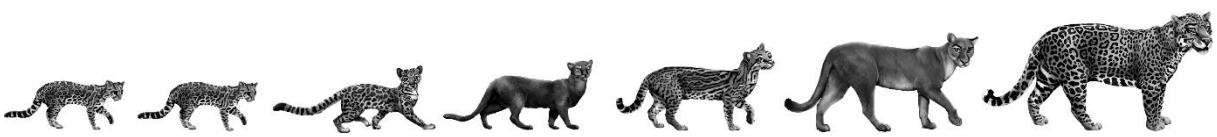


Figure B.24. Distribution of Neotropical felid richness in the Atlantic Forest according to climatic and landscape models with richness boundaries from 0 to 7. Also, observe the fully protected areas (FPAs).

CAPÍTULO 2:

THE FUTURE OF THE WILD FELINES UNDER CLIMATE AND LANDSCAPE CHANGES IN THE ATLANTIC FOREST

Submetido à revista *“Perspectives in Ecology and Conservation”.*



Ilustrações: Pedro Busana.

The future of the wild felines under climate and landscape changes in the Atlantic Forest

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ABSTRACT

Predicting how global climate change (GCC) and land use and land cover change (LULC) will influence the distribution patterns of wild felines is essential for their conservation. In this study we investigated the future impacts of GCC and LULC on feline richness in the Atlantic Forest (AF). We used Species Distribution Modeling for project optimistic and pessimistic scenarios for 2050 by evaluating stable areas, loss of suitable habitats, and permeability of areas. Higher altitudes tend to harbor more stable areas for maintaining feline richness. Habitat loss will occur in both scenarios, but will be higher in the pessimistic scenario due to the combination of GCC and LULC. Moreover, over 87% of the analyzed AF areas exhibit low permeability to feline richness. Therefore, felines will be threatened by the loss of suitable habitat and the inability to access new suitable areas. We strongly recommend the preservation of stable areas and restoration of the landscape to promote connectivity and species dispersal to stable and new suitable areas by 2050. These measures could mitigate the adverse effects of GCC and LULC on feline richness, and consequently help to preserve both biodiversity and ecosystem services within the AF domains.

Keywords: habitat loss; habitat suitability; permeability; stable areas

INTRODUCTION

Global climate change (GCC) and land use and land cover change (LULC) caused by human activities are the main threats to species extinction (Sala et al., 2000; Cardinale et al., 2012). In the Neotropical region, the combination of these threats is predicted to have a greater negative impact on biodiversity (Sala et al., 2000; Colwell et al., 2008). The LULC process is advancing rapidly in certain ecoregions, such as the Atlantic Forest (AF) (Bicudo et al., 2023). The AF is recognized as a biodiversity hotspot (Myers et al., 2000; Sloan et al., 2014), making it a global conservation priority. However, the AF has undergone deforestation, leading to the loss of natural areas in response to changes in land cover across space and time (Marques and Grelle, 2021; Ribeiro et al., 2009; Teixeira et al., 2017; Rosa et al., 2021; Vancine et al., 2024).

Changes in natural habitats are driving species redistribution. However, the anthropogenic matrix (i.e. pasture, agriculture, silviculture, and urban areas) between new and previously suitable areas is less permeable to movement and makes difficulty the dispersal of individuals, potentially leading to a reduction in species distribution area or even their local and regional extinctions (Zamora-Gutierrez et al., 2018). Large-bodied species that occupy higher positions in the trophic chain, such as top predators, are the first to be negatively impacted by habitat loss and reduction (Cardillo et al., 2004; Ripple et al., 2014). Under a given GCC and LULC scenario, it is expected that many mammals worldwide, including carnivores, will experience an decrease of 18–35% in abundance and an increase of 8 - 23% in extinction risk by 2050 (Visconti et al., 2016).

Felines exert a top-down effect on their prey and are key species for maintaining the proper functioning of ecosystems through direct and indirect trophic effects (Ripple et al., 2014). Therefore, the selective loss of feline species can negatively affect the functioning of ecosystems (Galetti and Dirzo, 2013). Moreover, due to their extensive home ranges, many feline species contributes with biodiversity conservation (Ray et al., 2002). Of the seven feline species distributed in the AF domain - which were assessed in this study - four are categorized as vulnerable (MMA, 2022). A previous study showed that currently, only 30% of the Atlantic Forest are suitable for felines, considering climate and landscape (Ribeiro-Souza et al., 2024). This may further endanger these species. However, few studies have simultaneously examined the future impacts of GCC and LULC on feline richness (e.g. Lima et al., 2019; Ma et al.,

2021; Tonetti et al., 2022), and no studies have been conducted on this group for the entire AF biodiversity hotspot. Therefore, predicting how GCC and LULC will influence the future distribution patterns of wild felines is essential for their conservation.

Based on analysis of the interactive effects of GCC and LULC on feline richness in FA, our objectives were: (1) Evaluate potential changes in the distribution and richness patterns of felines in the face of GCC and LULC and (2) identify the extent and location of permeable areas and low-permeability areas in the future (2050). Our general expectation is that the loss of areas suitable for feline richness in the AF will be greater under the combined effects of GCC and LULC. Furthermore, we assume that there will be more areas with low permeability in the future compared to the current condition.

MATERIAL AND METHODS

Feline occurrence records

We used occurrence records of seven feline species from the AF: *Leopardus emiliae*, *L. guttulus*, *L. pardalis*, *L. wiedii*, *Herpailurus yagouaroundi*, *Puma concolor*, and *Panthera onca*. We recognized *L. emiliae* as a valid species; therefore, all records of *L. tigrinus* in the northern AF were considered *L. emiliae* (Nascimento and Feijó, 2017). Occurrence records were extracted from data papers, other scientific articles, and databases (see Appendix 2). We only used records from 2000 onwards, accompanied by precise geographic coordinates (< 1 km precision). The records were obtained through camera traps, roadkill specimens, radiotelemetry, active search, and museum data. To reduce the spatial autocorrelation of occurrence records (Araújo and Guisan, 2006), we used the Spatially Rarefy Occurrence Data tool from SDMtoolbox (Brown et al., 2017). We selected less correlated occurrence records by considering if data was spatially clumped (within different distance radii) and if there was similar environmental heterogeneity among occurrences placed near each other. We created five classes of environmental heterogeneity using the percent of eigenvalues from the principal component analysis (PCA) of all the environmental predictors. The breakpoints for the five classes of heterogeneity were defined using the natural breaks classification to maximize the differences between the classes. We filtered occurrence data with similar environmental within different radius, ranging from 5 to 15 km buffer

for *L. guttulus*, *L. wiedii*, *H. yagouaroundi*, *L. pardalis*, *P. concolor*, and *P. onca*. For *L. emiliae*, we used a 5 km buffer due to the low sample size for this species. After filtering, we obtained 2,050 located within the boundaries of the AF (Appendix S1; Figure S3.1). We selected 17 records for *L. emiliae*, 222 for *L. guttulus*, 141 for *L. wiedii*, 248 for *H. yagouaroundi*, 271 for *L. pardalis*, 259 for *P. concolor* and 35 for *P. onca*.

Selection of predictor variables

We tested the influence of GCC and LULC under two future scenarios: (1) an optimistic scenario, in which current land use and land cover will remain unchanged (current LULC + GCC), and (2) a pessimistic scenario, which considers losses of suitable habitats as predicted by GCC and LULC (LULC + GCC). For each of the seven feline species, we used the variance inflation factor (VIF) < 2.0 to test for the correlation on the 19 bioclimatic variables with a resolution of 30 arc-seconds (0.0083° or ~1 km at the Equator) available in WorldClim v.2.1 (www.worldclim.org). We also tested the LULC variables (hereafter landscape) from different bases (Appendix S4). The climate and landscape variables selected are shown in Table S2.1. Considering the inherent uncertainties in climate change projections for 2050 (average between 2041–2060), we used two Shared Socioeconomic Pathways (SSPs): SSP2-4.5, representing an intermediate scenario for greenhouse gas emissions, and SSP5-8.5, the worst-case scenario for greenhouse gas emissions (Riahi et al., 2017). We named SSP2-4.5 as the “mild-case future” and SSP5-8.5 as the “worst-case future”. Therefore, we had two landscape optimistic scenarios (mild-case and worst-case futures) and two landscape pessimistic scenarios (mild-case and worst-case futures). To avoid uncertainties and adopt a more conservative approach (Varela et al., 2015), we used three of the best general circulation models (GCMs) from Coupled Model Intercomparison Project Phase 6 (CMIP6) (Cannon, 2020): MIROC6, MPI-ESM1-2-HR and IPSL-CM6A-LR. In SDM it is important to consider the most accessible areas for species (Soberon and Peterson, 2005). Because of this, and considering the integrated AF (Muylaert et al., 2018) (Figure S3.2), we tested buffers of 20% and 40% (Barve et al., 2011) of the known distribution area around the minimum convex polygon (MPC) for each species occurrence position. Subsequently, we selected the buffer size that showed the best

true skill statistic (TSS; Allouche et al., 2006) and the area under the receiver operating curve (AUC; Elith et al., 2006) values for the models.

Modeling procedures

We modeled and projected species distributions with the sdm package (Naimi and Araújo, 2016) within the R environment (R Core Team, 2023) using an ensemble forecasting approach (Araujo and New, 2007). We used three algorithms with different techniques: (1) maximum entropy (MaxEnt; Phillips et al., 2006); (2) predictive regression trees (Random Forest; Breiman, 2001); and (3) multiple discriminant analysis (MDA; Hastie et al., 1994). We selected 70% of the occurrence data for algorithm training and 30% for external testing, randomized 10 times to generate less biased models through the Bootstrap algorithm. From the 10 replicates, only those with a TSS above the average of the 30 TSSs (10 × three algorithms) were selected. This approach ensured the inclusion of only the best replicates in the ensemble. Model performance was assessed using the TSS analysis test and the AUC. Given the uncertainties regarding the evaluation metrics, we opted to present the results of both the TSS and the AUC (Hao et al., 2019; Shabani et al., 2018). After adjusting the models, we estimated the suitable areas for each species using the maximum decision threshold, maximizing the sum of sensitivity and specificity (max SSS; Liu et al., 2013). We obtained binary maps, where 0 = areas with unsuitable climate and landscape and 1 = areas with suitable climate and landscape for each species.

EcoLand and species richness

We conducted an EcoLand analysis to measure the extent of areas with climate and landscape suitability for each species (see Santos et al., 2020 and Sobral-Souza et al. 2021). To perform the EcoLand analysis for each species separately, we used the models developed with the 20% buffer for the smaller species (*L. emiliae*, *L. guttulus*, *L. wiedi*, *L. pardalis*, and *H. yagouaroundi*), while for *P. concolor* and *P. onca*, we used the 40% buffer. This was based on the best model performances for each buffer size, as previously described. To visualize the EcoLand for each species, refer to Appendix S3. To perform the EcoLand analysis for taxonomic richness, we had to select only one buffer size for all species. Therefore, we used the 20% buffer, as it was

the best for most species and showed good model performance for all of them. For this analysis, we summed all seven climate and landscape binary maps separately for each suitability type. Next, we reclassified the two resulting richness maps - one based on climate and the other on the landscape. This process yielded a single map with the predicted number of species (richness) per pixel across the AF. The data were distributed into four suitability categories (Santos et al., 2020): (1) low suitability predicted by both climate and landscape, (2) low suitability predicted by climate and high suitability predicted by landscape, (3) high suitability predicted by climate and low suitability predicted by landscape, and (4) high suitability predicted by both climate and landscape.

Suitable and unsuitable areas under future climate and land-cover change scenarios

For high feline richness (≥ 4 species) areas, we identified: (1) the pixels that are currently fully suitable for climate and landscape and are projected to remain so in the future (considered stable areas); (2) the altitude values associated with the pixels within the stable areas; and (3) the pixels that are currently fully suitable projected to become unsuitable in the future (classified as loss of suitable habitat). All the target species in our study exhibit some degree of dependence on forest formation within their distribution, and certain species, particularly the smaller ones, are more sensitive to human disturbance (Cruz et al., 2019; Regolin et al., 2017). The absence of forests can create a hostile matrix with low permeability, preventing the movement of some species (Uezu et al., 2008). Therefore, we assumed that fully suitable pixels and those suitable exclusively for landscape are permeable areas. In contrast, fully unsuitable pixels and those suitable exclusively for climate have low permeability.

RESULTS

Model performance and importance of predictor variables

The SDMs performed well for all species, with TSS > 0.41 and AUC > 0.80 (Table S2.2). Mean temperature of driest quarter was the climate variable most relevant for the distribution of *L. emiliae*, *L. guttulus*, *L. pardalis* and *P. concolor*. For *L. wiedii* and *H. yagouaroundi* the precipitation of coldest quarter was the climate variable most relevant, and isothermality for *P. onca*. Forest cover was the most representative landscape variable for *L. emiliae*, *L. guttulus*, *L. wiedii* and *H. yagouaroundi*, while human density was the most representative for *L. pardalis*, *P. concolor* and *P. onca*. (Table S2.2).

Habitat loss and stable areas

Habitat loss will be most pronounced in the worst-case future of the pessimistic scenario (~80%), exceeding the number of stable areas. In the other scenarios and GCC cases, the loss of areas with climate and landscape suitability will exceed 50%. Regarding the stable areas for climate and landscape in the optimistic scenario, 50% will remain stable in the mild-case future and 57% in the worst-case future (*Figure 1*). In the pessimistic scenario, 58% of these areas will remain stable in the mild-case future, whereas only 42% will remain suitable in the worst-case future (*Figure 2*). In both scenarios and both GCC cases, more than 73% of the stable areas are situated at altitudes above 500 m.

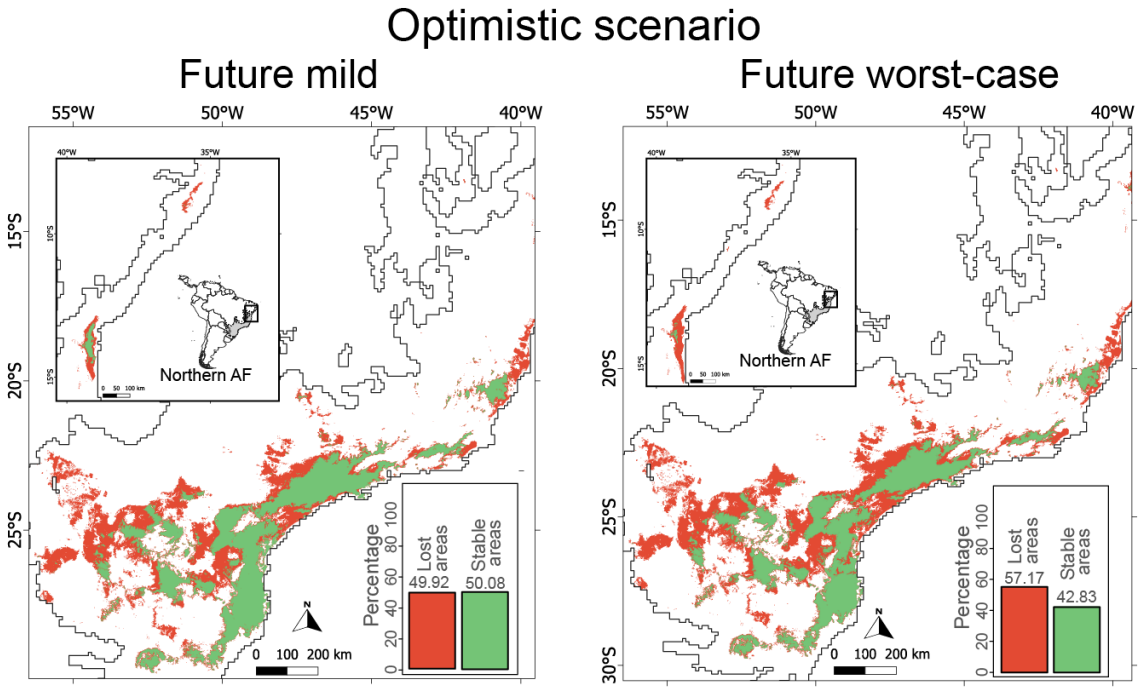

Figure 1. Stable areas (green); those that are fully suitable for ≥ 4 species of felines in the present and expected to remain suitable in the future. The figure also shows the suitable areas that are projected to be lost (red). These are the results of the landscape optimistic scenario, which includes only the effects of global climate change (GCC) and the two cases of GCC (mild-case future and worst-case future) in the Atlantic Forest. The bar graph shows the percentage of stable and lost areas.

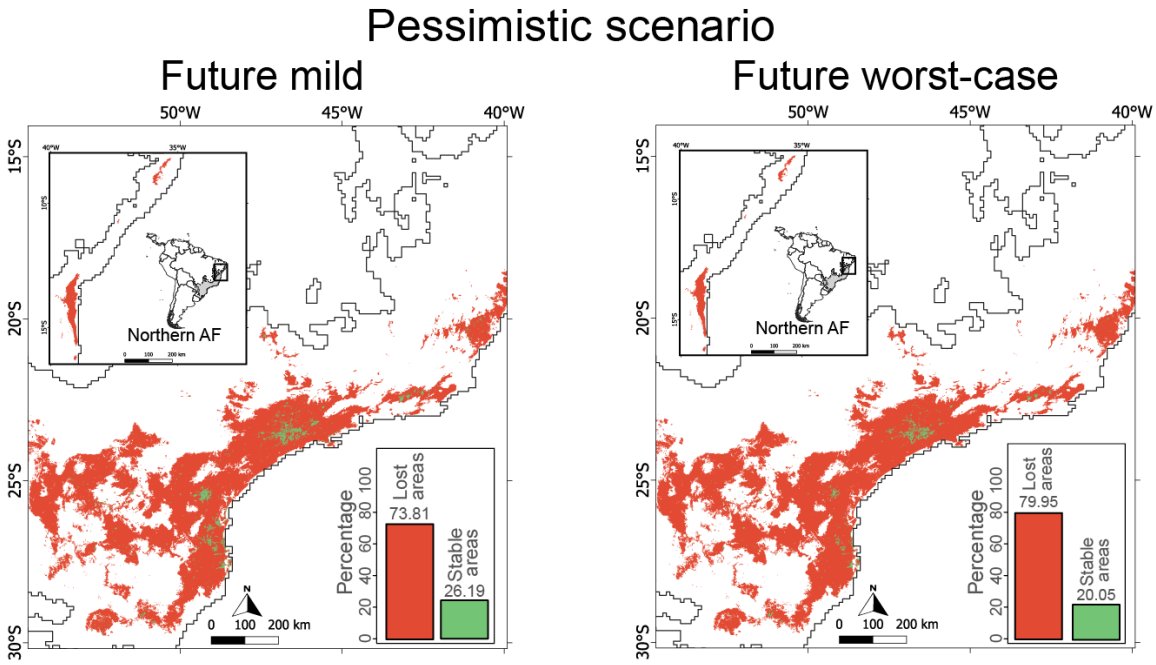

Figure 2. Stable areas (green); those that are fully suitable for ≥ 4 species of felines in the present and expected to remain suitable in the future. The figure also shows the suitable areas

that are projected to be lost (red). These are the results of the pessimistic scenario, which includes the effects of both global climate change (GCC) and land use and land cover change (LULC), as well as the two cases of GCC (mild-case future and worst-case future) in the Atlantic Forest. The bar graph shows the percentage of stable and lost areas.

Permeable and low permeability areas

Currently, only approximately 39% of the areas classified as fully suitable for ≥ 4 species are permeable, while approximately 61% have low permeability. When comparing permeability and low permeability in the optimistic scenario, no differences are observed between current conditions and the GCC scenarios, since changes will occur in the climate but not in the landscape in this scenario. In the pessimistic scenario, a decrease in permeable areas is predicted for the future, with this reduction being more pronounced in the worst-case future, with only 8% of areas remaining permeable (Figure S3.6). In the northern part of the AF, there is a concentration of fully adequate permeable areas (indicated in green), predominantly in a single region. Furthermore, a substantial portion of these areas will be lost in the future, particularly in the pessimistic scenario.

For the current and in the two future GCC scenarios, the largest proportion of permeable areas are those exclusively suitable for landscape (indicated in green). However, these areas are and will continue to be quite isolated from one another. In the southern region of the AF, the largest proportion of currently permeable areas are those that are fully suitable. However, this situation is projected to change in future scenarios, with a loss of suitable areas predicted by the landscape. As a result, the permeable areas, represented by the combination of climate and landscape are primarily concentrated in the southernmost region. It is in this area where the loss of permeability is most evident for the future (*Figure 3*).

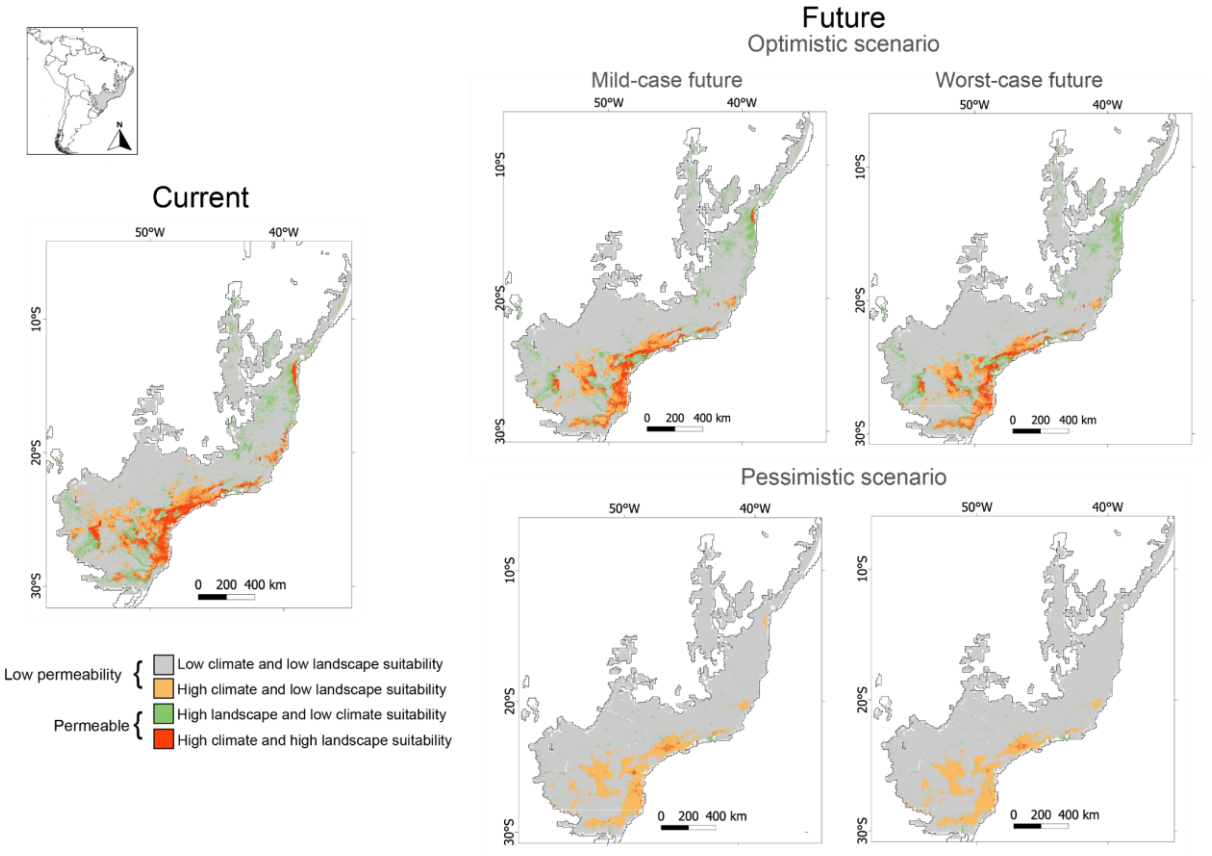

Figure 3. Permeable and low permeability areas for felines in the Atlantic Forest in the optimistic and pessimistic scenarios, as well as in the two global climate change scenarios (mild-case future and worst-case future).

DISCUSSION

This is the first study to consider the effects of the interaction between the two main drivers of species extinction, GCC and LULC, on feline richness in the AF. Our findings suggest that there will be a loss of suitable habitats for feline richness under both optimistic and pessimistic scenarios. However, this loss will be more pronounced in the pessimistic scenario due to the combined effects of GCC and LULC. Additionally, only a small proportion (39%) of these suitable areas are currently permeable. In the future, a reduction to 12 and 8% is estimated. As a result, AF feline species will be threatened by habitat loss and the inability to access new suitable areas, especially stable areas at higher altitudes. Management and conservation actions must consider habitat loss and the connectivity between areas suitable for conserving feline richness and the ecosystems of the AF.

We consider it extremely important to observe the optimistic scenario (in which only the effects of GCC will be present) as a less pessimistic alternative for the conservation of feline richness in the AF. Based on our results, we can address the following question: If we preserve the landscape under current conditions, what will be the future of feline species under GCC? The negative impacts would be lower in the optimistic scenario compared to the pessimistic one. Among all the landscape variables, forest cover was the most important variable influencing the presence of most species, corroborating previous studies conducted in the AF (Cruz et al., 2019; Regolin et al., 2017). Even in the face of the effects of GCC, the preservation of forests and, consequently, the landscape in its current conditions can mitigate the threats to feline richness in the AF. Although our projections indicate that the optimistic scenario is the most conservative, it remains essential to consider landscape restoration across the AF. This is crucial because many species in the AF are facing habitat loss, especially in recent decades, with the carnivore order being the most affected (Butti et al., 2022).

The loss of fully suitable areas exceeded the number of stable areas in the worst-case future in the pessimistic scenario. Thus, conserving suitable areas for high feline richness in the AF will become even more challenging under the effects of GCC and LULC. Although certain feline species may inhabit regions with low tree cover (Regolin et al., 2017), these areas are generally closer to human activities and may have lower prey availability (Bogoni et al., 2022; Paviolo et al., 2018). Given these circumstances, not only felines but also the entire biodiversity of the AF will face the consequences of these impacts, as the absence of top predators has negative, often irreversible, effects on the entire ecosystem (Galetti and Dirzo, 2013). We observed that the most stable areas in both scenarios and GCC cases are in high-altitude areas. This result was expected because LULC is lower at higher altitudes due to topographical complexities and Brazilian legislation that establishes Permanent Preservation Areas (Brazil, 1965). Conversely, lower altitude areas exhibit greater human activity, resulting in greater alteration of the landscape (Bicudo et al., 2020; Elsen et al., 2020). These stable areas are likely to become refuges for many of these species against not only landscape conversion but also the effects of GCC. Therefore, felines from the AF might be forced to migrate to higher altitude regions in search of suitable habitats. The limited number of stable areas for feline richness in the northern regions of the AF, in the worst-case future scenario, could jeopardize the persistence

of *L. emiliae*. This recently described species has a restricted distribution and has yet to be assessed for its vulnerability status (Nascimento and Feijó, 2017). Moreover, it is plausible that other feline species might face local extinctions due to the absence of stable areas between the southern and northern regions of the AF.

More than 60% of the areas exhibited low permeability in both scenarios. This phenomenon can be attributed to the fact that the AF is an immensely fragmented ecoregion, encompassing only 22.7% forest vegetation cover, and more than 97% of its remnants are smaller than 50 ha, with > 800 m of isolation (Vancine et al., 2024). The persistence of carnivore populations intrinsically depends on a connected landscape between suitable habitats (Crooks, 2002). However, our findings indicate that many stable areas situated at lower altitudes are smaller, considerably fragmented patches that are isolated within a matrix with low permeability. Recent research has shown that patches smaller than the *L. guttulus*' home range size account for approximately 95% of the patches used as stepping stones during the dispersal process (Diniz et al., 2021). These small, suitable patches identified in our study are important for promoting the dispersal of larger species over long distances and, therefore, need to be conserved. Another study concluded that forest loss significantly affected the functional connectivity for *P. onca*, a species with a greater dispersal capacity across the landscape (Martinez Pardo et al., 2023).

Small felines capable of traveling shorter distances and/or more forest-dependent species, such as *L. emiliae*, *L. guttulus* and *L. wiedii*, are likely to experience greater impacts due to low permeability. Many of these species have smaller home ranges and are more sensitive to environmental disturbance (Goulart et al., 2009; Kasper et al., 2016). These characteristics may impede their ability to disperse through smaller patches in search of new suitable areas. In such cases, landscape restoration between suitable areas will be essential to facilitate the dispersal of these species. The low permeability observed in northern AF must be monitored with great caution, as these areas are precisely among the few stable areas in the region. Although some species can travel long distances within a low permeability matrix, they will be exposed to direct threats due to increased contact with human activities (Gallego-Zamorano et al., 2020; Ripple et al., 2014). Even if they manage to reach new suitable areas, the establishment of new populations will also depend on factors other than the environmental one. For example, it will be necessary to conduct studies that consider biotic interactions and resource availability in these potentially colonized areas.

Finally, we conclude that conservation measures need to focus on reduce LULC associated with human activities that degrade the environment in the AF. Furthermore, we strongly recommend the preservation of stable areas and the restoration of the landscape to promote connectivity and species dispersal to stable and new suitable areas by 2050. These measures could mitigate the impacts of GCC on feline richness and, consequently, preserve the entire encompassing ecosystem.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

We thank all the researchers who contributed to the cat database we used for the analyses.

Funding

This work was supported by Coordination for the Improvement of Higher Education Personnel (CAPES; process #88887.519051/2020-00), National Council for Scientific and Technological Development - CNPq (process #130769/2021-5; #442147/2020-1; #440145/2022-8; #402765/2021-4; #313016/2021-6 and #440145/2022-8; 420094/2023-7) and FAPESP (processes #2013/50421-2; #2020/01779-5; #2021/06668-0; #2021/08322-3; #2021/08534-0; #2021/10195-0; #2021/10639-5; #2022/10760-1; #2014/23132-2 and #2021/02132-8; #2022/01899-6). This study is also part of the Center for Research on Biodiversity Dynamics and Climate Change, which is financed by the Sao Paulo Research Foundation - FAPESP.

Data Accessibility Statement

The feline occurrence data used in the analyses are available in Appendix S1. The maps resulting from the analyses will be made available on the Dryad repository. All variables used are third party data freely available online. Refer to the sources of the variables in Appendix S4.

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Supporting information 2

for manuscript

“The future of the wild felines under climate and landscape changes in the Atlantic Forest"

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1. Supplementary Material and Methods

Species data

We gathered occurrence records from the data papers, "Atlantic Mammals" (Souza et al., 2019), "Atlantic Camtraps" (Lima et al., 2017), and "Neotropical Carnivores" (Nagy-Reis et al., 2020), in addition to references from other articles (Sartor et al., 2021; Nascimento and Feijó, 2017). Furthermore, we accessed data from four distinct databases: GBIF (www.gbif.org), SiBBr (www.sibbr.gov.br), PortalBio (portaldabiodiversidade.icmbio.gov.br), and speciesLink (specieslink.net).

Species Distribution Models

In this study, we employed the ensemble of forecasting approach to assess distinct methodologies in a set of predictions (Araújo and New, 2007). As a result, the pixel values in the final potential distribution map exhibit standardized frequencies of predicted presences, achieved through consensus from all generated models. To accomplish this, we employed three algorithms utilizing varying techniques. Firstly, we employed the method that estimates species distributions by uncovering the distribution of maximum entropy, MaxEnt (Phillips et al., 2006). Secondly, we utilized a method based on decision trees, which combine multiple predictive regression trees for making forecasts, known as Random Forest (Breiman, 2001). This method employs a blend of predictive regression tree predictors. Lastly, we incorporated the method of

multiple discriminant analysis, relying on multiple models (MDA), which is a classification technique grounded in multiple models (Hastie et al., 1994).

Climate predictions exhibit considerable variation across General Circulation Models (GCMs), particularly within tropical regions (Varela et al., 2015). Thus, employing multiple models is recommended to mitigate uncertainties and model autocorrelation. In pursuit of a more conservative approach, we integrated two distinct Global Circulation Models (GCMs) from the SSP scenario: MIROC-ES2L and CanESM5 (Sanderson et al., 2015; Varela et al., 2015). This choice aims to enhance the robustness of our analysis by embracing a diversity of model perspectives.

Model calibration and evaluation

Given the persistent uncertainties about assessment metrics, we have opted to present results from both the True Skill Statistic (TSS) and the Area Under the Curve (AUC) (Hao et al., 2019; Shabani et al., 2018). These criteria stand independent of species prevalence within the data (Allouche et al., 2006; Zipkin et al., 2012). While the AUC has found application in a greater number of studies compared to the TSS (Hao et al., 2019), the TSS is the recommended choice for evaluating the models' capability to forecast species distributions (Shabani et al., 2018).

2. Supplementary Tables

Table S2.1. Values of the True Skill Statistic mean (TSS) and of the area under the receiver-operating characteristic curve mean (AUC).

Species	Buffer 20%		Buffer 40%	
	TSS	**AUC**	**TSS**	**AUC**
Landscape				
L. emiliae	0.82	0.90	0.73	0.82
L. guttulus	0.74	0.89	0.56	0.80
L. wiedii	0.50	0.81	0.40	0.80
H. yagouaroundi	0.48	0.83	0.47	0.79
L. pardalis	0.41	0.83	0.40	0.81
P. concolor	0.43	0.80	0.43	0.81
P. onca	0.67	0.84	0.69	0.85
Climate				
L. emiliae	0.77	0.86	0.74	0.85
L. guttulus	0.53	0.82	0.50	0.82
L. wiedii	0.75	0.92	0.72	0.91
H. yagouaroundi	0.64	0.88	0.64	0.87
L. pardalis	0.63	0.86	0.61	0.86
P. concolor	0.66	0.88	0.69	0.90
P. onca	0.70	0.86	0.72	0.87

Table S2.2. Values from Variance Inflation Factor (VIF) and relative importance predictor variable used in the SDMs, comprising landscape and climate variables.

Species	Predictor variable	Description	VIF	Relative importance
L. emiliae	Tree cover	Tree cover	1.01	0.38
	Terrain rug.	Terrain ruggedness	1.01	0.30
	Human density	Human density	1.00	0.29
	Water Frequency	Water Frequency	1.00	0.08
	Bio8		1.61	0.08
	Bio13	Precipitation of Wettest Month	1.43	0.12
	Bio18	Precipitation of Warmest Quarter	1.39	0.53
	Bio04	Temperature Seasonality	1.30	0.14
	Bio06		1.50	0.12
L. gutullus	Tree cover	Tree cover	1.01	0.48
	Human density	Human density	1.00	0.33
	Terrain rug.	Terrain ruggedness	1.01	0.18
	Water Frequency	Water Frequency	1.00	0.08
	Bio03		1.46	0.14
	Bio09	Mean Temperature of Driest Quarter	1.37	0.21
	Bio08	Mean Temperature of Wettest Quarter	1.44	0.14
	Bio07		1.20	0.13
	Bio18	Precipitation of Warmest Quarter	1.29	0.13
L. wiedii	Tree cover	Tree cover	1.01	0.45
	Human density	Human density	1.00	0.31

	Terrain rug.	Terrain ruggedness	1.01	0.24
	Water Frequency	Water Frequency	1.00	0.09
	Bio02	Mean Diurnal Range	1.35	0.15
	Bio08	Mean Temperature of Wettest Quarter	1.70	0.08
	Bio09	Mean Temperature of Driest Quarter	1.51	0.18
	Bio13	Precipitation of Wettest Month	1.11	0.07
	Bio19	Precipitation of Coldest Quarter	1.74	0.27
H. yagouaroundi	Tree cover	Tree cover	1.01	0.49
	Human density	Human density	1.00	0.29
	Terrain rug.	Terrain ruggedness	1.01	0.23
	Water Frequency	Water Frequency	1.00	0.09
	Bio02	Mean Diurnal Range	1.38	0.11
	Bio09	Mean Temperature of Driest Quarter	1.53	0.19
	Bio08	Mean Temperature of Wettest Quarter	1.76	0.11
	Bio13	Precipitation of Wettest Month	1.13	0.12
	Bio19	Precipitation of Coldest Quarter	1.72	0.21
L. pardalis	Tree cover	Tree cover	1.01	0.40
	Human density	Human density	1.00	0.46
	Terrain rug.	Terrain ruggedness	1.01	0.17

	Water Frequency	Water Frequency	1.00	0.04
	Bio02	Mean Diurnal Range	1.39	0.14
	Bio08	Mean Temperature of Wettest Quarter	1.71	0.10
	Bio09	Mean Temperature of Driest Quarter	1.43	0.32
	Bio19	Precipitation of Coldest Quarter	1.43	0.11
P. concolor	Tree cover	Tree cover	1.01	0.35
	Human density	Human density	1.00	0.52
	Terrain rug.	Terrain ruggedness	1.01	0.17
	Water Frequency	Water Frequency	1.00	0.07
	Bio09	Mean Temperature of Driest Quarter	1.84	0.21
	Bio13	Precipitation Seasonality	1.10	0.15
	Bio02	Mean Diurnal Range	1.32	0.13
	Bio08	Mean Temperature of Wettest Quarter	1.48	0.09
P. onca	Tree cover	Tree cover	1.01	0.30
	Human density	Human density	1.00	0.30
	Terrain rug.	Terrain ruggedness	1.00	0.35
	Water Frequency	Water Frequency	1.00	0.03
	Bio02	Mean Diurnal Range	1.19	0.09
	Bio03	Isothermality	1.26	0.47
	Bio08	Mean Temperature of wettest Quarter	1.30	0.14
	Bio13	Precipitation Seasonality	1.06	0.17

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Supporting information 3

for manuscript

“The future of the wild felines under climate and landscape changes in the Atlantic Forest"

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1. Supplementary figures

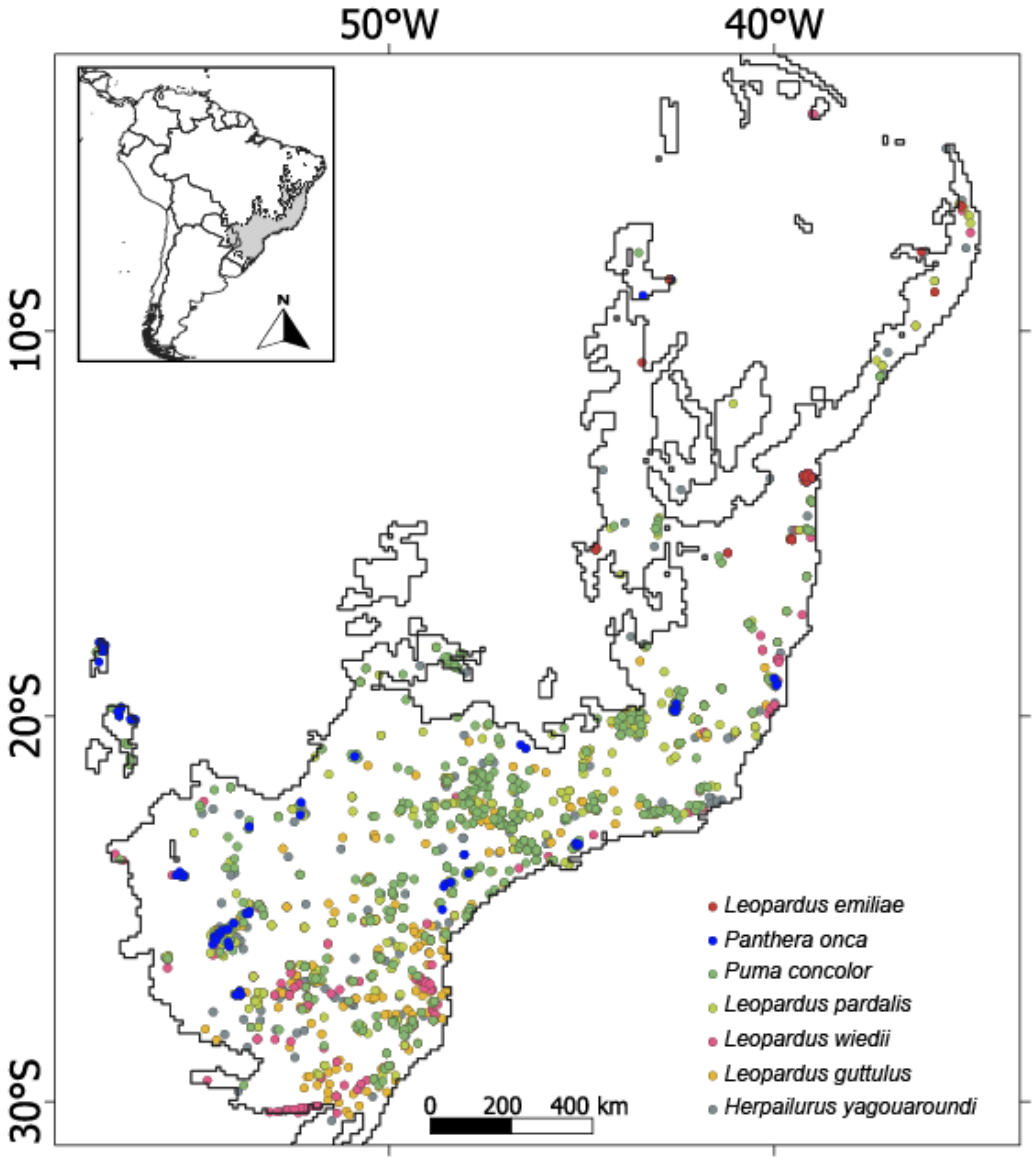

Fig. S3.1. Species occurrence records used in species distribution modeling.

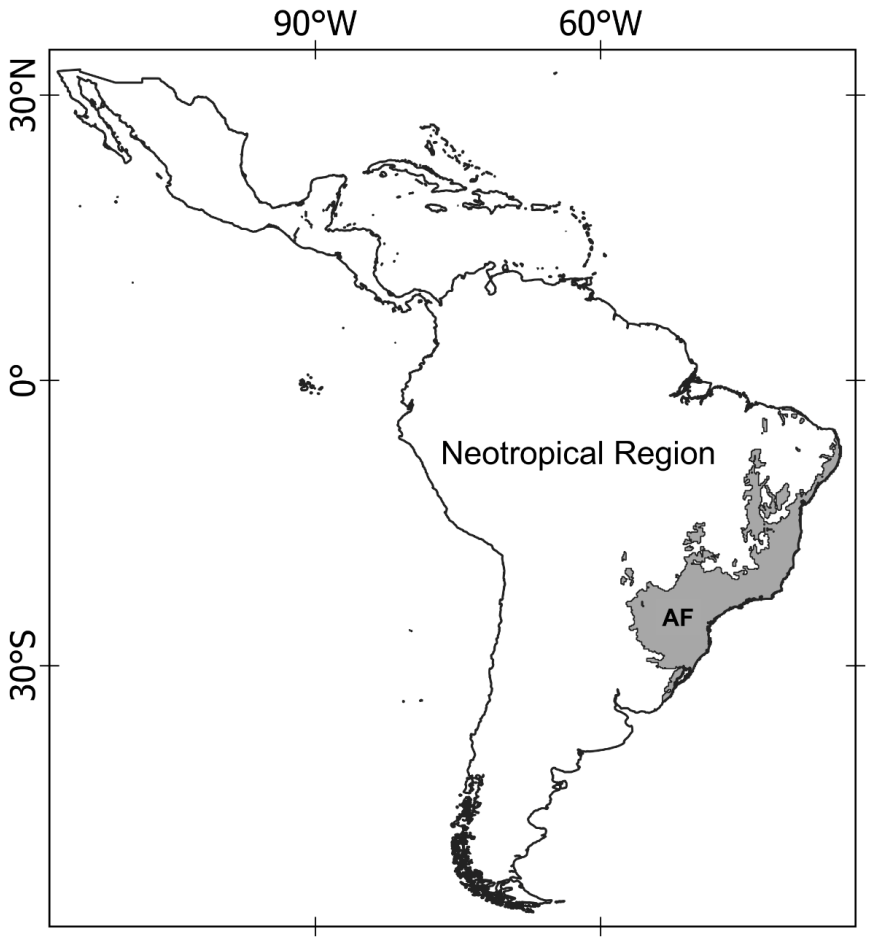

Figure S3.2. The boundaries of the study regions. The Atlantic Forest (AF) that was used for species distribution modeling.

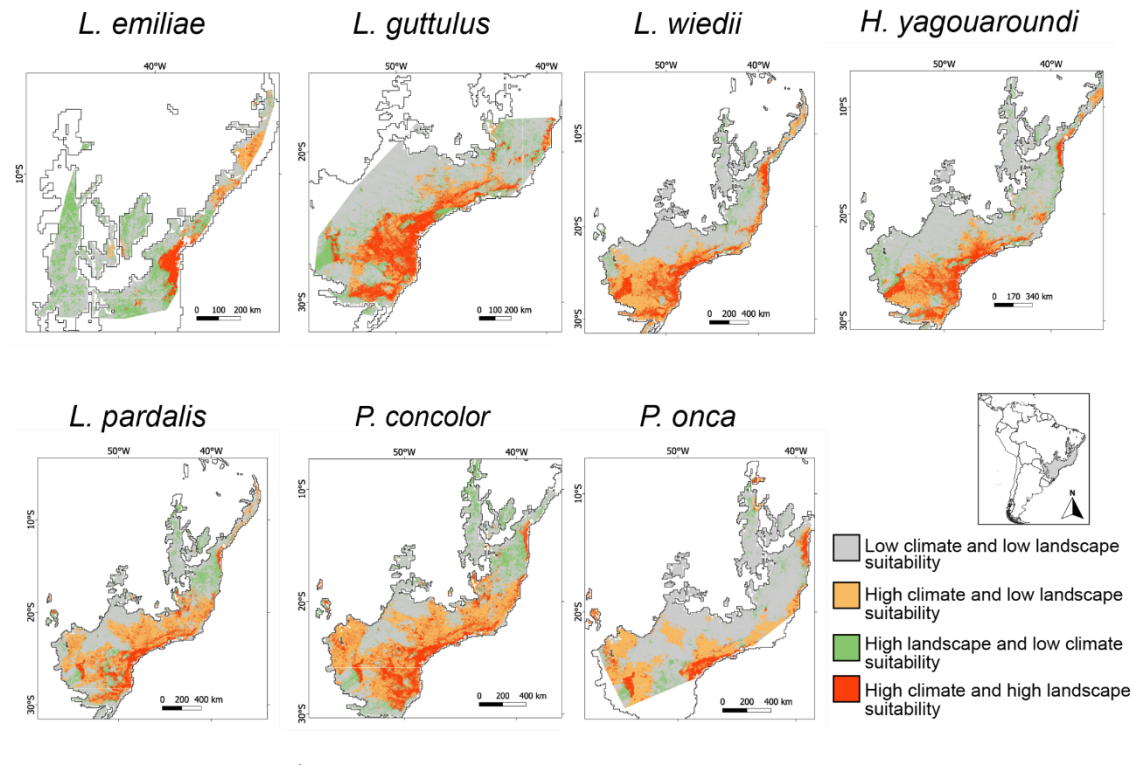

Fig. S3.3. Ecoland for the present for each feline species in the Atlantic Forest.

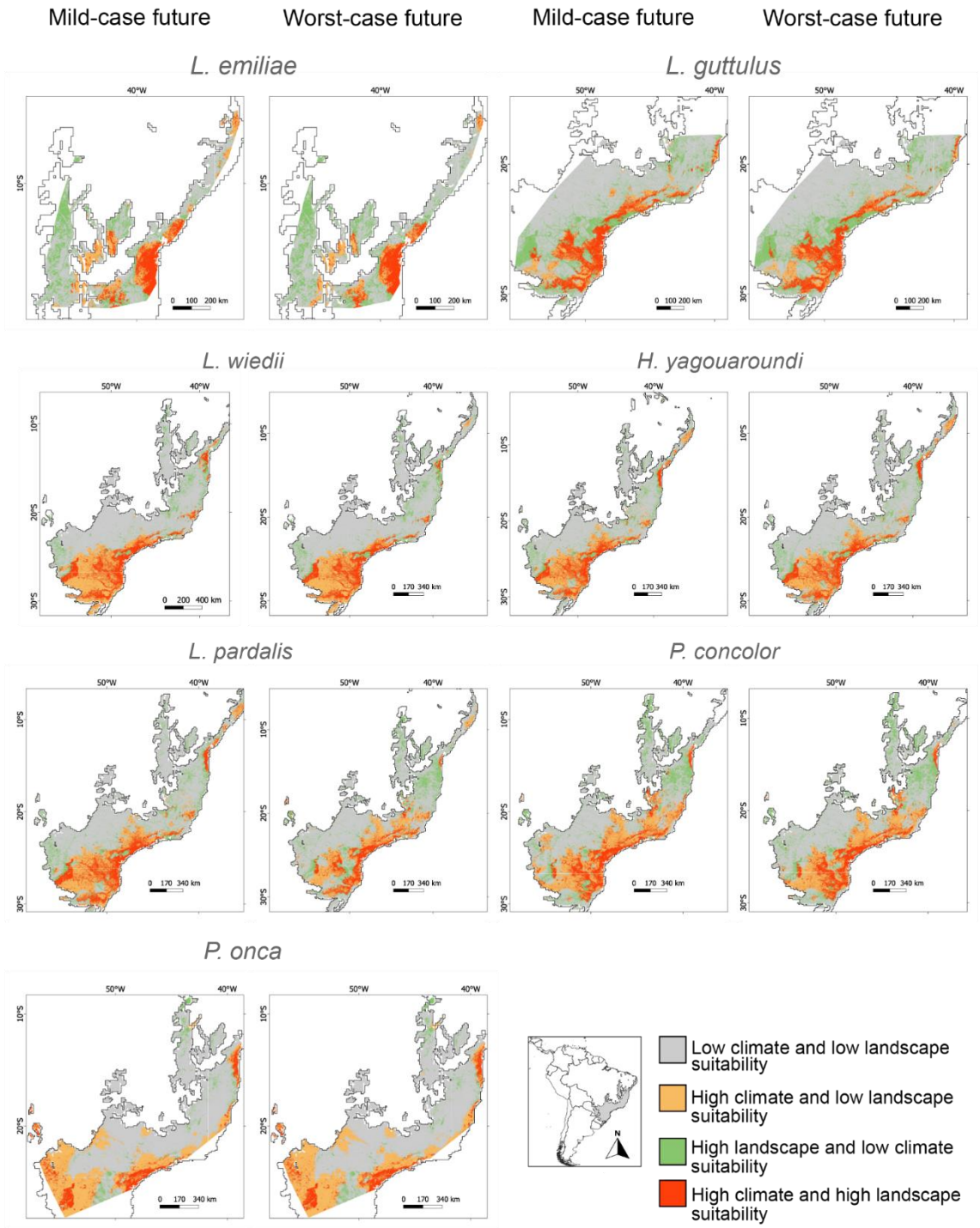

Fig. S3.4. Ecoland for the optimistic scenario that includes only the effects of Global Climate Change (GCC) and the two GCC cases (mild-case future and worst-case future), for each of the species in the Atlantic Forest.

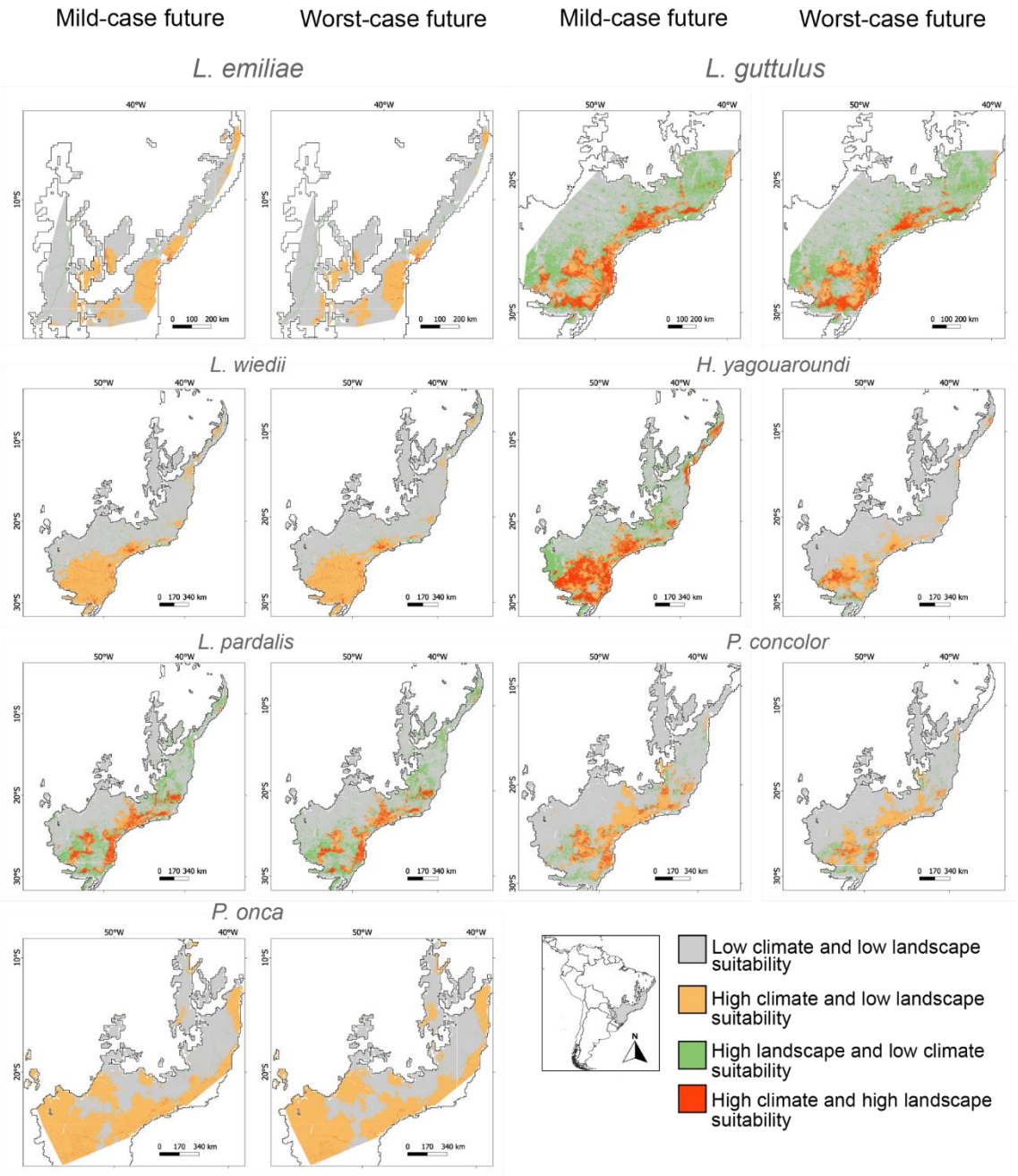

Fig. S3.5. Ecoland for the pessimistic scenario that includes the effects of both Global Climate Change (GCC) and Land Use Change (LULC), as well as the two GCC cases (mild-case future and worst-case future), for each of the species in the Atlantic Forest.

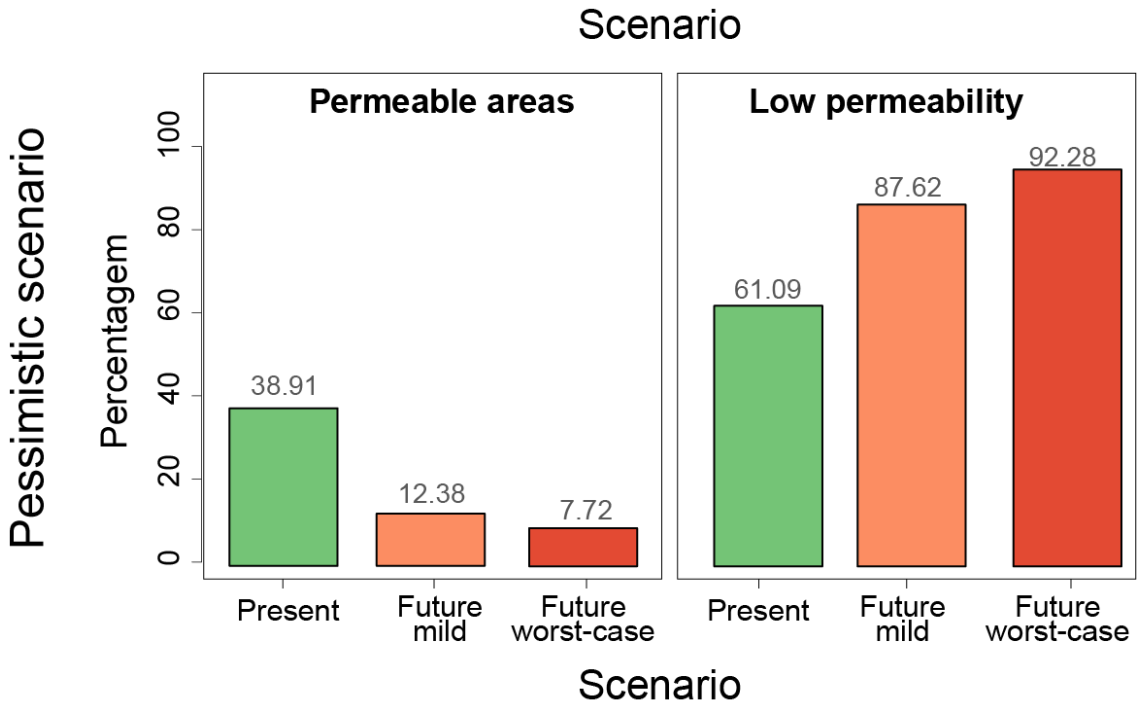

Fig. S3.6. Percentage of permeable areas (left) for felines in the Atlantic Forest and low permeability areas (right) in the present and future under both global climate change scenarios (mild-case future and worst-case future).

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CONSIDERAÇÕES FINAIS

Nesta tese investiguei como o clima e a paisagem e suas mudanças (GCCs e LULC, respectivamente) podem influenciar nos padrões de distribuição de sete espécies felinos da Mata Atlântica, bem como, identifiquei áreas prioritárias para conservação dessas espécies. De forma geral, os resultados mostraram que apenas 30% da Mata Atlântica são atualmente adequados para todas as espécies de felinos estudadas. Para o futuro (2050), a perda de áreas adequadas será mais pronunciada em um cenário pessimista, em que há a combinação da GCCs e da LULC.

No capítulo 1, apresentei que apenas 9% das áreas totalmente adequadas estão atualmente protegidas por UCPIs, com espécies como *L. emiliae* e *P. onca* tendo as menores porcentagens de proteção. A partir dos resultados desse capítulo, a sub-região Serra do Mar apresentou mais áreas totalmente adequadas para riqueza de felinos, sendo assim uma região importante para a conservação da biodiversidade, corroborando com estudos anteriores. A sub-região Araucária, incluindo as fronteiras do Brasil e Argentina, foi a segunda mais importante para conservação. Isso torna necessária a conectividade entre áreas protegidas além das fronteiras nacionais.

No capítulo 2, mostrei que em 2050 áreas com maior altitude abrigarão mais áreas estáveis para a riqueza de felinos. Além disso, aproximadamente 83% das áreas analisadas, da MA, apresentam baixa permeabilidade à riqueza taxonômica de felinos e apenas uma pequena proporção (39%) destas áreas adequadas são atualmente permeáveis. É importante considerar o cenário otimista (em que apenas os efeitos da GCC estarão presentes) como uma alternativa menos pessimista para a conservação da riqueza de felinos na Mata Atlântica. No entanto, é essencial considerar a restauração da paisagem nessa ecorregião frente a marcante perda de habitat que essas espécies estão presenciando nas últimas décadas.

Considero que há algumas limitações associadas a este estudo, tais como as incertezas atreladas a Modelos de Distribuição de Espécies e Modelos de Nicho Ecológico, assim como das projeções das GCCs e das LULCs. Adicionalmente, a precisão dos resultados dos modelos pode ser influenciada pela qualidade e abrangência dos registros de ocorrência utilizados.

Entretanto, esta pesquisa contribui substancialmente para o planejamento de estratégias de conservação na Mata Atlântica, evidenciando as áreas prioritárias para a conservação de felinos e a necessidade de criação e manutenção de UCPIs.

Também destaca a importância da restauração de paisagens e da promoção da corredores ecológicos. A integração de medidas de conservação com iniciativas de restauração e a criação de corredores ecológicos são cruciais para garantir a conservação das espécies aqui estudadas, e dos ecossistemas associados.