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The Abundance of the Remaining Mammalian Fauna and the Impacts of Hunting in a Biodiversity Hotspot's Hotspot in the Atlantic Forest of North-Eastern Brazil

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Abstract

Although hunting in the north-eastern Atlantic forest of Brazil began more than 500 years ago, no study to date has evaluated its impacts on the region's mammalian fauna. For one year we carried out diurnal and nocturnal surveys using the Line Transect method in seven forest fragments varying from 7.32 ha to 469.76 ha, within a 4000 ha forest island archipelago, in Pernambuco State, Atlantic forest of northeastern Brazil. We calculated species density, population size, biomass and synergetic biomass, and recorded direct and indirect human impacts along the study transects. We recorded 44 mammalian species, of which 45.5% (n = 20) went extinct through hunting. The smallest forest fragment had the lowest richness, diversity, population size, and total biomass. It also had no synergetic biomass. The largest fragment had the highest richness, total density, and population size. There was a statistically significant relationship between fragment area and number of gunshots heard and suspended hunting platforms found; between population size and gunshots heard, suspended hunting platforms, free-roaming and feral dogs, and between total density and free-roaming and feral dogs. After more than 500 years of colonization hunting is still devastating, with larger fragments being linked to more hunters. Higher mammal abundances attracted more free-roaming and feral dogs, which have adapted to hunt wildlife on their own. Unless we protect every single forest fragment and create sustainable landscapes, we will not be able to save this hotspot's hotspot.

Keywords

Atlantic Forest, Mammals, Abundance, Human Impact, Extinction

1. Introduction

The Earth's richest biota is currently undergoing an unprecedented mass extinction characterized by a profound loss of biodiversity across a relatively short period of time [1]-[9], a rate that is hundreds of thousands of times faster than the natural rate of the last tens of millions of years [2] [4] [10]. Unlike the five previous extinction events that occurred during Earth's history, the current species extinction wave has been caused solely by humans: human population growth, habitat conversion and overexploitation, invasive organisms, pollution, toxification, illegal trade, hunting, and climate change [1] [6] [9] [11]-[14], which, together, have driven the current wave of biological annihilation [6].

If current extinction rates continue unabated, the rate of vertebrate extinction, which has largely occurred over the last 500 years (1500 to present), will achieve impact levels similar to the five big previous extinctions in some 240 to 540 years [2] [15]-[17]. We are near the point of no return [18]. Yet, we have neglected the first stages of species extinctions, which are the extirpation of entire local populations (which occur orders of magnitude more frequently than species extinctions), and the dramatic declines in the abundance of the remaining populations, which has caused major contractions of their ranges, and ultimately, population extinctions [6] [14] [19] [20]. There is a strong tendency for research to focus exclusively on species extinctions, ignoring population extirpation, even though their disappearance at the local and regional levels is a prelude to the extinction of species as a whole [4] [6] [7] [21].

Hunting has caused alarming declines in the richness and abundance of tropical forest mammalian faunas. This has led to their local and regional extirpation, and ultimately, their mass extinction within entire hotspots [19] [22]-[24]. Together with habitat loss and fragmentation, hunting has been one of the key drivers of mammal species loss in tropical forest fragments [23]-[25]. In the north-eastern Atlantic forest of Brazil, hunting started earlier than in other regions of the country, with the first European colonizers exchanging machetes and combs for howler monkeys (*Alouatta belzebul*) and other goods more than 500 years ago [19] [26]. More specifically, it started in this hotspot's hotspot, the Pernambuco Endemism Center, in the north-eastern Atlantic forest of Brazil.

Hunting and the use of vertebrates in the Atlantic forest of north-eastern Brazil is a deeply rooted, and still present, cultural practice, even inside protected areas. It is motivated by a wide variety of factors, including subsistence, medicinal purposes, recreation/sport, retaliation, to obtain pets (for sale or personal use), punitive hunting (when wildlife prey on livestock or damage plantations), due to alleged risks for the hunter's health and that of their family. It is conducted ad hoc or as a profession [27]-[32].

Although hunters target mainly vertebrates, especially mammals and reptiles, due to their higher abundance and larger size, as in other parts of Brazil and the world [27] [28] [32]-[34], hunting is mostly opportunistic, with hunters taking whatever they can kill to meet their subsistence needs, especially when otherwise favored game species have become actually or functionally extinct [31] [35] [36].

Most hunters in Brazil are non-indigenous, and a shotgun constitutes their basic tool [27] [37] [38]. They hunt without or with domestic dogs, though their presence significantly increases hunting success [39], and either during the day or night [27]. Methods used by the hunters to obtain animals can be either active, in which hunters engage in active searching, which can involve tracking, waiting, calling, spotlighting, among others, or passive, where various types of mechanical traps are deployed [27] [29].

Species abundance in the tropics nowadays is a function of human hunting patterns [40]-[49]. In most cases, the impacts of such hunting are so intense that populations densities of the affected species are hugely reduced [50] [51]. Consequently overhunted, ecologically half-empty or empty, ecosystems [52] become the norm, with the extirpation of species due to hunting being documented across the tropics [22] [23] [46]-[49] [53].

Hunting effects in forest fragments are more deleterious than in continuous forests. This is because in fragments the species are more vulnerable not only to natural and human predators and free-roaming and feral cats and dogs, but also because the fragments may be the only habitat available to the species, so increasing further the probability of local and regional extinction [23] [54]-[56].

Dogs are used to both facilitate hunting and to protect livestock from wildlife predators [57] [58]. In this context, abandoned dogs may become either free-roaming or feral and, if living close to forest fragments, may hunt opportunistically—killing wild animals as small as rodents and as large as kudus [56] [59]. Additionally to predating what wildlife remains, they also compete with native predators and thus disrupt the dynamics of the remnant local fauna [56] [60] [61].

Studies by [19] [62] and [63] in the same hotspot's hotspot: 1) Analysed only the smallest (≤1000 ha) and the largest (c.a. 8000 ha) forest fragment archipelagos; 2) suggested that the mammalian fauna that survived in each forest fragment and archipelago vary widely and arbitrarily in composition and abundance; and 3) found that it depends on the strength, duration and nature of the impacts vested on such areas by the landowner and other local actors. Thus, we decided to further investigate a c.a. 4000 ha forest archipelago and test its veracity.

Most importantly, no studies to date had evaluated the human impact caused by hunting in this highly imperiled hotspot's hotspot in the Atlantic forest of north-eastern Brazil. This includes an absence of studies on the most pervasive impact, hunting. Therefore, we aimed to evaluate the impacts of both hunting and other forms of human disturbance. We did this by recording the number of gun shots heard, presence of free-roaming and feral dogs and the number of hunting platforms encountered (proxies for hunting intensity), and the number of locals encountered within each study forest, piles of human garbage, and number of human paths that traversed the study transects (proxies for general human disturbance). Combined, this allowed us to quantify the levels and types of human interference on the remaining mammalian community in one of the few remaining forest archipelagos of the region, and to propose conservation-based management alternatives.

2. Materials and Methods

2.1. Study Area

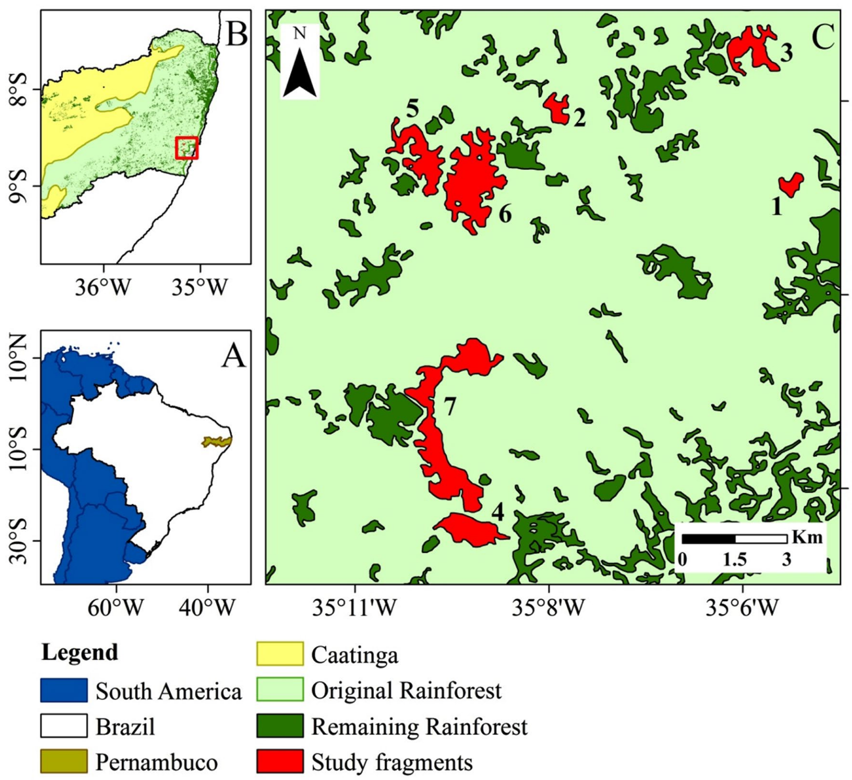

Figure 1. The location of the study area in South America (A), Brazil, Pernambuco State (B), the northeastern Atlantic forest, specifically, the Pernambuco Center of Endemism—CEPE (C), a hotspot's hotspot, showing its current and former forested areas and the studied forest fragments in the Trapiche archipelago (Spatial database provided by Fundanção SOS Mata Atlântica/INPE). 1: Pedra do Cão (08˚34'18"S; 35˚ 05'14"W); 2: Mata das Cobras (08˚33'04"S; 35˚08'50"W); 3: Boca da Mata (08˚32'04"S; 35˚05'46"O); 4: Xanguazinho (08˚39'35"S; 35˚10'20"W); 5: Aruá (08˚33'38"S; 35˚11'01"W); 6: Tauá (08˚33'47"S; 35˚10'11"W); 7: Xanguá (08˚38'50"S; 35˚10'15"W).

The study was carried out in the Brazilian Atlantic forest north of the São Francisco River, the Pernambuco Endemism Center (CEPE), a hotspot's hotspot [64] [65]. The study site was located in the 4000 ha archipelago of forest fragments (total remaining area of the CEPE: ~322,000 ha) of the Usina Trapiche (08˚37'S, 35˚11'W) (**Figure 1**), Sirinhaém municipality, Pernambuco State. Local climate is hot-humid, with a wet season between May and September with up to 2000 mm rainfall, with a mean annual temperature of 26˚C [66]. The vegetation is submontane evergreen forest [67] [68], located on hilltops up to 100 m high where regional topography prevented conversion of the pristine forests to sugar-cane fields. The area is classified as "of extreme biological importance" [69].

All studied forest fragments were isolated within a sugar-cane matrix, and had highly irregular shapes. The long history of local deforestation meant that there was no continuous forest to act as a control. All studied fragments had experienced some degree of human interference, including hunting, the presence of free-roaming and feral dogs, forest clearing, selective cutting, or intentional fires, in addition to being bisected by unmetalled roads used by people and domestic animals. Seven fragments were selected (**Figure 1**). Size was arbitrary, but accessibility and human safety were determining considerations. The smallest study fragment measured 7.32 ha, the largest 469.76 ha.

2.2. Former Mammalian Species from the CEPE

A list of the former mammalian fauna from the CEPE, north-eastern Brazil, was compiled [19] [70]-[80], and their current status assessed, according to the List of the Brazilian Fauna Threatened with Extinction [81], and the IUCN Red List [82].

2.3. Line Transect Surveys

The study was conducted between September 2008 and August 2009 using the Line Transect method [83] [84]. We obtained coordinates for the selected fragments and subsequently plotted one transect in each fragment using Google Earth. Transects measured between 750 and 2300 m in length and were 1 m wide. Trails were marked every 50 m with flags made of environmentally friendly material and cleaned of debris a few days prior to surveys to avoid disturbing the species before their detection by the observer. Transects were cut to cover the largest extension of each fragment and so were arbitrarily plotted in relation to habitat characteristics.

We standardized a sample effort at 15 km walked during the day and 10 km during the night for each kilometer of transect. Diurnal surveys were carried out between 06:00 and 16:30 h and nocturnally between 18:00 and 01:00 h, at a speed of 0.5 km/h, with regular stops to scan the habitat for movements and sounds. At each sighting the following information were gathered: species, time, location on the transect, animal-observer distance collected with the help of a measuring tape, sighting angle, vertical stratification, and animal activity at sighting. When the sighting was of a group, the animal-observer distance was taken from the geometric center of the group.

2.4. Additional Methods

To record those mammal species that were rare or that had densities below that detectable via systematic surveys, we also considered sightings made outside the transects (e.g. sugar-cane surrounding matrix), spoor, roadkill, captive animals in the nearby villages, and hunter's kills, following [85] and [86]. Such records were used only to build the species list and were not included in the calculations.

2.5. Human Impact

We recorded evidence of the human impact on the local mammalian assemblages, following [23] and [87]. Accordingly, we divided records into two categories: 1) Direct: Number of gunshots heard; presence of free-roaming and feral dogs and number of hunting platforms encountered, and 2) Indirect: Number of wood gatherers encountered; number of locals walking through the forest, and the number of human paths that traversed each study transects.

2.6. Data Analysis

We calculated individual density and species population sizes using the DISTANCE program version 5.0 [84], and following [88]. Sightings were analyzed for each species in each fragment. The total transect length for diurnal surveys was the sum of all single diurnal walks, and the nocturnal surveys, the total length of nocturnal walks. For those species active during the day and night, the total sampling length was taken as the sum of both diurnal and nocturnal walks.

Species biomass was estimated using the mean body weight of adult male and female, based on measurements given in [77] and [78], and multiplying this by the respective individual density [86]. We also calculated the synergetic biomass of each fragment, which comprised the biomass of all the species, excluding only common marmosets (*Callithrix jacchus*) and Brazilian squirrel (*Sciurus aestuans*) since, according to the local inhabitants (A. R. A. Melo, Unpubl. data), they are the only ones not hunted, and therefore, not used as food. We determined species diversity in the studied fragments with a Shannon-Wiener diversity index.

We used a Shapiro-Wilk test to assess the normality and homocedasticity of the following studied variables: richness (number of species), population size, density, biomass (and synergetic biomass), direct, and indirect human impact. We used a Pearson correlation coefficient to analyze the relationship between fragment area and recorded species richness (number of species), population size, density, biomass (and synergetic biomass); we also used a Pearson correlation coefficient to analyze the relationship between these above-mentioned variables and direct and indirect human impacts. Additionally, we used a Pearson correlation coefficient to test the effect of fragment area, richness, population size, density, biomass (and synergetic biomass) on the density and abundance of common marmosets. All statistical tests were performed using R software (R Core Development Team) version 2.13.2.

3. Results

3.1. Surveys Sample Effort

Total walked sample effort was 268.75 km (161.25 km during the day, and 107.5

km during the night) in the seven forest fragments studied. During this we recorded 247 sightings of the remaining mammals in 570 h of field surveys (**Table 1**). The most-frequently recorded species was common marmoset, *Callithrix jacchus*, with 76.52% (n = 189) of the sightings, followed by brown-throated sloth, *Bradypus variegatus*, with 7.69% (n = 19) of the sightings, and South American coati, *Nasua nasua*, with 3.66% (n = 9). The species with the lowest number of records were black-rumped agouti, *Dasyprocta prymnolopha*, yellow armadillo, *Euphractus sexcinctus*, and nine-banded armadillo, *Dasypus novemcinctus*, with one sighting (0.4%) each (**Table 1**).

Table 1. Studied forest fragments and effort in the Trapiche archipelago in the Pernambuco Endemism Center (CEPE), Atlantic forest of north-eastern Brazil.

Forest fragment	Area (ha)	Transect size (km)	Diurnal sample effort (km)	Nocturnal sample effort (km)	Number of sightings
Pedra do Cão (08˚34'18"S; 35˚05'14"W)	7.32	0.75	11.25	7.5	**19**
Mata das Cobras (08˚33'04"S; 35˚08'50"W)	40.03	0.85	12.75	8.5	**23**
Boca da Mata (08˚32'04"S; 35˚05'46"W)	94.11	1.45	21.75	14.5	**29**
Xanguazinho (08˚39'35"S; 35˚10'20"W)	100.57	1.6	24	16	**49**
Aruá (08˚33'38"S; 35˚11'01"W)	178.79	1.8	27	18	**42**
Tauá (08˚33'47"S; 35˚10'11"W)	280.33	2	30	20	**37**
Xanguá (08˚38'50"S; 35˚10'15"W)	469.76	2.3	34.5	23	**48**
Total			**161.25**	**107.5**	**247**
Overall total			**268.75**		

3.2. Former and Current Mammalian Fauna of the CEPE

[19] constructed a list of the former mammalian community of the CEPE that contained 43 medium-sized mammal species. Of these, 32.5% (n = 14) are threatened with extinction, according to the international [82] and/or Brazilian [81] list of threatened species (**Table 2**). In the Trapiche forest archipelago studied here, however, only 53.5% (n = 23) of the former mammalian fauna was recorded. Among the 46.5% (n = 20) of the species that are currently absent from the studied forest fragments, four (20%) went extinct before known (EX BK) or scientifically described (disappeared before modern times) (Mendes Pontes *et al.*, 2016), nine

(45%) are not included in the international [82] and/or Brazilian [81] list of threatened species, and only 10 (50%) are included in either the international [82] or Brazilian [81] list (Table 2).

Among these remaining 43 mammalian species, 21% (n = 9) were also recorded in the sugar-cane surrounding matrix, and of these, 19% (n = 8) were seen exclusively in this surrounding matrix (Table 2).

Table 2. Former and current mammalian fauna and their conservation status in the forest fragments of the Trapiche archipelago in the Pernambuco Endemism Center (CEPE), Atlantic forest of North-eastern Brazil.

Species	ICMBIO (2022)	IUCN (2022)	Survey	Carcass	Occasional (in the surrounding matrix)	Captivity	Footprint
Artiodactyla							
Cervidae							
Mazama sp. EX BK1		EX BK[a]					
Mazama sp. EX BK2		EX BK[a]					
Tayassuidae							
Tayassu pecari	VU	VU A2bcde + 3bcde					
Pecari tajacu[b]							
Carnivora							
Canidae							
Cerdocyon thous[c]				✓	✓		✓
Speothos venaticus	VU	NT					
Felidae							
Leopardus pardalis					✓		
L. tigrinus	EN	VU A2c			✓		
L. wiedii	VU	NT					
Panthera onca	VU	NT A2cd					
Puma concolor							
Herpailurus yagouaroundi	VU				✓		
Mustelidae							
Conepatus semistriatus							
Eira barbara[d]			✓	✓		✓	
Galictis c.f. vittata[e]				✓			
Lontra longicaudis		NT A3c					
Procyonidae							
Nasua nasua[d]			✓	✓		✓	✓
Potos flavus							
Procyon cancrivorus				✓	✓	✓	✓
Cingulata							

Continued

Dasypodidae							
Cabassous unicinctus							
Dasypus novemcinctus			✓				
D. septemcinctus							
Euphractus sexcinctus			✓				
Tolypeutes tricinctus[f]	EN	VU A2cd					
Perissodactyla							
Tapiridae							
Tapirus terrestris	VU	VU A2cde + 3cde					
Pilosa							
Bradipodidae							
Bradypus variegatus			✓				
Cyclopedidae							
Cyclopes didactylus							
Myrmecophagidae							
Myrmecophaga tridactyla	VU	VU A2c					
Tamandua tetradactyla			✓				
Primate							
Atelidae							
Alouatta belzebul[g]	VU	EN C2a(i)					
Ateles sp. EX BK3	EX BK[a]						
Callithrichidae							
Callithrix jacchus			✓		✓	✓	
Cebidae							
Saimiri sp. EX BK4	EX BK[a]						
Saimiri sciureus	Accidentally introduced					✓	
Sapajus flavius[i]	EN	EN A2acd; B2ab(ii, iii); C2a(i)			✓		
Rodentia							
Cuniculidae							
Cuniculus c.f. *paca*[c,j]				✓			✓
Dasyproctidae							
Dasyprocta prymnolopha			✓				
Dasyprocta sp.			✓				
Erethizontidae							
Coendou prehensilis[k]			✓				
Coendou speratus[l]	EN B1ab(iii)	EN B1ab(i, ii, iii, iv, v) + 2ab(i, ii, iii, iv, v)			✓		

Continued

Hydrochaeridae				
Hydrochoerus hydrochaeris				✓
Sciuridae				
Guerlinguetus alphonsei		✓		
Lagomorpha				
Sylvilagus brasiliensis	EN B2ab(ii, iii)		✓	

a: Extinct Before Known; We proposed this category to distinguish it from the other IUCN categories and criteria, which do not include species that went extinct before known or scientifically described; b: Last time seen in 2006. A new effort to find them and collect hair samples for genetic studies failed; c: Two morphotypes occur: the "*cat-faced*" and the "*dog-faced*" crab-eating fox. Urgent molecular studies needed; d: Currently common and widespread despite not listed to the region in the key publications. As a result of this study we extended its distributional range to the CEPE; e: During this study we saw, and also found a dead specimen in a burnt sugar-cane plantation, and concluded that the species is not *G. vittata.* Until urgent molecular studies are carried out, we assume it is *G.* c.f. *cuja*; f: Until recently this species was considered endemic to the dry-scrub caatinga forests of northeastern Brazil; During this long-term study we found out that the species once extended its distributional range into the CEPE and that it had been extinct before present-day scientists knew they occurred there; g: Vocalizations assumedly from this species has been heard by a local primatology student, but subsequent efforts to locate the group did not succeed; i: Single group discovered isolated for over 30 years in the smallest and last fragment studied (4 ha) (Mendes Pontes *et al.* (2006)); j: From the Amazonia to the Atlantic forest the genus *Cuniculus* has the same two morphotypes, the "*deep chin*", "*pitbull*" or "*ladle paca*", which is larger and has much deeper and wider zygomatic arch, and the "common", which has it much less conspicuous; Preliminary molecular analysis has shown that in the CEPE it is a different, therefore new species; Description in progress; k: This is the correct species referred and depicted by the first colonizers from the type locality Pernambuco State in the 17th century, upon which Linnaeus (1758) based his description; This species is endemic to the CEPE and other species described outside this distributional range needs revision; l: This species was only recently described by the authors during this project and is already considered threatened of extinction.

3.3. Community Parameters

The smallest forest fragment (Pedra do Cão: 7.32 ha) had the lowest diversity (0.0001), richness (n = 1), total biomass (38.91 kg/km^2), had no synergetic biomass, *i.e.*, the only mammal species present in this fragment was *Callithrix jacchus.* This area also had the smallest population size (n = 10) (Figure 2; Table 3). The lowest total density, however, was registered in Boca da Mata (94.11 ha) with only 87.21 ind./km^2. The largest fragment (Xanguá: 469.76 ha) possessed the highest richness (n = 7), total density (279.52 ind./km^2), and population size (n = 1298 individuals), but another fragment of intermediate size (Aruá: 178.79 ha) had the same richness (n = 7), and the highest diversity (0.597), total biomass (454.82 kg/km^2), and synergetic biomass (412.49 kg/km^2) (Figure 2; Table 3).

Table 3. Density, biomass and population size of the mammals in the forest fragments of the Trapiche archipelago in the Pernambuco Endemism Center (CEPE), Atlantic forest of north-eastern Brazil.

Forest fragment	Shannon-Weiner Diversity Index	Species	Density (ind/km^2)	Biomass (kg/km^2)	Synergistic biomass (kg/km^2)	Population Size
Pedra do Cão (7.32 ha) 08˚34'18"S; 35˚05'14"W	0.0001	*Callithrix jacchus*	133.25	38.91		10
		Total	**133.25**	**38.91**	**0**	**10**

Continued

Mata das Cobras (40.03 ha) 08˚33'04"S; 35˚08'50"W	0.254	*Callithrix jacchus*	131.14	38.29		52
		Dasyprocta sp.	2.09	9.34	9.34	1
		Dasyprocta prymnolopha	13.92	55.68	55.68	6
		Guerlinguetus alphonsei	7.41	1.3		3
		Total	**154.56**	**104.61**	**65.02**	**62**
Boca da Mata (94.11 ha) 08˚32'04"S; 35˚05'46"W	0.351	*Bradypus variegatus*	9.11	36.71	36.71	9
		Callithrix jacchus	66.6	19.45		63
		Coendou prehensilis	6.7	31.02	31.02	6
		Coendou speratus	4.8	6.48	6.48	5
		Total	**87.21**	**93.66**	**74.21**	**83**
Xanguazinho (100.57 ha) 08˚39'35"S; 35˚10'20"W	0.175	*Bradypus variegatus*	1.05	4.23	4.23	1
		Callithrix jacchus	247.89	72.38		249
		Coendou prehensilis	4.62	21.39	21.39	5
		Guerlinguetus alphonsei	4.91	0.86		5
		Coendou speratus	6.25	8.44	8.44	6
		Tamandua tetradacyla	5.36	30.02	30.02	5
		Total	**270.08**	**137.32**	**64.08**	**271**
Aruá (178.79 ha) 08˚33'38"S; 35˚11'01"W	0.597	*Bradypus variegatus*	4.45	17.93	17.93	8
		Callithrix jacchus	144.96	42.33		259
		Coendou prehensilis	40.83	189.04	189.04	73
		Dasypus novemcinctus	12.75	55.85	55.85	23
		Eira barbara	6.55	31.31	31.31	12
		Nasua nasua	22.28	113.63	113.63	40
		Guerlinguetus alphonsei	26.88	4.73		48
		Total	**258.7**	**454.82**	**407.76**	**463**
Tauá (280.33 ha) 08˚33'47"S; 35˚10'11"W	0.298	*Bradypus variegatus*	1.85	7.46	7.46	5
		Callithrix jacchus	131.67	38.45		369
		Dasyprocta sp.	0.56	2.51	2.51	2
		Nasua nasua	8.12	41.41	41.41	23
		Guerlinguetus alphonsei	1.3	0.23		4
		Coendou speratus	18.75	25.31	25.31	53
		Total	**162.25**	**115.37**	**76.69**	**456**
Xanguá (469.76 ha) 08˚38'50"S; 35˚10'15"W	0.434	*Bradypus variegatus*	10.37	41.79	41.79	34
		Callithrix jacchus	195.26	57.02		917
		Coendou prehensilis	4.42	20.46	20.46	21
		Euphractus sexcinctus	2.35	12.06	12.06	11
		Nasua nasua	35.39	180.49	180.49	166
		Coendou speratus	28.14	37.99	37.99	132
		Tamandua tetradacyla	3.59	20.1	20.1	17
		Total	**279.52**	**369.91**	**312.89**	**1.298**

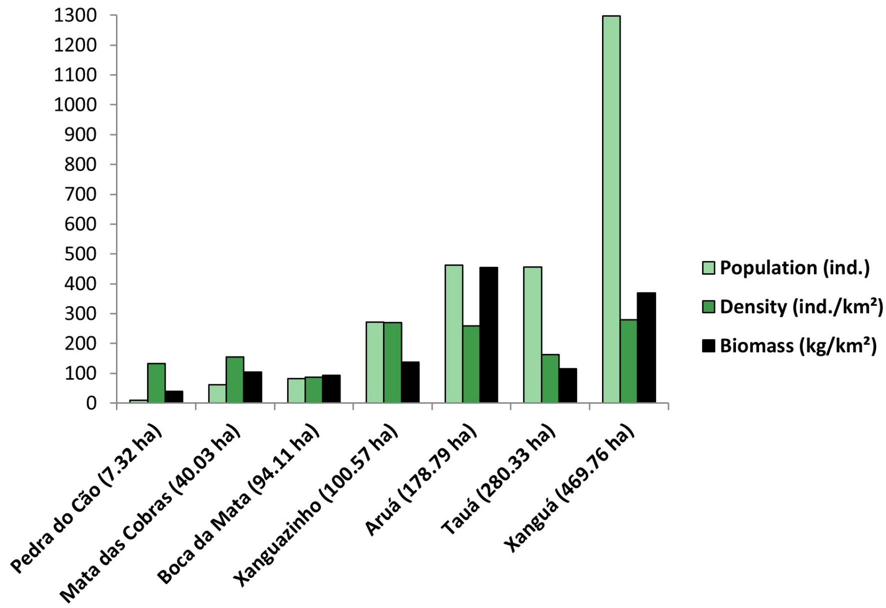

Figure 2. Total population, density (ind./km^2), and biomass (kg/km^2) of the mammalian community in the studied fragments at Trapiche archipelago, Pernambuco Center of Endemism, Atlantic forest, northeastern Brazil.

In all studied forest fragments the common marmoset was the species with the highest density (between 66.6 ind./km^2 in Boca da mata (94.11 ha) and 247.89 ind./km^2 in Xanguazinho (100.57 ha)) and population size (between 52 individuals in Mata das Cobras (40.03 ha) and 917 individuals in Xanguá (469.76 ha)) (Table 3). In contrast, biomass varied widely between fragments. *Coendou prehensilis* had the highest biomass of all in the fragment of intermediate size, Aruá (178.79 ha), with 189.04 kg/km^2, whereas *Guerlinguetus alphonsei* had the lowest biomass in Tauá (280.33 ha), with only 0.23 kg/km^2 (Table 3).

Table 4. Human direct and indirect impacts on the mammals in the forest fragments of the Trapiche archipelago in the Pernambuco Endemism Center (CEPE), Atlantic forest of north-eastern Brazil.

Forest Fragment	Human Direct Impact			Human Indirect Impact		
	Gun shots heard	Hunting suspended platforms	Free-roaming and feral dogs	Wood gatherers	Local passers	Man-made paths crossing the trails
Pedra do Cão (7.32 ha)	0	1	2	0	6	2
Mata das Cobras (40.03 ha)	0	1	10	0	1	2
Boca da Mata (94.11 ha)	8	1	6	6	10	5
Xanguazinho (100.57 ha)	6	1	13	27	11	29
Aruá (178.79 ha)	0	2	9	1	0	5
Tauá (280.33 ha)	4	2	7	1	4	17
Xanguá (469.76 ha)	30	3	18	15	15	24
Total	**48**	**11**	**65**	**50**	**47**	**84**

We heard from 4 (in Tauá; 280.33 ha) to 30 (in Xanguá; 469.76 ha) gunshots in five nights in a single forest fragment; found up to three (in Xanguá) hunting platforms, and between two (in Pedra do Cão; 7.32 ha) and 18 (in Xanguá) free-roaming and feral dogs (**Table 4**). Additionally, we found up to 27 (in Xanguazinho; 100.57 ha) wood gatherers in five nights in a single forest fragment; up to 15 (in Xanguá) locals walking through the forest, and up to 29 (in Xanguazinho) man-made paths crossing the study trail (**Table 4**). In total, we recorded 124 incidents of direct, and 181 of indirect human impact on the fragments during the study period (**Table 4**).

A statistically significant relationship was detected between area of the fragment and overall mammal population size ($r = 0.964$, $p < 0.0001$). There was no statistically significant relationship between fragment area and specie richness ($r = 0.725$, $p = 0.065$), diversity index ($r = 0.556$, $p = 0.195$), total density ($r = 0.549$, $p = 0.202$), total biomass ($r = 0.618$, $p = 0.139$), or synergetic biomass ($r = 0.602$, $p = 0.153$).

There was a statistically significant relationship between area of the fragment and number of gunshots heard ($r = 0.825$, $p = 0.022$) and of suspended hunting platforms ($r = 0.958$, $p = 0.001$), but not between fragment area and number of free-roaming and feral dogs ($r = 0.690$, $p = 0.086$). There was no statistically significant relationship between species richness and gunshots heard ($r = 447$, $p = 0.315$), suspended hunting platforms ($r = 0.686$, $p = 0.089$), or free-roaming and feral dogs ($r = 0.748$, $p = 0.053$). No statistically significant relationship was detected also between diversity index and gunshots heard ($r = 0.296$, $p = 0.519$), suspended hunting platforms ($r = 0.622$, $p = 0.136$) or free-roaming and feral dogs ($r = 0.444$, $p = 0.318$).

There was a statistically significant relationship between population size and gunshots heard ($r = 0.871$, $p = 0.011$), suspended hunting platforms ($rho = 0.896$, $p = 0.006$), and free-roaming and feral dogs ($r = 0.786$ e $p = 0.036$). No statistically significant relationship was detected between total biomass and gun shots heard ($r = 0.406$, $p = 0.367$), suspended hunting platforms ($r = 0.748$, $p = 0.053$), or free-roaming and feral dogs ($r = 0.577$, $p = 0.175$), or between synergetic biomass and gunshots heard ($r = 0.380$, $p = 0.444$), suspended hunting platforms ($r = 0.740$, $p = 0.057$), or free-roaming and feral dogs ($r = 0.519$, $p = 0.233$). There was a statistically significant relationship between total density and free-roaming and feral dogs ($r = 0.783$, $p = 0.037$), but not between total density and gunshots heard ($r = 0.434$, $p = 0.331$) and suspended hunting platforms ($r = 0.586$, $p = 0.167$).

No statistically significant relationship was detected between fragment area and number of wood gatherers ($r = 0.243$, $p = 0.599$), locals walking through the forest ($r = -0.353$, $p = 0.437$) or man-made paths ($r = 0.586$, $p = 0.167$). No significant relationship was detected between mammal species richness and number of wood gatherers ($r = 0.405$, $p = 0.367$), locals walking through the forest ($r = -0.227$, $p = 0.625$) or man-made paths ($r = 0.612$, $p = 0.144$). No significant relationship was detected between mammal species richness and number of wood gatherers (r =

−0.071, p = 0.880), locals walking through the forest (r = −0.379, p = 0.402) or man-made paths (r = 0.039, p = 0.934).

No statistically significant relationship was detected between mammal population size and number of wood gatherers (r = 0.339, p = 0.457), locals walking through the forest (r = −0.325, p = 0.477) or man-made paths (r = 0.597, p = 0.157). No significant relationship was detected between total mammalian biomass and number of wood gatherers (r = 0.102, p = 0.827), locals walking through the forest (r = −0.397, p = 0.378) or man-made paths (r = 0.195, p = 0.675). No significant relationship was detected between synergetic mammalian biomass and number of wood gatherers (r = 0.019, p = 0.967), locals walking through the forest (r = −0.423, p = 0.345) and man-made paths (r = 0.113, p = 0.809). No significant relationship was detected between total mammalian density and number of wood gatherers (r = 0.598, p = 0.156), locals walking through the forest (r = −0.134, p = 0.775) or man-made paths (r = 0.673, p = 0.098).

There was a statistically significant relationship between mammal species richness and common marmoset biomass (r = 0.822, p = 0.023) and density (r = 0.766, p = 0.045). No statistically significant relationship was detected between area of the fragment and common marmoset biomass (r = 0.479, p = 0.276) or density (r = 0.455, p = 0.305); between diversity and common marmoset biomass (r = 0.014, p = 0.977) or density (r = −0.02, p = 0.963); between mammal population size and common marmoset biomass (r = 0.416, p = 0.353) or density (r = 0.407, p = 0.365); total mammal biomass and common marmoset biomass (r = 0.382, p = 0.397) or density (r = 0.350, p = 0.442); synergetic mammal biomass and common marmoset biomass (r = 0.382, p = 0.398) or density (r = 0.350, p = 0.442), or between total density and common marmoset biomass (r = 0.417, p = 0.352) or density (r = 0.380, p = 0.400).

4. Discussion

4.1. Current Scenario of the Mammalian Fauna of the CEPE

After more than 500 years of the colonization process the Atlantic forest of northeastern Brazil, the biogeographical region above the São Francisco river, the Pernambuco Center of Endemism [89]-[92], a hotspot within a hotspot [64] [65] has lost c.a. 95% of its original pristine forests, no longer has a large continuous (source) forest for recolonization of the fragments, the largest forest fragment has only c.a. 3500 ha—the Coimbra forest, and c.a. 70% of the remaining fragments have a mean size of 2.8 ha [19]. These fragments are all immersed in a matrix of sugar-cane plantations, most are located in hill tops inappropriate to agriculture, have very irregular shapes, and a vegetation that is typical of forest borders rather than the interior [19] [63].

In this scenario, many species went extinct before being described by scientists, or even known, such as two deer species depicted in the 17th century [70] [71] [73] [75] [76]. Some others became locally extinct recently, such as the collared-peccary, *Pecari tajacu*, which was lost to the region in 2003 [93]. Despite this, there have still been contemporaneous discoveries of new medium-sized mammal species, such as the dwarf porcupine, *Coendou speratus* [94] (**Figure 3**).

Figure 3. The dwarf porcupine, *Coendou speratus*, recently found and described by the authors in the Atlantic forest of northeastern Brazil, the Pernambuco Endemism Center, a hotspot withing a hotspot.

Studying four of the best-preserved forest archipelagos of this hotspot's hotspot, [19] [62] [63], showed that an unprecedented mass extinction was taking place, with c.a. 50% of the medium-sized and all large mammals extinct, and that the fragments are too small to hold a minimum viable population of the remaining medium-sized mammals. They also showed that c.a. 22% of the remaining mammal species used the surrounding sugarcane matrix to fulfil their energetic demands, which makes them susceptible to the sink effect [62].

Thus, the remaining medium-sized mammal community is highly simplified and homogenized, which is also true for small mammals, and trees, most likely because the time lag between fragmentation and extinction has been long enough to affect the entire community [62] [95]. Species with critically small populations that are unlikely to survive without significant adaptation to human-altered landscapes or conservation intervention live in close association with humans. They depend on their ability to adapt to a novel and simplified diet, and/or on using the surrounding matrix effectively without being engulfed by the sink effect [19] [96].

Therefore, no significant differences were detected in the number of sightings or sighting rates among the fragments [62], and neither richness or abundance were predicted by fragment area, fragment isolation, vegetation type, or any interaction between them [19]. More importantly, neither fragment area, nor fragment isolation accounted for the detected nestedness pattern [97]-[100]. In other words, smaller fragments were not subsets of the larger ones [19].

According to [62], studying a c.a. 600 ha forest archipelago also in this hotspot's hotspot, the species most likely to persist were *Callithrix jacchus*, *Guerlinguetus alphonsei*, and *Nasua nasua*, because of their relatively broad diet, and because, according to them, they are not hunted by the local people. [19], studying four other forest archipelagos (one of c.a. 600 ha, two of c.a. 1000 ha, and the largest one of this entire hotspot's hotspot, of 8000 ha), suggested that its 21st century medium-sized mammalian fauna should comprise of just four species: *C. jacchus*, *Bradypus variegatus*, *G. alphonsei*, and *Sapajus flavius.* This discrepancy in the species that should survive in the different forest archipelagos and forest fragments results from the fact that their survival depends solely on the landowner and the local people who exploit them unsustainable and arbitrarily [19].

4.2. Future Scenarios for the Trapiche Archipelago: This Study

This study reinforced the study of [19] in showing that all the large mammals mentioned as present in the CEPE by the first colonizers are currently extinct, namely white-lipped peccary (*Tayassu pecari*), jaguar (*Panthera onca*), puma (*Puma concolor*), Brazilian tapir (*Tapirus terrestris*), giant anteater (*Myrmecophaga tridactyla*) and bush-dog (*Speothos venaticus*). [19] also showed that the occurrence of medium-sized mammals in this hotspot's hotspot was not controlled by vegetation type, fragment area or degree of isolation, but by the ability to adapt to a simplified novel diet, the efficient use of the surrounding matrix and possibly escaping hunting, although they did not quantify the human impact.

In fact, the three most abundant species were those that exploited food resources that were abundant in this highly depauperate scenario and that were not favored by hunters, namely, common marmoset (*Callithrix jacchus*), brown-throated sloth (*Bradipus variegatus*), and South American coatis (*Nasua nasua*). Key to common marmoset survival appears to be a remarkable increase of up to 98% in the investment of their feeding time in the exploitation of tree gum from the two most abundant pioneer trees currently growing in the interior of the remaining forest fragments, *Tapirira guianensis* (Anacardiaceae) and *Parkia pendula* (Fabaceae) [101].

This strategy has allowed these small primates to survive under conditions where other foods, such as fruit and animal matter, are extremely scarce [102]-[104]. Whenever they have access to orchards and backyards of neighboring houses the marmosets can exploit native or exotic fruit trees introduced by humans and even be fed by them [104] [105].

Although common marmosets can thrive even in totally urbanized areas, such as public squares and gardens [19], [104] showed that encounter probability is higher in larger forest fragments. In the current study we have shown that their abundance is higher in those fragments that have higher mammal species richness, which may ultimately be related to habitat quality.

Brown-throated sloths, *Bradypus variegatus*, are folivores that feed primarily on the leaves of *Cecropia* spp. [106]-[108], which are strictly pioneer trees that grow abundantly in clearings and forest borders. The surveyed forest fragments were all very small, isolated in a sugar-cane matrix, with a highly irregular shape, a high proportion of secondary forest species, and only border-like vegetation [92] [109] [110]. This has greatly benefitted sloths, which can be found in large numbers in forest border vegetation [111] [112]; current study.

South American coatis, *Nasua nasua*, are medium-sized generalist or opportunistic feeders [77] [113] [114] that have extensively exploited the introduced African palm, *Elaeis guineensis*, currently widespread in the study area, especially in depressions near water bodies (Mendes Pontes pers. obs.). This plant has also been responsible for the survival of the fourth most abundant species, the blond capuchin (*Sapajus flavius*) [96]. Coatis are also able to exploit native or introduced fruit trees in orchards and backyards of neighboring houses, as well as preying on small livestock (notably chickens) and even raiding rubbish bins. As mesopredators, coatis appear to have also been benefitted from the regional extinction of the former top predators, *Panthera onca* and *Puma concolor*, from the extinction of their competitor *Speothos venaticus*, and from the dramatic decrease in the abundance of their other competitors, such as tayras (*Eira barbara*) [19] [115] [116].

The smallest fragment in this study had the lowest richness, diversity, population size, biomass and had no synergetic biomass, since the only species present was the common marmoset. This fragment measured 7.32 ha, which is still larger than the vast majority of the remaining fragments in the entire CEPE, where the mean size is only 2.83 ha (±2.24) [19]. Consequently, only common marmosets would be expected to persist in this region in the long term. Unsurprisingly, common marmosets mean density and population size in the studied fragments were at least one order of magnitude higher than those of any other mammal species.

The positive significant relationship detected between fragment area and population size confirms that most of the CEPE forest fragments are empty or nearly empty in terms of their mammalian species [52] [117], since more than 70% (n = 13,619) of the remaining fragments are no more than 10 ha in area, only 0.13% (n = 23) measure more than 1000 ha, the largest fragment measures only around 3500 ha, and there is no extensive forest area to act as a source [19]. Most of the 50% of the species that still persist in the studied fragments occur at densities below that detectable in surveys (e.g., greater grison, *Galictis* cf. *vitatta*) and are likely to be at the brink of regional extinction.

More than 500 years since the beginning of the non-indigenous colonization process, half of the mammalian species formerly inhabiting this hotspot's hotspot are now extinct. Most of the remaining species are composed of populations with sizes below those considered sustainable in the long-term and where the synergetic species had abundances below those detectable via standard methods. Despite such low abundances, hunting continues at high levels, with 30 gunshots heard in a single forest fragment over a period of only five nocturnal surveys.

The local mammalian assemblage is highly depauperate, with all large, and around half of all, mammal species extinct and with the populations of all remaining species present at very low abundances. Under such circumstances, hunters know those forest fragments where they can still find species to hunt. Larger fragments had larger population sizes and those were where more gunshots were heard and where more suspended hunting platforms were found. Hunters also adopted a very unselective strategy, including in their game repertoire any species that they could find, excluding only common marmoset and Brazilian squirrel (*Guerlinguetus alphonsei*), reportedly due to their small size.

Under such circumstances, richness, diversity, biomass, or even synergetic biomass did not significantly influence hunter prey choice; in any of the more densely populated forest fragments they can encounter potential prey. In other regions, human impact, especially through hunting, is inversely related to forest quality [23] [87] [118] [119], but in the region investigated for the current study, where very few mammals remain, hunters have learned to identify those few forest fragments where investing time in hunting efforts will still bring rewards.

An additional threat to the mammalian species currently remaining is that larger mammalian population sizes and higher total densities attracted more free-roaming and feral dogs. These can cause further declines in the biodiversity of this hotspot's hotspot by killing and eating wildlife [56] [61], competing for scarce natural resources [120] [121], or even chasing away the local mammal populations by their mere presence (Lenth *et al.*, 2008), further jeopardizing conservation efforts. In this case, the area of the fragment was not important since they can easily hear and/or smell and locate the potential prey in any forest fragment [56] [61].

This study showed that half of the former mammal species from the CEPE are extinct; that the remaining species occur in very low densities, and that, despite the vast majority of the forest fragments measuring less than 10 ha, larger fragments had higher richness, population size, and total biomass, suggesting that the remaining populations are not sustainable in the long term. Even more striking is that hunting is still rampant and that the better the quality of the fragment, the higher the human impact. Free-roaming and feral dogs appeared to have learned to hunt on their own in these fragments, so posing an additional serious threat to the survival of these mammalian species.

4.3. Implications for Conservation and Alternatives

The regional extinction of some species (e.g. jaguar, *Panthera onca*), or the imminent regional extirpation of others still present at CEPE in low numbers (e.g. ocelot, *Leopardus pardalis*), implies in a decrease of at least 3000 km^2 in their former range. We suggest that national lists of threatened species assess the status of the species per region, rather than by the country as a whole, as this would allow consideration of the early stages of extinction and would help to direct investments to those areas most in need of protection.

The remaining mammals of the CEPE are present at low abundances and occur in small forest fragments that cannot support populations in the long-term. Additionally, the impact of hunting is still devastating and increases with the quality of the fragment. Thus, we suggest that every single forest fragment be considered potential restoration polygons, be protected against human interference, and reconnected to create sustainable metapopulations. Such initiatives could be achieved with the support of the relevant environmental authorities at the national, state, and municipal levels. Free-roaming and feral dogs should be compulsorily removed from the forest fragments and possibly sent to one of the many existing animal shelters in collaboration with local Government, via community-led initiatives.

It is crucial that we promote the awareness of the local people through environmental education campaigns. Since the largest archipelagos of forest fragments are within the vast private properties of the sugar-cane mills, environmental education could start in the schools of these sugar-cane mills by their own trained teachers. Additionally, authorities had to address the socio-economic factors that perpetuate hunting and human disturbance in the study area and create alternatives. In northeastern Brazil, hunting is practiced mainly due to a lack of resources of local people to buy animal protein from domestic animals, instead of hunting game species. This implies that, in order to promote the food security of their families, breadwinners have to hunt the remaining wildlife. Thus, the protection of the remaining mammalian fauna depends on authorities providing better livelihoods, basically decent jobs and salaries that would allow them a better existence.

Finally, smaller forest fragments hold less species, and don't hold a significant number of the threatened species (**Table 5**). Density, biomass, and synergistic biomass varied randomly, depending not on the fragment's attributes, but on the level of direct and indirect human impact on them (**Table 5**). This study showed that these forest archipelagos, such as in this study, are not enough to safeguard the remaining medium-sized mammal community, their reconnection being compulsory.

Table 5. Summary of key findings for each forest fragment.

Forest Fragment	Number of species	Number of threatened species	Total density (ind/km^2)	Total Biomass (kg/km^2)	Total synergistic biomass (kg/km^2)	Population size	Gun shots heard	Hunting suspended platforms	Free- roaming and feral dogs	Wood gatherers	Local passers	Man-made paths crossing the trails
Pedra do Cão (7.32 ha)	1	0	133.25	38.91	0	10	0	1	2	0	6	2
Mata das Cobras (40.03 ha)	4	0	154.56	104.61	65.02	62	0	1	10	0	1	2
Boca da Mata (94.11 ha)	4	1	87.21	93.66	74.21	83	8	1	6	6	10	5
Xanguazinho (100.57 ha)	6	1	270.08	137.32	64.08	271	6	1	13	27	11	29
Aruá (178.79 ha)	7	0	258.7	454.82	407.76	463	0	2	9	1	0	5
Tauá (280.33 ha)	6	1	162.25	115.37	76.69	456	4	2	7	1	4	17
Xanguá (469.76 ha)	7	1	279.52	369.91	312.89	1.298	30	3	18	15	15	24

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Author Contribution

ERAM collected and analyzed the data and wrote the manuscript; JRG collected and analyzed the data; LRRL analyzed the data; ARMP designed the experiment, collected and analyzed the data, and wrote the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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