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Editors

Animal Biodiversity and Conservation in Brazil's Northern Atlantic Forest

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Preface

The Atlantic forest biome stretches over 3000 km from the state of Rio Grande do Norte south to Rio Grande do Sul. This huge distance spans great latitudinal, climatic, and economic differences, from only 8° south of the equator to the subtropics in the south. Thus, the *Araucaria* forests in the south, and the forests of the Serra do Mar in the states of Rio de Janeiro and São Paulo are cooler, better protected, and much better studied than the northeastern forests in Alagoas, Pernambuco and Paraíba. The northeastern Atlantic forests formed a narrow fringe extending only 50–100 km inland, over terrain that is relatively flat. Thus, they were easily cleared for farming and especially for huge sugarcane plantations. The remaining fragments are critically endangered as are their flora and fauna.

Studies of the plants and animals have been ongoing in northeastern Brazil, but with several differences. Collections of plants, regardless of the taxonomic order, are grouped together while those of animals are usually held separately, in part because they require different methods of storage. Also, although plants are more difficult to identify than most groups of vertebrates, they are much easier to identify than the incredibly diverse invertebrate fauna. Over the last 20 years, there has been significant progress in digitizing animal and plant specimen data, and images of the specimens themselves. In part, because plant specimens are flat and grouped together, great progress has been made in making Brazilian plant specimen data available online through SpeciesLink and the REFLORA program. Although the Brazilian zoological community is making great strides now to digitize their specimen data (almost 2 million records available on SpeciesLink), the amount of data currently available is roughly only 20% of the data available for plants. The data provided in this book, therefore, are both timely and unavailable elsewhere.

The first chapter puts the remaining chapters in context by describing the vegetation, forest fragmentation, endemism, and protected areas in the region. Ten chapters detail the diversity, biogeography, and endemism of different animal groups in the Atlantic forest of northeastern Brazil, especially within the Pernambuco Center of Endemism. While the chapters on mammals, birds, and reptiles are to be expected, the data they contain on species diversity, numbers of endemic and endangered species, and biogeography are new and up to date. The Amphibia are less well-known in the region, but the analysis of literature and specimen records also provides the most current information available on this threatened group. Of the animals discussed in the chapters of this book, the fish are unique in that they do not inhabit forests, but are found in the streams that flow through, or used to flow through, the forests. They are under heavy threat and pressure from fishing and from agricultural runoff.

One of the unique features of this book are the five chapters on invertebrate groups. Two chapters are on conspicuous insects, butterflies and scarab beetles. These chapters detail the numbers of species, their biogeographic patterns, and their conservation requirements. A less well-understood group of insects, the termites are also discussed, including details of their diversity, urban ecology, and conservation. Although everyone knows of spiders, few understand their diversity and ecological impact. These are discussed here along with their high level of endemism in the region. The most mysterious and least well-known group of animals discussed here are the harvestmen (Opiliones). They are evolutionarily ancient and spider-like in appearance, with many in the northeastern Atlantic forest still undescribed today.

Two chapters discuss the anthropic pressure on the terrestrial vertebrates and fishes. The hunting pressure on large terrestrial animals is intense and has led to at least seven species being included on the IUCN Red List. Fishing pressure is high, as is the effect of agricultural runoff, leading to 17 fish species being included in the Brazilian Red List of endangered species. The last chapter summarizes the region's rich diversity and the environmental pressures leading to erosion of forest integrity and species diversity. It ends with recommendations for governmental actions required to preserve what is left of this amazing forest.

This is an enormous contribution to our knowledge of the fauna in the northeastern Atlantic forest area and unites a huge amount of previously unavailable data.

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William Wayt Thomas

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1 An Introduction to the Knowledge of Animal Diversity and Conservation in the Most Threatened Forests of Brazil

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and Gentil Alves Pereira Filho

Abstract

This chapter provides a brief overview on the following chapters and highlights the relevance of research focusing on the current animal knowledge in the Northern Atlantic Forest. The book was written by more than 70 researchers from more than 20 universities and institutes from Brazil, China, and Sweden and sought to provide a comprehensive update on biodiversity, biogeography, and the conservation status of a sector that presents high anthropogenic pressure and that has the lower original cover of the Atlantic Forest.

Keywords

Anthropogenic pressures · Atlantic Forest · Biodiversity · Biogeography · Conservation status

1.1 Introduction

The importance of the Atlantic Forest, both biologically and economically, is already widely known and published (Galindo Leal and Câmara 2003; Scarano and Ceotto 2015; Rezende et al. 2018). This biome harbors stupendous biodiversity and an enormous rate of endemism, even though it has been facing massive impacts from exploitation and fragmentation (Ribeiro et al. 2009; Scarano 2014). Endemic species with geographic distribution restricted to different portions of the Atlantic Forest were fundamental for the comprehension and recognition of regions with different biogeographic histories known as centers of endemism (Silva and Casteleti 2003). The Northern Atlantic Forest (NAF), also called by several authors as the Pernambuco Endemism Center (PEC) or Pernambuco Center of Endemism, is the section of the Atlantic Forest located in Northeast Brazil northern from São Francisco River and distributed through the states of Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte (Silva and Casteleti 2003; Tabarelli and Roda 2005; Chap. 2).

The "Pernambuco" was one of the "Centers of Rainforest Endemism" first suggested by the British botanist Ghillean Tolmie Prance (1982). Prance found floristic similarities and endemic species in distinct regions, defining them as 26 distinct "Centers of Rainforest Endemism." For the Atlantic Coastal Brazil, Prance recognized three well-defined areas: Pernambuco, the most northern area; Bahia and northern Espírito Santo, located in the middle range of the biome; and Rio de Janeiro and Espírito Santo south of the Rio Doce, the southernmost area (Prance 1982).

Although these "Centers of Endemism" have been reviewed in subsequent papers, the Pernambuco Endemism Center (or Northern Atlantic Forest) has remained as a distinct unit through several different works (Silva and Casteleti 2003; Tabarelli and Roda 2005; Tabarelli et al. 2010; Carvalho et al. 2021). Despite its importance, the NAF represents less than 5% of the original Atlantic Forest, and the remaining forest is now comprised of small forest fragments scattered in urban and agricultural matrices throughout its distribution (Silva and Tabarelli 2001).

Human impact on the NAF has been taking place since before the European occupation of the Brazilian Northeast in the beginning of the sixteenth century (Dean 2004). However,

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the arrival of the Portuguese and the successive cycles of colonization of the northeastern coast intensified the damage in this region. The exploitation started with the extraction of timber of Pau-Brasil (*Paubrasilia echinata*), then land clearing for pastures, and culminated in the establishment of large sugar cane plantations, for sugar production and, more recently, for production of fuel alcohol (Coimbra-Filho and Câmara 1996) (Fig. 1.1). The history of occupation and fragmentation of the Brazilian Atlantic Forest, especially the NAF, has been documented by several authors (Freyre 1985; Dean 2004; Siqueira Filho and Leme 2006; Scarano 2014). Nevertheless, we can consider that the ecological history of the NAF has been characterized by strong resistance and high resilience. Even after centuries of intensive occupation and use resulting in this high degree of fragmentation (see Chap. 2), the region still has high biodiversity in various animal groups, high heterogeneity throughout its geographical range (Fig. 1.2), and high rates of endemism, as can be seen in all the chapters in this book.

All forest patches found in different ecoregions through the extension of the NAF still provide a glimpse of the biological magnitude that this area contained in the past. Nowadays, this environmental diversity extending from tropical moist forests (Pernambuco coastal forest and Pernambuco interior forest or "brejos de altitude") to Mangrove forests and tropical semideciduous forests (Tabuleiro), still forms a background for the emergence and recognition of new species such as the frog *Adelophryne nordestina* (Lourenço-de-Moraes et al. 2021), the snake *Caaeteboia gaeli* (Montingelli et al. 2020), or the bird *Trogon muriciensis* (Dickens et al. 2021). On the other hand, local extinction and population decline of vertebrate species have been recorded throughout the Atlantic Forest and a long and consistent history of hunting pressure, habitat conversion and fragmentation, or a synergistic combination of both (Canale et al. 2012).

As the human pressure on these NAF fragments remains high, we are looking at the countdown to extinction for many endemic species (Brooks and Rylands 2003). Undeniably, the NAF is one of the regions on the planet where conservation efforts are most needed. It should be considered a hotspot within one of the most important and threatened hotspots—the Atlantic Forest (Tabarelli and Roda 2005).

1.2 Why This Book?

The publications about the animal diversity of the NAF reflect a phenomenal effort, but there is an absence of a single literature source gathering general information of the animal diversity of the region. We decided to write this book with the collaboration of experts on the vertebrate and invertebrate fauna. This was a hard task and demanded a massive effort of 81 scientists from more than 20 universities and institutions from Brazil, China and Sweden.

This book presents the first synthesis of the knowledge of animal ecology and conservation of NAF. Although work has already been published about some groups, for example, mammals (Asfora and Pontes 2009; Garbino et al. 2018), snakes (França et al. 2020; Pereira Filho et al. 2021), birds (Silva et al. 2004), and bees (Nemesio and Santos Jr 2014), all chapters of this book present new and detailed information and are far from a simple species list, since many ecological and biogeographical analyses were performed. Dealing with such a highly diverse region, some questions easily come to mind, such as: How much forest is left in this region? How is the richness, diversity, and endemism of each studied group? Where are the gaps of knowledge and what areas are the most surveyed? Are there new species to be described, and are there species that are disappearing? Is there a congruence for the richest areas or those with fewer species when comparing different animal groups? Which animal groups are facing the countdown to extinction? Each of these questions is answered in detail in all chapters of this book.

The book is organized into 15 chapters. Following this introduction, Chap. 2 presents an overview of the landscape, fragmentation, vegetation cover, and the distribution of protected areas in the NAF. This chapter provides a reviewed base-map of the area that will be referred to in all the following chapters. An analysis of more than 2000 native forest satellite images gives approximately 750,000 ha of native Atlantic Forest remnants. Most of the patches are small, with 41% smaller than 1 ha, and only 11% of the PEC region is within Protected Areas.

Chapters 3, 4, 5, 6, 7, and 8 deal with the invertebrate diversity of the NAF. Taxonomy, ecology, biodiversity shortfalls, biogeographical patterns, and conservation data of ants (Hymenoptera), butterflies (Lepidoptera), beetles (Coleoptera, Scarabaeinae), harvestmen's (Opiliones), spiders (Aranae), and termites (Isoptera) are investigated, described, and summarized. Chapters 9, 10, 11, 12, and 13 focus on vertebrate diversity of the NAF. The authors explored the richness and endemism, biogeographical dynamics, and conservation status for freshwater fishes (Osteichthyes), frogs, toads, and caecilians (Lissamphibia), turtles, lizards, snakes, and caimans (Reptilia), birds (Aves), and mammals (Mammalia). Finally, Chaps. 14 and 15 provide an overview of the ethnozoology studies in the NAF. Chapter 14 discusses the importance of fishery activities in the region. Chapter 15 finishes the book's information about vertebrates of NAF used by human population,

With the vast amount of information distributed in all 15 chapters, we do hope the Northern Atlantic Forest can be considered as an emergency area for conservation and biological research. This is not the first time this sector of the

Fig. 1.1 Sugarcane fields (**a**) and pastures (**b**) cleared from the Northern Atlantic Forest in Paraiba and Alagoas, respectively

Atlantic Forest has been considered fundamental for conservation, although efforts like the creation of new protected areas and environmental inspection to combat deforestation and hunting are still scarce. Considering the coastal fragments and the inland remnants (Brejos de Altitude), the panorama is more severe in the inland forests, once these regions

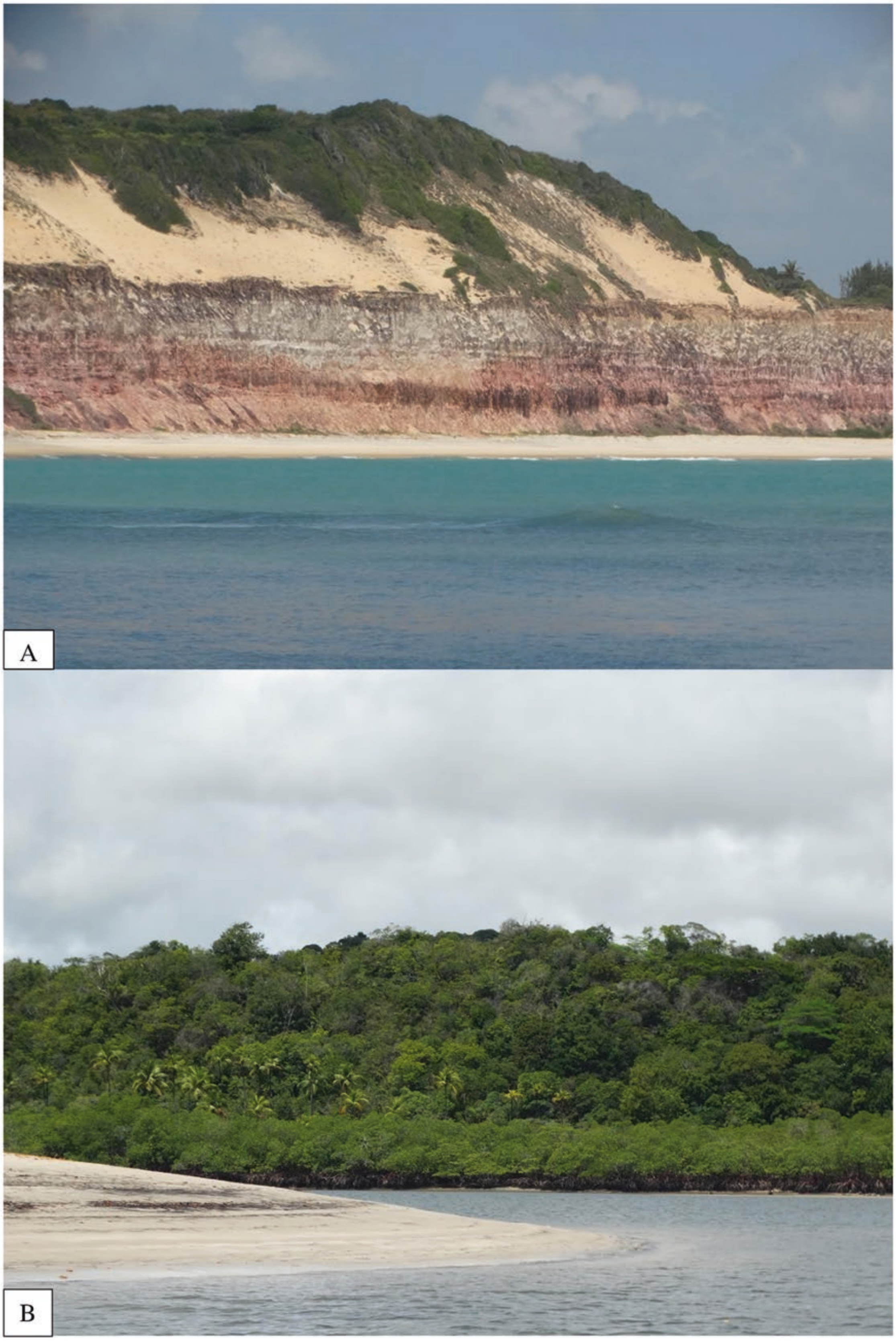

Fig. 1.2 Examples of environmental heterogeinity in the Northern Atlantic Forest. (**a**) Restinga forest and coastal cliffs (Rio Grande do Norte) (**b**) Coastal Mangrove forest (Pernambuco)

are less protected by the actions of the environmental inspections and now face an accelerated rhythm of deforestation for housing purposes and water exploitation (Pereira-Filho et al. 2021). The fact is that one of the richest portions of the Brazilian Atlantic Forest is under permanent threat and in need of more scientific research and creation of protected areas. Certainly, the tipping point for the Atlantic Forest is closer than we thought, and the statistics of deforested area and extinction rates are strong evidence of this panorama. We are facing an imminent risk of losing this forest if serious measurements are not taken in a short amount of time.

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2 Northern Atlantic Forest: Conservation Status and Perspectives

Adriana M. Almeida and Alexandre F. Souza

Abstract

The Atlantic Forest is a biodiversity hotspot and is widely known both for its high species richness, including many endemics, and also by its high degradation, with few forested areas left. The Northern Atlantic Forest (NAF) lies in the northernmost part of the biome, suffering from an old fragmentation process and with little remaining forest. In Northeastern Brazil, we also find some areas called "Brejos Nordestinos" that are enclaves of high-altitude humid forests embedded in the Caatinga semiarid region. A careful analysis of a 2019 forest cover map revealed a total of 747,926 ha of remaining forest (18.8%) distributed in 63,048 fragments (41% are smaller than 1 ha). There are only 896 forest fragments larger than 100 ha, covering an area of 437,434.6 ha. The NAF region has a few large fragments with large interior (core) forests. When considering a 90-m-edge influence, core area drops to 216,628.0 ha (30% of the area in fragments larger than 1 ha and 5.4% of the NAF area). A total of 10.5% of the NAF region is composed of Protected Areas (PA), from which 9.7% is under sustainable use and 0.8% is under strictly protection. More protected areas are needed to achieve the global goal of 17% of protected areas, and their placement should be considered in order to efficiently conserve the NAF biodiversity and its ecosystem services, creating a landscape with high connectivity. Protected Areas also must have efficient management plans, so that biodiversity protection will be effective.

Keywords

Centro de Endemismo de Pernambuco · Pernambuco Endemism Center · Brejos Nordestinos · Brejos de Altitude · Rain forest · Habitat fragmentation · Landscape analysis

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2.1 The Brazilian Atlantic Forest

The Atlantic Forest occurs along most of the Brazilian coast and the beautiful view of the forest landscape may be the first image of Brazil to most foreign visitors. Already inhabited by various indigenous groups, in the sixteenth century, it was colonized by Europeans (Solórzano et al. 2021). The Atlantic Forest is home to more than 125 million people (ca. 60% of Brazil's population and 35% of the South American population) (Scarano and Ceotto 2015; Lima et al. 2020), contributes to 70% of the gross domestic product (GDP), two-thirds of the industrial economy, and has some of Brazil's most productive land (more than half of the national land dedicated to horticulture) (Joly et al. 2014; Rezende et al. 2018). Metropolises like São Paulo and Rio de Janeiro are situated within Atlantic Forest domain. The Atlantic Forest is worldwide known both for its high species diversity and degradation. With little forested area left, and divided into small and isolated fragments, it is considered one of the most fragmented tropical/subtropical forests in the world (Laurance 2009; Metzger 2009; Ribeiro et al. 2009; Rezende et al. 2018; Lima et al. 2020).

The original Atlantic Forest spanned a latitudinal gradient from 3°S to 31°S, and from 35°W to 60°W, covering 3300 km of Brazilian coastline and 148,194,638 ha (approximately 17.4% of the Brazilian territory) (Metzger 2009; Ribeiro et al. 2009). It also spans into Paraguay and Argentina, comprising mostly evergreen and seasonally dry forests (Metzger 2009; Ribeiro et al. 2009). With both a long latitudinal gradient and a great altitudinal variation (from sea level to ca. 2800 m), the Brazilian Atlantic Forest encompasses many diverse climates, soils, and reliefs (Metzger 2009).

The Atlantic Forest climate is highly heterogeneous, including many Köppen climate zones, with a strong north-

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south temperature gradient (Alvares et al. 2013). Most of the climate in this Atlantic region is tropical, varying from humid tropical climates in the north to temperate climates with moderate summer in the south (Alvares et al. 2013). In its southeastern and southernmost portions, the Atlantic Forest covers a rough topography that includes major mountain ranges along the coastline, such as “Serra do Mar,” “Serra da Mantiqueira,” and “Serra Geral,” where altitudes reach up to ca. 2800 m (Metzger 2009, Cantidio and Souza 2019). In Northeastern Brazil, with one exception, topography has no major accidents, and altitude variations are restricted to smaller mountain ranges with well-marked limits in relation to the surrounding lowlands. The exception is “Chapada Diamantina,” in Bahia state, with altitudes that reach up to 2000 m. Further north, the Borborema highlands (“Serra da Boborema”) runs in a north-south direction for about 400 km, spanning Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte states. In Northeastern Brazil, we can also find mountainous refuges known as “Brejos Nordestinos” or “Brejos de Altitude” (Northeastern Forest islands), which are mountains with tropical wetter climate located further west, representing enclaves inserted in semiarid regional climates (the Brazilian biome called Caatinga) (Porto et al. 2004; Alvares et al. 2013).

Being home to native pre-Colombian populations since Late Pleistocene, a period in which it was subjected to little anthropogenic changes (Lira et al. 2021; Solórzano et al. 2021), the Atlantic Forest has suffered extensive deforestation since the sixteenth century, with European arrival. First with logging and hunting, and lately with deforestation to agriculture and human settlements (e.g., Dean 1997; Cabral and Cesco 2008; Lins-e-Silva et al. 2021; Lira et al. 2021; Solórzano et al. 2021).

Recent studies accessed the remaining Atlantic Forest cover. Ribeiro et al. (2009), considering patches larger than 3 ha, estimated that native forest cover ranges from 11.4% to 16%. A more recent study based on 5-m-high-resolution imagery showed that native vegetation cover in 2013 had a 28% coverage, from which 26% was forest cover and 2% was nonforest native formations (Rezende et al. 2018). Rosa et al. (2021) studied the Atlantic Forest native forest cover dynamic (gains and losses) from 1990 to 2017. They showed that the apparent stability of vegetation cover hides the fact that older forests are being replaced by younger ones, resulting in a “rejuvenation” of the forest. This observation is alarming, since not all species are able to live in young forests, and such forests may not provide all ecosystem services, in comparison to mature forests (Rosa et al. 2021). Atlantic Forest fragments’ size and isolation are also a problem, since few fragments are really large, undisturbed, and really protected from human influences (Ribeiro et al. 2009; Lima et al. 2020).

In the Atlantic Forest, a multitude of productive and diverse environments are home to a huge number of species, many endemics. The Atlantic Forest is globally recognized for its high species diversity, accounting from 1% to 8% of the world’s plant and vertebrate species (Myers et al. 2000). Studies suggest that there are at least 20,000 species distributed through vascular plants, amphibians, reptiles, birds, and mammals (Figueiredo et al. 2021). Endemism is also high, accounting for 57% of its vascular flora and 77% of its epiphytic vascular flora (Freitas et al. 2016). Animals also present high endemism, with 16% bird, 27% mammal, 31% reptile, and 60% amphibian fauna only found there (Mittermeier et al. 2005; Metzger 2009; Figueiredo et al. 2021). Taking into consideration Atlantic Forest’s high degradation and high levels of species richness and endemism, it is considered a biodiversity hotspot (Myers et al. 2000), and maybe even “the hottest hotspot” (Laurance 2009). Hotspot areas concentrate half of the species in the planet, within 1% of its area and are key points for conservation (Myers et al. 2000; Laurance 2009).

A recent study (Lima et al. 2020) estimated that human-induced impacts on forest biodiversity and biomass are pervasive across the Atlantic Forest fragments, with impacts that can be 42% higher if compared to the predicted for a human-free scenario. Human-induced losses are stronger in the abundance of endemic tree species, suggesting that endemics are being replaced by generalist species. They also found that late-successional tree species abundance is also strongly impacted by humans. Important to remember that large trees are ecosystem engineers and play a fundamental role in community structure (Lima et al. 2020).

With its past and present impacts, humans now have a chance to turn the Atlantic Forest’s trajectory of degradation into a new path of nature protection and restoration, warranting a sustainable future, where society’s vulnerability to climate change is reduced. Some initiatives such as restoration programs and payment for ecosystem services are reasons for optimism (Scarano and Ceotto 2015). Atlantic Forest still has a chance to be transformed from a hotspot to a hopespot (Scarano and Ceotto 2015; Rezende et al. 2018; Lira et al. 2021).

Species composition in the Atlantic Forest is not distributed homogenously and presents some “Endemism Centers” (Andrade-Lima 1982; Silva and Casteleti 2003, 2005). Considering endemic species of birds, primates and butterflies, Silva and Casteleti (2003, 2005) identified five endemism centers and three transition zones. With one exception to “Serra do Mar,” in southeastern Brazil, all other four centers are in Northeastern Brazil. They are all composed of humid forests and are called: Pernambuco, Diamantina, Bahia and “Brejos Nordestinos” centers. Since the

"Pernambuco Endemism Center" spans four Brazilian states, in this text it will be called "**Northern Atlantic Forest**" (**NAF**) from now on. The term is synonym to "Pernambuco Endemism Center" (Andrade-Lima 1982; Silva and Casteleti 2003) and "Pernambuco biogeographical sub-region" (Lins-e-Silva et al. 2021) in previous studies.

The Northeastern Brazilian coast is cut by a large river, the São Francisco River, which separates Alagoas and Sergipe states. North of São Francisco River we can find two Brazilian endemism centers, the Northern Atlantic Forest and "Brejos Nordestinos" (Andrade-Lima 1982; Silva and Casteleti 2003; Porto et al. 2004; Tabarelli et al. 2005). The Northern Atlantic Forest (NAF) is a subset of Atlantic Forest in its most northern part, occurring from latitudes 5.0°S to 10.5°S, in Northeastern Brazil, encompassing four Brazilian states: Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), and Alagoas (AL) (Fig. 2.1). The "Brejos Nordestinos" are found in elevations covered by semideciduous forest vegetation. Also known as "Brejos de Altitude," they occur in altitudes and present vegetation that differs from the smaller, deciduous predominant one on the drier lowlands (Fig. 2.2) (Lopes et al. 2017). The "Brejos Nordestinos" enclaves occur mainly in Pernambuco and Paraiba, but also in Rio Grande do Norte and Ceará states. Although all are important, here we consider only the "Brejos" in the east of Borborema highlands, in Pernambuco and Paraíba states (Table 2.1).

2.2 The Northern Atlantic Forest

The region occurs mainly through Barreiras Formation and Borborema highlands. Barreiras is a sedimentary geological formation widespread along the Brazilian coast, occurring throughout the Northeastern and Southeastern regions up to Rio de Janeiro State, being particularly well represented along numerous but discontinuous coastal cliffs (Rossetti and Goes 2009). The NAF relief is mostly plain with maximum altitude ca. 1000 m in Borborema Highlands, in Pernambuco and Paraíba States. NAF has a humid tropical climate (Köppen's As'), with dry summer and autumn-winter rains, rainfall ranging from 750 to 1500 mm per year, and monthly-average temperatures above 18 °C (Tabarelli et al. 2006; Alvares et al. 2013). Vegetation is composed mainly of humid tropical forests

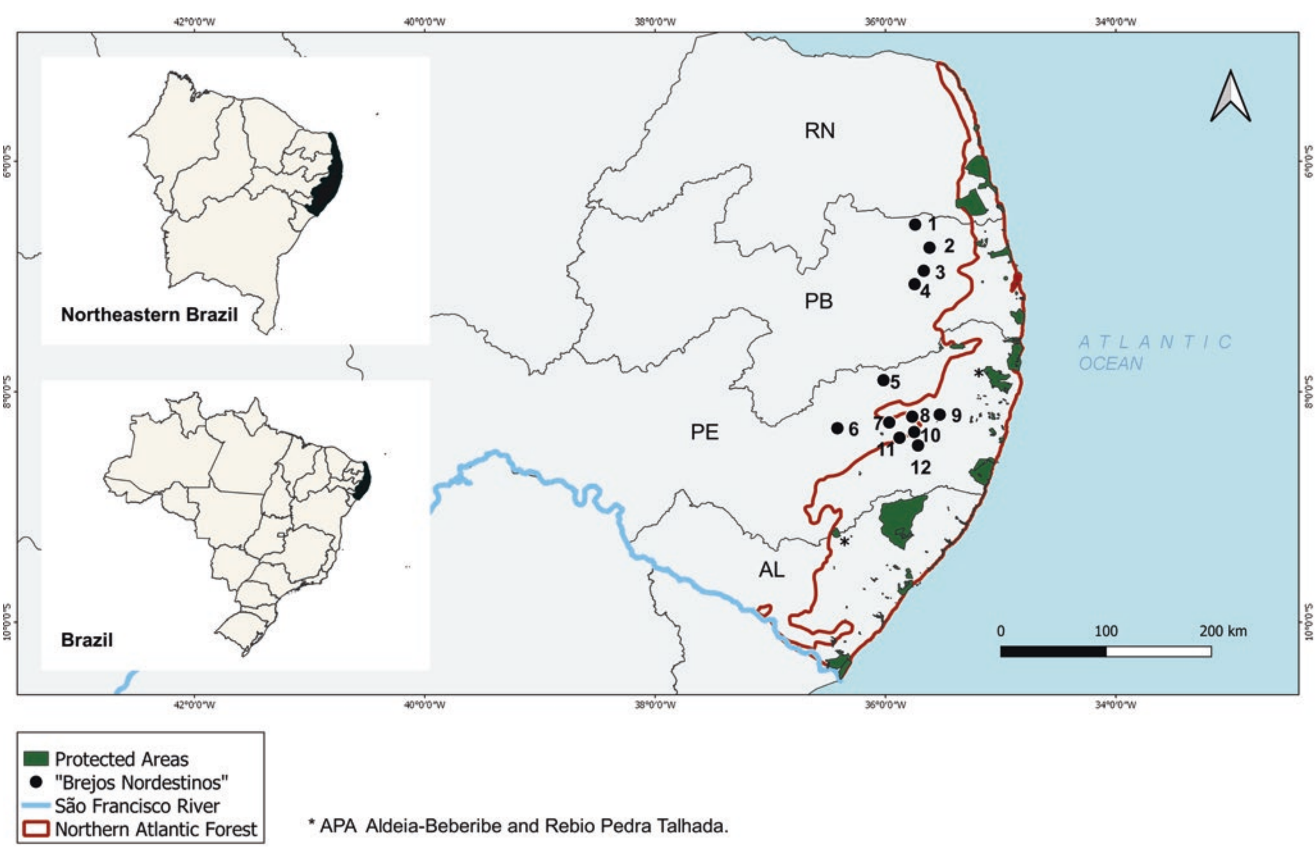

Fig. 2.1 Northern Atlantic Forest and "Brejos Nordestinos" (black dots), in Brazil. Numerals in Brejos refer to Table 2.1. RN—Rio Grande do Norte state, PB—Paraíba state, PE—Pernambuco state and AL—Alagoas state

Fig. 2.2 "Brejos Nordestinos" are enclaves of high-altitude humid forests embedded in the semiarid climate. (**a**) Areia, Paraiba state (point 3 in Fig. 2.1 and Table 2.1). (**b**) Bonito, Pernambuco state (point 12 in Fig. 2.1 and Table 2.1). (Credit photos to: Flávia Maria da Silva Moura)

Table 2.1 Geographical and administrative information on the "Brejos Nordestinos" considered (code numbers refer to Fig. 2.1)

Code	Name	State	Municipality	Latitude (°W)	Longitude (°S)	Altitude (m)
1	Araruna	PB	Araruna	6.55	35.73	532
2	Bananeiras	PB	Bananeiras	6.75	35.62	500
3	Areia	PB	Areia	6.95	35.67	540
4	Alagoa Nova	PB	Alagoa Nova	7.07	35.75	531
5	Taquaritinga	PE	Taquaritinga	7.90	36.02	765
6	Bezerros	PE	Bezerros	8.32	36.42	671
7	Brejo dos Cavalos	PE	Caruaru	8.27	35.97	550
8	Serra Negra	PE	Bezerros	8.22	35.77	560
9	Gravatá	PE	Gravata	8.20	35.53	518
10	Camocim de São Felix	PE	Camocim de São Felix	8.35	35.75	656
11	Agrestina	PE	Agrestina	8.45	35.93	560
12	Bonito	PE	Bonito	8.47	35.72	655

in a mosaic of ombrophilous and semideciduous forests, encompassing also "restingas," "tabuleiros," and mangroves (the Atlantic Forest lato-sensu) (Tabarelli et al. 2006).

Although the Northern Atlantic Forest encompasses only a small portion of Atlantic Forest's original geographical range, it is home to many species. Roda (2003) estimated that two-thirds of all bird species and subspecies of Atlantic Forest are found there, with 417 endemic bird species occurring only in NAF. In a recent biogeographical analysis of the Atlantic Forest flora, the NAF has been confirmed as having a distinctive flora of tree, shrub, and palm species (Cantidio and Souza 2019).

Two Brazilian states (Rio Grande do Norte and Paraíba) are sometimes excluded from Atlantic Forest studies in the NAF area (e.g., Tabarelli et al. 2005; Ribeiro et al. 2011). Occurring in a narrow and small area and covered by many clouds, being situated in the intertropical convergence zone, this region is difficult to visualize in satellite images. In the present study, the entire scope of the NAF area is considered, covering all the four Brazilian states.

2.3 "Brejos Nordestinos" or "Brejos de Altitude"

The geomorphology of the Brazilian northeastern region is marked by the occurrence of mountain ranges and plateaus with local climates that are more humid and rainier than the average of the surrounding plains. Regionally these elevations were, and to a large extent still are, covered by semideciduous forest vegetation known as "Brejos de Altitude" occurring in altitudes mostly above 500 m, with greater biomass and complexity than the smaller, deciduous vegetation predominant on the drier lowlands (Lopes et al. 2017). These areas have thus functioned as refugia for tree and shrub species adapted to less stressful thermal and hydric conditions, including many Myrtaceae, and many species that occur in the neighboring vegetational domains of the Atlantic Forest, the Amazon, and the Cerrado savanna (Diogo 2017).

In Northeastern Brazil, most of the Atlantic Forest is inserted in a relatively narrow strip of lowland broadleaved semideciduous and rain forests along the coastline. Further inland the Atlantic Forest occurs as several disjunct broadleaved forest islands embedded in the drier lowlands dominated by seasonally dry forests and woodlands (Queiroz et al. 2017). Overall, the different lowland seasonally dry Caatinga vegetation types are strongly limited by rainfall (Salimon and Anderson 2017), and forest islands are located on the windward slopes of highlands that receive orographic rainfall able to sustain semideciduous or evergreen forests mainly in Pernambuco and Paraiba, but also in Rio Grande do Norte and Ceará states.

Orographic rainfall produces resource gradients running from hotter and drier climates in lowlands to cooler and wetter climates upland. Data from two sites in Paraíba pointed to changes in vegetation and soil properties accompanying elevational changes in temperature and rainfall (Ramos et al. 2020). The increase in productivity with altitude led to changes in vegetation structure: tree density declines but total aerial biomass increases with altitude, indicating habitat change from lowland vegetation dominated by many thin and branched trees to submontane vegetation with fewer but larger trees. Increases in elevation are accompanied by increased soil clay content, acidity, aluminum, and organic matter, and reduced base saturation. Drought stress reduction with increased elevation is the likely cause in the increased species diversity in higher altitudes (Silva et al. 2014; Lopes et al. 2017; Ramos et al. 2020). Few studies have investigated vegetation response to different topographic positions and terrain exposures like top, windward, and leeward slopes. However, available evidence indicates significant effects on stem density, basal area, species richness, and dominance

(Silvera et al. 2020; Diogo et al. 2021), with species like *Senegalia polyphilla,* associated with drier leeward slopes and species like *Cupania impressinervia*, associated with windward slopes (Diogo et al. 2021). Mountain tops seem to be less affected by tree fall and display higher basal area while rainier windward slopes may show increased stem density. This suggests increased natural mortality in windward slopes, perhaps by increased treefall gaps.

There is evidence that species composition follows the diminishing stress conditions with increased altitude, segregating species groups at different altitudinal belts (Lopes et al. 2017). The issue, however, of which mechanisms exactly determine species sorting between different mountain ranges and between sectors within each mountain range remains debated. It has been shown that niche differences between dry forest species produce spatial segregation along soil nutrient, disturbance history, and wetness gradients (López-Martínez et al. 2013; Ramos et al. 2020). Other results, however, indicate broad niche overlap between species across environmental gradients (Pulla et al. 2017). In the lack of more conclusive studies, the issue of the relative importance of ecological factors like changing temperature, rainfall, soil texture, soil nutrients, and anthropogenic disturbance on the species community assembly of the Caatinga mountain ranges remains to be fully resolved. A confounding factor that accompanies the changes in productivity with elevation is human disturbance. Lowland dry forest sites usually suffer from chronic anthropogenic disturbance by removal of firewood and grazing by goats and cattle, and these impacts tend to reduce with altitude (Silva et al. 2014). Chronic anthropogenic disturbance is believed to favor pioneer species like *Cenostygma pyramidale*, *Croton heliotropiifolius*, and *Croton blanquetianus* (Ribeiro et al. 2015; Rito et al. 2017), which have been found to be abundant in lower altitudes of the mountain ranges (Ramos et al. 2020).

In several mountainous forests of northeastern Brazil, Myrtaceae is the most abundant botanical family, and Myrcia splendens is frequently one of the most dominant species (Silvera et al. 2020; Diogo et al. 2021). A macroecological comparison of 24 broadleaved semideciduous forests in northeastern Brazil, many of them located in mountainous localities, found a broad division between windward and leeward slopes. Forests located on the windward and wetter slopes of the Borborema mountain range had greater floristic affinity with the Atlantic Forest. To the west, we find those species located on the drier leeward slopes of the Borborema plateau and isolated eroded peaks that punctuate the semiarid Caatinga lowlands (Rodal et al. 2008). This second and drier mountainous group includes a more heterogeneous mixture of genera originating in the Caatinga lowlands like *Myracroduon* and *Schinopsis*, and genera originating in wetter more forested areas like Rollinia and Diospyros. Comparisons spanning geographically more scattered sites have revealed that the floristic composition of the Caatinga mountain forests is considered as a mixture of species with Amazon, Atlantic Forest, and Caatinga distributions, and suggested that western forest enclaves like Baturité in Ceará State have closer affinities with the Amazon flora than with other enclaves within the Caatinga (Santos et al. 2007). The largest macroecological comparison of the "Brejos Nordestinos," however, has been carried out by Diogo (2017), using thousands of localities scattered across the entire Amazon, Caatinga, Cerrado, and Atlantic Forest biomes. Contrary to the conception that mountain enclaves would be floristically more similar to the Atlantic Forest to the east, to the Caatinga seasonally dry forest to the west, and to the Amazon flora in the north (Queiroz et al. 2017), he found a great number of exclusive trees and shrubs in the enclaves, characterized the composition of the mountainous enclaves as distinct from that of all studied biomes, and identified the Brazilian Northeast Mountain Forests (BNMF) as a new bioregion with its exclusive species and characteristics. Diogo (2017) identified that the most common species in BNMF were *Manilkara rufula*, *Wedelia villosa*, and *Guettarda angelica*, and the most indicative species were *Guettarda angelica* and *Manilkara rufula*.

During parts of its geological past, Northeastern Brazil was under wetter climates, which have been associated with the southward displacement of the Intertropical Convergence Zone (Wang et al. 2004). The isolated mountain forests embedded in the seasonally dry Caatinga vegetation are regarded as interglacial microrefugia, or relics of a past expansion of forested connections between the Amazon and the Atlantic Forest (Santos et al. 2007; Montade et al. 2014). This conclusion has received support from the macroecological analyses of floristic relationships between the mountainous enclaves (Diogo 2017), palynological reconstructions (Montade et al. 2014), niche modeling (Silveira et al. 2019), and cladistic aerogram analyses (Santos et al. 2007). Projection of abiotic niche envelopes of 13 species representative of the semideciduous to humid Northern Atlantic Forest suggests an expansion of wetter forests into what is currently seasonally dry forest and woodland during the Last Glacial Maximum, with enclaves in Paraiba and Pernambuco having moderate connectivity with coastal Atlantic Forest (Silveira et al. 2019).

2.4 Northern Atlantic Forest History

The region occupied by the NAF is the nearest to Europe and was heavily visited for brazilwood extraction (pau-brasil: *Paubrasilia echinata* (Lam.) Gagnon, H. C. Lima & G. P. Lewis) in the first years of the sixteenth century (Dean 1997; Lira et al. 2021; Solórzano et al. 2021). Pernambuco state is situated in the middle of NAF and was an important point of brazilwood extraction since the beginning of colonization (Dean 1997; Lins-e-Silva et al. 2021; Lira et al. 2021; Solórzano et al. 2021). Brazilwood extraction was quickly added to sugarcane agriculture. The sugarcane cycle ("ciclo da cana") started very early in 1516 in Itamaracá island (PE), only 16 years after Brazil's discovery. Soon, in 1549, Pernambuco state had already 30 sugar farms and was considered the richest region in Brazil (Dean 1997). Sugarcane farms spread to the coasts of all states of NAF, with a strong impact in its Atlantic Forest (Dean 1997; Lins-e-Silva et al. 2021; Lira et al. 2021; Solórzano et al. 2021). The Atlantic Forest degradation took some steps. First of all, came deforestation to clean the area for sugarcane. Sugarcane planting was also based on burning the areas, so that it is easier to plant again. Such burning practice impoverished the soil in a few years, and more deforestation for new planting areas were needed. Sugarcane farms also used firewood in its sugar production process, which impacted surrounding forests even more (Dean 1997; Lins-e-Silva et al. 2021; Lira et al. 2021; Solórzano et al. 2021).

For five centuries, NAF was converted mostly for sugarcane plantations, but also for other human uses, such as settlements, cattle, and mining (Lins-e-Silva et al. 2021; Lira et al. 2021; Solórzano et al. 2021). More recently, from the 1970s, Brazil implemented a sugarcane agriculture stimulus called "Pró-álcool," with many incentives to alcohol production as a green fuel as a substitute to gas fuel (Lins-e-Silva et al. 2021; Lira et al. 2021; Solórzano et al. 2021). This stimulus has reinforced sugarcane farms in the area. Nowadays, the Atlantic Forest in NAF is considered the least protected and the most endangered region in all Atlantic Forest (Ranta et al. 1998; Silva and Casteletti 2005; Tabarelli et al. 2006).

2.5 Northern Atlantic Forest Landscape Analysis

A forest cover map of the year 2019 was obtained from the MapBiomas Project, version 5.0. The MapBiomas Project is a multi-institutional initiative to generate annual land-use and land-cover maps from automatic classification processes applied to satellite images with a 30 m resolution (http://mapbiomas.org) (Souza et al. 2020). We considered only the "Forest formation" class ("Florestas Nativas," classes 1 and 2) inside the NAF shape. This image has 87.1% accuracy. Since our objective was to analyze forest formations, the classes "restingas," sand dunes and mangroves, mostly composed of shrubs, were not considered here. The "Brejos Nordestinos" enclaves outside NAF were not considered in the landscape analysis, because of the unavailability of their border's delimitation.

To obtain a recent land use and land cover assessment of NAF, we first defined its external limits (shape). We used the recent Atlantic Forest shapefile definition created by INPE ("Instituto Nacional de Pesquisas Espaciais"—Brazilian National Institute for Space Research). This shapefile is recent (2019) and is very accurate with both the Brazilian Atlantic Forest Law (Law 11428/2006) and Brazilian coastline (Assis et al. 2019). This shape is the one used nowadays to monitor deforestation in the area (Assis et al. 2019). The Atlantic Forest shape was then cut by the São Francisco River, to create a Northern Atlantic Forest polygon delimitation in QGIS (2021).

The Mapbiomas map was then used to access the NAF current situation in relation to forest cover and fragmentation. Fragmentation occurs when a continuous area is "broken" into smaller and isolated parts, called fragments (Fahrig 2003, 2017). Fragments of different sizes, degrees of isolation and shapes tend to present distinct influences on the species that will be able to inhabit it. In general, larger, more regular-shaped, and more heterogeneously filled fragments support more species (McGarigal 2015; Turner and Gardner 2015 and references therein).

Fragmentation creates edges. Forests near the edge suffer changes in abiotic conditions and, consequently, on species and ecological process when compared to patch interiors (called core areas). Forest edges in general have increased light availability, are warmer, with drier microclimates than the forest's core. Forest edges are also in constant contact with the surrounding matrix, and susceptible to external influences, such as fire, exotic species, pesticides, and even increased human impacts (selective logging and hunting) (Gascon et al. 2000; Cochrane and Laurance 2002; Ewers and Didham 2006; Lima et al. 2020). The core area is especially important to interior species and is not directly related to area, but to fragment's shape, since large fragments may not have large core areas to support interior species if they are simultaneously long and narrow, for example (McGarigal 2015). It is important to note that the relative amount of edge versus interior habitat varies with patch size and shape. Considering fragments of regular shapes, smaller ones will have a greater portion of edge area than larger fragments (Turner and Gardner 2015). The edge's extension varies greatly among fragments and regions, and different species respond differently, with some effects being deeper than others, and changing under the influence of factors such as edge age, number of nearby edges, and the adjoining matrix of modified vegetation surrounding fragments (Laurance et al. 2011).

Fragment area is of great importance to biodiversity. When considering fragments of regular shape, larger fragments support more species and more individuals when compared to smaller ones in the same region (Turner and Gardner

2015). Larger fragments may have a higher local environmental heterogeneity, with more food and habitat resources. Larger areas also support larger populations, which assures a high genetic diversity, with increased adaptive potential (Reed and Frankham 2003; Dixo et al. 2009). Larger areas also support larger-sized species, mostly top-predator ones, that control herbivores and warrant a high diversity of plant species (e.g., Estes et al. 2011). Fragment shape is also of crucial importance, and fragments of the same size can present diverse shapes. Shape refers to the form of the fragment. For the same area, a circular shape will have the least edge area, and a long narrow shape (riparian forests, for example) may present an only-edge habitat (depending on the width) (Turner and Gardner 2015). Complex, irregular shapes translate into strong edge effects (Ewers and Didham 2006; McGarigal 2015; Turner and Gardner 2015).

Finally, isolation must also be considered. Species need minimum size areas to keep a population. In a fragmented habitat, connectedness is necessary to sum small areas and keep the minimum viable population size. Different species present distinct dispersal abilities, and isolation may be a very important factor. In this context, small fragments (stepping-stones) and corridors may be crucial in facilitating connectedness and mitigating isolation deleterious effects (Villard and Metzger 2014; Siqueira et al. 2021).

To access the landscape configuration within NAF, some landscape metrics were calculated, considering the 8-neighbor rule, in Fragstats v. 4.0 (McGarigal et al. 2012) and analyzed in R (2021). First, metrics related to area and perimeter were obtained to all existing fragments (ca. 60,000 fragments). Then, some specific metrics were applied to the subset of fragments larger than 1 ha (ca. 37,400 fragments). Fragments smaller than 1 ha are very numerous and may not be adequate to keep populations of most species. On the other hand, they have high conservation value as stepping stones, being important in connectivity, and considered as "small landscape elements" (SLE) by Siqueira et al. (2021). The calculated metrics were fragment size (AREA), shape (SHAPE) and Euclidean nearest neighbor distance (ENN). The area index (AREA) gives the area of each patch (in ha). The Shape index (SHAPE) compares the fragment form to a square of the same area and varies from 1 when shape is a square and increases without limit as fragment shape becomes more irregular (McGarigal 2015). The Euclidean nearest neighbor distance (ENN) is the shortest straight-line distance between the focal patch and its nearest neighbor, based on the distance between the cell centers of the two closest cells from the respective patches (McGarigal 2015).

To access the amount of edge effect and core area, we also applied the metrics: core area (CORE), number of core areas in each patch (NCORE), and core area index (CAI) to the subset of fragments larger than 1 ha. The core area index (CORE) is the area within a patch that is not influenced by edge effect. To obtain CORE, first, we must define the edge size, or how far edge effects penetrate the fragments. CORE is zero when the whole fragment is under edge influence, and value grows as more interior area remains. Core area was calculated considering an edge effect of 90 m (3 pixels). Previous studies have shown that 90–100 m is a good estimator of edge influence to tropical forests (Cochrane and Laurance 2002; Paula et al. 2016) and more specifically Atlantic Forest (Lima et al. 2020). At least one study showed that the 100 m is a good estimator of edge effect for trees in NAF (Oliveira et al. 2004). The number of core areas in each patch (NCORE) gives the number of disjunct interior core areas in each patch after the influence of the edge effect is applied. The core area index (CAI) quantifies the percentage of the patch that comprises the core area (McGarigal 2015).

To analyze the area under protection in NAF, we obtained data from State and Federal Protected Areas (PAs). Brazilian law considers protected areas under strictly protection (IUCN categories I–IV) or sustainable use ones (IUCN categories V–VI) (National System of Conservation Units—SNUC, Law 9.985/2000). Protected areas shapefiles were obtained in the official database on protected areas of the Ministry of Environment (MMA 2021). In Brazil, government-managed protected areas can be federal, state, or municipal, depending on the hierarchical level of its creation and administration. Protected Areas under municipal administration were not considered here since it is difficult to obtain their data. Private Natural Heritage Reserves (RPPN, "Reserva Particular do Patrimônio Natural") are sustainable use PAs and were also considered. Their shapefiles and data were obtained also in the official database on protected areas of the Ministry of Environment (MMA 2021) and complemented with SIMRPPN database ("Sistema Informatizado de Monitoria de RPPN," RPPN Monitoring System) (ICMBio 2021). A total of 10 RPPNs did not have available shapefiles. In this case, the UC area was obtained from the SIMRPPN site.

A total of 17 small, protected areas are situated inside the limits of seven larger APAs (locally known as "Environmental Protection Areas," a class of sustainable use PA) in NAF: APA Aldeia-Beberibe, APA Barra do Rio Mamanguape, APA Bonfim-Guaraíra, APA do Catolé e Fernão Velho, APA Guadalupe, APA Murici, and APA Santa Cruz. These 17 small PAs sum 68,567.52 ha, and their overlapping area was not considered in the sum of PA area in NAF. The APA definition allows for the existence of nested private lands inside their limits. This class of PA may be the one with the least protection in Brazil, and Lima et al. (2020), analyzing biodiversity and biomass erosion on Atlantic Forest, observed that this class performed worse than both strictly protection and sustainable use PAs. Silva et al. (2022) found that an important portion of the functional diversity of the Atlantic Forest is only weakly protected because they are found mostly within APAs.

2.6 Current Status of Vegetation Cover

The Northern Atlantic Forest (NAF) encompasses an area of almost 4,000,000 ha (3,986,988.10 ha). This area corresponds to a very small portion of 2.70% of all the Atlantic Forest area. In NAF, we detected 747,926.73 ha of forest cover (18.76%), distributed in 63,048 fragments, varying from 0.09 ha (the pixel size) to 25,175.43 ha (but see below). The amount of forest cover in NAF is a little more than the 11–16% cover detected by Ribeiro et al. (2009) (but they did not consider fragments smaller than 3 ha), but lower than the 28% cover detected by Rezende et al. (2018) (but they considered also nonforest natural formations). Species loss is expected under a fragmentation threshold of 10–30%, since habitat loss may be fatal for most species (Fahrig 1997; Villard and Metzger 2014). Forest cover in NAF is thus in a critical condition and deserves careful attention.

In the NAF, fragment size distribution is strongly influenced by very small fragments, which are very numerous, but sum a small area. Only 37,397 fragments are larger than 1 ha, showing a worrisome value of almost half (40.7%) of fragments of tiny size (less than 1 ha). There are only 896 fragments larger than 100 ha and they represent 1.42% of the total number (Fig. 2.3). When considering larger than 1 ha fragments, their area is 705,144.8 ha, representing 17.69% of the total NAF area, while larger than 100 ha fragments span an area of 437,434.6 ha and represent 10.97% of NAF area. Fragments larger than 100 ha represent 58.49% of the remaining forest (Fig. 2.3).

Other regions in the Brazilian Atlantic Forest present a better situation than found in NAF, with much larger forest remnants. In all the Atlantic Forest, only one remnant has an area of more than 1 million ha of continuous forest and is situated in "Serra do Mar," along the coastal mountains of São Paulo. This mountain range, in fact, has many forest fragments larger than 50,000 ha (Ribeiro et al. 2009). Few other remnants larger than 50,000 can be also found in Santa Catarina and Iguaçu National Park (both southern Brazil) (Ribeiro et al. 2009). In Bahia region (Northeastern Brazil, but south of NAF), the largest one is 29,000 ha large (Ribeiro et al. 2009).

A careful inspection of the fragments' size results detected that the mapping resolution (30 m pixel) generated a coarse map that resulted in the fusion of smaller patches and created artificial patches that seemed to be very large. In the NAF, when observing the three fragments larger than 10,000 ha in a finer resolution in Google Earth Pro 7.3.4.8248 (64-bit) (November 2021), we detected that what seemed to be a large fragment is in fact a group of fragments. One example is the third "largest fragment," situated in Rio Grande do Norte state (RN). It is in fact a group of fragments connected

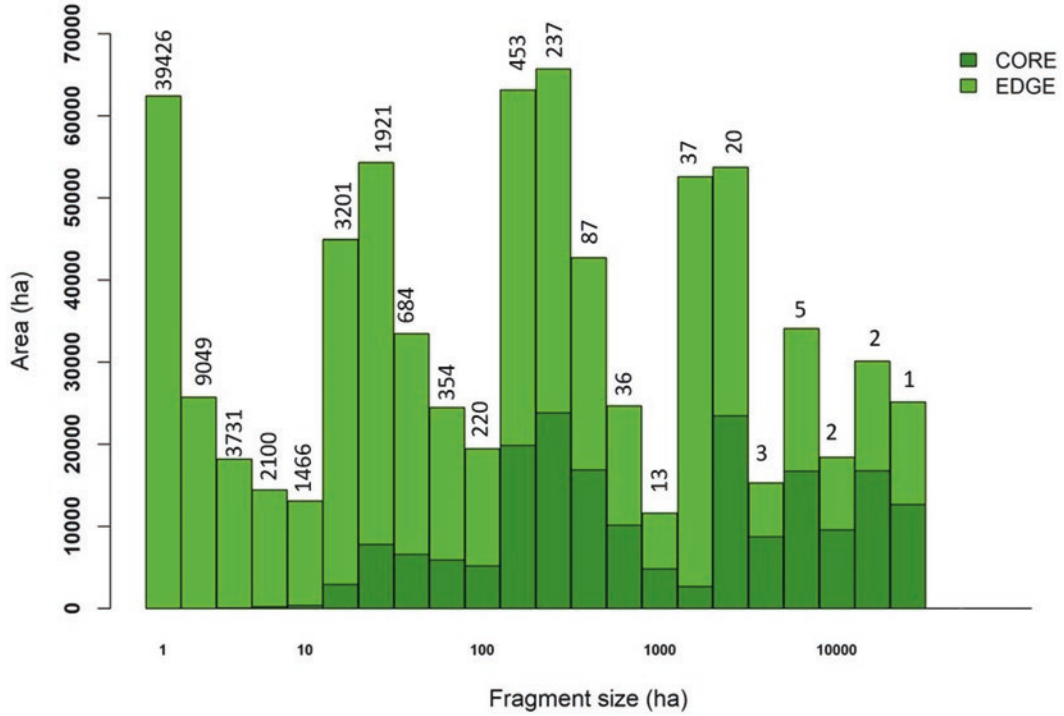

Fig. 2.3 Forest coverage in Northern Atlantic Forest, Brazil, distributed per fragments class size. Bars are divided into core (interior) (darker green) and edge areas, considering a 90 m of edge influence. Values above columns are the number of fragments in each class. Note that the x-axis is log-transformed

Fig. 2.4 Atlantic Forest fragment in Northern Atlantic Forest, Rio Grande do Norte. This is an example of a fragment that seems to be large, but, in fact, is an artifact of the use of the 8-neighbor-rule and a 30 m pixel. This fragment is almost totally inserted in a sugarcane farm, and windbreaks connected some small fragments, mistakenly creating a nonexisting large remnant in the area (see Fig 2.5). (Map generated using Google Earth. Google Earth Pro 7.3.4.8248 (64-bit) (November. 2021). Usina Estivas. Rio Grande do Norte. Brazil. 06°12′36″S. 35°14′04″W. Eye alt 42 km. Borders and labels; places layers. Images: SIO. NOAA. USNavy. NGA. GEBCO. 2020. http://www.google.com/earth/index.html (Accessed November 21, 2021))

by windbreaks (most of them composed of *Eucalyptus*, but also by degraded secondary forest) and are mostly inside a sugarcane farm (Figs. 2.4 and 2.5). This is a clear example of what seemed to be a good forest fragment, but, in fact, is a group of smaller ones of poor quality. Important to note that we used the same map and method to all NAF analysis, and this “resolution artifact” could also have occurred in fragments of all sizes.

Fragment size should not be used singly as an estimator of good habitat condition. In Fig. 2.6, it is possible to compare two large fragments found in the area. The first one is in APA Aldeia Beberibe (Pernambuco state, PE), with 18,604.9 ha but with an irregular size and 61% of core area (Fig. 2.6a, Table 2.2). The second one is in REBIO Serra Talhada (also in PE) with 6261.8 ha but with a more regular shape and 72.4% of core area (Fig. 2.6b, Table 2.2).

Taking into consideration that the fragments’ size may not be the best surrogate for native forest health in NAF, we decided to rank fragments by core area, instead of fragment area. When considering an edge influence of 90 m in fragments larger than 1 ha in the NAF, only 8186 fragments present core area with at least 0.09 ha (one pixel) (only 21.9% of the fragments larger than 1 ha). Also, the interior (core) area falls to a worrisome value of 216,628.0 ha (only 30.72% of the area of remnants above 1 ha) (Figs. 2.2 and 2.7a). The smallest fragment with 0.09 ha core area is 3.3 ha large. Only two fragments had core areas summing more than 10,000 ha, but they are also a junction of smaller ones. The largest core area was found in Santa Rita (Paraíba state, PB) in the largest remnant, with a core area of 12,711.96 ha, but divided in 582 small parts. The second largest remnant, considering core area, is in Pernambuco state with a core area of 11,384.82 ha, but divided into 251 parts (Table 2.2). The high number of core areas reflects the irregular shape of the fragments and reinforces the observation that functionally such fragments may correspond to fragmented habitats for the subset of late-successional plant and animal species.

Most fragments larger than one ha in NAF presented irregular shapes, observed by the SHAPE metrics. Shape values varied from 1 (a square shape) to 38.43 (very irregular shape) (Fig 2.7c). Only 277 fragments with more than 1 ha (less than 1%) had a shape value of 1.0 (square shape) (Fig. 2.7c). All square-shaped fragments are small, and do not exceed 4 ha, showing that regular shapes are more easily found in small fragments. In contrast, four fragments had a shape index value above 25.0, and all of them are among the five largest remnants (with disjunct core areas, see discussion above) (Table 2.2). Shape is correlated to fragment area ($r_s = 0.683$; $p < 0.001$), core area ($r_s = 0.435$; $p < 0.001$) and consequently to edge effect. Core area, together with shape, can also be a good estimator of fragment health, since the more irregular the shape, the more the edge influence in the fragment.

Both shape and edge influence will indicate the amount of good interior forest (core). In the NAF, the percentage of core area per fragment varied from 0% to 81% as shown by the CAI index (Fig. 2.7b). A total of 29,210 fragments larger than 1 ha (78.1%) present no core area. Taking into consider-