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Mammal species biodiversity in a Costa Rican protected tropical rainforest environment

Abstract

Tropical rainforest deforestation has led to old-growth forest loss and declines in species diversity worldwide. In the 1980's, Costa Rica began innovative reforestation efforts and currently 52% of Costa Rica is a tropical forest environment. However, the impact of Costa Rica's reforestation efforts on regaining species biodiversity is less known. The aim of this study was to consider longitudinal changes in mammal biodiversity at La Selva Biological Station (LSBS) following reforestation. Mammal species census data were collected between 1994 and 2017 by 30-60 trained and experienced Citizen Scientists. We calculated the total number of different species sighted per year, their relative abundance, and the Shannon Index to estimate biodiversity. Linear regression was used to consider change over time and ANOVA was used to consider differences in land and water use by mammal species ($p<0.05$). Results suggest the total number of different species observed declined, their relative abundance declined, and the Shannon index of biodiversity declined ($p<0.05$). This decline is similar to that reported for avian fauna, terrestrial amphibian, and dung beetle species reported at LSBS. Our study highlights the concern that past deforestation continues to lead to species decline and the ongoing need for tropical forest stewardship.

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Introduction

Tropical rainforest deforestation is a leading cause of species decline worldwide.[1] Deforestation leads to old-growth forest loss and concomitant species dependence on secondary forest environments and forest patches. This change can negatively impact ecosystem function and result in decreased species diversity.[1,2] This study considers changes in mammal species biodiversity over time in a protected and reforested tropical rainforest environment. We focused on La Selva Biological Station (LSBS) in Costa Rica. Costa Rica is a model country with innovative conservation policies and reforestation efforts.[3] However, it hasn't always been the case.[4] In the 1950's, 70% of Costa Rica was a biodiverse, rich, tropical forest environment. However, rapid deforestation from the 1950s to the 1980s resulted in a significant decline in tropical forest with only 21% tropical forest remaining.[3] With strong government conservation support and landowner monetary incentives, Costa Rica now includes 52% tropical forest environment.[3,4] However, the impact of Costa Rica's reforestation efforts on regaining biodiversity among mammals is less known.[5] We do know that the restoration of tree species is generally linked to mammal persistence.[6] However, it is unclear whether the decades of deforestation limited the viability of mammal populations.[5]

Mammals are key to rainforest ecology. Large mammalian herbivores modulate ecosystem interactions. They are seed predators and dispersers.[7] Small mammals act as both predators and prey and help maintain the integrity and stability of the ecosystem.[8] They also consume damaged plant tissues, overturn soil, and have a positive impact on nutrient cycling within the rainforest environment.[7] Likewise, large carnivores are key to regulating faunal community size, structure, and behavior.[9] They also leave behind carcasses for scavenging by other community members which affects soil chemistry and nutrient cycling.[9]

Primate mammals are particularly important to maintaining the forest ecosystem.[10] Most primates are frugivorous or folivorous, ingesting fruit, flowers, and seeds, and they defecate seeds throughout their environment.[11] As a result, they are important seed dispersers in a rainforest environment.[12] Seed dispersal contributes to plant and tree species survival. If plants and trees grow too close together, they compete for available light, water, and soil nutrients. As a result, primates allow plants to cover a broad area to avoid resource competition. Primates regulate where and when seeds disperse and structure plant community interactions.[12] They are likewise useful for understanding how behavior is influenced by anthropogenic change and provide an important analog to understanding the impact of environmental change on human evolution.[11] Monitoring the longitudinal impact of reforestation on mammals, including primates, is difficult. Studies require extensive time, a team of trained field assistants, and extensive financial support.[13] Trained citizen scientists are becoming increasingly important for longitudinal biodiversity monitoring.[14] This study highlights the important work of trained, amateur scientists to monitor species biodiversity and their contribution to the scientific community worldwide.[13] Data analyzed here represent 23 years of mammal census data collected at the LSBS by trained citizen scientists. Boyle and Sigel previously published their analysis of longitudinal changes in avifauna diversity of the LSBS based annual citizen science census counts.[14] Here we present longitudinal changes in mammal fauna diversity concomitantly collected.

LSBS has been an important biodiversity research site for several decades.[15] Studies dating back 40+ years document more than 400 avian, 48 amphibian, 437 ant, and 4000 moth species.[15] Avifauna biodiversity is monitored annually under the direction of the Audubon Society and the Organization for Tropical Studies (1990-Present).[14] Arthropod biodiversity was monitored via Project ALAS (Arthropods of La Selva) (1990-2000). Mammals have historically received less attention. Timm,[16] provides an overview of mammal species reported at LSBS based on published accounts. Romero[17] and colleagues conducted a 2-year survey of LSBS mammals. They report 25 mammal species including 13 nocturnal and 17 diurnal species with three primate species (*Alouatta palliata*, *Ateles geoffroyi*, *Cebus capucinus*). The current study expands on these by adding a longitudinally collected data set.

LSBS research suggests biodiversity has fluctuated over time with significant declines in bird species dependent on the forest understory.[14] Boyle & Sigel,[14] suggest declines represent a delayed response to deforestation.[5] Likewise, Whitefield et al.[18] report declines in terrestrial amphibian species due to climate-driven reduction in standing leaf litter, a critical microhabitat component. Arthropod biodiversity research suggests there is room for optimism with reports of new species of bark beetles[19] and crickets.[15] However, Escobar et al.[20] report a decline in biodiversity among 50 dung beetle species. The major concern here is that deforestation and concomitant tropical forest fragmentation has have a long-term negative impact on species diversity. This concern is fueled by large-scale studies that suggest the long-term effects of past deforestation continues to lead to species decline due to increased dependence on secondary forests, the connection between forest patches, and a resultant increase in competition, stress, and disease resulting in biodiversity decline.[21]

This study expands on previous biodiversity research at LSBS to include a longitudinal analysis of mammal species diversity at LSBS between 1994 and 2017. We address the following research questions:

- Have mammal species diversity declined over time? If so, which mammal species are rare and which species are consistently censused?
- Are mammal species censused more often in old-growth forest or are they using reforested, secondary forest areas?
- How effective is citizen science as a longitudinal measurement of mammal species biodiversity?

Methods

LSBS is located on the Caribbean slope of the Cordillera Central, in the province of Heredia, Costa Rica. It is owned and operated by the Organization for Tropical Studies and includes ~1611 ha of tropical wet forest and disturbed habitat. Average annual precipitation is 3962 mm and the mean monthly temperature ranges from 24.7°C to 27.1°C, consistent with a tropical wet-forest life zone.[22] LSBS is connected to the 50,000 ha Braulio Carrillo National Park by a 5–10 km wide corridor along its southern boundary up to 700 meters. LSBS is located at the confluence of the Sarapiqui and Puerto Viejo rivers. Smaller rivers and streams provide a variety of water resources for plants and animals. LSBS includes 55% primary forest, 7% selectively logged primary forest, 11% young secondary forest, 18% early successional pasture, 8% abandoned plantation, 0.5% other purposes, and 1% developed buildings that include offices, a library, laboratory space, and lodging areas. LSBS can be traversed by a system of trails and paths that transect the research site.[22]

Data were collected by a trained and consistent group of 30–60 citizen scientists who participated in the annual day-long survey each year in December. The mammal census was completed concurrently with the Audubon Christmas Bird Count LSBS program. It should be noted that controlling confounding factors may be difficult, but the census teams represent a relatively high skill level and knowledge of the local fauna of the LSBS. Teams walked 15 terrestrial routes that covered much of the LSBS property. Data were consistently sampled by route and sampling methods did not change across the longitudinal period of study between 1994 and 2017, making the LSBS data set particularly robust.[14]

Data was collected on paper sheets by the trained citizen scientist observation teams. Binoculars were standardly used, and observations were recorded in Spanish. Data sheets were curated by the LSBS Research Manager and kept in binders for each data collection year. These data were entered into an Excel spreadsheet program and included raw data variables: Year, Date, Time of Day, Route, Trail, and Meter Marker. Spanish entries were translated into English by the first author. To the raw dataset, we added the longitude and latitude for each census observation point, identified land use types, water resources, and the relative distance to the closest water resource and to the confluence of the major rivers (Sarapiqui, Puerto Viejo). Data included in this analysis represent all available CBC LSBS census data collected across the 18-year period from 1994 to 2017. Data for the years 2002 to 2005 were not available at the time of data entry and analysis.

Data were summarized by year and abundance for each mammal species. We counted the total sightings for each mammal species for each census year. For estimations of biodiversity, we calculated the total number of different species sighted per year, the relative abundance, and the Shannon Index. We used linear regression to plot change across years ($p<0.05$). We then calculated the frequency of sightings per year for each species and linear regression was used to consider change in sightings by species across years ($p<0.05$). We used an ANOVA statistic to consider how frequently mammal species used each land use type (old-growth forest, secondary forest, or other land use type) and were observed by each water resource type (major river, minor river, or stream). To approximate a normal distribution, we transformed frequency data using an arcsine-square root transformation. We also compared mammal diversity results to previously published accounts to consider how well citizen scientists identified mammals at LSBS.[16,17] Results were considered significant if the p-value was less than 0.05. Analysis was conducted in R studio.

The research protocol was reviewed by the University of Colorado, Colorado Springs Office of Sponsored Programs and Research Integrity (28 August 2019) and deemed exempt under 9 CFR 2. The study complied with the legal requirements of the Costa Rican government (current SINAC Approval #52308222). Funding for this study was provided by the University of Colorado, Colorado Springs.

Results

Overview and Comparison

Six mammal orders, representing 12 families, and 21 species were observed between 1994 and 2007 (Table 1). Most species were medium-sized mammals active during daylight hours. We did not observe members of the order Marsupial or Chiroptera and there were few observations of Rodentia.[16] Table 1 We estimated the relative number of sightings as abundant, common, uncommon, and rare in keeping with Timm[16] and compared our results to Timm's 1994 results previously published (Table 1). Results suggest a potential increase in sightings for *Cebus capucinus* (white-faced capuchin; common to abundant), *Tamandua mexicana* (Northern tamandua; uncommon to common), *Conepatus semistriatus* (Striped hog-nosed skunk; rare to common), *Potos flavus* (Kinkajou; uncommon to common), and *Mazama americana* (Red brocket deer; rare to uncommon). Results suggest a potential decline in sightings for *Ateles geoffroyi* (Geoffroy's spider monkey; abundant to common), *Sciurus variegatoides* (Variegated squirrel; common to uncommon), and *Felis pardalis* (Ocelot; uncommon to rare). Results also include sightings of *Canus latrans* (Coyote; rare) not previously reported at La Selva.[16]

If we compare the species observed to those previously reported by Romero et al.[17] we can report most diurnal and nocturnal/diurnal species reported by Romero et al.[17] were also reported by our citizen scientists (Table 2). There were only two exceptions: the *Coendou mexicanus* (Prehensile-tailed porcupine, rare) and the *Philander*

opossum (Gray four-eyed opossum; uncommon). Neither were observed in the current study. Also, most nocturnal species reported by Romero et al.[17] were not observed in the current study. They included five mammal species: *Agouti paca* (Paca, uncommon), *Bassaricyon gabbii* (Olingo, rare), *Didelphis marsupialis* (Southern opossum, abundant), *Marmosa mexicana* (Mexican mouse-opossum, uncommon), and *Sylvilagus brasiliensis* (Forest rabbit, uncommon). There were also five species reported by the citizen scientists but not reported by Romero et al.[17] These mammals included the following: *Procyon lotor* (Raccoon, rare), *Felis pardalis* (Ocelot, rare), *Canis latrans* (Coyote), and *Tapirus bairdii* (Tapir, uncommon).Table 2

Table 1 Species Observed 1994-2017. Relative abundance estimated in keeping with Timm (1994) for comparison. Observed = number of sightings per annual census across LSBS

				Observed Abundance	Documented Abundance
Order	**Family**	**Genus and species**	**Common Name**	**(1994-2017)**	**Timm[16]**
Primates	Atelidae	*Alouatta palliata*	Mantled howler monkey	abundant	abundant
	Cebidae	*Ateles geoffroyi*	Geoffroy's spider monkey	abundant	common
	Cebidae	*Cebus capucinus*	White-faced capuchin	common	abundant
Edentata	Bradypodidae	*Bradypus variegatus*	Three-toed sloth	common	common
	Choloepidae	*Choloepus hoffmanni*	Two-toed sloth	uncommon	uncommon
		Dasypus novemcinctus	Nine-banded armadillo	uncommon	uncommon
	Myrmecophagidae	*Cyclopes didactylus*	Silky anteater	uncommon	uncommon
		Tamandua mexicana	Northern tamandua	uncommon	common
Rodentia	Sciuridae	*Sciurus granatensis*	Red-tailed squirrel	common	common
		Sciurus variegatoides	Variegated squirrel	common	uncommon
	Dasyproctidae	*Dasyprocta punctata*	Central American agouti	abundant	abundant
Carnivora	Mustelidae	*Conepatus semistriatus*	Striped hog-nosed skunk	rare	common
		Eira barbara	Tayra	common	common
	Procyonidae	*Nasua narica*	White-nosed coati	common	common
		Potos flavus	Kinkajou	uncommon	common
		Procyon lotor	Raccoon	rare	rare
	Felidae	*Felis pardalis*	Ocelot	uncommon	rare
	Canidae	*Canis latrans*	Coyote	rare	not observed
Artiodactyla	Tayassuidae	*Tayassu tajacu*	Collared peccary	common	common
	Cervidae	*Mazama americana*	Red brocket deer	rare	uncommon
Perissodactyla	Tapiridae	*Tapirus bairdii*	Baird's tapir	uncommon	uncommon

Table 2 Species Observed at La Selva between 1994-2017 at La Selva Biological Station

				Timm[16]	**Romero et al.[17]**	**(1994-2017)**	**IUCN**	**IUCN**
Order	**Family**	**Genus and species**	**Common Name**	**Documented Abundance**	**Diurnal/ Nocturnal**	**Observed (Yes/No)**	**Category**	**Trend**
Marsupialia	Didelphidae	*Caluromys derbianus*	Woolly opossum	uncommon	Nocturnal	no	Least Concern	Decreasing
		Chironectes minimus	Water opossum	uncommon	not observed	no	Least Concern	Decreasing
		Didelphis marsupialis	Southern opossom	abundant	Nocturnal	no	Least Concern	Stable
		Marmosa mexicana	Mexican mouse-opossum	uncommon	Nocturnal	no	Least Concern	Stable
		Philander opossum	Gray four-eyed opossum	uncommon	Diurnal	no	Least Concern	Stable
Primates	Atelidae	*Alouatta palliata*	Mantled howler monkey	abundant	Diurnal/ Nocturnal	yes	Vulnerable	Decreasing
	Aotidae	*Aotus lemurinus*	Night monkey	rare	not observed	no	Vulnerable	Decreasing
	Cebidae	*Ateles geoffroyi*	Geoffroy's spider monkey	common	Diurnal	yes	Endangered	Decreasing
	Cebidae	*Cebus capucinus*	White-faced capuchin	abundant	Diurnal	yes	Vulnerable	Decreasing
Edentata	Bradypodidae	*Bradypus variegatus*	Three-toed sloth	common	Diurnal	yes	Least Concern	Decreasing
	Choloepidae	*Choloepus hoffmanni*	Two-toed sloth	uncommon	Diurnal/ Nocturnal	yes	Least Concern	Decreasing
	Dasypodidae	*Cabassous centralis*	Five-toed armadillo	rare	not observed	no	Data Deficient	Unknown

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Table 2 Continued...

				Timm[16]	Romero et al.[17]	(1994-2017)	IUCN	IUCN
Order	**Family**	**Genus and species**	**Common Name**	**Documented Abundance**	**Diurnal/ Nocturnal**	**Observed (Yes/No)**	**Category**	**Trend**
		Dasypus novemcinctus	Nine-banded armadillo	uncommon	Diurnal/ Nocturnal	yes	Least Concern	Stable
	Myrmecophagidae	*Cyclopes didactylus*	Silky anteater	uncommon	not observed	yes	Least Concern	Unknown
		Myrmecophaga tridactyla	Giant anteater	extirpated	not observed	no	Vulnerable	Decreasing
		Tamandua mexicana	Northern tamandua	common	Diurnal/ Nocturnal	yes	Least Concern	Unknown
Lagomorpha	Leporidae	*Sylvilagus brasiliensis*	Forest rabbit	uncommon	Nocturnal	no	Endangered	Decreasing
Rodentia	Sciuridae	*Microsciurus alfari*	Alfaro's pygmy squirrel	uncommon	not observed	no	Least Concern	Stable
		Sciurus granatensis	Red-tailed squirrel	common	Diurnal	yes	Least Concern	Stable
		Sciurus variegatoides	Variegated squirrel	uncommon	Diurnal	yes	Least Concern	Stable
	Geomyidae	*Orthogeomys cherrieri*	Cherrie's pocket gopher	uncommon	not observed	no	Not listed	Not listed
	Heteromyidae	*Heteromys desmarestianus*	Desmarest's spiny pocket mouse	abundant	not observed	no	Least Concern	Stable
	Muridae	*Nyctomys sumichraasti*	Sumichrast's vesper rat	rare	not observed	no	Not listed	Not listed
		Oryzomys alfari	Alfaro's rice rat	rare	not observed	no	Not listed	Not listed
		Oryzomys bombycinus	Long-wiskered rice rat	rare	not observed	no	Not listed	Not listed
		Oryzomys caliginosus	Dusky rice rat	common	not observed	no	Not listed	Not listed
		Oryzomys fulvescens	Pygmy rice rat	rare	not observed	no	Not listed	Not listed
		Tylomys watsoni	Watson's climbing rat	rare	not observed	no	Least Concern	Stable
	Erethizontidae	*Coendou mexicanus*	Prehensile-tailed porcupine	rare	Diurnal	no	Least Concern	Unknown
	Agoutidae	*Agouti paca*	Paca	uncommon	Nocturnal	no	Least Concern	Stable
	Dasyproctidae	*Dasyprocta punctata*	Central American agouti	abundant	Diurnal	yes	Least Concern	Stable
	Echimyidae	*Hoplomys gymnurus*	Armored rat	uncommon	not observed	no	Least Concern	Stable
		Proechimys semispinosus	Tomes' spiny rat	common	not observed	no	Least Concern	Stable
Carnivora	Mustelidae	*Conepatus semistriatus*	Striped hog-nosed skunk	common	not observed	yes	Least Concern	Unknown
		Eira barbara	Tayra	common	Diurnal	yes	Least Concern	Decreasing
		Galictis vittata	Grison	rare	not observed	no	Least Concern	Stable
		Lutra longicaudis	Southern river otter	common	not observed	no	Near Threatened	Decreasing
		Mustela frenata	Long-tailed weasel	rare	not observed	no	Least Concern	Stable
	Procyonidae	*Bassaricyon gabbii*	Olingo	rare	Nocturnal	no	Least Concern	Decreasing
		Nasua narica	White-nosed coati	common	Diurnal	yes	Least Concern	Decreasing
		Potos flavus	Kinkajou	common	Nocturnal	yes	Least Concern	Decreasing
		Procyon lotor	Raccoon	rare	not observed	yes	Least Concern	Increasing
	Felidae	*Felis concolor*	Puma	rare	not observed	no	Least Concern	Decreasing
		Felis onca	Jaguar	uncommon	not observed	no	Near Threatened	Decreasing
		Felis pardalis	Ocelot	rare	not observed	yes	Least Concern	Decreasing
		Felis wiedii	Margay	rare	not observed	no	Not listed	Not listed

Table 2 Continued...

				Timm[16]	Romero et al.[17]	(1994-2017)	IUCN	IUCN
Order	**Family**	**Genus and species**	**Common Name**	**Documented Abundance**	**Diurnal/ Nocturnal**	**Observed (Yes/No)**	**Category**	**Trend**
		Felis yagouaroundi	Jaguarundi	uncommon	not observed	no	Least Concern	Decreasing
	Canidae	*Canis latrans*	Coyote	not reported	not observed	yes	Least Concern	Increasing
Artiodactyla	Tayassuidae	*Tayassu pecari*	White-lipped peccary	extirpated	not observed	no	Vulnerable	Decreasing
		Pecari tajacu	Collared peccary	common	Diurnal/ Nocturnal	yes	Least Concern	Stable
	Cervidae	*Mazama americana*	Red brocket deer	uncommon	Diurnal	yes	Data Deficient	Unknown
		Odocoileus virginianus	White-tailed deer	uncommon	not observed	no	Least Concern	Stable
Perissodactyla	Tapiridae	*Tapirus bairdii*	Baird's tapir	uncommon	not observed	yes	Endangered	Decreasing

Species diversity

To consider species diversity, we began by considering the total number of different species observed for each year (1994-2007) (Figure 1). Results indicate a significant decline in the total species observed over time (r (16) =-0.689, p=0.0016). Next, we considered the relative abundance of species per year. We calculated the abundance of species relative to the abundance of that species in our baseline year (1994). Results also indicate a significant decline in the number of species observed over time (r (16) =-0.5883, p=0.0102) (Figure 2). Last, we calculated the Shannon-Weiner index H to consider mammal biodiversity over time. Index values were relatively low (1-3) and indicate a decline in species diversity over time (r (16) = -0.6019, p=0.0082) (Figure 3).

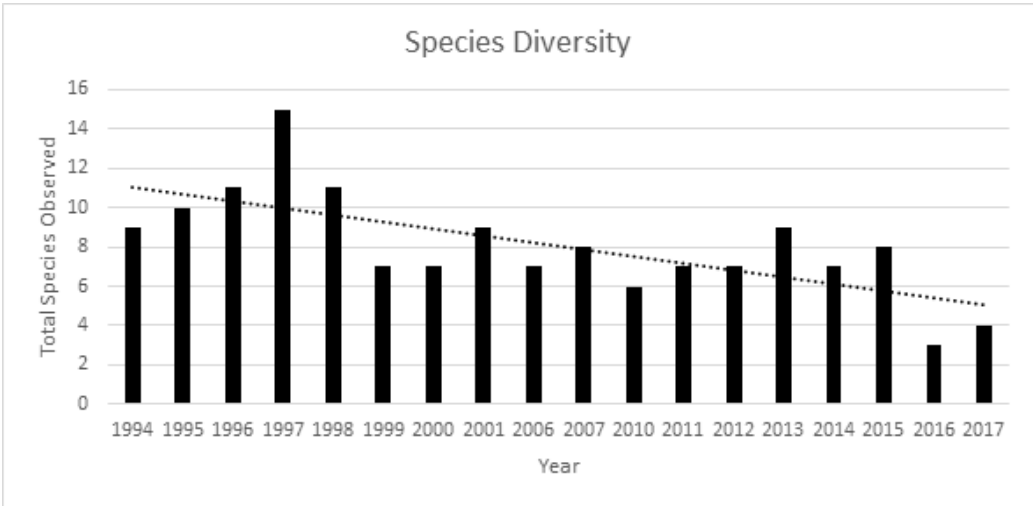

Figure 1 Species diversity across observed years (1994-2017).

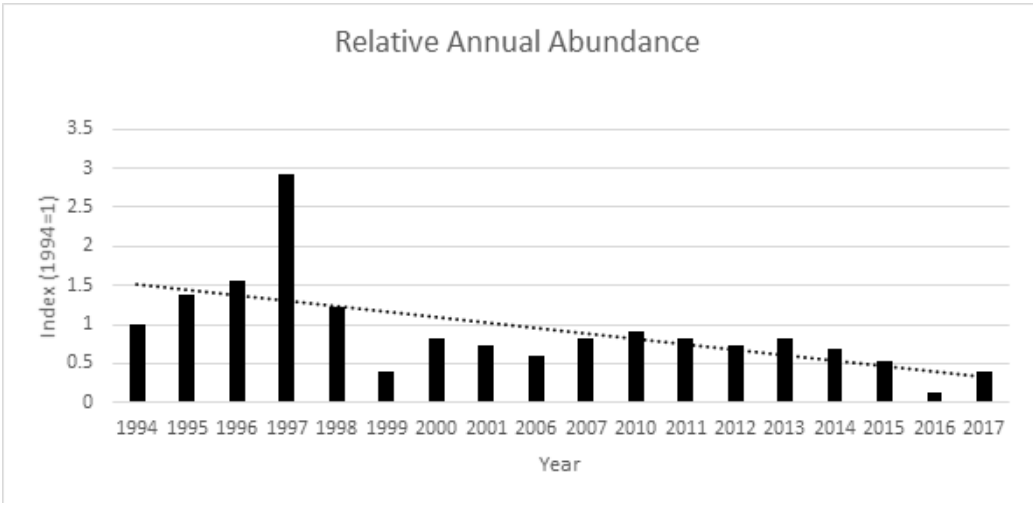

Figure 2 Relative annual species abundance across observed years (1994-2017).

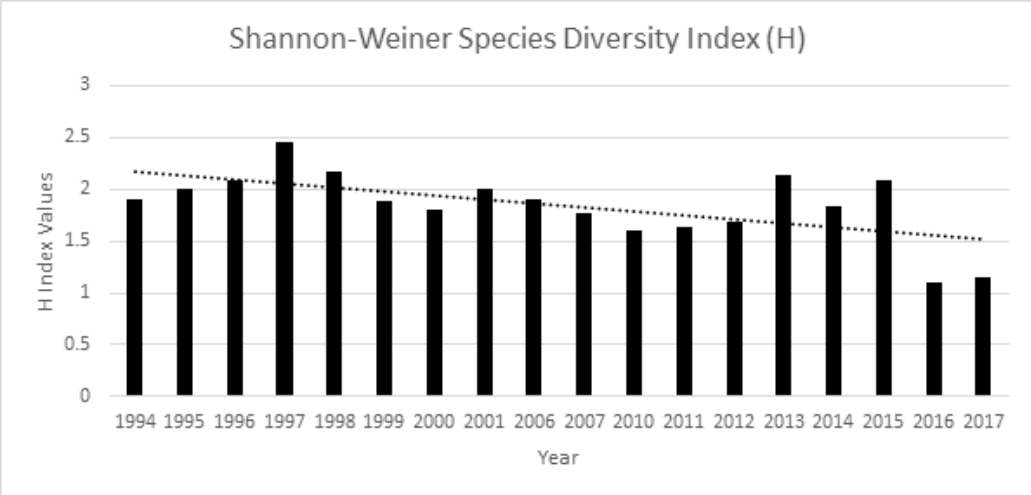

Figure 3 Shannon-Weiner species diversity index across observed years (1994-2017).

Regression calculations for each observed species are provided in Table 3. Sightings over time for all species within the orders Edentata and Perissodactyla were non-significant (p>0.05). Within the order primates, the frequency of sightings of *Cebus capucinus* (white-faced capuchins) increased over time (r(16)=0.602; p=0.0082). Within the remaining orders, we report a significant decline in the frequency of sightings for three species including: *Sciurus granatensis* (red-tailed squirrel) (*r* (16) =-0.7424, p=0.0004), *Potos flavis* (kinkajou) (*r* (16) = -0.0007, p=0.0439) and *Tayassu tajucu* (collared peccary) (*r* (16) = -0.8288, p=0.0000). Table 3

Table 3 Regression by species observed (1994-2017)

Order	Family	Genus and species	Common Name	df	r	p
Primates	Atelidae	*Alouatta palliata*	Mantled howler monkey	16	0.2456	0.326
	Cebidae	*Ateles geoffroyi*	Geoffroy's spider monkey	16	-0.0771	0.7612
	Cebidae	*Cebus capucinus*	White-faced capuchin	16	0.602	0.0082
Edentata	Bradypodidae	*Bradypus variegatus*	Three-toed sloth	16	-0.0368	0.8885
	Choloepidae	*Choloepus hoffmanni*	Two-toed sloth	16	-0.0263	0.9175
		Dasypus novemcinctus	Nine-banded armadillo	16	-0.1401	0.5793
	Myrmecophagidae	*Cyclopes didactylus*	Silky anteater	16	0.2497	0.3176
		Tamandua mexicana	Northern tamandua	16	-0.1059	0.6758
Rodentia	Sciuridae	*Sciurus granatensis*	Red-tailed squirrel	16	-0.7424	0.0004
		Sciurus variegatoides	Variegated squirrel	16	-0.294	0.2363
	Dasyproctidae	*Dasyprocta punctata*	Central American agouti	16	-0.0024	0.4492
Carnivora	Mustelidae	*Conepatus semistriatus*	Striped hog-nosed skunk	16	-0.235	0.3478
		Eira barbara	Tayra	16	0.3648	0.1366
	Procyonidae	*Nasua narica*	White-nosed coati	16	-0.4329	0.0727
		Potos flavus	Kinkajou	16	-0.0007	0.0439
		Procyon lotor	Raccoon	16	-0.2659	0.2862
	Felidae	*Felis pardalis*	Ocelot	16	0.409	0.0919
		Canis latrans	Coyote	16	0.1973	0.4326
Artiodactyla	Tayassuidae	*Tayassu tajacu*	Collared peccary	16	-0.8288	0
	Cervidae	*Mazama americana*	Red brocket deer	16	-0.1424	0.573
Perissodactyla	Tapiridae	*Tapirus bairdii*	Baird's tapir	16	0.3159	0.2019

Land and water resource use

ANOVA results suggest a land use type preference for Old Growth Forest compared to Secondary Forest and Other Land Types (Figure 4) although the result only approached significance (F (2) = 2.9735, p=0.0601). ANOVA results suggest a water resource type preference for Minor Rivers compared to Major Rivers and Streams (Figure 5) and this result was significant (F (2) = 4.4093, p = 0.0171) Figure 4 & 5.

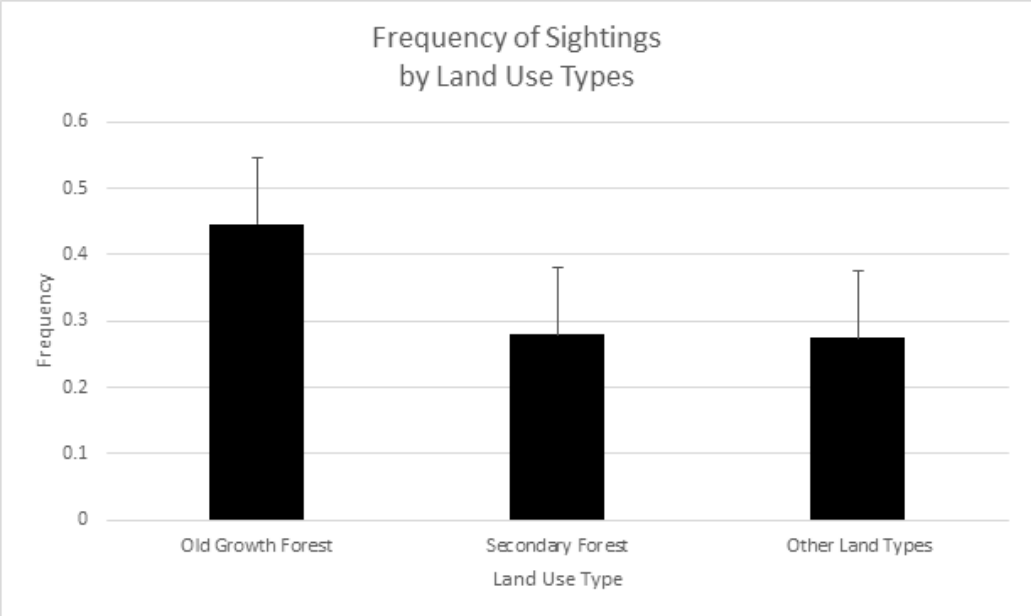

Figure 4 Frequency of Sightings by Land Use Type across observed years (1994-2017).

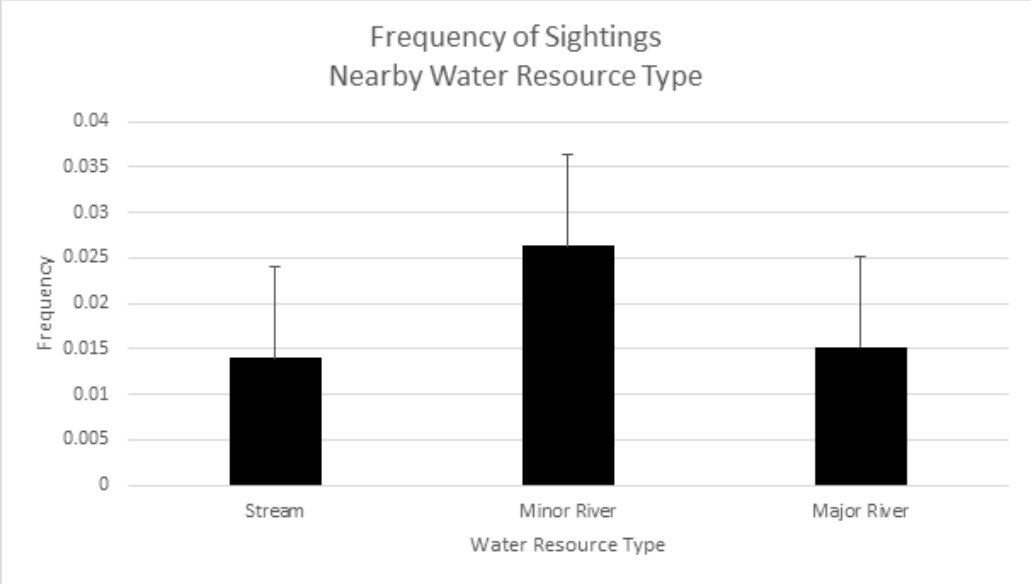

Figure 5 Frequency of Sightings by Water Resource Type across observed years (1994-2017).

Effectiveness of citizen science

Annual data collection by citizen scientists provided an accurate measure for medium to large-sized diurnal mammals. If we compare the species observed to those previously reported by Timm[16] for La Selva Biological Station, we see that census teams observed abundant species, common and uncommon species, and even some rare species (Table 2). A particularly interesting finding was the sighting of *Canis latrans* (coyote) since it was not reported previously at La Selva Biological Station. However, bats, marsupials, and small rodents (rats and mice) were not observed by census teams.

Citizen science data allowed consideration of mammal species biodiversity and provided a general picture of mammal land and water resource use. However, more intensive census counts are needed for vulnerable or endangered species (Table 2). This includes three primate species. *Alouatta palliata* (mantled howler monkey) and *Cebus capucinus* (white-faced capuchin) are both vulnerable to decreasing populations.[23] *Ateles geoffroyi* (Geoffroy's spider monkey) is endangered with decreasing numbers. In addition, more intensive census counts are also needed for *Tapirus bairdii* (Baird's tapir) as they are also considered endangered with a decreasing population. See Table 3 for IUCN status.[23]

Discussion

Results suggest mammal species diversity declined between 1994 and 2017. The total number of different species observed declined, their relative abundance declined, and the Shannon index of biodiversity declined ($p<0.05$). Species declines were significant for the red-tailed squirrel (*Sciurus granatensis*), kinkajou (*Potos flavis*), and collared peccary (*Tayassu tajucu*). However, results did indicate a significant increase in sightings of the white-faced capuchin (*Cebus capucinus*). Mammal sightings tended to be greater in the old-growth

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forest as compared to secondary forests or other land types. Mammals were sighted significantly more often near minor rivers compared to major rivers and streams. The use of citizen scientists for mammal biodiversity was effective for sightings of most diurnal mammal species. We report the first sightings of the *Canus latrans* (coyote) at La Selva that were not previously reported by Romero et al.[17] or Timm.[16] In addition, citizen scientists also sighted uncommon or rare species not observed by Romero et al.[17] although included in Timm:[16] *Procyon lotor* (raccoon), *Felis pardalis* (ocelot), and *Tapirus bairdii* (tapir).

The decline in mammal biodiversity reported here is similar to that reported avian fauna at the site. This decline is also like that reported for terrestrial amphibian and dung beetle species at La Selva Biological Station.[18,19] Our study highlights concern that past deforestation continues to lead to species decline.[21] Maintaining biodiversity in Costa Rica, and globally, is one of the key challenges today.[24] Global changes bring about deforestation and fragmentation associated with a decline in species diversity.[24] However, additional research for several species is needed. The decline in red-tailed squirrel (*Sciurus granatensis*) species should be further considered. They are generally arboreal omnivores with dependence on fruits and seeds with seasonal availability.[25] They maintain caches high in the forest canopy that may not be easily observed making consistent observation tenable.[25] Likewise, the decline in the kinkajou population (*Potos flavis*) should be further studied. Observation may also be difficult for this nocturnal arboreal omnivore as our annual diurnal count may not have accurately accounted for nocturnal mammals.[26]

The decline reported for the collared peccary (*Tayassu tajucu*) needs consideration. The collared peccary has been reported to be the most observed mammal at LSBS.[27] Romero et al.[27] report that collared peccaries increased in abundance in the past decade after the extirpation of white-lipped peccaries which were previously abundant. So, it is puzzling to report a significant decline here. We do know, however, that there has been a recent decline (2022-2023) in collared peccary sightings (Howell, personal observation) and some have suggested disease or hunting as potential culprits. Given their frequent sightings near trails used by humans,[27] citizen scientists would have little difficulty sighting this diurnal mammal. This should be sorted out in future research as the collared peccary is an important ecosystem engineer acting as seed predators/dispersers and helping modify plant diversity and composition by trampling seedings within the forest floor.[27]

While mammal species diversity has declined, results did include a significant increase for white-faced capuchins (*Cebus capucinus*). This is particularly heartening because the IUCN[23] reports this species as vulnerable and decreasing. Capuchins are important seed predators and dispersers and flexible omnivores.[28] As forest generalists, they are known to cope with the effects of deforestation. It would be helpful to have estimates of the current population size for this vulnerable species. We have initiated transect counts for all three primate species including the vulnerable white-faced capuchins (*Cebus capucinus*), the vulnerable mantled howler monkey (*Alouatta palliata*) and the endangered Geoffroy's spider monkey (*Ateles geoffroyi*). We have not included the night monkey (*Aotus lemurinus*); while reported by Timm[16] as a rare species, it has not been sighted here or reported since.[17]

Results suggested a trend for Old Growth Forest land use preference for mammals. However, it did not reach statistical significance. This result is consistent with Romero et al.[17] who compared use of primary to secondary forest use at La Selva[29,30] and reported no significant difference in overall sightings in either locale. The preference for Minor Rivers over Major Rivers and Streams was significant and needs further study. This may be impacted by two confounds. First, data were collected during December each year throughout the study; this is known to be a time of greater rainfall[31] that can impact water levels. Second, there are only two major rivers but 18 minor rivers. There are also relatively few streams. As a result, it may be more likely for mammal populations to be near minor rivers.

Annual citizen science data collection at LSBS continues to monitor mammals and avian species each December. Citizen scientists play a critical role in assessing biodiversity at LSBS and worldwide and are, in fact, valuable rainforest stewards both for data collection and consistent monitoring. Census data collected were efficient for monitoring most diurnal mammal species and provided a good estimate of diurnal mammal species diversity. New species were sighted (e.g., *Canis latrans*, coyote), rare species were censused (e.g., *Procyon lotor*, raccoon; *Felis pardalis*, ocelot), and most diurnal species were consistently sighted. However, most nocturnal species were not sighted during daytime hours. Among the nocturnal Marsupials, for example, the *Didelphis marsupialis* (Southern opossum) was reported as abundant at LSBS[16] but was not sighted in this study. Rodents also need further attention. Several rodent species were considered rare by Timm.[16] Rodents (rats and mice) were not censused by Romero et al.[17] or within our study. A live catch-and-release method may be better suited to monitoring rodent species diversity for small rodents (rats and mice). We suspect that rodent species diversity is a complex issue better suited to focused study.

It should be noted that there were also limitations to this study. More intensive census tracking is needed for vulnerable or endangered mammal species. This includes all three primate species that are endangered or vulnerable.[23] Other mammals that need additional census tracking include the endangered tapir (*Tapirus bairdii*) and forest rabbit (*Sylvilagus brasiliensis*). In addition, the Southern river otter (*Lutra longicaudis*) is near threatened; while considered common by Timm,[16] it was not sighted in this study or in Romero et al.[17] Second, while we assessed mammal species diversity, we had to estimate the frequency of species as the total number of years observed. Individual animals were infrequently counted. Third, we collected data at the same time every year. Some species may alter their behavior seasonally or reproductively and, consequently, are more difficult to sight in December compared to other times of the year. Last, it should be noted that citizen scientists had the dual role of avian and non-avian tract census counts. This may prove generally difficult at LSBS where upwards of 236 avian species could potentially be identified, potentially making mammal counts relatively secondary in importance.[32]

The study outlines several potential directions and challenges for future research. First, it may be important to conduct an annual citizen scientist count for mammals separate from the avian count to ensure no species are missed. Second, additional species monitoring is needed for nocturnal species as well as small-bodied rodents not included here.[33,34] That may mean alternate sampling methods need to be considered as well. Third, vulnerable and endangered species need more consistent consideration and observation to ensure their ongoing survival. We are making a start here as intensive transect counts have been initiated for all three primate species. Last, additional research for declining species, particularly the collared peccary, is needed to ensure maintenance of ongoing species biodiversity at the station.[35,36]

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Conflicts of interest

The authors declared that there are no conflicts of interest.

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