MATHEUS TORRES WALDER

INFLUÊNCIA DO CONTEXTO DE PAISAGEM SOBRE A DEGRADAÇÃO DE REMANESCENTES FLORESTAIS DA MATA ATLÂNTICA DO SUL DA BAHIA AO LONGO DE UMA SÉRIE TEMPORAL

ILHÉUS-BAHIA
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Dissertação apresentada ao Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade da Universidade Estadual de Santa Cruz como parte dos requisitos para obtenção do grau de Mestre em Ecologia e Conservação da Biodiversidade.

Linha de pesquisa: Ecologia e conservação de populações.

Orientadora: Dra. Maíra Benchimol
Co-orientador: Dr. Carlos Leandro de Oliveira

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SUMÁRIO

Chapter 1: Agricultural expansion and landscape heterogeneity explain forest degradation in the threatened Atlantic Forest

RESUMO

A degradação florestal tem sido causada por vários fatores antrópicos nas florestas tropicais, incluindo o desmatamento e a fragmentação da paisagem, afetando diretamente a qualidade dos remanescentes florestais. De fato, bordas florestais adjacentes a coberturas antropogênicas podem estar mais expostas a mudanças abióticas e bióticas e, consequentemente, levar à deterioração do interior da floresta. Porém, o efeito das coberturas terrestres circundantes nesse processo é pouco conhecido. Aqui, investigamos a influência do contexto da paisagem para explicar os padrões de degradação florestal ao longo de 35 anos em duas regiões que exibem diferentes padrões de desmatamento na ameaçada Mata Atlântica do sul da Bahia, no Brasil. Avaliamos a degradação florestal por meio do Índice de Umidade por Diferença Normalizada (NDMI) e pelo Índice de Vegetação Aprimorada (EVI) no centro de 50 remanescentes florestais inseridos em diferentes quantidades de cobertura florestal, cobertura agrícola e heterogeneidade da paisagem. Em particular, avaliamos esses índices e o contexto da paisagem em uma série temporal de 1985 a 2020, com intervalo de 5 anos, com base na classificação de uso da terra MapBiomas e imagens Landsat. Posteriormente, realizamos Modelos Mistos Lineares Generalizados para avaliar a influência das coberturas de uso da terra ao longo do tempo em NDMI e EVI dos remanescentes focais. Nossos resultados indicam que a degradação florestal foi intensificada de acordo com o aumento da cobertura agrícola, embora locais inseridos em paisagens mais heterogêneas tenham apresentado degradação reduzida. Observamos também que remanescentes florestais circundados por maior cobertura agrícola sucumbiram a maior estresse hídrico, principalmente nos anos iniciais da série temporal. Portanto, enfatizamos a importância de conter a expansão agrícola e promover iniciativas de restauração florestal para reduzir a degradação florestal de longo prazo nos remanescentes da Mata Atlântica.

Palavras-chave: Degradação florestal; Ecologia de paisagem; Sensoriamento remoto; Índices de vegetação.

ABSTRACT

Forest degradation has been caused by several anthropogenic drivers in tropical forests, including landscape deforestation and fragmentation, thereby directly affecting the quality of forest remnants. In fact, forest edges adjacent to anthropogenic covers can be more exposed to abiotic and biotic changes and consequently lead to the deterioration in the forest interior. Yet the effect of the surrounding land covers on this process has been poorly known. Here, we investigate the influence of landscape context in explaining patterns of forest degradation over 35 years in two regions exhibiting different deforestation patterns in the threatened Atlantic Forest of southern Bahia, in Brazil. We assessed forest degradation through the Normalized Difference Moisture Index (NDMI) and the Enhanced Vegetation Index (EVI) in the center of 50 forest remnants embedded within different amount of both forest and agriculture cover, and landscape heterogeneity. In particular, we evaluated these indices and landscape context in a time series from 1985 to 2020, at 5-year interval, based on MapBiomas land-use classification and Landsat imagery. We thus performed Generalized Linear Mixed Models to assess the influence of land-use coverages over time on NDMI and EVI of focal remnants. Our results indicate that forest degradation was intensified according to the increase in agricultural cover, although sites inserted in more heterogeneous landscapes showed reduced degradation. We also observed that forest remnants surrounded by greater agricultural cover succumbed to higher water stress, especially in the initial years of the time series. We therefore emphasize the importance of curbing the agricultural expansion and promote initiatives towards forest restoration to reduce the long-term forest degradation in Atlantic Forest remnants.

Key-words: Forest degradation; Landscape ecology; Remote sensing; Vegetation indices.

INTRODUÇÃO GERAL

Um dos principais drivers de alteração de paisagens naturais é a expansão agropastoril, convertendo principalmente áreas de florestas em mosaicos antrópicos (Ellis et al., 2010; Barlow et al., 2020). Esse processo tem ocorrido principalmente nas florestas tropicais e é a causa principal da perda direta da cobertura florestal e de fragmentação das florestas (Fischer et al., 2021). A fragmentação florestal é caracterizada como a redução de manchas contínuas de vegetação em manchas menores e separadas entre si por uma matriz de diferente uso (Wilcove, 1986). Atualmente, em escala global, as florestas tropicais ainda sofrem processos de desmatamento e fragmentação (Fischer et al., 2021) e mesmo com políticas mundiais para desacelerar a perda florestal e incentivar programas de reflorestamento, o processo de fragmentação das florestas é inevitável (Taubert et al., 2018; Fischer et al., 2021).

O processo de fragmentação das florestas tropicais expõe os fragmentos florestais ao efeito de borda, i.e., alterações ecológicas que ocorrem nas bordas criadas nos fragmentos florestais (Didham et al., 1998). Em particular, ocorrem nestes ambientes pronunciadas alterações no microclima, como o aumento da intensidade dos ventos e da incidência de luz (Laurance & Curran, 2008). Essas mudanças podem levar a morte de indivíduos arbóreos no gradiente borda-interior ao longo do remanescente florestal e provocar alterações na composição de espécies vegetais na borda. Em consequência, menos indivíduos arbóreos e de menor porte são encontrados na borda do que no interior do fragmento florestal, levando a perdas na estocagem de carbono do remanescente florestal (Kapos 1989; Laurance et al., 1997; Magnago et al., 2015; Silva Junior et al., 2020). Além da exposição ao efeito de borda, a fragmentação de habitat também torna os remanescentes florestais suscepitíveis a outros fatores que influenciam diretamente na qualidade da vegetação, tais como a extração de madeira e as queimadas (Asner et al., 2005; Cochrane et al. al., 1999; Rutishauser et al., 2015). A intensidade desses fatores pode influenciar direta e/ou indiretamente as interações ecológicas dos fragmentos florestais, e afetar diretamente a funcionalidade dos ecossistemas.

A degradação dos fragmentos florestais é um fenômeno que ocorre concomitantemente com o desmatamento, e que tem merecido maior atenção de cientistas e tomadores de decisão. No entanto, não existe uma definição unificada para o tema, com impactos diretos sobre medidas de conservação (Ghazoul & Chazdon, 2017). Em nosso estudo, definimos degradação como a redução persistente de algum atributo relativo a uma condição (não degradada) (Ghazoul &

Chazdon, 2017). A degradação florestal pode ocorrer em diversos níveis de escala, desde a degradação do solo que causa alterações das caraterísticas químicas do solo, até a degradação em uma escala de paisagem modificando a incidência solar e umidade regional, por exemplo (Ghazoul & Chazdon, 2017). A grande variação das escalas dificulta o monitoramento e a realização de estudos voltados a compreender os efeitos da degradação florestal. Porém, é possível compreender estes efeitos através do estudo de seus *drivers*, como o efeito de borda, desmatamento e mudanças climáticas (Lapola et al., 2023), bem como obter dados em uma escala temporal. De fato, os efeitos da degradação podem ser medidos anos após o evento de fragmentação (Milodowski et al., 2021).

O avanço das tecnologias de sensoriamento remoto, incluindo a disponibilização de imagens em alta resolução de forma gratuita (e.g., Landsat, com 30 m de resolução), vem permitindo monitorar a degradação florestal de diferentes formas, especialmente utilizando índices de vegetação (IV). Em particular, o índice de vegetação de diferença normalizada (NDVI – *Normalized Difference Vegetation Index*), o Índice de Vegetação Aprimorada (EVI – *Enhanced Vegetation Index*) e o Índice de Umidade de Diferença Normalizada (NDMI – *Normalized Difference Moisture Index*) tem sido os mais amplamente utilizados (Bullock et al., 2020; Aljahdali et al., 2021; Delgado-Moreno & Gao, 2021). A série Landsat, que atualmente fornece dados temporais desde 1985 até os dias de hoje (Woodcock et al., 2008), permite que sejam realizadas análises de séries temporais, possibilitando analisar as mudanças ambientais ao longo dos anos. Em específico, as imagens óticas dos sensores do Landsat permitem analisar as variações nos IV ao longo do tempo, permitindo inferir os distúrbios nos fragmentos florestais (Huang et al., 2010; Kennedy et al., 2010). Além disso, os usos desses índices permitem o mapeamento da degradação florestal dos remanescentes ao longo do tempo. Isso pode ser feito através da resposta espectral do dossel, onde através da interpretação do valor desses índices, pode ser feita a identificação de áreas prioritárias para a conservação e permitir também o monitoramento da regeneração de áreas naturais pós alterações (Hojas-Gascon et al., 2015; Aljahdali et al., 2021; Delgado-Moreno & Gao, 2021). As análises das imagens em diferentes anos permitem compreender como características da paisagem afetam a degradação florestal. Estudos nesse escopo possibilitam acompanhar como a comunidade vegetal dos remanescentes responde a alterações que ocorrem na paisagem, como sucessão retrogressiva (substituição de espécies climax por espécies pioneiras) (Santos et al., 2008; Sansevero et al., 2017).

A Mata Atlântica é um *hotspot* tropical em estado crítico de conservação (Ribeiro et al., 2009), que atualmente apresenta somente cerca de 20% da sua cobertura original e as áreas remanescentes são compostas de pequenos fragmentos (<50 ha) espalhados entre si e expostos ao efeito de borda (Ribeiro et al., 2009). A perda de sua cobertura original é atribuída principalmente a ocupação humana, onde grande parte das áreas de floresta foram convertidas para criação de cidades e expansão agrícola (Marques & Grelle, 2021). Apesar das históricas alterações, nos últimos anos o bioma apresentou uma diminuição na taxa de perda de cobertura florestal. O que se observa atualmente é a perda de florestas secundárias em determinadas regiões, e o reflorestamento ou programas de restauração em outras áreas, mantendo-se assim a porcentagem total de cobertura do bioma (Rosa et al, 2021; da Silva et al., 2023). Porém, mesmo diante deste cenário são poucos os estudos que visam compreender como a degradação florestal atua nesse bioma, principalmente oriundos dos usos de solo antrópico que circundam os remanescentes.

A região Sul da Bahia é caracterizada pela fragmentação da paisagem de Mata Atântica. Essa região, popularmente conhecida como a “Hileia Baiana” (Andrade-Lima, 1966), apresenta um alto endemismo vegetal, riqueza de espécies e altos níveis de degradação, sendo por isso considerada um *hotpoint* dentro de um *hotspot* de biodiversidade global (Thomas et al., 1998; Martini et al., 2007). Historicamente, a região se destaca por converter florestas em áreas destinadas a produção agrícola. Ademais, desde os anos iniciais da chegada portuguesa no litoral Baiano até os dias atuais, o cultivo agrícola nas áreas de Mata Atlântica foi variado e distinto, seguindo padrões regionais (Marques & Grelle, 2021). Na região sul da Bahia, se destacam duas regiões com padrões distintos de uso de solo. A região composta pelos municípios de Una, Arataca e Santa Luzia apresentam uma alta cobertura florestal, enquanto os municípios de Belmonte, Mascote e Canavieiras se apresentam como uma região com baixa cobertura florestal. Na região altamente florestada, grandes áreas são destinadas a produção de cacau em sistemas agroflorestais de cacau (localmente conhecidos como cabruca) (Sambuichi et al., 2012), além de abrigara Reserva Biológica de Una, sendo assim responsáveis por reter grandes áreas vegetacionais. Por outro lado, a região desmatada não possui grandes áreas destinadas à conservação, e a conversão de florestas em áreas agrícolas foi além do cultivo do cacau, incluindo grande proporção de pastagens. Próximo aos anos 2000, esta região desmatada apresentou uma drástica redução no cultivo de cacau e uma expansão na extração de madeira e silvicultura, impulsionados principalmente pela chegada de grandes empresas na região (Sayre, 2003; Marques & Grelle, 2021), enquanto a região florestada permaneceu com suas grandes áreas de cabruca e florestas. É possível que o contraste de uso de solo entre as regiões afete a degradação florestal dos remanescentes florestais de forma distintas, porém são inexistentes estudos que avaliaram essa potencial influência.

Diante disso, o presente estudo teve como objetivo avaliar como o uso e cobertura da terra circundantes aos remanescentes florestais influenciou na degradação florestal em seu interior ao longo de 30 anos, a partir uma série de imagens históricas e dados de cobertura de solo de 1985 a 2020. As informações obtidas com o mesmo fornecem um panorama geral de como os usos de solo da região vem afetando os remanescentes de Mata Atlântica da região. Dessa forma, a presente dissertação é apresentada em formato de artigo científico, formatado segundo a revista *Land Degradation & Development.*

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Agricultural expansion and landscape heterogeneity explain forest degradation in the threatened Brazilian Atlantic Forest[1]

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Abstract

Forest degradation has been caused by several anthropogenic drivers in tropical forests, including landscape deforestation and fragmentation, thereby directly affecting the quality of forest remnants. In fact, forest edges adjacent to anthropogenic covers can be more exposed to abiotic and biotic changes and consequently lead to the deterioration in the forest interior. Yet the effect of the surrounding land covers on this process has been poorly known. Here, we investigate the influence of landscape context in explaining patterns of forest degradation over 35 years in two regions exhibiting different deforestation patterns in the threatened Atlantic Forest of southern Bahia, in Brazil. We assessed forest degradation through the Normalized Difference Moisture Index (NDMI) and the Enhanced Vegetation Index (EVI) in the center of 50 forest remnants embedded within different amount of both forest and agriculture cover, and landscape heterogeneity. In particular, we evaluated these indices and landscape context in a time series from 1985 to 2020, at 5-year interval, based on MapBiomas land-use classification and Landsat imagery. We thus performed Generalized Linear Mixed Models to assess the influence of land-use coverages over time on NDMI and EVI of focal remnants. Our results indicate that forest degradation was intensified according to the increase in agricultural cover, although sites inserted in more heterogeneous landscapes showed reduced degradation. We also observed that forest remnants surrounded by greater agricultural cover succumbed to higher water stress, especially in the initial years of the time series. We therefore emphasize the importance of curbing the agricultural expansion and promote initiatives towards forest restoration to reduce the long-term forest degradation in Atlantic Forest remnants.

Key-words: Land-use cover; Landscape ecology; Remote sensing; Vegetation indices.

Introduction

Deforestation is currently the major threat to tropical forests, with agricultural expansion comprising one of the main drivers of land-use changes and likely reducing the quality of the remaining forest patches (Barlow et al., 2020). Those novel, anthropogenic forest landscapes further face long-term changes, and can continuously provoke alterations in the structural and functional components of forest remnants (Laurance et al., 2012), with some land-uses exerting even greater impact than others. For instance, the conversion of forested areas to croplands can cause an increase of up to three times in the surface temperature than forest conversion into pastures in small rural settlements (Maeda et al., 2021). Furthermore, the land-use surrounding the remnant influences its quality, remnants located in more urbanized landscapes have a lower diversity of adult individuals (Wang & Yang, 2022). When inserted in cultivated areas, forest remnants present greater aboveground carbon losses (Ordway and Asner, 2020), and may also present a reduction in soil quality and plant richness, due to the intensification of agriculture (Didham et al., 2015; Ren et al., 2023). As a result, anthropogenic land-uses can exert drastic influence on forest integrity, mostly triggered by edge effects.

Forest remnants in highly fragmented landscapes dominated by contrasting anthropogenic land covers are prone to be greatly affected by edge effects (i.e., increase in temperature, speed of wind and ecological alterations that occur at the created edges of forest fragments; Kapos 1989; Didham et al., 1998; Laurance et al., 1997; Fahrig, 2003.), in addition to become more exposed to other anthropogenic activities such as logging and fires (Asner et al., 2005; Cochrane et al. al., 1999; Rutishauser et al., 2015). As a result, it is expected that the greater are the edge effects, more pronounced will be forest degradation inside forest remnants, with subsequently effects on forest functionality. For instance, agricultural lands nearby forest remnants led to reduced aboveground biomass, subsequently enhancing carbon dioxide emissions into the atmosphere (Bourgoin et al., 2021). Furthermore, landscape heterogeneity can also affect forest degradation, as land-uses more structurally similar to forest remnants likely attenuate the impact of forest loss. For instance, agroforestry systems cause fewer changes in wind intensity and light incidence in adjacent forest sites compared to a contrasting matrix such as pasture (Travassos-Britto et al., 2023). Hence, the landscape context can expose forest remnants to local degradation, and ultimately compromise forest functionality.

Forest degradation, which among several definitions (see Ghazoul & Chazdon, 2017) can be defined as the reduction persistent reduction of some attribute relative to a preferred (nondegraded) condition (Ghazoul & Chazdon, 2017) and occurs at various spatial scales. Large-scale degradation can thus affect landscapes and even ecosystems, by disrupting vital ecosystem services like climate regulation, erosion control, and pollination, whereas fine-scale degradation acts at the local level, by affecting soil quality, decomposition processes, and the forest seed bank with further consequences to biodiversity maintenance (Ghazoul & Chazdon, 2017). As a result, the interconnected nature of spatial scales hampers the effectively monitoring of forest degradation (Sloan, 2008). In addition, forest remnants may not exhibit a reduction in total area over time but can still undergo degradation driven by local and landscape factors. For instance, forest remnants under selective logging still show signs of degradation for even 11 years after the event, reflected by a lower canopy and fewer tree individuals (Milodowski et al., 2021). Thus, the long-term monitoring of forest quality is fundamental to observe potential evidence of degradation inside the remnants. If observed, the subsequent assessment of the key drivers of forest degradation is essential to define sound mitigation practices and land managements required to prevent further deterioration in forest quality in the long-term.

An increasing number of studies has been focusing on evaluating patterns of forest degradation in tropical forests using different remote sense approaches (Souza Jr et al., 2003; Hojas-Gascon et al., 2015; Delgado-Moreno & Gao, 2021). In particular, the advancement of remote sensing technologies combined with the availability of high-quality satellite images have improved the identification of key drivers of forest degradation, including deforestation, logging and fires (Gao et al., 2020). In addition, the existence of satellite images at different years allows the monitoring of forest degradation across time series, as periods of stability, punctuated/continuous occurrences of degradation and even regeneration can be identified in a remnant (Huang et al., 2010; Kennedy et al., 2010; Verbesselt et al., 2010). Among effective ways to monitoring forest quality, the use of vegetation indices through remote sensing along a time series can be considered a useful tool to assess forest degradation in tropical remnants. For instance, the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) evaluate the photosynthetic response of the canopy, indicating therefore the vegetation quality and enabling the estimation of carbon emissions (Huete et al., 2002; Garroutte et al., 2016; Maeda et al., 2014). Other indices, such as the Normalized Difference

Moisture Index (NDMI), can also be used to monitor the degradation and regeneration of natural areas (Aljahdali et al., 2021; Delgado-Moreno & Gao, 2021). Delgado-Moreno and Gao (2021) used the trend in vegetation indices (NDVI and NDMI) over time to identify the occurrence of vegetation regeneration (in case of a positive trend in the indices) or their degradation (negative trend in the indices), thus being able to map the main forest areas that were degrading. Nevertheless, there is a scarcity of studies that comprehensively evaluated the drivers of forest degradation at a wider spatial and temporal scales, even though land-use changes over time comprise one of the primary drivers of forest degradation in tropical regions (Gao et al., 2020). In particular, biodiversity hotspots comprise the most exposed regions to degradation drivers worldwide, given that are sites continuously succumbed to a myriad of anthropogenic stressors, including overexploitation of natural resources, deforestation and fragmentation of natural areas.

Among terrestrial biodiversity hotspots on Earth, remnants of the Atlantic Forest biome are highly susceptible to high rates of forest degradation caused by anthropogenic land-use changes. This vulnerability arises from the biome's critical conservation status, with over 80% of its current area currently comprised by small fragments (<50 ha) that are prone to be affected by edge effects (Ribeiro et al., 2009). Nevertheless, over the past two decades, the Atlantic Forest has not exhibited a decrease in their overall forested area (da Silva et al., 2023). However, this does not imply that its forest remnants are not suffering degradation. Instead, forest composition has been drastically changed, reflected by the loss of old-growth forests and the expansion of young forests (Rosa et al., 2021). In addition, Rocha-Santos et al. (2016) clearly revealed that forest fragments inserted in highly deforested landscapes presented a simplified vegetation structure (e.g., characterized by shorter and thinner trees) and therefore greater degradation, with subsequent consequences on forest functionality (see Faria et al., 2023). Therefore, the landscape context seems to greatly affect the quality of forest remnants, yet studies have not evaluated the influence of different land-use types on forest degradation in this key conservation area.

Here, we use remote sensing data to examine how different land-use types have affected the degradation of forest remnants within a high-priority conservation portion of the threatened Brazilian Atlantic Forest, over 35 years (1985 to 2020). Specifically, we assessed how (i) different types of land-use surrounding forest remnants changed over time in two regions exhibiting different deforestation patterns; (ii) these spatial (i.e., land-use types) and temporal (along the time series) factors affected different vegetation indices of focal forest remnants in these two regions. We expected to detect (i) an increase in the amount of agricultural cover and landscape heterogeneity, and a decrease in the amount of forest cover across the time series, given the marked deforestation and agricultural expansion, especially in the most deforested region (Sayre, 2003; Marques & Grelle, 2021); (ii) that forest remnants surrounded by a greater amount of agricultural cover will show a sharp reduction in forest vegetation indices (NDMI and EVI) throughout the time series, due to the intensification of changes caused by edge effects (i.e., increase in temperature, speed of wind and mortality of tree individuals (Kapos 1989; Laurance et al., 1997; Fahrig, 2003)), thus affecting the quality of forest remnants over time. We ultimately expected that greater landscape heterogeneity will lead to a reduction in vegetation indices of forest remnants, given that patches surrounded by homogeneous and hostile land-use types (e.g., pastures) are prone to be succumbed to greater edge effects and consequently undergo higher forest degradation (Travassos-Britto et al., 2023).

Methods

Study area

We conducted this study in forest remnants (Figure 1) located in the southern Bahia in Brazil, a biodiversity *hotpoint* within the threatened Atlantic Forest (Martini et al., 2007). The regional climate is hot and humid (Gouvêa, 1969), characterized by an average annual rainfall of 2000 mm/year and an average annual temperature of 24°C. In fact, the study area harbors one of the greatest floristic diversity in the world, with an estimated 144 species in 0.1ha of forest, including high level of endemism (Thomas et al., 1998, Martini et al., 2007). Nevertheless, this Atlantic Forest portion has been facing a critical conservation status – indeed, Bahia stands out as one of the Brazilian states that exhibited the greatest rates of Atlantic Forest loss in recent years, mostly driven by agricultural expansion among other anthropogenic land-uses (MapBiomas, 2022). Consequently, natural forest landscapes have been converted into heterogeneous human-modified landscapes encompassing pastures, farmlands, cocoa agroforestry systems, whereas remaining forested areas exhibit different successional stages (Pardini et al., 2009). Nevertheless, the southern Bahia is highly heterogeneous in terms of landscape patterns. We therefore selected two regions presenting different land-use patterns to perform this study. In particular, the northernmost is a more forested region (referred to as high forest cover (HFC) region, Fig. 1a), predominantly comprised of forest remnants and cocoa agroforestry systems. In contrast, the southern portion is highly deforested (referred to as low forest cover (LFC) region, Fig. 1b) and fragmented, being dominated by pastures. These patterns are results of the land-use history of occupation in the study region, where HFC maintained forests and agroforestry cultivation, while LFC prioritized the replacement of forested areas in favor of pastures, also reducing agroforestry areas (Sayre, 2003; Marques & Grelle, 2021.)

Forest remnants selection

We selected 50 forests remnants embedded within contrasted landscapes in both regions., In particular, we selected forest remnants that have already been sampled in previous studies to ensure that the remnants were never undergone conversion to other land-use types, mostly belonging to our research group, the SISBIOTA network– a project that sought to understand how deforestation affects patterns of biodiversity in this important portion of the Atlantic Forest (Faria et al., 2023), and the Eco-nomia das cabrucas, a project that aims to understand the importance of cocoa agroforestry systems and the composition of the landscape for preserving biodiversity (Araújo-Santos et al., 2021). As selection criteria, remnants needed to be comprised of ombrophilous forests and characterized by intermediate to high levels of successional stages, separated by a minimum distance of 2.5 km from each other. All forest remnants exhibited similar soil, topography, and floristic characteristics (Benchimol et al., 2017). Regarding the size of the studied remnants, we observed that for the year 2020 the average was 956ha (SD±3311), where the largest of the remnants (29) were less than 100ha in size. The largest remaining areas studied were 14900ha and 18700ha, both being conservation units, respectively, the Serra das Lontras National Park and the Una Biosphere Reserve.

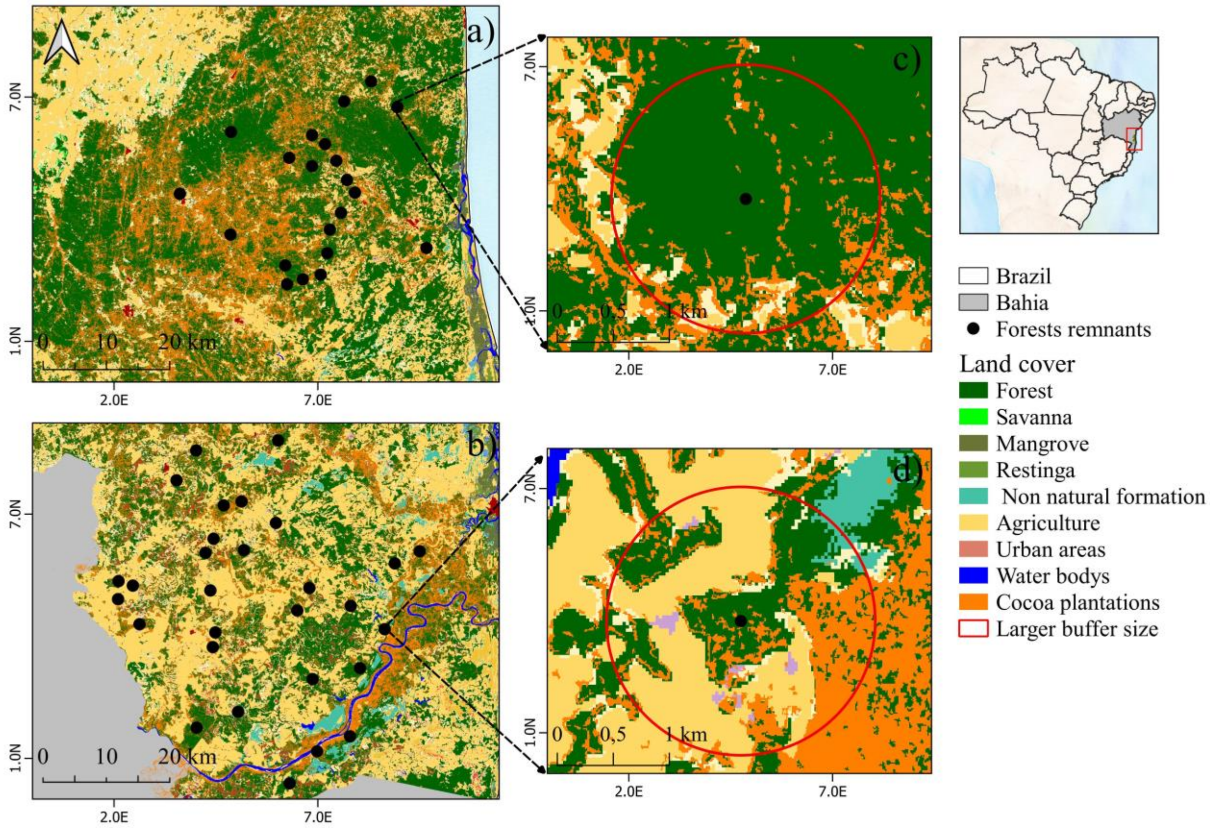

Figure 1. Distribution of the 50 focal forests remnants used in this study, located in the (a) high forest cover (HFC) and (b) low forest cover (LFC) regions in southern Bahia, Brazil (a). where (c) demonstrates the greater predominance of forest areas in the HFC landscape while (d) highlights the heterogeneity of the landscape in the LFC. Land use cover is based on MapBiomas for 2020.

We used land-use and land cover mapping (LULC) products provided by the MapBiomas initiative, which has classified land-use cover throughout the national territory since 1985 (Souza et al., 2020). MapBiomas classifies LULC types into broad categories. In particular, agricultural production areas (such as coffee, sugar cane, soy, rice, among others), pastures, and forestry are grouped together under a broader category called ‘Agriculture’. Similarly, native forest areas and shade-cocoa plantations are grouped under a category named as ‘Forest’. In fact, shade-cocoa areas are characterized by the maintenance of emergent trees, and therefore exhibit vegetation structure similar to forest sites and provide a suitable environment for several faunal and floristic species (see Cassano et al., 2009; Cassano & Pardini, 2012). Due to this structural similarity of the canopy, the spectral response of both forest and shade-cocoa plantations are extremely similar at the level of satellite monitoring.

We used satellite images from the Landsat series (30 m – spatial resolution), starting with the Landsat 5 (Thematic Mapper (TM) sensor), Landsat 7 (Enhanced Thematic Mapper Plus (ETM+) sensor) and Landsat 8 (Operational Land Imager (OLI) sensor). Landsat imagery was used given its historical availability (1985 - present day) and because is the same satellite used by the MapBiomas initiative (Souza et al., 2020), thus generating information from the same data source and avoiding possible errors. We obtained those Landsat images through the Google Earth Engine platform (GEE, Gorelick et al., 2017), which feature georeferencing, atmospheric correction and masks to reduce the influence of clouds. We selected images from September to December (months with fewer clouds) to reduce the presence of clouds, and then we chose images from a 5-year interval (1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2020), as we noted relatively low land-use changes within a 5-year timeframe in our study region. Using the GEE, we thus created mosaics with all those available satellite images for the selected, also obtaining land use information for the same years through the data from the MapBiomas project (MapBiomas, 2022). We then used the free geoprocessing software QGIS (QGIS, 2022) and manual masks, which were created by manually selecting cloud pixels and cloud shadows, which were then automatically selected using the dzetsaka semi-automatic classification tool (Karasiak, 2016) to remove clouds and cloud shadows from mosaics.

Local forest degradation

We used two vegetation indices as proxies of forest degradation - the Enhanced Vegetation Index (EVI) and the Normalized Difference Moisture Index (NDMI), which have been widely used to assess the physiological stress of forest remnants through the spectral response of the canopy of forest remnants (Garroutte et al., 2016; Maeda et al., 2014). Indeed, both indices indicate the photosynthetic activity of the vegetation through the canopy reflectance (Huang et al., 2021). The NDMI is calculated through the difference between spectral bands (Red, Near Infra-red (NIR) and short wave infra-red (SWIR), whereas the EVI presents mathematical corrections to account for potential errors caused due to the reflectance of the understory and the soil. All these indices vary from -1 to 1 and when monitored over time, preserved remnants tend to show continuous values of these índices. The value of the vegetation index can be associated with disturbances in the remaining forest (i.e., climatic phenomena such as periods of drought, deforestation processes), and changes in the index over time related to the impacts of these factors allow the indices to be used as a proxy for forest degradation through monitoring this variation (Fiorella & Ripple, 1995; DeVries et al., 2015; Delgado-Moreno & Gao, 2021).(see Table S1 in Supplementary Material for further information). In this way, we monitor the forest degradation of the remnants by analyzing the variation in the value of vegetation indices over time.

To obtain a value of each vegetation index that represented the degradation, we selected a central pixel of the forest fragment and four nearby pixels, totaling values of 5 pixels (Fig. S1) to estimate both vegetation indices. The spectral values of this set of points were collected in the eight years of the time series. When any of the central pixels was covered by clouds and/or shadows, we used the nearest pixel. We thus used the mean values of five pixels per forest remnant in each year in data analyses.

Landscape metrics

We initially established four buffer sizes (600, 800, 1000 and 1200 m) from the center of each forest remnant to calculate the landscape metrics. The smallest and largest buffer sizes were chosen, respectively, to obtain variations within each landscape metric among sampling sites and avoid landscape overlapping. Similar to MapBiomas, we grouped cattle pastures and agriculture (such as coffee) into a category called ‘agricultural areas’, and our “forested areas” also considered both native forests and shade-cocoa agroforests. We thus characterized the landscape structure around each forest fragment by measuring the amount of the most recorded land-use covers across our sampling sites (i.e., agriculture and forest cover) within each buffer, in addition to a metric of landscape heterogeneity that incorporates other land-use types. Specifically, we used the Shannon index to estimate the landscape heterogeneity, which is among the most recommended indices given that both configurational and composition aspects of landscape heterogeneity are represented (see Tonetti et al., 2023). In fact, Shannon index considers the number of land-use classes and the quantity of each class within the landscape. It ranges from 0 to ∞, which zero corresponds to a homogeneous landscape composed by a single type of land-uses, whereas highest values represent extremely heterogeneous landscapes dominated by various land-uses. In our study, a highly heterogeneous landscape refers to a landscape composed of multiple agricultural and natural land-uses, such as pasture, coffee plantations, water-bodies and *restinga*, whereas more homogeneous landscapes primarily consist of either predominant forest cover or agricultural land-use.

Data Analyses

We first fitted linear models to assess the 'scale of effect', i.e., the spatial extent at which the landscape predictor (forest cover, agricultural cover and landscape heterogeneity) exerts the strongest effect on each forest degradation index. Based on the coefficient of determination of each model, we identified that 600 m was the best scale of effect for both indices regardless of the landscape metric (Table S2).

We further used Generalized Linear Mixed Models (GLMMs) to assess the influence of each landscape metric, region (i.e., HFC and LHC) and year (8-years interval) on both EVI and NDMI, with our global model incorporating the focal forest remnant as random effect and using gaussian as the family. For each vegetation index, we performed Multimodel Inference, which compares all subsets of models with all possible combinations of explanatory variables in addition to a model containing the interaction between landscape metrics and year, in addition to the null model. We priory used the Variance Inflation Factor (VIF) to verify potential collinearity among the predictor variables and considered values higher than 3 as collinear. In fact, a high collinearity was observed between forest cover and agricultural cover, so these variables were not included in the same model. We ranked the models based on the Akaike Information Criterion (AIC), where models with $\Delta AIC \leq 2.00$ were considered parsimonious. We also took into account the weight and number of parameters to determine which model should be considered the most appropriate to describe our indices. Using the DHARMa package (Hartig, 2020), we tested for potential spatial autocorrelation and checked the distribution of the residues of our models. We detected no spatial autocorrelation (Table S4) and all models presented a normal distribution of residues. All analyzes were performed in the R software (R Core Team, 2000), using the packages *glmmTMB* (Magnusson et al., 2017) and *bbmle* (Bolker et al., 2017).

Results

Considering our studied time series, we observed that the average of EVI and NDMI indices was, respectively 0.68 (SD ±0.11) and 0.41 (SD ±0.06). Regarding the landscape context, for the 600m buffer, land-use types varied over time among our 50 landscapes; forest cover ranged from 5% to 100%, agriculture cover ranged from 0% to 94% and landscape heterogeneity varied from 0 to 1.35 (Shannon index). In particular, the percentage of forest cover changed over the temporal series, whereas several landscapes showed an increase in agriculture cover, especially in the LFC region (Fig. S2). Specifically, 34 landscapes showed reduced forest cover in 2020 contrasting to 1985. We also noticed that 29 landscapes presented higher heterogeneity in their land-use types over time, whereas 18 landscapes showed a reduction in heterogeneity over the time series. Overall, the majority of landscapes transitioned from homogeneous to heterogeneous over time, with only a few landscapes displaying minimal variation in this metric (Fig. S3).

Based on model selection approach, we detected that two models were parsimonious in explaining NDMI and four models in predicting EVI (Table 1). We observed that the interaction of agricultural cover and year, additively with landscape heterogeneity, best explained patterns of NDMI. The second-best model for predicting this vegetation index also included the region yet exhibited lower weight. In both parsimonious models, agricultural cover exerted a negative and significant influence on NDMI index (Fig. 2A), whereas landscape heterogeneity had a positive effect on NDMI (Fig. 2B). Furthermore, the interaction of agricultural cover and year was also a significant factor affecting NDMI (Fig. 2C) (Table S4). Although presented in the second-best model in explaining NDMI, the region did not exert a significant effect (Table S4). Regarding EVI, models including agriculture cover with year, forest cover with year, the interaction between agriculture cover and year and the model containing landscape heterogeneity and year were parsimonious (Table 1). In particular, forest remnants surrounded by lower agricultural cover (Fig. 2D) and greater forest cover (Fig. 2E) presented higher EVI index. Finally, year exerted a significant and positive influence on EVI (Table S4), in which the two last examined years (i.e., 2015 and 2020) showed a notable increase in EVI (Fig. 2F).

Table 1. Model selection table based on all parsimonious models (i.e., ΔAIC <2) explaining the influence of landscape predictors (forest cover, agriculture cover and landscape heterogeneity), year and region on NDMI and EVI indices of 50 forest remnants of the southern Bahia, Brazil.

Model	**ΔAICc**	**df**	**weight**
NDMI ~ Agriculture cover*Year + Landscape heterogeneity + (1 | Site)	0.0	7	0.709
NDMI ~ Agriculture cover*Year + Landscape heterogeneity + Region + (1 | Site)	2.0	8	0.258
EVI ~ Agriculture cover + Year + (1 | Site)	0.0	5	0.194
EVI ~ Forest cover + Year + (1 | Site)	0.5	5	0.148
EVI ~ Agriculture cover*Year + (1 | Site)	1.0	6	0.115
EVI ~ Landscape heterogeneity + Year + (1 | Site)	2.0	5	0.071

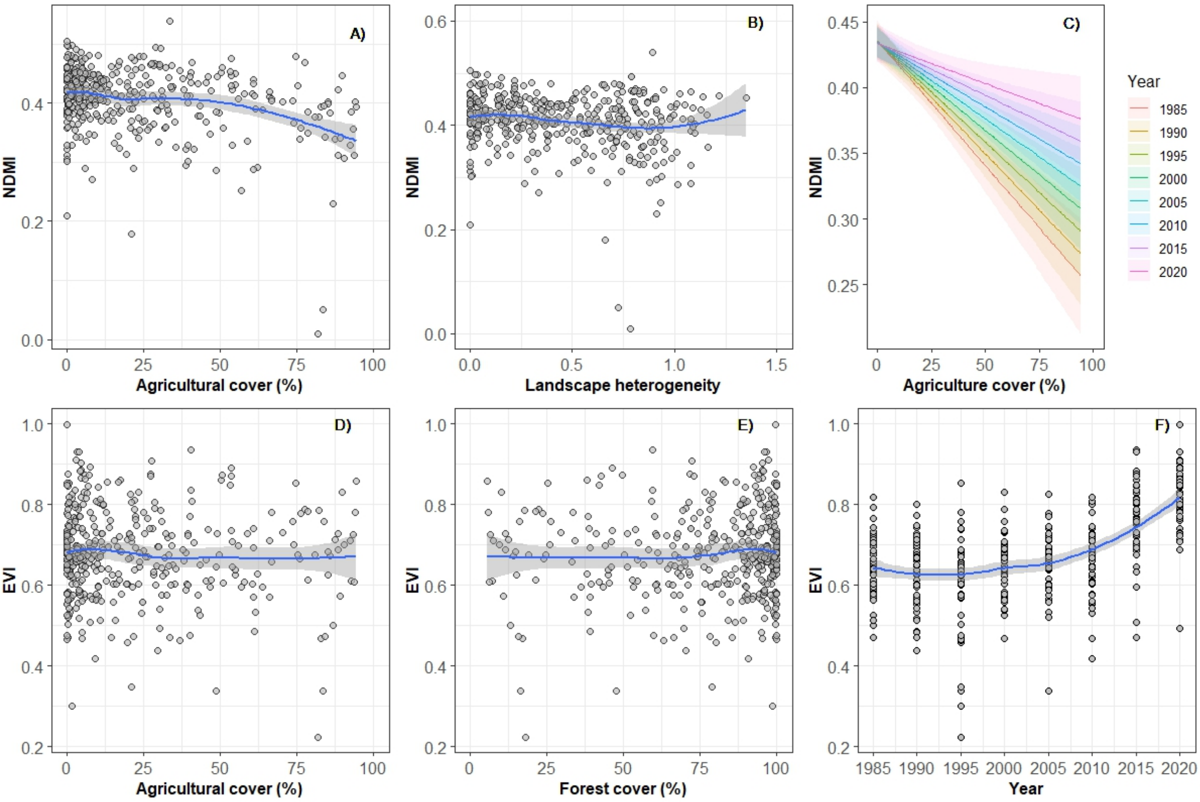

Figure 2. Effect of significant predictors in explaining patterns of NDMI and EVI of 50 forest remnants located in southern Bahia, Brazil.

Discussion

In our study, we revealed the influence of landscape context on patterns of local degradation within the center of forest remnants located in a key conservation region of the threatened Atlantic Forest, the southern Bahia. By using remote sensing tools and free available land-use classification from the Brazilian MapBiomas initiative, we observed that forest remnants surrounded by greater amount of agricultural lands and within lower heterogeneous landscapes exhibit reduced vegetation quality along the time series. In particular, agricultural landscapes exerted a pervasive influence on forest degradation through the increase in water stress, especially in the beginning of our temporal series (i.e., 1985). Furthermore, the landscape heterogeneity had a positive influence on the mitigation of vegetation degradation in our remnants. Based on our outcomes, we emphasize the detrimental influence of anthropogenic land-uses on modulating the quality of forest remnants and highlight the importance of environmental policies to restore the Atlantic Forest, especially in those agricultural lands.

Over the last three decades, the southern Bahia region has experienced profound changes in land-use composition, indicated by a reduction in forest cover and a concomitant increase in the amount of agriculture lands, especially in the deforested region (LFC region). Indeed, coffee plantations and cattle pastures comprised the main agricultural land-uses along 1985 to 2000 in both regions (MapBiomas, 2022). In addition, we noted an increase in *Eucalyptus* spp. plantations starting in 2000, specifically in the LFC region. Therefore, these land-uses changes are intrinsically linked to patterns of landscape heterogeneity across the studied landscapes, due to the increase in areas devoted to pastures or conversion of pastures for eucalyptus areas. This cascade of land-use changes reflects the historical and recurrent deforestation patterns throughout the Atlantic Forest, where native forests have been deforested and replaced by agricultural lands over the centuries. Since the arrival of Portugueses in Brazil, a set of incentives to convert forests into agricultural and urban areas were provided (Marques & Grelle, 2021). Nevertheless, we observed different patterns of land-use changes in our study regions, where landscapes located in the highly forested region exhibited reduced deforestation and consequently lower variation in landscape heterogeneity. This result may be associated with the extensive areas destined for shade-cocoa plantations over the last two centuries, especially in the municipalities of Una, Arataca and Santa Luzia. Indeed, cocoa trees started to be cultivated in agroforest systems that maintain native tree species for more than 200 years in the region (Rocha, 2008; Sambuichi et al., 2012) and therefore has been responsible until to date for preventing drastic deforestation in the region (Marques & Grelle, 2021). In contrast, the deforested region experienced drastically replacement of forests for cattle pastures and cultivated a lower area of shade-cocoa plantations (MapBiomas Cacau, 2023), creating therefore a highly fragmented region presenting reduced amount of forest. In addition, eucalyptus plantations have emerged in the LFC region around the 2000s, mainly due to the establishment of large timber companies in the region (Sayre, 2003; Marques & Grelle, 2021).

As predicted, local degradation in the center of forest remnants was modulated by land-use types at the landscape scale, especially due to the advance of agricultural areas and reduction of forest cover. In particular, the increase in agricultural areas affected both degradation indices, and was intrinsically associated with physiological changes in the vegetation (EVI) (Huete et al., 2002) due to the greater water stress in focal remnants (i.e., reduction in NDMI) (Gao, 1996). In fact, as deforestation progresses and agricultural areas expand, forest remnants are exposed to greater edge effects, therefore directly harming forest structure. Indeed, more pervasive land-use types adjacent to forest remnants induce to substantial changes in vegetation structure in forest edges, mediated by an increase in light and wind incidence, which create adverse conditions for the establishment and maintenance of several native plant species (Kapos 1989; Laurance et al., 1997; Fahrig, 2003). In particular, shade-tolerant species are more likely to experience several declines along forest edges, leading to a homogenization of tree assemblages that ultimately will affect forest structure. Indeed, created forest edges retain smaller trees and with smaller basal area than the interior of the forest (Magnago et al., 2015), becoming a more simplified forest in terms of structure than intact, undisturbed forest sites. Furthermore, edge effects can penetrate into great distances from edges to forest interior, reflecting in floristic composition changes up to 300 m in Amazonian forests (Benchimol & Peres 2015). Therefore, forest remnants embedded within higher proportion of agricultural lands in southern Bahia have likely experienced greater and more pervasively edge effects, which directly affected the physiological functions of plants and generate an intensified hydric stress even in forest interior.

Landscape heterogeneity also explained patterns of forest degradation of southern Bahia Forest remnants, as reflected by its positive influence on NDMI. In our study sites, highly heterogeneous landscapes are composed by a mixed of forests, eucalyptus areas, flooded fields, pastures and coffee plantations. It is known that pervasive edge effects can reduce the number of tree individuals and consequently the plant biomass along forest edges when compared to forest interior of tropical remnants (Laurance et al., 1997; Magnago et al., 2015), subsequently reducing the number of stems regulating the microclimate through photosynthesis. Therefore, the combination of varied land uses can mitigate the pervasive edge effects on the center of forest remnants when compared to the effects generated by a more hostile type of land use, such as pasture (Travassos-Britto et al., 2023). In addition, landscapes dominated by agricultural crops can affect the quality of water resources available in the landscape (Qiu et al., 2015), likely acting as another factor that generates water stress inside forest remnants embedded within more homogeneous landscapes. Thus, we suggest that heterogeneous landscapes, at least in our study region, can mitigate edge effects on forest remnants. This implies that policies towards promoting varied land-use types in rural properties should be favored in detrimental of homogeneous, hostiles matrices such as pastures.

Contrary to our expectations, the quality of vegetation in forest remnants improved over 35-years, as indicated by high EVI index in recent years, especially in 2015 and 2020. In particular, the increase in EVI indicates greater photosynthetic activity in forest canopy (Huete et al., 2002). Given that canopy trees present unique physiological responses, the detected changes in EVI suggest that tree species composition has been shifting across the years, potentially led by the replacement of secondary to old-growth species which exhibit high rate of photosynthesis (Sant’Anna et al., 1995; Steininger, 1996; Zaitunah et al., 2018; Zutta et al., 2023). Nevertheless, other factors might also have affected EVI over the studied years, such as the ‘La Niña’ that occurred in 2020. This climatic phenomenon causes an increase in precipitation in the study region (Grimm, 2004), thus providing greater water availability and allowing the increase in photosynthetic activity within forest remnants. Given that retrogressive succession (i.e., the degeneration forest process led by pervasive edge effects that culminate in fewer tree species and lower biomass over time) has been posing as a common trajectory in other Atlantic Forest remnants (Santos et al., 2008; Sansevero et al., 2017), our unexpected result can shade light on the hope of forest recovery in southern Bahia. Nevertheless, long-term monitoring of vegetation indices linked to forest degradation may contribute to the understanding of the potential resistance of forest remnants to disturbances and should be prioritized by environmental-governmental agencies.

Finally, agriculture cover acted synergistically with years in explaining forest degradation measured by NDMI, in which forest remnants embedded within highly agricultural landscapes were exposed to greater degradation in the initial years of our time series. This detrimental impact may have been caused by the substantial shifts in the land-use context mainly from 1970 onwards (Marques & Grelle, 2021), in which agricultural expansion has drastically modified the landscape composition and subsequently affected the structure and functionality of forest remnants (Faria et al., 2023). Therefore, forest remnants in the first subsequent years have become intensively degraded by both the direct and indirect effects of agricultural expansion, whereas further years were less affected. In fact, just after the landscape deforestation and forest fragmentation processes, remaining fragments suffer the most drastic alteration in forest structure and vegetation quality mostly driven by edge effects, becoming also more likely to be exposed to other anthropogenic disturbances such as timber extraction (Laurance & Vasconcelos, 2009). Nevertheless, edge effects can be attenuated and forest therefore recovered over the years, reflecting in the replacement of pioneer to old-growth species in forest remnants (Delamônica 2001; Laurance & Vasconcelos, 2009; Magnago et al., 2015). Further studies monitoring vegetation indices associated to field measurements in our study area are required to assess if forest remnants have become resistant to abrupt landscape changes and are recovering over the years. This poses crucial given its intrinsic relation to the ability of Atlantic Forest remnants in sequestering and storing carbon and consequently in mitigate climate change.

Conclusions

Forest degradation is known to affect nearly 100 million ha of forest per year on Earth, with tropical forests subjected to higher deterioration levels (FAO, 2006). In this context, our study brings novel information on the landscape drivers of forest degradation in the threatened Atlantic Forest of southern Bahia, a region characterized by high levels of biodiversity and drastic shifts in landscape structure along the decades (Marques & Grelle, 2021; MapBiomas, 2023). Based on our results, we revealed that the landscape context matters for forest degradation process, with agricultural expansion detrimentally affecting vegetation quality independently of the level of deforestation at the region level. Given that forest degeneration is intrinsically related to forest functionality, conservation practitioners should avoid further forest degradation and propose management actions towards the fast and effective recovery of remaining forests. In particular, more friendly agricultural systems, such as the traditional cocoa agroforests, should be fomented by governmental agencies as can contribute to curb deforestation in the region, in addition to simultaneously provide ecosystem services and boost local economy (Araújo-Santos et al., 2021; Faria et al., 2021). In addition, landscape heterogeneity played a positive role in forest quality of studied remnants, suggesting that mixed land-use types can be more favorable in attenuate forest degradation than homogeneous anthropogenic landscapes, such as cattle pastures.

Looking at the bright side, forest remnants seem to be structurally recovering after pervasive landscape changes that occurred specially on the 70s. Indeed, the quality of vegetation measured by EVI indicated greater values over 35-years, especially in 2015 and 2020. Long-term monitoring poses as crucial to enhance our understanding on the patterns of forest degradation in southern Bahia, but the maintenance of high levels of forest cover combined with cocoa agroforests seem to contribute to recovery patterns in studied remnants. As we are in the Decade of Restoration declared by the United Nations, and the Pact for the Atlantic Forest aims to restore 15 Mha across the biome until 2050, we call attention to policy actors and governmental agencies on the great opportunity in investing in restoration actions in the unique

Atlantic Forest of southern Bahia. The potential high rates of recovery could contribute in carbon storage and consequently in mitigate climate changes.

Finally, we also emphasize that remote sensing technologies, combined with free-available satellite images, are good and useful tools to monitoring the vegetation quality of forest remnants. Nevertheless, the used MapBiomas Atlantic Forest series has a caveat in identifying shade-cocoa agroforests, so we recommend that future studies evaluate how this type of cultivation can mitigate forest degradation of the Atlantic Forest remnants in the region, more specifically using newly published mapping data for the current year of cocoa areas (i.e., MapBiomas Cacau project), along with analysis of vegetation indices and field data collection.

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Supplementary material

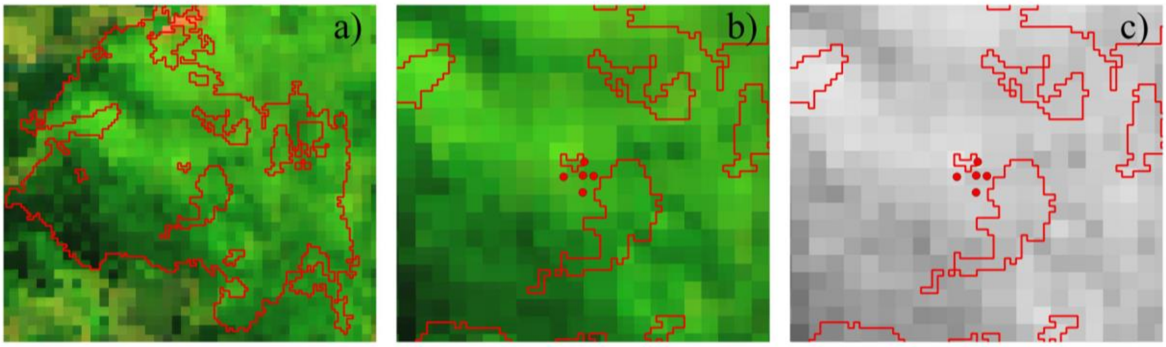

Figure S1. Steps for obtaining the average of vegetation indices where the remaining area was first delimited (a), followed by the creation of the centroid and four points in the nearby pixels (b), and then extraction of the average of the rasterized product of the vegetation indices vegetation (c).

Table S1. Description of the two vegetation indices used in our study, where NIR stands for near infra-red and SWIR for short wave infra-red. G refers to the gain factor, L the adjustment factor for soil and C1 and C2 are coefficients for the effect of aerosols from the atmosphere (their coefficient values are, respectively: G = 2.5; L=1; C1 = 6; C2 = 7.5). For more information, see Justice et al., 1998.

Vegetation Index	**Formula**	**Range**	**Description**
Normalized Difference Moisture Index	NDMI = (NIR – SWIR) / (NIR +SWIR)	-1 to 1	Used to detect disturbances and recovery, this index detects the water content variation of the vegetation and it is correlated with the canopy water content. Also, can differentiate the content of soil and vegetation moisture. Lower values indicate hydric stress in the region.

Enhanced Vegetation Index	$EVI = G*(NIR - Red) / (L+NIR + C1 * Red - C2 * Blue)$	-1 to 1	This index indicates the vigor of the vegetation by using the balance between the reflected chlorophyll in the infrared portion of the electromagnetic spectrum. Generated from the Near infra-red, red and blue bands for the time series studded. Higher EVI values indicate greater vigour of the canopy, while lower EVI values indicate physiological degradation. The EVI shows sensitive to background canopy variation and soil reflectance.

Table S2. Results of the ‘scale of effect’ analysis to evaluate the best landscape scale (i.e., buffer size) used in further analysis for each vegetation index.

Index	**Forest cover (R^2)**	**Agricultural cover (R^2)**	**Landscape heterogeneity (R^2)**	**Buffer size (m)**
EVI	0.0007	0.0014	0.0012	600
	-0.0007	-0.0002	-0.0008	800
	-0.0020	-0.0018	-0.0002	1000
	-0.0024	-0.0010	-0.0025	1200
NDMI	0.0834	0.0857	0.0255	600
	0.0712	0.0726	0.0240	800
	0.0521	0.0515	0.0396	1000
	0.0618	0.0586	0.0335	1200

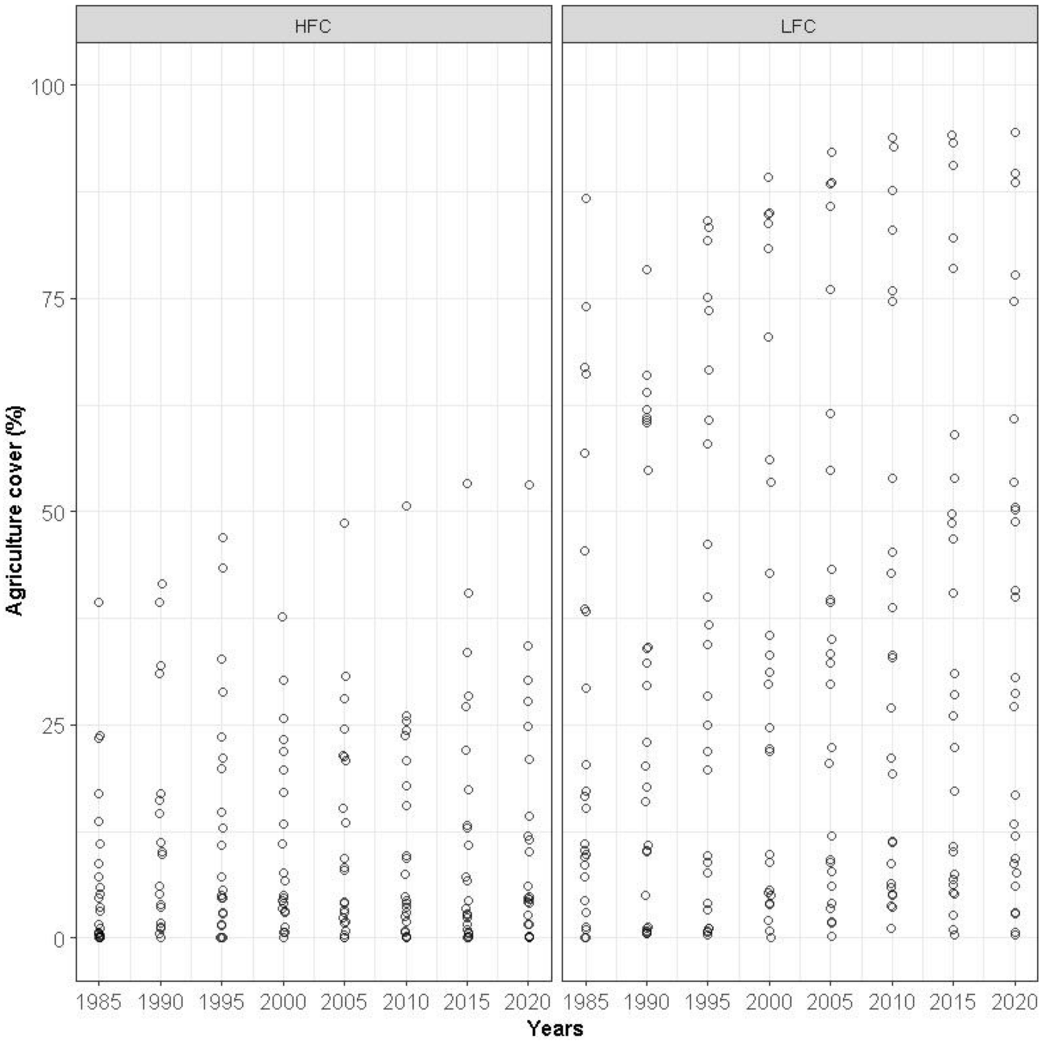

Figure S2. Percentage of agricultural coverage around forest remnants in both regions studied (High Forest Cover and Low Forest Cover) over the last 35 years.

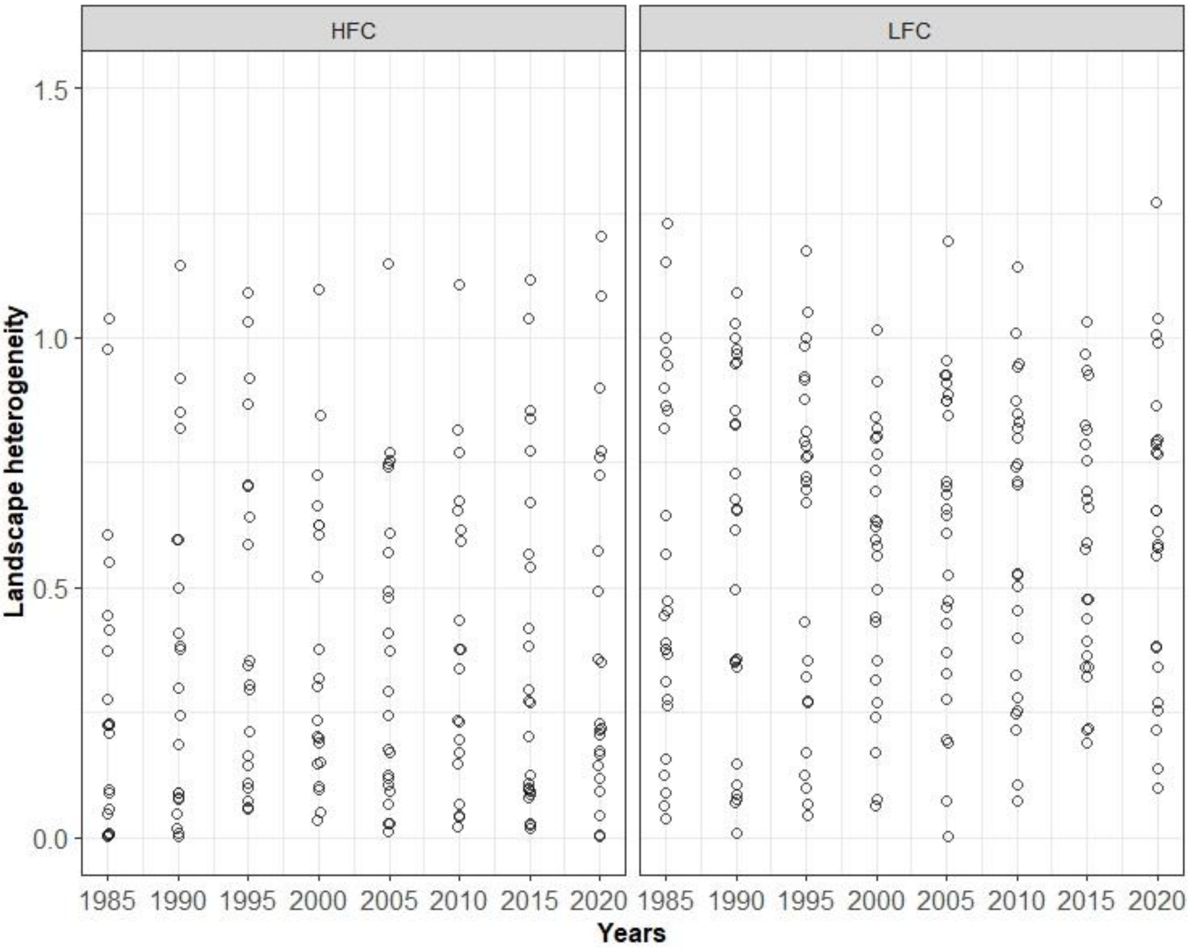

Figure S3. Variation in landscape heterogeneity in both study regions (High Forest Cover and Low Forest Cover) over the last 35 years.

Table S4. Coefficient estimates of the predictors included in the parsimonious models explaining NDMI and EVI. Predictors that exerted a significant effect are highlighted in bold.

Vegetation index	Model	Estimate	Std.Error	Z-Value	P-Value
NDMI	Agriculture cover*Year + Landscape heterogeneity				
	Intercept	5.57^{-1}	5.63^{-1}	0.989	0.322
	Agriculture cover	**-8.04^{-2}**	**1.86^{-2}**	**-4.313**	**1.61^{-5}**
	Year	-7.18^{-5}	$2,81^{-4}$	-0.255	0.79
	Landscape heterogeneity	**4.73^{-2}**	**1.50^{-2}**	**3.149**	**0.001**
	Agriculture cover*Year	**3.95^{-5}**	**9.28^{-6}**	**4.258**	**2.06^{-5}**
NDMI	Agriculture cover*Year + Landscape heterogeneity + Region				

	Intercept	5.709^{-1}	5.642^{-1}	1.012	0.311
	Agriculture cover	**-8.00^{-2}**	**1.865^{-2}**	**-4.291**	**$p < 0.01$**
	Year	-8.09^{-5}	2.822^{-4}	-0.287	0.774
	Landscape heterogeneity	**4.73^{-2}**	**1.495^{-2}**	**3.163**	**0.001**
	Region	$7{,}317^{-3}$	7.944^{-3}	0.921	0.357
	Agriculture cover*Year	**2.935^{-5}**	**9.282^{-6}**	**4.239**	**$p < 0.01$**
EVI	Year + Agriculture cover				
	Intercept	-9.28	0.81	-11.31	$p < 0.01$
	Year	**0.004**	**0.0004**	**12.16**	**$p < 0.01$**
	Agriculture cover	**-0.004**	**0.0002**	**-2.17**	**0.03**
EVI	Year + Forest cover				
	Intercept	-9.326	0.82	-11.34	$p < 0.01$
	Year	**0.004**	**0.0004**	**12.149**	**$p < 0.01$**
	Forest cover	**0.0004**	**0.0002**	**2.016**	**0.04**
EVI	Year*Agriculture cover				
	Intercept	-8.39	1.06	-7.85	$p < 0.01$
	Year	**4.53^{-3}**	**5.34^{-4}**	**8.49**	**$p < 0.01$**
	Agriculture cover	-4.44^{-2}	3.41^{-2}	-1.3	0.193
	Year*Agriculture cover	2.195^{-5}	1.73^{-5}	1.28	0.197
EVI	Year + Landscape heterogeneity				
	Intercept	-9.19	0.819	-11.213	$p < 0.01$
	Year	**0.004**	**0.004**	**12.052**	**$p < 0.01$**
	Landscape heterogeneity	-0.027	0.164	-1.651	0.09

Conclusão geral

Nossos resultados contribuem no entendimento de como o contexto da paisagem pode afetar a degradação florestal em remanescentes florestais da Mata Atlântica do sul da Bahia, área prioritária para conservação dentro da ameaçada Mata Atlântica. Especificamente, observamos através da interação do tempo com a cobertura agrícola, como a expansão agrícola ocorrida na década de 70 contribuiu para elevada degradação dos remanescentes florestais nos primeiros anos da nossa série temporal (i.e., 1985), via aumento do estresse hídrico. No entanto, os anos mais recentes refletiram em aumento da qualidade da vegetação, potencialmente indicando uma alta capacidade de recuperação destas florestas a médio prazo. Uma vez que a expansão agrícola leva a degradação florestal dos remanescentes da Mata Atlântica, ressaltamos a necessidade de políticas públicas que impeçam a conversão de áreas florestais em áreas agrícolas pervasivas, como pastagens. Ressaltamos também como as paisagens heterogêneas em nossa região de estudo auxiliaram na redução da degradação florestal dos remanescentes, sendo essa característica da região outro fator a ser ponderado na tomada de políticas públicas para conservação.

Por fim, ressaltamos a importância do uso de tecnologias de sensoriamento remoto para a realização de pesquisas em maiores escalas tanto espaciais quanto temporais, onde recomendamos a utilização desses dados combinados com dados de campo para que se possam gerar informações mais precisas para a conservação dos remanescentes da Mata Atlântica do sul da Bahia. Ademais, é importante mencionar que a principal limitação do nosso trabalho está atrelada a ausência de dados históricos precisos que permitam a separação de áreas de agroflorestas de cacau e remanescentes florestais. A semelhança estrutural das agroflorestas de cacau com remanescentes florestais permite que esse sistema produtivo promova a conservação da biodiversidade e reduza o impacto da degradação, porém com a ausência desses dados se torna impreciso o quanto esse tipo de cultivo atua na preservação da estrutura dos remanescentes florestais próximos. Com a nova iniciativa do MapBiomas Cacau na região, será possível que futuros estudos melhor avaliem a influência deste cultivo agrícola sobre padrões de degradação florestal.