UNIVERSIDADE FEDERAL DO PARANÁ

CAMILA NAOMI LERMEN

DINÂMICA ESPAÇO TEMPORAL DA QUALIDADE DE HABITAT COMO FERRAMENTA PARA POLÍTICAS PÚBLICAS NO ESTADO DO PARANÁ

CURITIBA

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Dissertação apresentada ao curso de Pós-Graduação em Ecologia e Conservação, Setor de Ciências Biológicas, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Mestre em Ecologia e Conservação.

Orientadora: Prof.ª Dra. Márcia Cristina Mendes Marques

Coorientador: Prof. Dr. Vinicius Marcilio-Silva

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Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação ECOLOGIA E CONSERVAÇÃO da Universidade Federal do Paraná foram convocados para realizar a arguição da dissertação de Mestrado de **CAMILA NAOMI LERMEN** intitulada: **DINÂMICA ESPAÇO TEMPORAL DA QUALIDADE DE HABITAT COMO FERRAMENTA PARA POLÍTICAS PÚBLICAS NO ESTADO DO PARANÁ**, sob orientação da Profa. Dra. MARCIA CRISTINA MENDES MARQUES, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.
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RESUMO

A qualidade de habitat é a capacidade do ambiente em fornecer condições e recursos adequados para a persistência de indivíduos ou populações. A mudança no uso da terra é uma das principais atividades dos seres humanos para transformar o ambiente natural e interferir na qualidade do habitat. O objetivo desse trabalho foi avaliar a dinâmica espaço-temporal da qualidade de habitat no Paraná entre 1985 e 2020, tendo como organismos foco árvores e gramíneas nativas. Para mapear a qualidade de habitat foi utilizando o software InVEST (*Integrated Valuation of Ecosystem Services and trade-offs*). No Paraná predominam áreas de baixa qualidade de habitat, tanto para floresta quanto para campos, sendo que a distribuição não foi uniforme no Estado. A qualidade de habitat para florestas teve tendência de queda no decorrer dos anos, enquanto a qualidade de habitat para campos apresentou uma tendência de declínio até os anos 2000 seguida de um aumento. De modo geral, as regiões do Paraná que tiveram maior qualidade de habitat foram oeste, sudeste, metropolitana de Curitiba e centro-sul. Por outro lado, as regiões noroeste, norte-central, norte-pioneiro, sudoeste e centro-ocidental apresentaram baixa qualidade de habitat. Encontramos diferenças na qualidade de habitat dentro e fora de áreas protegidas, sedo que a primeira categoria apresentou maiores valores de qualidade. Ressaltando a importância das áreas protegidas para a manutenção da qualidade de habitat da vegetação nativa. Os fatores que influenciam a qualidade do habitat no Paraná são a baixa cobertura de vegetação nativa e a ocupação e uso intensivo do solo pela agricultura e pastagem. Com isso, políticas públicas voltadas para a restauração de locais com baixa qualidade de habitat e manutenção de locais com alta qualidade de habitat são necessárias para garantir a conservação da biodiversidade e serviços ecossistêmicos no Paraná.

Palavras-chave: Biodiversidade. InVEST. Mata Atlântica. Serviços Ecossistêmicos.

ABSTRACT

Habitat quality is the ability of the environment to provide adequate conditions and resources for the persistence of individuals or populations. Change in land use is one of the main activities of human beings to transform the natural environment and interfere in the quality of the habitat. In this study we evaluate the spatio-temporal dynamics of habitat quality in Paraná between 1985 and 2020, focusing on native forests and grasslands. To map habitat quality, the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) software was used. In Paraná, areas of low habitat quality predominate for both forests and grasslands, presenting an uneven distribution. Habitat quality for forests had a decreasing trend over the years, while habitat quality for grasslands showed a declining trend until the 2000s followed by an increase. In general, the State regions that had the highest habitat quality were west, southeast, and center-south. On the other hand, the north, southwest, and central-west regions presented low habitat quality. When comparing habitat quality inside and outside protected areas, we found that protected areas had higher mean values of habitat quality. Highlighting the relevance of protected areas for maintaining the habitat quality of native vegetation. Habitat quality in Paraná was mainly influenced by the low coverage of native vegetation and the intensive land use and occupation by agriculture and pasture. Therefore, public policies aimed at restoring places with low habitat quality and maintaining areas with high habitat quality are necessary to guarantee the conservation of biodiversity and ecosystem services in Paraná.

Keywords: Biodiversity. InVEST. Atlantic Forest. Ecosystem services.

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1 INTRODUÇÃO GERAL

Biodiversidade pode ser definida como a variabilidade entre organismos e espécies de todas as origens (Convention on Biological Diversity, 2011), incluindo ecossistemas terrestres e aquáticos e os complexos ecológicos dos quais eles fazem parte (Mace; Noris; Fitter, 2012). A biodiversidade é componente chave da provisão de serviços ecossistêmicos, ou seja, ela dá suporte às características, funções e processos ecológicos que direta ou indiretamente contribuem para o bem-estar humano (Costanza, 2020). Apesar desses benefícios, a discrepância entre interesses socioeconômicos e ambientais tem levado a níveis crescentes de degradação dos recursos naturais (Borsatto *et al*., 2007), através de uma pressão crescente das atividades humanas sobre habitats e ecossistemas ao redor do globo (Nematollahi *et al*., 2020). Para ecossistemas terrestres e de água doce, mudanças no uso do solo têm causado os maiores impactos relativos na natureza desde 1970 (IPBES, 2018). Tais ações levam à fragmentação de paisagens, diminuindo a conectividade e qualidade de habitats biológicos (Zheng; Wang; Li, 2023).

Habitats são ambientes onde plantas, animais e outros organismos podem crescer, viver e se reproduzir. A qualidade de habitat se refere à habilidade de ecossistemas em prover condições apropriadas para a sobrevivência de indivíduos e populações (Broquet *et al*., 2024). Pode ser considerada um termo abstrato, que tenta sumarizar o quão adequado um ecossistema é em relação a um estado ideal de referência (Aneseyee *et al.,* 2020). A qualidade de habitat pode ser percebida como um *proxy* para a biodiversidade, uma vez que quanto maior a qualidade de habitat, maior a capacidade do ecossistema em fornecer recursos para a persistência de diferentes espécies e consequentemente maior a biodiversidade (Sharp *et al*., 2018).

Atualmente, os métodos de avaliação da qualidade do habitat podem ser divididos em duas categorias: uma envolvendo a obtenção de parâmetros de qualidade do habitat por meio de pesquisas de campo e outra envolvendo o uso de modelos (Wang; Cheng, 2022). A primeira categoria de métodos demanda mais tempo e mão de obra, tendendo a se concentrar em pequenas áreas ou habitats de espécies únicas, e dificultando a realização de análises de dados de longo prazo. O uso de modelos também tem suas limitações já que estes são aproximações e simplificações dos fatos observados, mas suas vantagens de operacionalização e aplicação em largas escalas espaciais e temporais se sobressaem (Chen; Liu; Bi, 2023).

O modelo InVEST (*Integrated Valuation of Ecosystem Services and Tradeoffs*) de qualidade do habitat (InVESThq) faz parte de um software gratuito e *open source* desenvolvido pela Universidade de Stanford, Universidade de Minnesota, The Nature Conservancy e World Wildlife Fund (Natural Capital Project, 2024). O InVESThq tem sido amplamente utilizado para avaliar a qualidade do habitat em ecossistemas naturais em diferentes regiões do mundo (Aneseyee *et al.* 2020; Hu *et al*., 2023). Por exemplo Zheng, Wang e Li (2023) quantificaram mudanças espaço-temporais na qualidade de habitat em duas bacias hidrográficas da China. Polasky *et al*. (2011) quantificaram as mudanças na provisão de serviços ecossistêmicos em Minnesota, EUA. Apesar do reconhecimento global, o número de trabalhos que utilizaram InVESThq no Brasil ainda é reduzido. Duarte, Ribeiro e Paglia (2016) definiram áreas prioritárias para a conservação no quadrilátero ferrífero, utilizando modelos InVEST de qualidade de habitat, estoque de carbono e retenção de sedimentos. E mais recentemente, Broquet *et al*. (2024) fizeram previsões do impacto da mudança do uso do solo sobre a qualidade de habitat na Bacia Hidrográfica do Alto Paraguai, Brasil.

O modelo InVESThq quantifica a qualidade do habitat com base em mapas de uso do solo (*Land Use Land Cover*), a adequação de cada categoria de LULC como habitat e a densidade de ameaças e seus impactos na qualidade do habitat (Terrado *et al*., 2016). Ameaças são fontes de distúrbios ambientais ou antropogênicos à biodiversidade (Akbari; Pittman; Feick, 2021), ou seja, qualquer tipo de impacto que leva a uma diminuição na adequabilidade para a ocorrência de uma espécie ou grupo. A mensuração da qualidade de habitat pode ser realizada para diferentes grupos ecológicos, ou seja, para táxons, guildas e comunidades. Quando analisamos a qualidade de habitat para espécies específicas, podemos obter como resultado uma distribuição que destaca os locais mais restritos, com alta qualidade de habitat, que pode ser utilizado para a conservação de espécies ameaçadas de extinção (Abdollahi; Zeilabi; Xu, 2023). Outros trabalhos mensuram a qualidade de habitat para espécies de diferentes grupos, por exemplo mamíferos, pássaros, anfíbios répteis e plantas (Duarte; Ribeiro; Paglia, 2016), obtendo padrões mais gerais de qualidade de habitat. Um caminho do meio pode ser a mensuração da qualidade de habitat para comunidades com formas de vida e necessidade de recursos parecidas.

O InVESThq fornece informações sobre como as mudanças nos ecossistemas provavelmente levarão a mudanças nos fluxos de qualidade de habitat, podendo auxiliar na tomada de decisões sobre a gestão de recursos naturais (Sharp *et al*., 2018). Compreender as dinâmicas da qualidade de habitat é de grande importância para evidenciar mudanças e os causadores de tal dinâmica (He *et al.*, 2023). Isto ajuda na preparação para o futuro, saber se essa dinâmica deve se repetir ou não, e quais medidas podem ser tomadas para evitar mudanças negativas e para promover aumento na qualidade de habitat. Além disso, a mensuração precisa das mudanças no uso do solo e na dinâmica da paisagem, é uma importante ferramenta para as políticas regionais de conservação e manejo (Kauano *et al*., 2012), dando aos tomadores de decisão a oportunidade de planejar operações de gestão com base em informações científicas (Sharafatmandrad; Mashizi 2023).

Entre os habitats florestais da Terra, a Mata Atlântica é considerada um *hotspot* de biodiversidade, sendo um dos biomas mais ricos em espécies do mundo, com altos níveis de endemismo (Mittermeier *et al*., 2011). A Mata Atlântica constitui um complexo de ecossistemas de grande importância para a manutenção da biodiversidade (Zwiener *et al*., 2017). Dado o intenso desmatamento e perturbação humana, a maior parte da Mata Atlântica remanescente existe em pequenos fragmentos isolados uns dos outros e são compostas por florestas secundárias em estágios iniciais a médios de sucessão (Ribeiro *et al*., 2009). Ameaças comuns às florestas tropicais, incluindo a Mata Atlântica, são agricultura e pecuária, expansão urbana desordenada, exploração de plantas (madeireiras, ornamentais), fragmentação de áreas protegidas, industrialização e poluição (Carlucci; Marcilio-Silva; Torezan, 2021).

Os campos do Sul do Brasil (campos sulinos) são outro ecossistema sob constante pressão antrópica (Overbeck *et al*., 2015). As principais ameaças antrópicas aos campos nativos brasileiros são agricultura e plantações de árvores exóticas (Segatto *et al*., 2024). A vegetação dos campos sulinos é altamente diversa e muitas vezes formam mosaicos com fragmentos de Mata Atlântica nos estados do Paraná e Santa Catarina (Behling, 1997). Apesar da alta diversidade, os campos sulinos historicamente foram negligenciados em termos de estudos e ações de conservação (Overbeck *et al*., 2022).

O Paraná, localizado no sul do Brasil, tem um dos exemplos mais preocupantes de perdas de área de Mata Atlântica (Sampaio *et al*., 2023). Originalmente a área total do estado era coberta por 83% de Mata Atlântica e 14% de campos (Roderjan *et al*., 2002), mas, atualmente, essa porcentagem diminuiu para 11.6% de cobertura Mata Atlântica e 0.16% de campos (Fundação SOS Mata

Atlântica, 2021). O processo de perda e fragmentação dos ecossistemas naturais do Paraná foi uma consequência de uma ocupação desordenada e sem restrições (Campos, 2005). Impulsionada inicialmente pela extração seletiva de madeira ao que se seguiram atividades agropecuárias e cultivos extensivos de grãos, todos de caráter eminentemente econômico (Roderjan *et al*., 2002).

Atualmente há uma demanda pela avaliação dos impactos antrópicos na degradação florestal da Mata Atlântica e nos campos sulinos (Mohebalian, *et al*. 2022; Overback, 2015). Neste sentido, o Paraná é um ótimo local para avaliar as mudanças no uso e cobertura da terra e as dinâmicas da qualidade do habitat ao longo do tempo nos biomas da Mata Atlântica e dos campos. Esse objetivo vai ao encontro com a necessidade de aumentar os conhecimentos relacionados a padrões de biodiversidade ao longo de tempo no Estado, para embasar melhor gestão ambiental, uma vez que a mensuração precisa das mudanças no uso do solo e na dinâmica da paisagem é uma importante ferramenta para políticas regionais de conservação e manejo (Kauano *et al.*, 2012).

2 CAPÍTULO 1[1]

[1] Capítulo preparado no formato de artigo científico

Spatio-temporal dynamics of habitat quality in Paraná State Brazil

Camila Naomi Lermen[*a], Vinicius Marcilio-Silva[a,b], Marcia C. M. Marques[a]

a- Laboratory of Plant Ecology, Department of Botany, Federal University of Parana, Brazil
b- Cavender-Bares Lab, Department of Ecology, Evolution and Behavior, University of Minnesota, USA
* correspondence author: cnlermen@gmail.com

ABSTRACT

Habitat quality is the ability of the environment to provide adequate conditions and resources for the persistence of individuals or populations. Change in land use is one of the main activities of human beings to transform the natural environment and interfere in the quality of the habitat. In this study we evaluate the spatio-temporal dynamics of habitat quality in Paraná between 1985 and 2020, focusing on native forests and grasslands. To map habitat quality, the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) software was used. In Paraná, areas of low habitat quality predominate for both forests and grasslands, presenting an uneven distribution. Habitat quality for forests had a decreasing trend over the years, while habitat quality for grasslands showed a declining trend until the 2000s followed by an increase. In general, the State regions that had the highest habitat quality were west, southeast, and center-south. On the other hand, the north, southwest, and central-west regions presented low habitat quality. When comparing habitat quality inside and outside protected areas, we found that protected areas had higher mean values of habitat quality. Highlighting the relevance of protected areas for maintaining the habitat quality of native vegetation. Habitat quality in Paraná was mainly influenced by the low coverage of native vegetation and the intensive land use and occupation by agriculture and pasture. Therefore, public policies aimed at restoring places with low habitat quality and maintaining areas with high habitat quality are necessary to guarantee the conservation of biodiversity and ecosystem services in Paraná.
Keywords: Atlantic forest, Biodiversity, InVEST, Ecosystem services

2.1 INTRODUCTION

Land use change is one of the main human activities that transform the natural environment by removing habitats and reducing the quality of habitat remnants (Zhang *et al*., 2020; IPBES 2018). Changes in the extent and composition of forests, grasslands, wetlands, and other ecosystems that are habitats for a high diversity of taxa, decrease biodiversity and the provision of ecosystem services (Polasky *et al*., 2011). Habitat quality can be understood as the ability of environments to provide conditions for appropriate individual or population persistence (Zhang *et al*., 2022). Thus, a positive relationship exists between habitat quality and biodiversity, with habitat quality indicating the quantity and quality of resources available to the communities (Duarte; Ribeiro; Paglia, 2016). To mitigate the impacts of human activities, it has been necessary to quantify the status of ecosystem services (Nematollahi *et al.,* 2020), such as habitat quality.

The measurement of land use and habitat quality changes can be an important tool for understanding landscape dynamics. One broadly used approach for assessing habitat quality through remote sensing is the Integrated Valuation of Environmental Services and Tradeoffs model of habitat quality (InVESThq) (Wang; Cheng, 2022). The model proceeds with data on land use and land cover (LULC), anthropogenic threats, habitat suitability, and expert knowledge, providing a spatially explicit representation of habitat quality (Terrado *et al*., 2016). It can replace sophisticated methods such as species surveys and it does not need species distribution data (Aneseyee *et al.,* 2020), resulting in research that is both cost-effective and time-efficient.

The availability of high-quality remote sensing data has increased significantly in recent years. For example, MapBiomas is a Brazilian initiative mapping LULC change with high spatio-temporal resolution and standardized classification (Souza Jr. *et al*., 2020). This type of data allows analysis of habitat quality to be applied to larger spatial and temporal scales. Measuring spatio-temporal changes in habitat quality driven by LULC dynamics can guide regional conservation practices and management policies (Chen; Liu; Bi, 2023). Mapping habitat quality can make the spatial distribution of nature's benefits to people explicit, by highlighting areas with low and high habitat quality as well as which LULC types are associated with habitat quality loss and gain. Leading to the formulation of significant policies for conservation and restoration of biodiversity and ecosystem services (Broquet *et al*., 2024).

The Brazilian Atlantic Forest is a hotspot of biodiversity, and one of the most threatened and important biomes for conservation (Marques *et al*., 2021). Another critically important ecosystem that occurs in all Brazilian biomes is grassland ecosystem (Overbeck *et al*., 2022). Common threats to dense forests and grasslands, including the Atlantic Forest, are LULC changes related to agriculture and livestock farming, uncontrolled urban expansion, and fragmentation (Carlucci; Marcilio-Silva; Torezan, 2021). There is a demand for a refined understanding of how landscape structure varied over time in the Atlantic Forest and grasslands (Vancine *et al*., 2024; Overbeck *et al*., 2015).

The Paraná State in the southern Brazil exemplifies a good study site for evaluating LULC change and habitat quality dynamics over time in Atlantic Forest and grassland biomes. The state presents Atlantic Forest formations with spots of grasslands that have gone through massive vegetation loss (Vicente; Vanzela; Torezan, 2009). Historically, Paraná's biggest natural habitat loss happened between 1890 and 1980 (Campos, 2005), initially forests and grasslands were lost for mining extraction, followed by wood exploration, coffee production, finally grains and pasture production (Campos, 1996). Nowadays, the Paraná Atlantic Forest is still vulnerable to deforestation and habitat degradation (Mohebalian *et al*., 2022), therefore there is a need for understanding habitat quality dynamics in the State, to support better environmental management.

Here, we analyzed the spatio-temporal dynamics of habitat quality for native trees and grasses in Paraná State and the land use land cover changes associated with habitat quality dynamics. Our main questions were: a) Did the habitat quality change over time in Paraná? b) Were there more losses or gains in habitat quality? C) How is the habitat quality spatially distributed on the State? D) Is the habitat quality higher inside protected areas than in non-protected areas? To respond these questions, we built habitat quality maps based on LULC maps of Paraná through the InVESThq model from 1985 to 2020, then analyzed the habitat quality and LULC dynamics of the State. Our findings can help to improve habitat quality for different regions of Paraná by providing reliable data and recommendations for stakeholders and policy making.

2.2 METHODS

2.2.1 Study area

Paraná State is located in southern Brazil (48º-52º W, 22º-25º S, Fig. 1), encompassing a total area of 199.298 km2 (IBGE, 2024). With an estimated population of 11.5 million inhabitants, the State is historically home to indigenous communities, including the Guarani, Kaingang, and Xetá (Bonfim *et al*., 2016). Paraná constitutes Brazil's fifth-largest State economy, presenting a notable agro-industrial profile (IBGE, 2024). The climate varies from tropical in the northern region, to subtropical in the south-central region, with distinct thermal and rainfall regimes throughout its territory.

The main vegetation type in Paraná is the Atlantic Forest, a tropical rain forest, which originally covered 97% of the State (Kauano *et al.*, 2012). Nowadays forests occupy 23.150km^2 (Fundação SOS Mata Atlântica, 2021), represented by three major forest types: Atlantic Dense Forest, Seasonal Forest, and Araucaria Mixed Forest (Carlucci; Marcilio-Silva; Torezan, 2021). Paraná Atlantic Forests have distinctive flora and fauna with a high degree of species richness, rare habitats, unusually high taxa, and endemic tree species (Vancine *et al*., 2024). Grasslands are the other vegetation type present in Paraná, with approximately 282 km^2 (Fundação SOS Mata Atlântica, 2021) mainly located in the central east region (Roderjan *et al*., 2002). They occur in elevated sections of plateaus, in gently wavy relief, where the climate is subtropical, cold, and dry with double seasonality (Vicente; Vanzela; Torezan, 2009).

Grasslands in Paraná are restricted to the central east region, occupying a small area with a diffuse spatial distribution, where the environmental conditions are more suitable for this vegetation (Behling, 1997). The remaining native grasslands are practically restricted to areas where the soil is shallow, rocky, or very wet, or where the terrain is very hilly essentially, areas where it is not possible to implement agricultural crops (Vélez-Martin *et al.,* 2015).

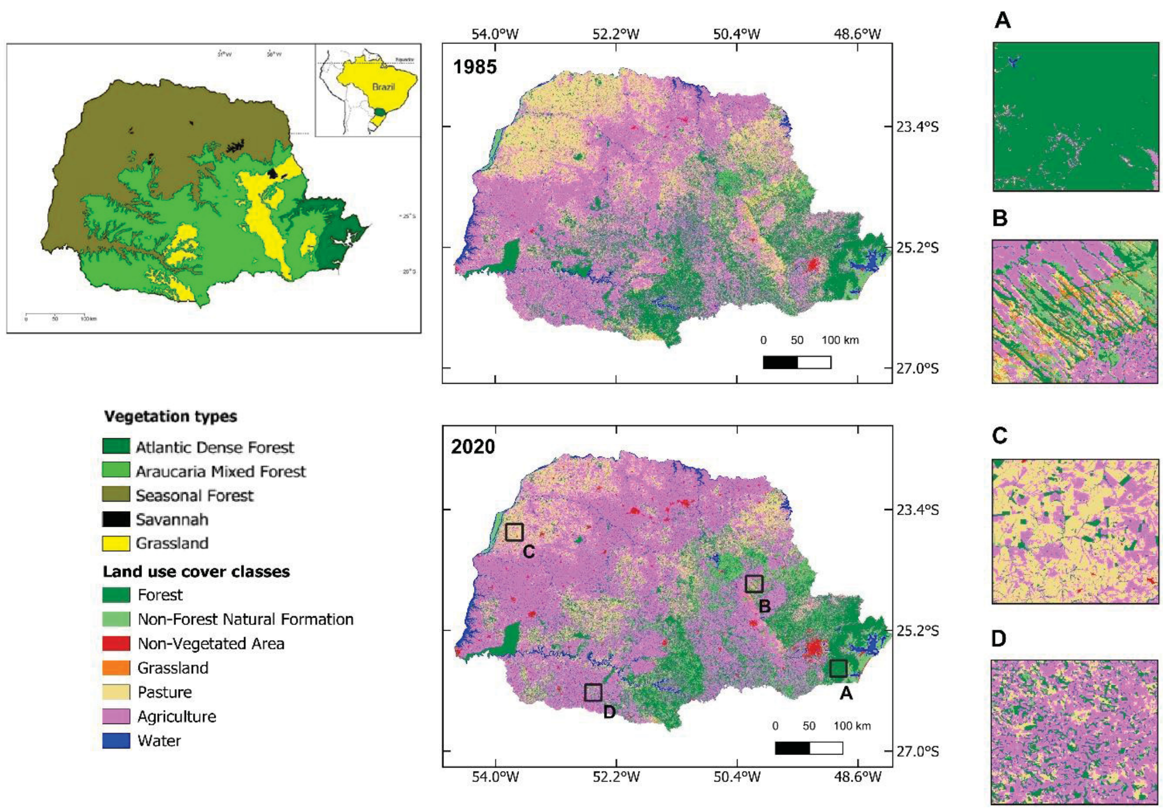

Figure 1: **Study site details.** Location of Paraná State in Brazil and original distribution of vegetation types in Paraná (left) obtained from Maack (1950 modified, cited by Roderjan *et al.*,

2002). Land use land cover maps of Paraná from 1985 and 2020 (middle) obtained from MapBiomas initiative (MapBiomas 2023). Selected sites (A, B, C, D) exemplify LULC in different regions of Paraná (right). Site A is mainly covered by forests, B shows part of the grasslands in the State, C encompasses a mosaic of pasture and agriculture and small forest fragments, and in site D the main threat to forest habitats is the expansion of agriculture.

2.2.2 Evaluation of habitat quality

We calculated the habitat quality for forests and grasslands in the Paraná State using the InVESThq 3.14 model. InVEST is a set of open-source software models developed as part of the Natural Capital Project (Natural Capital Project, 2024; Polasky *et al.*, 2011). The InVESThq model quantifies habitat quality based on LULC rasters, the suitability of each LULC category as habitat, and threat density and its impacts on habitat quality. The model inputs are: LULC raster, sensitivity table, and threat table. A habitat suitability index (H_j) addresses which LULC should be considered habitat, score values vary from 0 (non-habitat) to 1 (habitat). Here, we used forests and grasslands as the only habitats for native trees and grasses respectively, assigning a score of 1 for each one, while the other LULC types had a score of 0.

Threats are spatial sources of environmental or anthropogenic disturbances to the habitat, we considered threats land-uses as agriculture, pasture, mosaic of agriculture and pasture, mining, and urban infrastructure. The impact of threats on habitat in a given location (pixel) is mediated by four factors: i) Weight of each threat (ωr); ii) Maximum distance of threat effect (d_{rMax}), iii) Decay type (exponential or linear; i_{rxy}), and iv) Sensitivity of each habitat type to each threat on the landscape (S_{jr}). The total level of threat (D_{xj}) in a particular pixel (x) with a given habitat class (j) is given by the equation:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) r_y i_{rxy} \beta_x S_{jr}$$

where r is the threat source, *R* is the number of threat sources, y is the grid number of threat source *r*, *Yr* is the number of grids occupied by threat sources, β_x is the accessibility level of grid *x*. The habitat quality (Q_{xj}) in a given pixel (x) is the result of the equation:

$$Q_{xj} = H_j \left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right)$$

where H_j is the habitat suitability of land use type *j*, *Dxj* is the habitat degradation degree in land use type *j*, *z* is the normalization constant (2.5) and k is the half-saturation constant (set to 0.40 in forests and 0.30 in grasslands, based on model guidelines).

The parameters used in the threats and suitability tables were determined using expert knowledge. We reached out to 6 forest and 5 grassland experts, they had at least one published paper related to their specific vegetation type that took place in Paraná. We contacted experts via email, sending them a description of the InVESThq model, an explaning how each parameter (weight, maximum distance, decay and sensitivity of each threat) works. A baseline threats and suitability table containing mean values of each parameter taken from studies done in tropical ecosystems was presented and the experts should fill a blank table in according to their knowledge (Appendix A and B). We got responses from 3 experts of each vegetation type. Based on their answers, we calculated mean values for each parameter and gathered them on a final threats and suitability table (Table 1).

Table 1: Threat sources parameters used in the Habitat Quality Model.

	Trees				**Grasses**			
Threats	**Maximum distance (km)**	**Weight**	**Decay**	**Sensitivity**	**Maximum distance (km)**	**Weight**	**Decay**	**Sensitivity**
Agriculture	3	0.8	Exponential	1	1.25	0.7	Linear	0.5
Mosaic	2	0.72	Exponential	0.75	1	0.75	Linear	0.65
Mining	1.5	1	Exponential	0.9	3	0.8	Exponential	0.7
Pasture	1	0.65	Exponential	0.5	0.75	0.8	Linear	0.8
Urban infrastructure	4	0.9	Linear	1	2	1	Exponential	0.65
Other	2.75	0.94	Linear	0.95	2.5	0.9	Exponential	0.67

We produced 8 maps of habitat quality for the State, one for every five years over the past thirty-five years (1985-2020). The resulting habitat quality maps show the relative level of habitat quality per pixel, with a score that varies from 0 (low) to 1 (high). Areas with greater habitat quality and larger areas are likely to sustain higher biodiversity; in contrast, a reduction in habitat size or a rise in nearby threats over time is expected to result in biodiversity loss. (Broquet *et al.*, 2024). From the habitat quality resulting maps, we calculated the mean habitat quality values in grasslands and forests for each studied year and evaluated the spatial distribution of habitat quality.

To have a detailed understanding of habitat quality dynamics for forests in Paraná we utilized the subdivision of the State into 10 geographic mesoregions, following the Regional Division of Brazil into Immediate Geographic Regions (IBGE 2017). This cutout has socioecological meaning as each mesoregion has distinct combinations of ecoregions, LULC dynamics, and crop production. As a consequence, more specific policy recommendations can be made by analysis made at the mesoregion scale. This subdivision in mesoregions was not necessary to evaluate habitat quality in grasslands as they have a restricted occurrence concentrated in the North East region of the State.

We calculated habitat quality loss and gain from the subtraction of habitat maps every five years. The subtraction resulted in a map with pixel values varying from -1 to 1, where -1 to 0 represented habitat quality gain from that year to the other year and 0 to 1 represented HQ loss. We then created 4 different categories of habitat quality loss and gain (high 1 – 0.75, medium-high 0.75 – 0.5, medium-low 0.5 – 0.25, and low 0.25 – 0). We only considered habitat quality values greater than zero in all data analyses.

2.2.3 Land use and cover data source

LULC maps of Paraná were compiled from MapBiomas Brazil collection 8 (Souza Jr. *et al.*, 2020), every 5 years in the period from 1985 to 2020, adding up to 8 rasters. This dataset offers reconstructions of land use and land cover information, with a spatial resolution of 30 meters. These data originate from Landsat satellite collection processed using a pixel-based classifier implemented within the Google Earth Engine platform.

2.2.4 Habitat quality inside and outside protected areas

We carried out a complementary analysis to evaluate the impact of protected areas on the habitat quality of forests and grasslands in 1985 and 2020. To do so, we merged the resulting InVESThq maps of forests and grasslands into the map of native vegetation for each of analyzed year. Then, we removed all zero values in order to compare only areas with natural vegetation inside and outside protected areas and no other LULC. Finally, labeled the protected and non-protected areas, and gathered values of habitat quality into a data frame where each cell corresponded to a pixel. Given the lack of normality of distribution on the data (Kolmogorov-Smirnov test: $D = 0.081787$, $p < 2.2e\text{-}16$; Appendix C), we compared the mean habitat quality inside and outside protected areas through the Wilcoxon Signed Rank test. We also compared the mean habitat quality variation inside protected areas in 1985 and 2020, and in non-protected areas in 1985 and 2020, to test if there was variance inside protection categories, using the same methodology.

We considered as protected areas: federal and state conservation units, established by the National Sistem of Conservation Unities (Federal Law 9985/2000 – Brasil, 2000), and indigenous lands, established by the Indigenous People Status (Federal Law 6.001/1973 – Brasil, 1973). Overall, there were 48 protected areas in 1985 and 121 in 2020 (Figure 3). Protected areas spatial limits were obtained from Chico Mendes Institute for Biodiversity Conservation (ICMBio 2020), Parana's Water and Land Institute (IAT, 2024) and the National Foundation of Indigenous People (FUNAI, 2024).

All data analyses were conducted in R software version 4.4.0 (R Foundation, 2024) and QGIS 3.36.3 (QGIS, 2024) was used for data visualization and map development.

2.3 RESULTS

The average habitat quality for trees showed small variation over the years, with mean values of 0.77 in 1985, 0.76 in 2005, and 0.74 in 2020. Despite not having drastic changes throughout time, there was a declining trend in habitat quality for trees (Fig. 2). In general, the forest habitat quality maps show that areas of low quality predominate in Paraná. Habitat quality is also not evenly distributed throughout the State, presenting a similar distribution throughout the entire study period (Fig. 3). The East and West regions concentrated large areas with high habitat quality, the North region had small and distant areas with high habitat quality surrounded by areas with no quality and the Central South region had a mix of a lot of small fragments with high quality and areas with no quality.

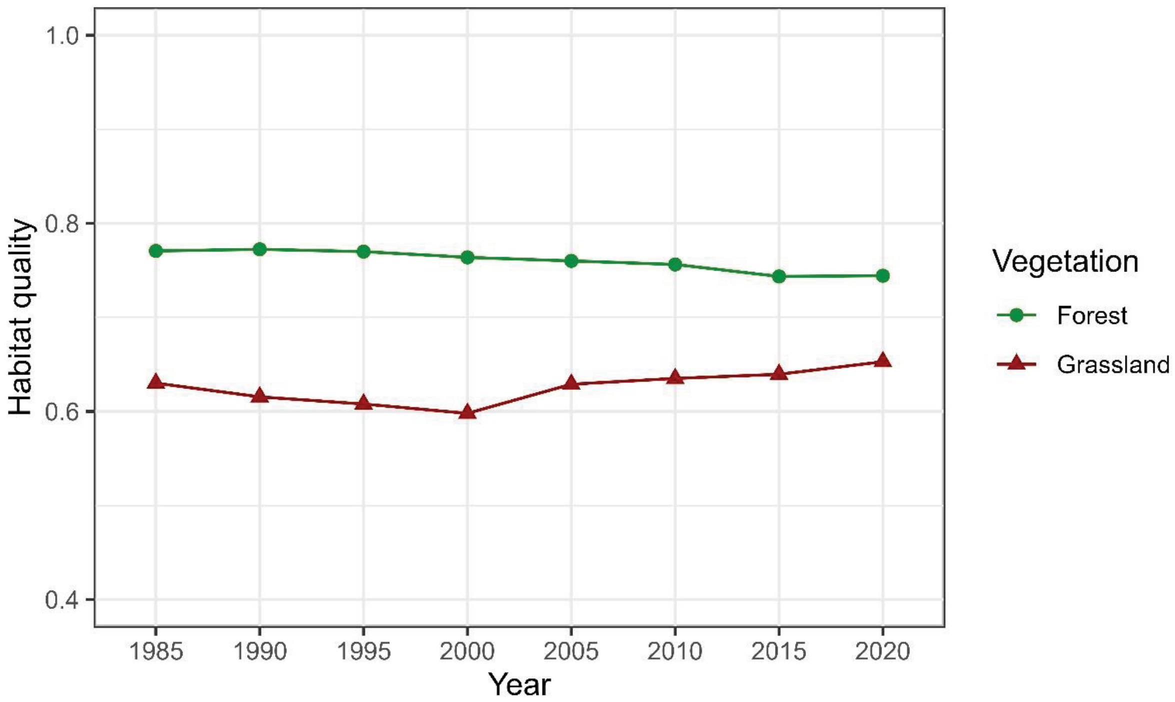

Figure 2: Mean values of habitat quality for forests and grasslands in 1985, 1990, 1995, 2000, 2005, 2010, 2015 and 2020 from low (0) to high (1) quality.

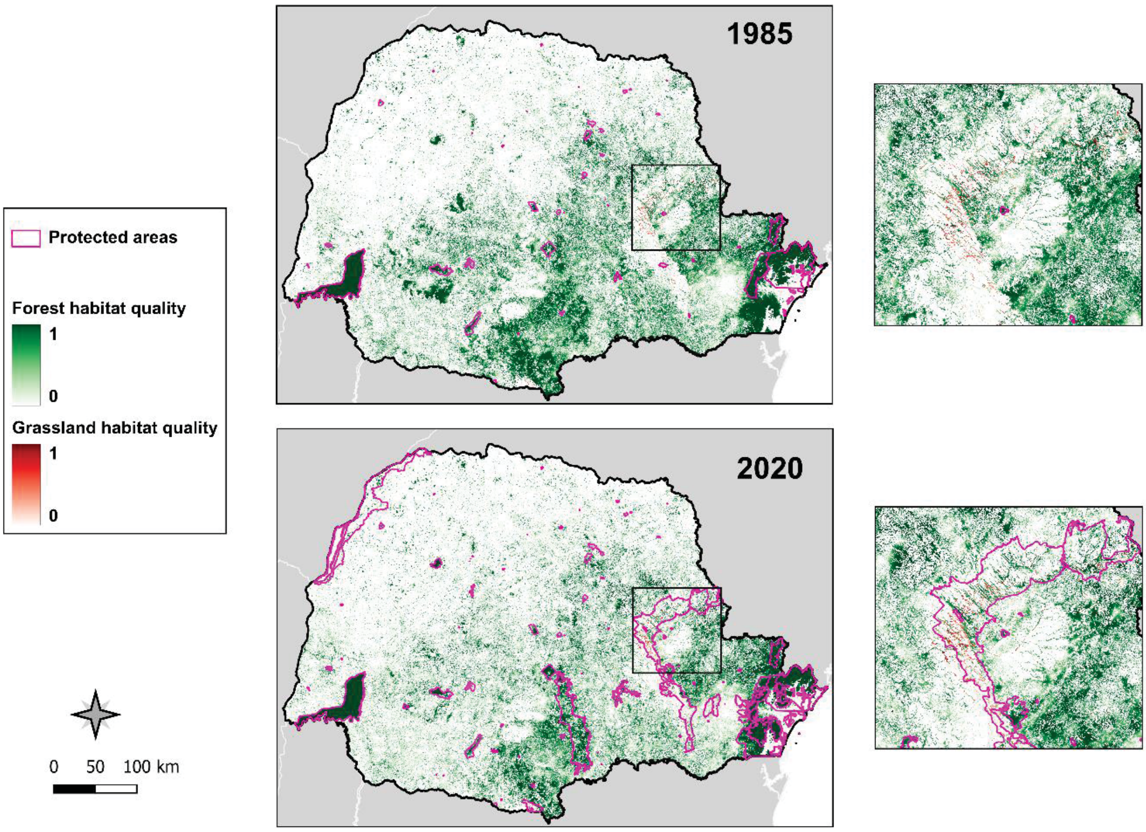

Figure 3: Spatio-temporal variation of habitat quality for forests (green) and grasslands (red), distribution of protected areas (pink) in Paraná from 1985 (top) to 2020 (bottom). Habitat quality ranges from low (0) to high (1).

Based on the assessment results, habitat quality for forests was divided into 10 mesoregions (Fig. 4). Mesoregions 1, 2, 3, 4 and 7 showed average habitat quality dynamics lower than the average of Paraná, with mesoregion 7 having the lowest averages and a decreasing tendency. Mesoregions 5, 8 and 9 presented a similar pattern to the State. Lastly, mesoregions 6 and 10 had the highest means of habitat quality compared to Paraná and the other mesoregions.

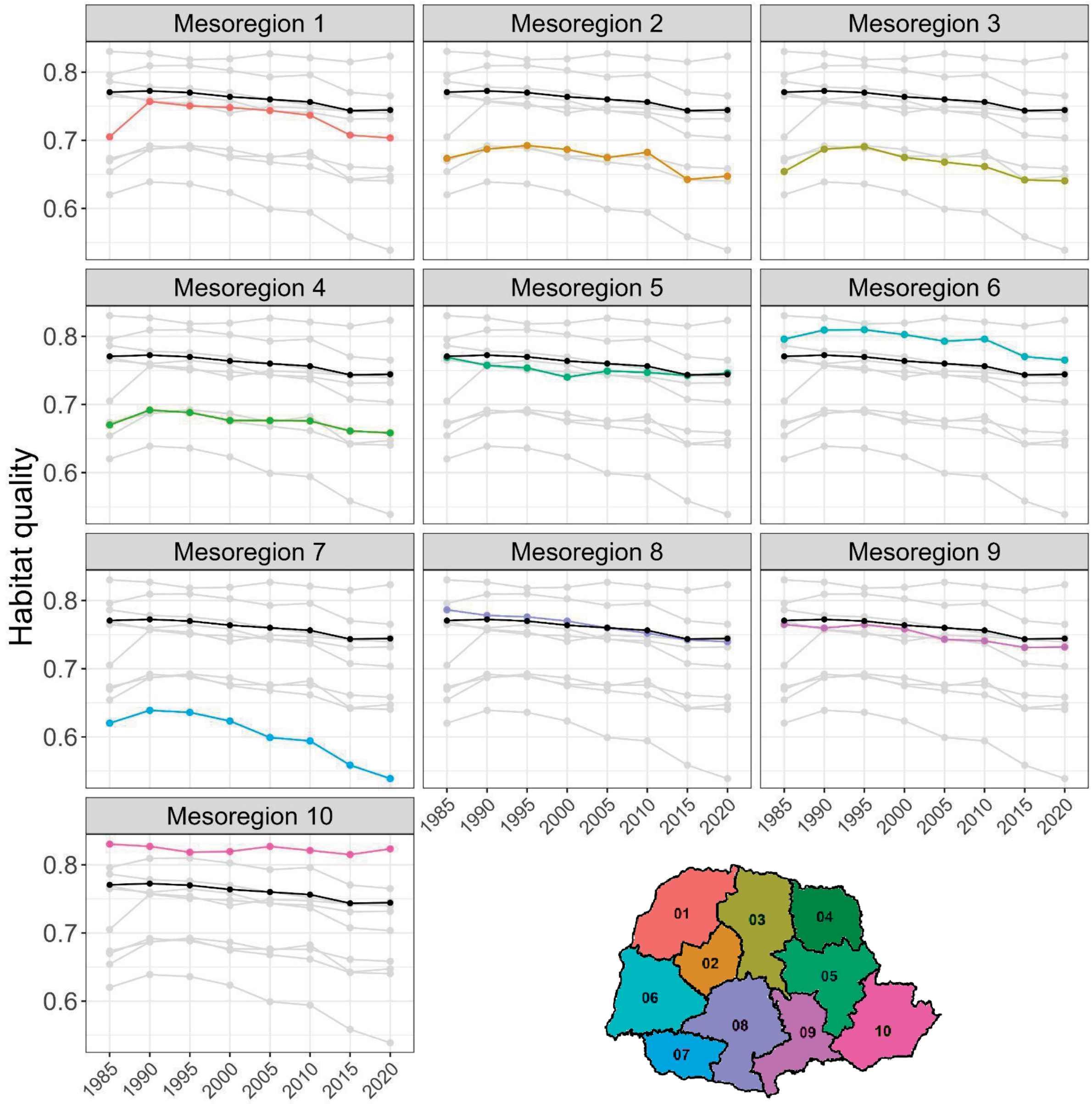

Figure 4: Habitat quality means for forests in the 10 different mesoregions of Paraná, from 1985 to 2020. The black line represents the mean habitat quality in Paraná State. Map of the 10 mesoregions of Paraná with the corresponding color from the mean graphs.

When evaluating the LULC in Paraná, the most frequent LULC classes overall were agricultural uses, followed by forests, pastures, mosaic of pastures and crops, others (urban infrastructure and mining) and grasslands. Over time there was a turnover between agriculture and pasture uses with the first one increasing, there were losses of 468.000 ha of forest cover and grasslands presented a stable average area of coverage in the State. When we take a closer look into the mesoregions, 1 and 4 are mainly occupied by pastures, 2, 3, 6, 7 are mainly covered by agricultural uses and 5, 8, 9 and 10 have forest cover as their most common LULC (Fig. 5).

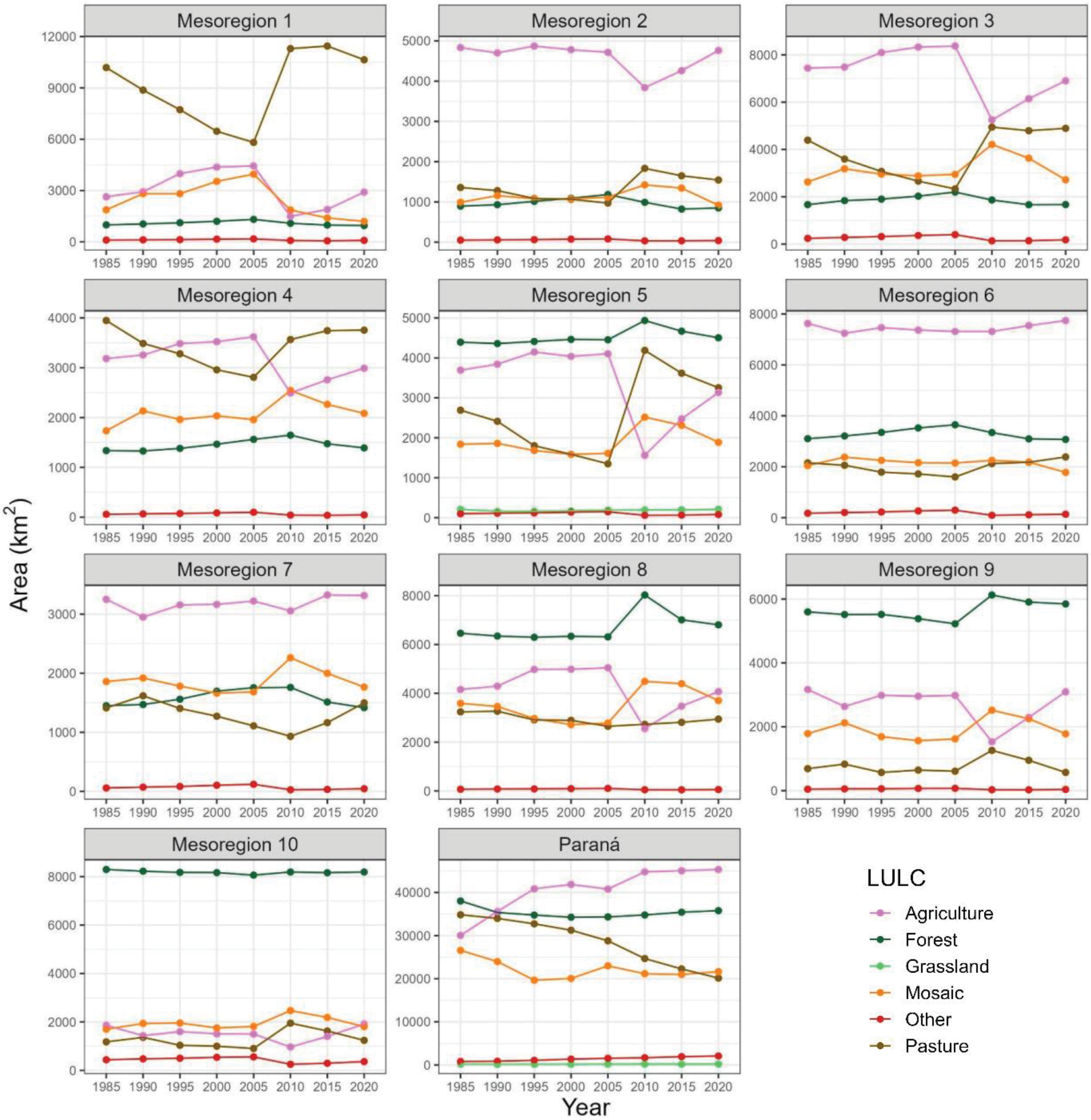

Figure 5: Land use land cover (LULC) dynamics in mesoregions and Paraná State from 1985 to 2020. LULC categories were: agriculture, forest, grassland, mosaic of pasture and agriculture, pasture and other (mining, urban and other non vegetated areas).

In forests there was a similar pattern of habitat quality loss and gain throughout the years, with more areas losing habitat quality than gaining (Fig. 6). Between the years 1985 and 1990 were observed the highest habitat quality loss and nearly 20,000 km^2 had a loss in habitat quality. When breaking the losses into categories, the low category (0 - 0.25) represented the majority of losses in all years. Habitat quality gain was about the same between all years, around 6,000 km^2 had gains in habitat quality, with the low (0 - 0.25) and medium-low (0.25 - 0.5) being the most representative categories.

In grasslands, habitat quality averages were 0.63 in 1985, 0.59 in 2000 and 0.65 in 2020 (Fig. 2), showing an initial tendency of reduction of habitat quality, followed by an increase. Areas of high habitat quality for grasslands were concentrated in the central east region and demonstrated a fluctuation over time. Habitat quality losses and gains did not show a yearly pattern (Fig. 6). The gains were evenly distributed into the low (0 - 0.25), medium-low (0.25 - 0.5) and medium-high (0.5 - 0.75) categories, while there was a very small gain in high quality. The losses occurred mainly in low habitat quality, followed by medium-high (0.5 – 0.75) losses.

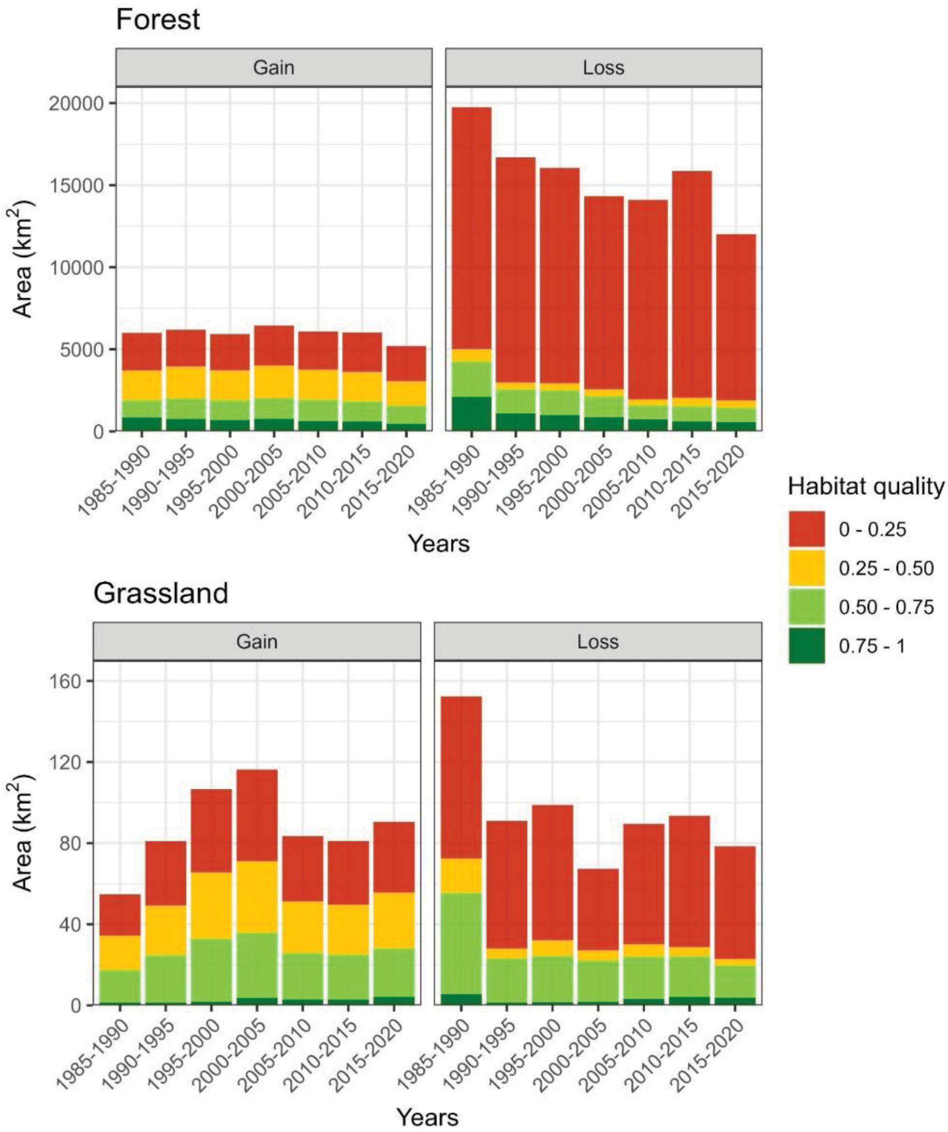

Figure 6: Habitat quality loss and gain dynamics (km^2) in forests (top) and grasslands (bottom), within high (1.0 - 0.75), medium-high (0.75 - 0.50), medium-low (0.50 - 0.25) and low (0.25 - 0) categories from 1985 to 2020.

Protected areas presented higher habitat quality than non-protected areas both in 1985 (W = 1.2794e+14, p < 2.2e-16) and 2020 (W = 2.0267e+14, p < 2.2e-16), with average values of 0.95 in 1985 and 0.88 in 2020 for protected areas and 0.74 in 1985 and 0.67 in 2020 for non-protected areas (Figure 7). We found differences among protected areas when testing habitat quality of protected areas in 1985 and 2020 (W = 1.68e+13, p < .001), the same was observed in non-protected areas (W= 7.60e+14, p < .001).

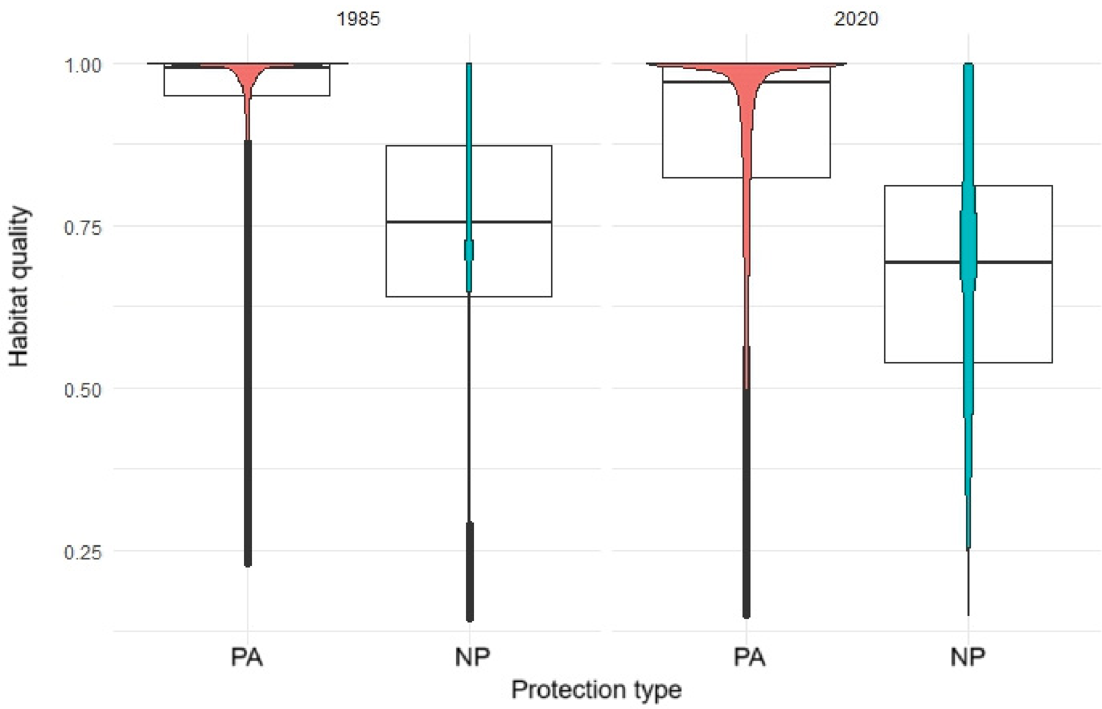

Figure 7: Boxplot of habitat quality in protected areas (PA) and non-protected areas (NP) in 1985 (left) and 2020 (right).

2.4 DISCUSSION

Here we illustrate the importance of considering habitat quality patterns across time and space, by applying InVESThq model for forests and grasslands of Paraná from 1985 to 2020. Overall, the State is predominantly covered by areas of low habitat quality, resulting from decades of natural vegetation loss and fragmentation (Carlucci; Marcilio-Silva; Torezan, 2021). We found a decline in the mean habitat quality of forests and a decrease followed by an increase in the habitat quality of grasslands in Paraná State in the past 35 years. The habitat quality variation observed on the past

35 years is linked to the dynamics of LULC in the State, where 468.000 ha of forests were converted to productive areas (especially for pastures and agriculture), affecting the results negatively. Furthermore, changes in land use that occurred prior to the studied period influenced the observed habitat quality, such as forest and grassland losses that occurred before 1980 when 71.3% of Paraná's territory was logged (Campos, 2005; Gubert Filho, 2010). This highlights that past policies that stimulated the occupation of Paraná by agriculture and livestock have supplanted conservation policies, impacting habitat quality in recent years. Future actions that compensate for losses will be necessary for the conservation and restoration of forests and natural grasslands in the region.

Our results indicate the existence of inequalities in habitat quality across forests in Paraná. Habitat quality scores of zero were predominant in the State, covering 75% of the territory in 1985 and 78% in 2020. These areas were occupied by non-habitat LULC, mainly agricultural or pasture uses. Mesoregions 1, 2, 3, 4 and 7 presented low habitat quality compared to the State mean. In these mesoregions, the few areas with high habitat quality were small, fragmented, and isolated forest patches with low connectivity. This can be attributed to the most recent cycle of deforestation, linked to the conversion of forests into soybean fields, which reduced forest cover to just 2% in some landscapes in northern Paraná (IPARDES, 1993). The area of a forest patch is closely linked to its ability to accommodate greater species diversity, with larger areas offering better conditions for species-habitat interactions, consequently supporting viable populations of local species (Metzger *et al*., 2009). Therefore, small patches in fragmented landscapes have lower habitat quality. Additionally, these mesoregions have a history of occupancy of agricultural, pasture, and mosaic land uses and have undergone intense deforestation (Ferreira *et al*., 2018).

Mesoregions 6 and 10 have higher habitat quality distributed in large fragments. The presence of protected areas contributed to the higher values of habitat quality in these areas. Areas with high habitat quality support higher biodiversity (Sharp *et al*., 2018) which can provide ecosystem services (Pires *et al*., 2021). The conservation of landscapes focusing on the quality and quantity of habitats brings positive effects on the conservation of biodiversity (Bastos *et al*., 2023), carbon stocks (Capellesso *et al*., 2021), water supply (Joly; Metzger; Tabarelli; 2014), and pollination (Varassin *et al*., 2021) in the Atlantic Forest. Therefore, gains in habitat quality in Paraná can enhance the provision of ecosystem services related to biodiversity, as well increasing connectivity between fragments, genetic flow through the surrounding matrix and promote the patch colonization process (Ferreira *et al*., 2018).

The patterns of habitat quality throughout the years reveal that the net habitat quality for forests was negative. The losses were concentrated in the low-quality category (between 0 and 0.25) and the gains were more even between quality categories. Fontoura *et al.* (2024) also found a decline in habitat quality for the same period in Caatinga Semi-arid, Cerrado Savanna, and Atlantic Forest formations in Brazil using InVESThq model. The habitat quality losses in the low-quality category can be associated with LULC changes, such as the conversion of threats into other more harmful threats leading to habitat quality losses. For example, agricultural land use poses a higher threat to forests than pastures, because according to the threats table (Table 1) agriculture threatens more forests habitat quality than other threat sources. On the other hand, changes in LULC can benefit habitat quality when the new LULCis less threatening in terms of quantity or intensity.

Between 1985 and 2020 about 468.600 ha of forests were converted into other LULC classes, causing the loss of areas with high habitat quality. The logging was mostly related to agricultural uses.There is a clear imbalance between crop production and biodiversity conservation in Paraná, where agricultural activities led to the loss and fragmentation of both forests and grasslands (Roderjan *et al.,* 2002; Sampaio *et al.,* 2023). With emphasis on the soybean plantations, that occupied almost 80% of the agricultural land and generated over R$39 million reais in 2022 (IBGE, 2024). Despite being important for the State's economy, there is no need for further conversion of native vegetation to enhance crop and beef production in Brazil (Vieira *et al*., 2018). In fact, Marcilio-Silva, Marques and Cavender-Bares (2018) propose that crop production and revenue can be enhanced alongside increased restoration and conservation of biodiversity in the Atlantic Forest.

The grassland habitat quality varied slightly during the study period, tending to decrease between 1985 and 2000, and then rising from 2000 to 2020. The growth in habitat quality starting in 2000 may be related to the creation of Escarpa Devoniana protection area in 1992 (Paraná, 1992). The total area occupied by grasslands remained constant and restricted to the central east region over the study period.

Although our results point out that habitat quality in grasslands seems to be increasing, studies have reported that native grasslands of Paraná have been undergoing intense fragmentation, mainly caused by extensive livestock farming (Dalazoana; Barbosa; Moro, 2009). Grasslands of Paraná are also threatened by invasive exotic species, such as *Pinus elliottii* and *P. taeda*, that are cultivated for the cellulose industries (Ziller; Galvão, 2002; Andrade *et al.*, 2019), once more highlighting the prevalence of crop production over biodiversity. Another possible explanation for the quality improvement of grasslands during the period is differences in image quality in the MapBiomas platform, which was not considered in this study.

Grasslands and forests had a different dynamic of habitat quality, with grasslands presenting lower mean habitat quality, smaller area of distribution and a more balanced dynamic of habitat quality loss and gain. The two vegetation types present different structures, and the community is composed of different sets of species ecological strategies (Jardim, 2023). Despite having their particular characteristics, both vegetation types present high biodiversity and are highly degraded and fragmented in the State, therefore, should be the target of conservation and restoration efforts. Environmental legislation regulates the amount of natural vegetation that must be conserved on each property, that being 20% for the Atlantic Forest and grasslands (Brasil 2012). The vegetation deficit, meaning the lack of native vegetation on rural properties to meet the minimum legal requirements, is estimated at 19 million hectares in Brazil (Guidotti *et al*., 2017). Therefore, the current legal requirement to restore natural vegetation represents a unique opportunity with significant gains for biodiversity and conservation (Bergamo *et al*., 2021). Restoring degraded areas in mesoregions with low habitat quality will enhance habitat corridors and the ecosystem services provided by biodiversity. These measures of biodiversity restoration and conservation align with targets set by the Convention on Biological Diversity, to which Brazil is a committed member.

Paraná's protected areas presented higher habitat quality compared to non-protected areas both in 1985 and 2020. Which highlights the importance of protected areas for maintaining the habitat quality of native vegetation, effectively protecting natural areas in Paraná (Mohebalian *et al*., 2022). Gonçalves-Souza *et al*. (2021) demonstrated that the likelihood of destruction within the protected area network is four times lower compared to unprotected areas in Brazil. The "Serra do Mar", located on

Paraná's coast (mesoregion 10), is a great example of an area where several protected areas were established over the last decades (Grise *et al*., 2009), conserving a core part of the Atlantic Forest remnants corridor (Kauano *et al*., 2012). Other example is the Iguaçu National Park located in the West region of Paraná (mesoregion 6), the largest Brazilian non-Amazonian protected area with 185.000 ha of Seasonal Forest (Souza *et al*., 2017).

Despite being important tools for the biodiversity conservation, protected areas did not maintain the same habitat quality throughout the years. In fact, there was a decrease in mean values of habitat quality from 1985 to 2020 inside protected areas. These results can be associated with differences among protected areas in Brazil: the strictly protected areas that promote full protection is recognized as more effective to biodiversity conservation than sustainable-use protected areas (Grelle *et al.*, 2021). It is possible that the decrease in habitat quality inside the protected areas is due to a proportional higher area of sustainable-use areas, which was not considered in this study.

Policies aimed at increasing protected areas (in accordance with Law 9985/2000), ensuring the integrity and expansion of Indigenous lands (Law 6.001/1973), restoring native vegetation (Law 12.651/2012), among others, are necessary to ensure the provision of high habitat quality in Paraná. The creation of new protected areas should consider the conservation of all native vegetation types and be distributed in a more balanced manner across the State (Vicente; Vanzela; Torezan, 2009; Overbeck *et al*., 2015). Also, protected areas must receive adequate resources for proper maintenance and management, ensuring that habitat quality remains high.

It is important to emphasize that this study did not take into consideration vegetation age, successional stage, or forest structure. Recent studies have highlighted that the destruction of older forests in Brazil's Atlantic Forest has been hidden by the gain of younger forests (Rosa *et al*., 2021). The analysis of only forest covers can mask the habitat quality, overpredicting habitat quality in forests that may be young and that do not provide the necessary conditions for the persistence of native species. Therefore, further advancements in modeling and data are necessary to enhance the reliability of estimates regarding habitat quality in native vegetation

(Polasky *et al*., 2011). In addition, we could have better estimates of habitat quality if we had included roads as an additional threat in our study. In future research, other InVEST models could be used for assessing other ecosystem services in the landscape, such as carbon storage, water supply and food provision. Additionally, evaluating the synergies and trade-offs between habitat quality and ecosystem services can be beneficial for identifying opportunities for financial and political support for biodiversity conservation (Duarte; Ribeiro; Paglia, 2016; Costanza, 2020).

2.5 CONCLUSION

Our results demonstrate significant habitat quality losses over the past 35 years in the state of Paraná, especially outside protected areas and Indigenous lands. Habitat quality is not evenly distributed, with most of the State covered by low habitat quality areas. This results from many years of deforestation, fragmentation, and intensive agricultural and pasture uses. In the past 35 years there were tendencies of decrease in forests habitat quality and decrease followed by increase in grasslands. The changes in habitat quality are related to LULC dynamics on the State and highlight the need for enhancement of native vegetation cover. Restoration actions represent an opportunity to increase habitat quality and the provision of ecosystem services, and ultimately are required by law. Protected areas are important to maintaining the habitat quality of forests and grasslands across the State. Still, the appropriate maintenance and management of protected areas are important to ensure the conservation of biodiversity and the provision of ecosystem services. Furthermore, studies assessing biodiversity patterns, ecosystem services, and socioeconomic indicators are still required for sustainable development in the State.

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APPENDIX

Appendix A – Email sent to experts

My name is Camila Lermen, and I am a master's student. I am currently in the process of developing my dissertation "Spatio-temporal Dynamics of Habitat Quality as a Tool for Public Policies in the State of Paraná." My goal is to map habitat quality for different vegetation types in Paraná (forest trees and grassland grasses) to serve as a basis for the development of conservation and restoration public policies. To continue my research, I need the consultancy of some experts to carry out my modeling, and I believe your expertise can help me.

To explain briefly: Habitat quality can be considered the ability of an environment to provide suitable conditions and resources for the persistence of individuals or populations.

How is the modeling done? To map habitat quality, I use the INVEST software model. The model inputs are: land use and cover map, sensitivity table, and threats table. Some land uses are considered habitats (forest and grassland), while other land uses are considered threats (pasture, agriculture, cities, mining). Generally, we consider threats as types of land use and cover modified by human activities, which cause fragmentation, edge effects, and habitat degradation in neighboring areas. The model calculates habitat quality based on the land use and cover map and the values contained in the threat and sensitivity tables.

Habitat quality for whom? We have established two species guilds to assess habitat quality: forest specialist trees and grassland specialist grasses. The specialists are always native species that occur predominantly in the mentioned habitat (forest or grassland).

The problem: To run the models, it is necessary to establish values for different indices (threat impact, maximum distance, decay, and sensitivity) for each guild. There is only one study done for Brazil (in the Minas Gerais region), and the values from this study may not be accurate for my case. Therefore, I decided to consult experts to establish these values, which is why I am requesting this help.

What do I need help with?

1. Defining relative impact values for each threat: This means assessing the impact of each threat on habitat quality relative to the other threats. It is suggested to rank the threats from the one that most affects the guild to the one that least affects it. Based on the ranking, assign values between 0 and 1 for the relative impact of each threat.

2. Defining maximum distance values (km): This is the approximate distance over which each threat affects habitat quality. The impact of each threat diminishes to zero at this maximum distance. For example, consider what the maximum distance is over which agriculture will affect habitat quality for the guild.

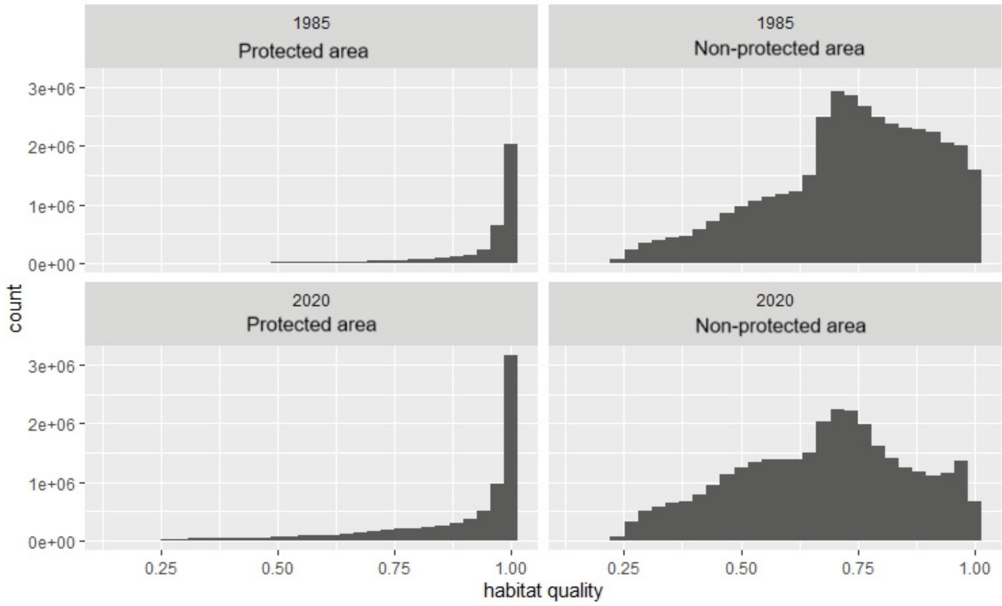
3. Defining the type of decay for each threat: This involves determining how the impact of the threat behaves over distance. There are two categories: exponential (the effects of the threat decay exponentially with distance from the threat) or linear (the effects of the threat decay linearly with distance from the threat).

4. Defining the relative sensitivity values of each habitat to each threat type: Where 1 represents high sensitivity and 0 indicates that it is not affected. Consider how much this threat impacts the survival, reproduction, and population persistence of your specific guild.

General guidelines that may help: The values on the table below (relative impact, distance, decay, and sensitivity) are averages of values found in scientific articles conducted in tropical environments. These values are general and consider biodiversity as a whole. Therefore, I ask that suggestions for more appropriate values be made considering the vegetation of your specialty and Paraná. When defining the index values, consider the following: the model input is a raster of Paraná (a map of 60x60 meter pixels). For each pixel, we will have its land use. Think about how much a pixel or set of threat pixels will affect an adjacent pixel or set of habitat pixels, the distance at which the threat will still influence the habitat, the decay of this threat... Example: consider the relative impact value of agriculture on the forest.

Appendix B – Table with baseline parameter values for forests and grasslands from tropical environments

	Trees				**Grass**			
Threats	**Maximum distance (km)**	**Weight**	**Decay**	**Sensitivity**	**Maximum distance (km)**	**Weight**	**Decay**	**Sensitivity**
Agriculture	3	0.8	Exponential	1	5	0.7	Exponential	0.5
Mining	2	0.7	Exponential	0.6	3	0.8	Exponential	0.7
Pasture	2	0.6	Exponential	0.7	3	0.9	Linear	0.8
Urban infrastructure	4	1	Linear	1	3	0.6	Exponential	0.6



Appendix C – Histogram of habitat quality data distribution inside and outside protected areas in 1985 and 2020.

3 CONSIDERAÇÕES FINAIS

Neste trabalho, avaliamos a qualidade do habitat para florestas e campos no estado do Paraná. Observamos que a qualidade do habitat das florestas diminuiu ao longo dos anos, enquanto a qualidade do habitat de campos diminuiu até os anos 2000 e aumentou até 2020. Os campos apresentaram menor qualidade de habitat e menor distribuição geográfica em relação as florestas. Os fatores que influenciam a qualidade do habitat no Paraná foram a baixa cobertura de vegetação nativa e a ocupação e uso intensivo do solo pela agricultura e pastagem. Áreas protegidas apresentaram maiores valores médios de qualidade de habitat do que áreas não protegidas. Porém, no decorrer dos anos houve uma diminuição na qualidade de habitat tanto em áreas protegidas quanto não protegidas. Nossos resultados demonstram a necessidade de restauração da vegetação nativa no Paraná, principalmente nas regiões noroeste, norte-central, norte-pioneiro, sudoeste e centro-ocidental, indo ao encontro à demanda pelo cumprimento da lei 12.651/2012 da proteção a vegetação nativa (Brasil, 2012). Da mesma forma, é também necessária a manutenção e gestão corretas de áreas protegidas, a fim de garantir a conservação da biodiversidade e provisão de serviços ecossistêmicos. Destacamos a importância de considerar os padrões de qualidade de habitat nas decisões políticas e tomadas de decisão no estado, com o objetivo de promover aumento na qualidade de habitat e cobertura de vegetação nativa, além de garantir a proteção da biodiversidade e serviços ecossistêmicos no Paraná.

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