

## Research Article

# Wings Above Wilderness: Diversity and Ecological Significance of Winged Vertebrates in Nusa Barung Island Wildlife Reserved, East Java, Indonesia

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## ABSTRACT

Nusa Barung Island is a small conservation area at one of Indonesia borders in the Indian Ocean. There is limited data on biodiversity due to the accessibility and the freshwater sources availability. Data on bird species at this location is still limited; even bat data is completely absent. This study aims to identify the bird and bat species and their ecological roles. We conducted bird surveys using point count and sound recording methods and captured bats using mist and sweep nets. We found 389 individuals in 32 birds, with a diversity index ( $H'$ ) value ranging from 2.23 to 2.58. The *Pycnonotus plumosus*, *Chalcophaps indica*, and *Collocalia esculenta* recorded having wide distribution and high abundance. We identified 10 species from 141 captured bats, while *Pteropus vampyrus* colonies were directly observed. The  $H'$  index of bat species ranged from 0.46 to 0.78. The *Rousettus amplexicaudatus* were most captured. The ecological role of birds and bats includes trophic interactions in food webs and ecosystem services (insect control, seed dispersal, prey population controlling, and pollinator). The diversity of bird and bat species is relatively moderate and low, respectively, but their role in maintaining ecology is essential. The study included new records of all bats found and ten previously unreported bird species that are a basis for improving area protection.

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## INTRODUCTION

Indonesia is an archipelagic country with thousands of islands stretching more than 140 thousand km along the equator (BPS Indonesia 2024). Nusa Barung Island, one of Indonesia outermost small islands, plays a strategic role in defending the country's outermost borders. On the other hand, this island is also an essential habitat for various wildlife species. The existence of wildlife has important values for human life, including ecology, economy, aesthetics, society, and culture, as well as for science (Atmoko 2022). Ecologically, wildlife helps keep the environment in balance by controlling tropic networks, pollinating plants (Franks & Farquhar 2024), spreading seeds (Chandru et al. 2020), controlling pests, monitoring ecosystem health, keeping soil fertility high, protecting habitats, and starting new life cycles. They are an important part of biodiversity (Doley & Barman 2023).

Wildlife plays an irreplaceable role in the ecosystem of isolated small islands such as Nusa Barung (also known as Nusa Barong). Winged vertebrates such as birds and bats are two taxa that play essential role in facilitating vegetation regeneration, maintaining plant population dynamics as pollinators and seed dispersers, and controlling insect populations (Enriquez & Rodriguez 2023; García et al. 2024). Bats that are active at night complement the role of birds during the day; both works alternately. Bats, as the only flying mammals, can utilize habitats inaccessibly compared to other species, such as caves and rock crevices, contributing additional ecological complexity to the ecosystem (Sakoui et al. 2020). Given the central role of birds and bats in energy and material cycles on islands, birds and bats are intriguing taxa to understand biodiversity patterns and ecological interactions.

According to the theory of island biogeography, small islands with limited populations tend to have high levels of endemism but they are also very vulnerable to extinction (Ratter 2018). The small and uninhabited island of Nusa Barung is located six kilometers off the mainland. Nusa Barung maintains limited ecosystem and population that receive little nor outside immigration to balance population dynamics. Isolated geographic small islands by waters with other islands around them are very vulnerable, likewise Nusa Barung Island. Ecological disturbances, such as climate change, invasion of alien species (Pringle et al. 2023), or habitat changes due to human activities, can increase threat to the survival of existing species (Banks-Leite et al. 2020). Small islands' limited resources and space require each species to adapt uniquely (Ciarle et al. 2024). Ecological specialisation, if disturbed, can lead to the collapse of the island ecosystem.

The isolated geographical characteristics of Nusa Barung Island provide ideal conditions for studying the island biogeography, biodiversity, species evolution, ecosystem dynamics, and the impact of geographic isolation on biodiversity. However, there are still limited publications related to its flora and fauna. There have only been two reported studies on the flora of Nusa Barung (Jacobs 1958; Partomihardjo & Ismail 2008) and one study on the fauna has focused on macro-moth taxa (Sutrisno 2007). The Natural Resources Conservation Agency (NRCA) East Java (BBKSDA Jawa Timur) conducted a bird survey in 2023, but the results remain unpublished. Uninhabited island, high seas, unpredictable weather, and a shortage of freshwater sources are limitations for staying longer on this island, which causes rare research on this island.

This is the first research concerning bat and bird species on Nusa Barung Island. This study examined and evaluated the diversity of bird and bat species, their ecological functions within the island, and their contributions to ecosystem services.

## MATERIALS AND METHODS

### Study area

The research was conducted over two weeks on Nusa Barung Island, which is administratively located in Puger Kulon Village, Puger District, Jember Regency, East Java, Indonesia (Figure 1).

The research site is a conservation area as a wildlife sanctuary managed by the NRCA East Java (BBKSDA Jawa Timur). This island, as part of the of outermost islands series in Indonesia, is located off the southern coast of Java Island. The area of the island is 79.6 km<sup>2</sup>; in general, the topography along the north coast is steeper than the south, with a maximum height of 280 meters above sea level (m a.s.l.) with an average height of 127 m a.s.l., while the coast in the southwest is gentler than other locations (<https://earthexplorer.usgs.gov/>). The primary habitat types found on the island are coastal forests, karst, mangroves, and inland forests (Partomihardjo & Ismail 2008).

Jeruk, Cambah, and Ceret Bay are the northern coasts of the island, with sloping to steep rocky topography. Coastal forests and lowland forests cover these areas in general. There are bat caves, rain-fed lakes in Pucung Prau, and bunkers from World War II in Jeruk Bay around. Cambah Bay is the starting point of the entrance route to Kedok Watu, and between them is a rain-fed lake in Sumber Gempol. Kedok Watu is the deepest terrestrial part of the island that the research can reach. It has mineral soil and karst conditions; lowland forest types and freshwater sources were found. Kandangan Bay is the only accessible southern part of the island, with cliffs almost along the southern coast. The area also encompasses Monyetan Bay and Endog-endogan, which feature coastal forest types, karst, and a small portion of a mangrove.

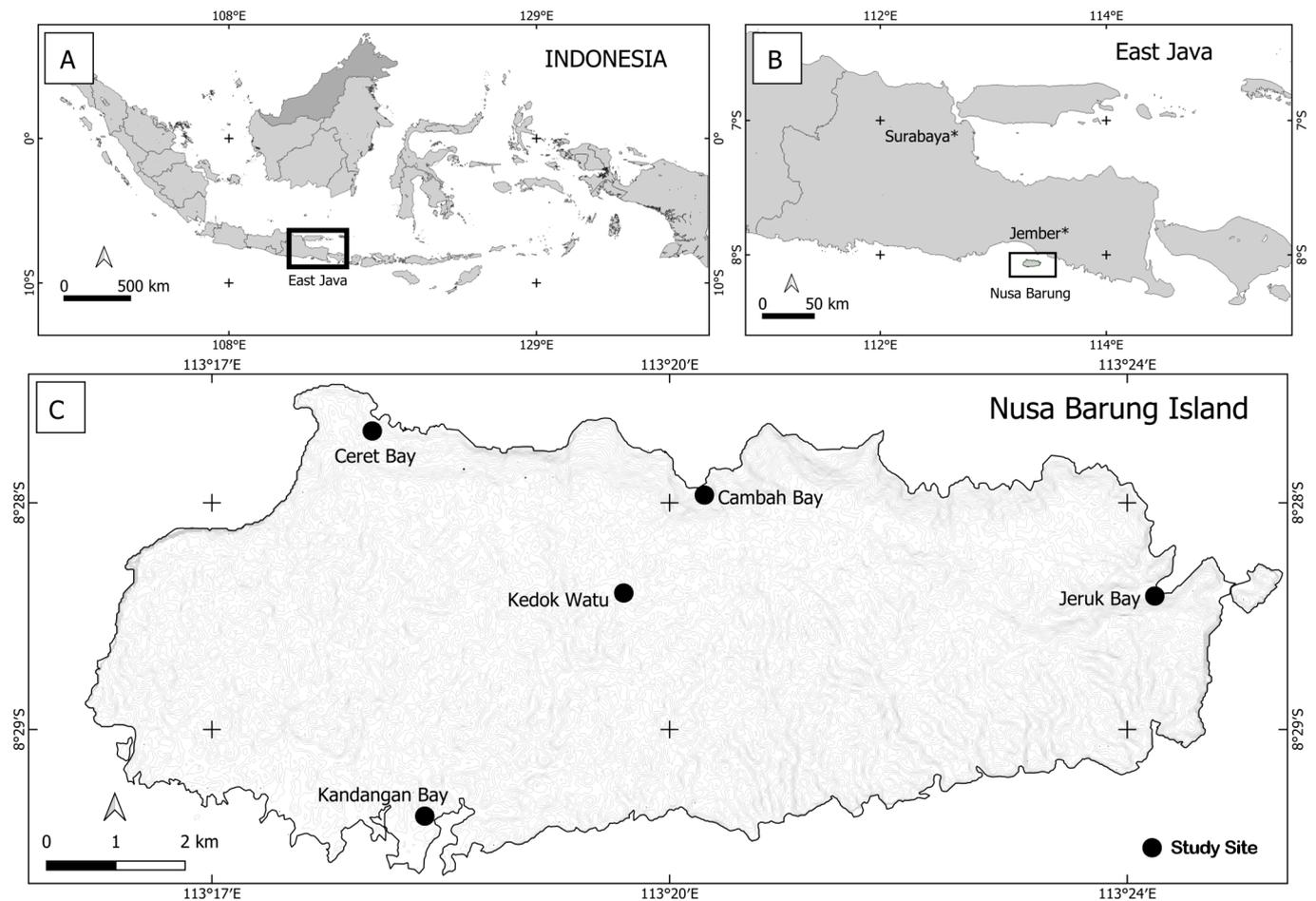


Figure 1. Maps of study site in Nusa Barung Island, East Java, Indonesia.

## Data collection procedures

### Birds detection

Bird observations used the point count method (Joel et al. 2024). In this method, observers walk at a constant speed along the transect and then stop every  $\pm 200$ –300 m to record all species of birds observed for 15–20 minutes. We conducted diurnal bird observations in the morning at 06:30–09:00 and in the afternoon at 15:30–18:00. Bird observation locations are Kandangan Bay, Jeruk Bay, Cambah Bay, and Ceret Bay. The observation duration for each location is two days, except in Ceret Bay, which is only one day due to time constraints and weather conditions turning bad. We identified the bird species using a bird field guide (Eaton et al. 2021). The total number of bird observation points was 35. We also identify bird sounds by recording and analyzing them using the BirdNET v. 1.93 application on a smartphone.

### Bats survey

The bat survey used the capture method with mist nets. We installed a total of 44 net nights in Kandangan Bay (16 net nights), Jeruk Bay (25 net nights), and Kedok Watu (3 net nights). Each set of 14 m long mist nets was stretched between two 3 m high aluminum poles placed at the border of the forest, targeting Megachiroptera and the forest alley for Microchiroptera. We installed the mist net approximately from 18:00 to 05:00. We also conducted surveys in the bat caves around Jeruk Bay using sweep nets. We conducted mist net inspections every hour at night to prevent bats from dying due to entanglement. We carefully released the captured bats from the nets and then placed them in calico bags to further identify their families based on general morphology such as leaf nosed, snout, tail, and ear. We determined the species level by measuring the forearm (FA), tail (T), wing length (W), and ear length (E) with calipers and weighing the animals with digital scales. Sex is identified based on the presence of more prominent nipples in females and the presence of a scrotum in males. We used Suyanto's (2001) guide for bat identification.

### Data analysis

We used the Shannon index ( $H'$ ) to measure alpha diversity and Bray-Curtis dissimilarity for beta diversity. We also determined the evenness index ( $J$ ) of bird and bat species to assess the relative abundances of species within a community. We used the open-access program PAST 4.03 (Hammer et al. 2001) for data analysis. An analysis of the ecological role of birds and bats is based on the literature (Green & Elmberg 2014; Sheherazade et al. 2017; Setianto et al. 2017; Taylor 2019; Kruskop et al. 2019; Duya et al. 2020; Chan et al. 2021; Martínez-Núñez 2021; Prakarsa et al. 2023; Mariyappan et al. 2023). We conducted a species diversity analysis on bat species caught in nets during the survey in Kandangan Bay, which represents the south, and Jeruk Bay, which represents the north. We directly observed bats caught using sweep nets in bat caves and bunkers but excluded those caught in Kedok Watu from the analysis because the data was insufficient.

## RESULTS AND DISCUSSION

### Bird diversity

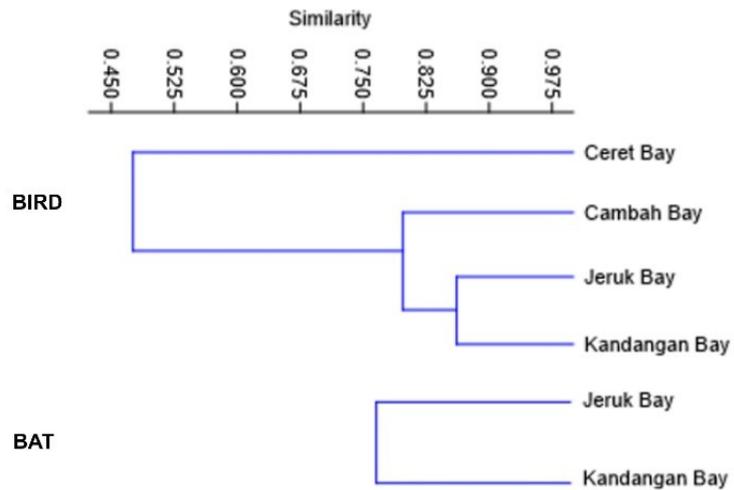
The observation results from four different locations successfully identified a total of 32 bird species, with a total of 389 individuals. The number of species recorded at each observation site varied, ranging from 12 to 22 species. The results of the species diversity index ( $H'$ ) calculation showed moderate values that were not much different between locations, namely in the range of 2229 to 2576. Meanwhile, the species evenness index ( $J$ ) showed that, in general, each observation location had moderate to high index values in the range of

0.541 to 0.774. At the study location, the distribution of individual birds within the community was uniform (Table 1).

**Table 1.** Bird species diversity and evenness index.

Parameters	Location			
	Kandangan Bay	Jeruk Bay	Cambah Bay	Ceret Bay
Number of individuals	92	115	149	33
Number of Species	20	22	16	12
Diversity Index (H')	2.576	2.476	2.350	2.229
Evenness Index (J)	0.657	0.541	0.657	0.774

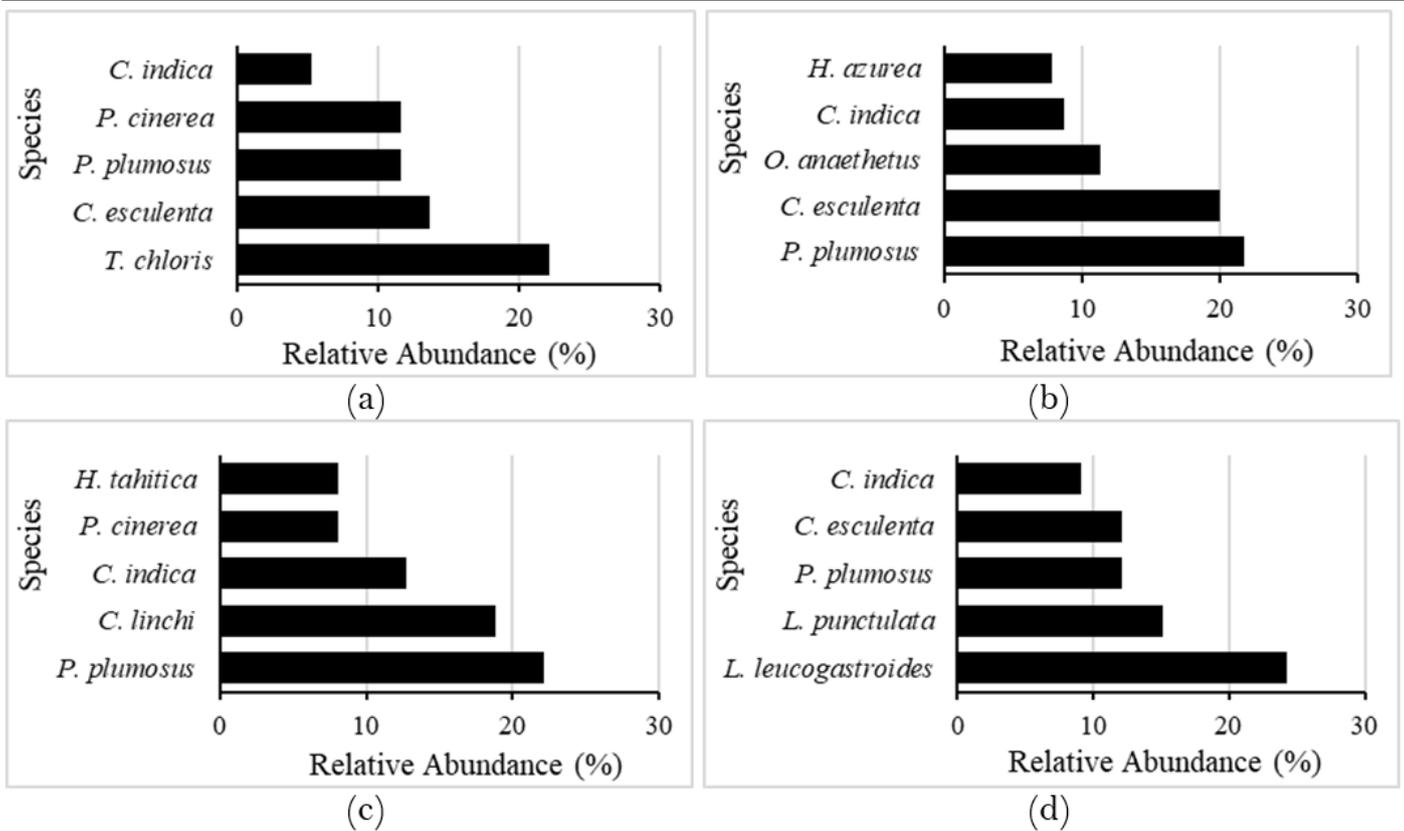
Ceret Bay is the most distinct location, clustering separately with similarity level for around 0.45, indicating a significantly different bird composition (Figure 2). In contrast, Cambah Bay, Jeruk Bay, and Kandangan Bay form more similar group, with Jeruk Bay and Kandangan Bay showing the highest similarity (above 0.90), suggesting nearly identical bird assemblages. Cambah Bay is slightly similar but still closely related to this cluster (around 0.825 similarity). These patterns may be influenced by habitat characteristics, food availability, or other ecological factors that shape bird distributions. Additionally, the shorter bird observation period in Ceret Bay may have contributed to its distinct species composition.



**Figure 2.** Beta diversity of birds and bats based on Bray-Curtis similarity.

Several bird species appeared to have wide distribution and high relative abundance values, such as olive-winged bulbul (*Pycnonotus plumosus*), grey-capped emerald-dove (*Chalcophaps indica*), and glossy swiftlet (*Collocalia esculenta*). These species are always present in the top five bird species with the highest relative abundance at each location (Figure 3). The distribution of these birds tends to be wide and occupies the entire island habitat. They are species with the ability to adapt in various types of habitats. The adaptability of a species is very important to avoid extinction and to maintain its ecological role. However, several species are found only in certain locations, such as *Caprimulgus macrurus* in Kandangan Bay, *Hemiprocne longipennis* in Jeruk Bay, and *Accipiter trivirgatus* in Jeruk Bay.

A total of nine bird species in this study are protected species based on Indonesian Regulations (Table 2). One of these bird species is the Javan hawk-eagle, which is also categorised as endangered in the IUCN Red List and Appendix I in the CITES list. However, the majority of bird species are still in the least concern category. Of the five bird species that have been included in the CITES appendix list, all belong to the raptor group (eagle/falcon).



**Figure 3.** Top five bird species based on relative abundance (a) Kandangan Bay (b) Jeruk Bay (c) Cambah Bay (d) Ceret Bay.

All bird species recorded on Nusa Barung Island are the same as those found on the Java mainland. If we combine the richness of bird species in this study with previous surveys that recorded 53 bird species (BBKSDA Jawa Timur 2023), we found total of 67 species. We have added ten species to the list that were previously unreported. They are *Accipiter trivirgatus*, *Lalage nigra*, *Corvus enca*, *Cacomantis variolosus*, *Dicrurus leucophaeus*, *Hemiprocne longipennis*, *Onychoprion anaethetus*, *Pachycephala cinerea*, and *Gallus varius*. *Corvus enca* is an exception, as it is not a naturally occurring species but rather the result of a release (Pers. Comm. Wawan; area's staff manager). It's crucial to update the species that persist as the island's challenging terrain conditions have prevented exploration in all areas. However, the small-island effect phenomenon and biphasic species-area relationship (Chisholm et al. 2016) suggest that an increase in area does not always lead to a proportional increase in the number of species.

The total number of bird species on Nusa Barung Island is currently equivalent to 12.96 % of all bird species recorded in Java-Bali, which is 517 species (Burung Indonesia 2024). Several study sites on the islands in the Indian Ocean south of Java Island have reported a variety of bird species richness, including 66 species on Sempu Island (Sukistyanawati et al. 2016), 148 species on Nusa Kambangan Island (Suripto & Hamidy 2006), and 149 species on Christmas Island (James & McAllan 2014). Although karst forest types dominate both islands, their sizes and levels of habitat heterogeneity naturally differ. Nusa Barung Island, together with Sempu Island, is the smallest island among the others, so habitat variation is more limited. In addition, on Nusa Barung Island, the presence of freshwater as one of wildlife's basic needs is minimal, which impacts the carrying capacity of wildlife habitats (Grebner et al. 2022).

The shrubby magpie (*Pycnonotus plumosus*) has a wide distribution and abundant population. This species is known to adapt well from coastal areas to the island's interior. In various other locations, this species is also known

**Table 2.** List of birds, conservation status, and its distribution in Nusa Barung Island.

No	Family	Species	Protected status and conservation category			Feeding guild	Distribution
			Protected status	IUCN Red List	CITES		
1	Accipitridae	<i>Haliaeetus leucogaster</i>	√	LC	App.II	Car	a b d c
2	Accipitridae	<i>Spilornis cheela</i>	√	LC	App.II	Car	b c
3	Accipitridae	<i>Nisaetus bartelsi</i>	√	EN	App.I	Car	b d
4	Accipitridae	<i>Accipiter trivirgatus</i>	√	LC	App.II	Car	b
5	Alcedinidae	<i>Todiramphus chloris</i>	-	LC	-	IP	a b c d
6	Alcedinidae	<i>Ceyx rudiforsa</i>	-	LC	-	IP	a b c
7	Apodidae	<i>Collocalia esculenta</i>	-	LC	-	Ins	a b c d
8	Apodidae	<i>Collocalia linchi</i>	-	LC	-	Ins	a b
9	Ardeidae	<i>Egretta sacra</i>	-	LC	-	IP	a b d
10	Artamidae	<i>Artamus leucorhynchus</i>	-	LC	-	Ins	a
11	Campephagidae	<i>Lalage nigra</i>	-	LC	-	Ins	a
12	Caprimulgidae	<i>Caprimulgus macrurus</i>	-	LC	-	Ins	a
13	Columbidae	<i>Spilopelia chinensis</i>	-	LC	-	Gran	a
14	Columbidae	<i>Chalcophaps indica</i>	-	LC	-	Frug	a b c d
15	Corvidae	<i>Corvus enca</i>	-	LC	-	FI	b
16	Cuculidae	<i>Cacomantis variolosus</i>	-	LC	-	Ins	b c
17	Dicruridae	<i>Dicrurus leucophaeus</i>	-	LC	-	Ins	b c
18	Estrildidae	<i>Lonchura leucogastroides</i>	-	LC	-	Gran	d
19	Estrildidae	<i>Lonchura punctulata</i>	-	LC	-	Gran	d
20	Falconidae	<i>Falco peregrinus</i>	√	LC	App.I	Car	b c
21	Hemiprocnidae	<i>Hemiprocne longipennis</i>	-	LC	-	Ins	b
22	Hirundinidae	<i>Hirundo tahitica</i>	-	LC	-	Ins	a c
23	Laridae	<i>Onychoprion anaethetus</i>	√	LC	-	IP	a b
24	Laridae	<i>Sterna sumatrana</i>	√	LC	-	IP	a b
25	Monarchidae	<i>Hypothymis azurea</i>	-	LC	-	Ins	a b c d
26	Nectariniidae	<i>Cinnyris jugularis</i>	-	LC	-	NI	a c d
27	Pachycephalidae	<i>Pachycephala cinerea</i>	-	LC	-	Ins	a b c d
28	Phasianidae	<i>Gallus gallus</i>	-	LC	-	Om	a b
29	Phasianidae	<i>Gallus varius</i>	-	LC	-	Om	c
30	Pycnonotidae	<i>Pycnonotus goiavier</i>	-	LC	-	FI	a c
31	Pycnonotidae	<i>Pycnonotus plumosus</i>	-	LC	-	FI	a b c d
32	Rhipiduridae	<i>Rhipidura javanica</i>	-	LC	-	Ins	b

Notes: a. Kandangan Bay; b = Jeruk Bay; c = Cambah Bay; d = Ceret Bay; Car = carnivore; IP = insectivore/carnivore; Ins = insectivore; Gran = granivore; Frug = frugivore; FI = frugivore/insectivore; NI = nectarivore/insectivore; Om = omnivore.

as an adaptive species (Suripto & Hamidy 2006) and is considered a non-forest-dependent species (Tang et al. 2015). Meanwhile, the high abundance and wide distribution of barn swifts (*Collocalia esculenta*) on Nusa Barung Island are a natural phenomenon, primarily due to the island's karst dominance, where numerous caves serve as the primary habitat for swiftlets. Nusa Kambangan and Christmas Islands also record abundant populations of this species, classifying it as an adaptive bird species (Suripto & Hamidy 2006; James & McAllan 2014).

### Bats diversity

Nets and sweep nets caught a total of 141 individual bats during the survey, representing 10 species from five families (Table 3). At dusk, we observed a colony of large flying foxes (*Pteropus vampyrus*) flying around Kandangan Bay. The five bat species found in the bat caves around Jeruk Bay are Dusky leaf-nosed bat (*Hipposideros ater*), Lesser-wooly horseshoe bat (*Rhinolophus sedulus*), Creagh's horseshoe bat (*Rhinolophus creaghi*), Diadem leaf-nosed bat (*Hipposideros diaderma*), and Javan pipistrelle (*Pipistellus javanicus*). Kedok Wa-

**Table 3.** Species and conservation status of bats in Nusa Barung Island.

No	Family	Species	English Name	Red List IUCN	CITES	Distributions
1	Hipposideridae	<i>Hipposideros ater</i>	Dusky leaf-nosed bat	LC	no CITES	d
2	Hipposideridae	<i>Hipposideros diadema</i>	Diadem leaf-nosed bat	LC	no CITES	d
3	Megadermatidae	<i>Megaderma spasma</i>	Lesser false vampire	LC	no CITES	a, e
4	Pteropodidae	<i>Cynopterus brachyotis</i>	Lesser dog-faced fruit bat	LC	no CITES	a, b
5	Pteropodidae	<i>Cynopterus horsfieldi</i>	Horsfield's fruit bat	LC	no CITES	a, c
6	Pteropodidae	<i>Pteropus vampyrus</i>	Large flying-fox	EN	App. II	a
7	Pteropodidae	<i>Rousettus amplexicaudatus</i>	Geoffroy's rousette	LC	no CITES	a
8	Rhinolophidae	<i>Rhinolophus creaghi</i>	Creagh's horseshoe bat	LC	no CITES	d
9	Rhinolophidae	<i>Rhinolophus sedulus</i>	Lesser-wooly horseshoe bat	NT	no CITES	d
10	Vespertilionidae	<i>Philetor brachypterus</i>	Short-winged pipistrelle	LC	no CITES	c
11	Vespertilionidae	<i>Pipistrellus javanicus</i>	Javan pipistrelle	LC	no CITES	d

Notes: a = Kandangan Bay, b = Jeruk Bay, c = Kedok Watu, d = Goa Kelelawar, e = Bunker.

tu, a forest area in the central part of Nusa Barung Island, is home for two species of bats: the short-winged pipistrelle (*Philetor brachypterus*) and the Horsfield's fruit bat (*Cynopterus horsfieldi*). We only caught the lesser false vampire (*Megaderma spasma*) in the net twice, in Kandangan Bay and Jeruk Bay. However, its presence is hundreds in the bat cave and Japanese bunker around Jeruk Bay.

The diversity of bat species in the southern area (Kandangan Bay) is 0.46, lower than in the northern part (Jeruk Bay), which is 0.78. The species of bats in Jeruk Bay are more evenly distributed than in Kandangan Bay, with Evenness Index (J) values of 0.433 and 0.335, respectively. Meanwhile, the community similarity between the two locations is 75 % (Figure 2).

The discovery of all bat species marks a new record for Nusa Barung Island. Most of them are unprotected. The large flying fox (*Pteropus vampyrus*) is the only endangered species and is included in CITES Appendix II. Other species are included in Least Concern, except the lesser-wooly horseshoe bat (*Rhinolophus sedulus*), which is listed in Near Threatened.

Males dominated the sex composition of bats caught in nets, accounting for 66 %. Specifically, for the *R. amplexicaudatus* species, which is the most frequently caught in nets, the number of females was only 34 % of the 123 individuals caught.

Bat morphological measurements are one of the bases for identification. However, these sizes often vary for the same species in different habitat locations. Furthermore, the maturity status of individual bats also influences their size. In addition to other characteristics, such as the presence of a tail, claws on the second digit, tragus, and body weight, the forearm serves as a useful reference for identification (Table 4). The diadem leaf-nosed bat (*Hipposideros diadema*) was the largest of the species captured (FA: 8.5–9.6 cm), while the large flying bat (*Pteropus vampyrus*) was the largest bat observed. The length of the forearm of the bats found in the study area shows that it is relatively within the size range of bats in general, except for the *R. amplexicaudatus*, which has a smaller forearm with an average of 63 mm, while the general size range is 77–87 mm (Suyanto 2021).

The karst ecosystem on Nusa Barung Island has many caves that are the best habitat for bats. The creagh's horseshoe bat (*Rhinolophus creaghi*) is a species that relies on the karst area for its habitat (Suyanto & Struebig 2007). However, due to limited time, the researchers have only explored one cave, the Goa Kelelawar in Jeruk Bay, and even then, they only caught several spe-

**Table 4.** Mophometric of bats in Nusa Barung Island.

Species	N	Fore Arm	Weight	Tail	Ears	Wings
		$\bar{x}$ (Range) (mm)	$\bar{x}$ (Range) (g)	$\bar{x}$ (Range) (mm)	$\bar{x}$ (Range) (mm)	$\bar{x}$ (Range) (mm)
<i>Rousettus amplexicaudatus</i> *	123	63 (50-74)	27.7 (16.0-57.0)	1.4 (0.7-2.0)	1.4 (1.1-1.9)	37.2 (305-470)
<i>Cynopterus horsfieldi</i> *	7	71 (61-81)	49.4 (31.3-75.0)	1.2 (0.7-1.8)	1.7 (1.4-1.9)	440 (370-520)
<i>Cynopterus brachyotis</i> *	6	59 (54-64)	27.9 (22.6-33.7)	1.0 (0.8-1.5)	1.4 (1.2-1.5)	363 (320-400)
<i>Hipposideros diadema</i> */**	2	88 (85-96)	44.0 (41.4-46.5)	4.7 (4.2-5.3)	2.4 (1.9-3.0)	510 (480-540)
<i>Megaderma spasma</i> *	2	57 (55-59)	18.0 (18.0)	-	3.8 (3.7-3.8)	430 (390-470)
<i>Hipposideros ater</i> **	1	37.9	46.0	2.4	1.7	220
<i>Rhinolophus creaghi</i> **	1	52.8	10.8	1.7	2.2	280
<i>Rhinolophus sedulous</i> **	1	41.6	57.0	2.1	2.2	250
<i>Philetor brachypterus</i> *	1	28.6	53.0	2.8	0.8	220
<i>Pipistrellus javanicus</i> **	1	35.4	36.0	3.5	0.6	243

Note: \* Mistnet captured, \*\*Captured in the cave

cies of bats for identification. There was a thick layer of guano on the cave floor and there were several piles of bags containing it at the mouth of the cave. According to Wawan (Pers. Comm.), the area's staff manager, there was an attempted guano theft at that location, but the forest ranger successfully prevented it. In addition, there are at least two Japanese heritage bankers from World War II between Jeruk Bay and Ketimo Beach, also inhabited by dozens of lesser false-vampires (*Megaderma spasma*). Generally, these bats roost in caves, tunnels, and wooden holes and live in abandoned buildings around the garden (de Mel et al. 2024).

### Ecological roles

The ecological role of birds and bats includes two roles, namely trophic interactions in their involvement in food webs and ecosystem services such as pest/insect control, seed dispersal, controlling the population of prey, and pollinator. Specifically, Table 5 groups the role of birds at the tropic level into eight feeding guilds, encompassing 32 identified species. Table 6 presents the general functions of each species of bat.

Insectivorous birds have an essential ecological role in controlling insect populations in karst ecosystems. Karst ecosystems with many rock crevices and caves have provided ideal microhabitats for various insects. Insects, together with arachnids, are the most dominant taxa in various karst ecosystems worldwide (Culver & Pipan 2019). Groups of granivores, frugivores, and other generalist birds help the plant regeneration process on Nusa Barung Island. Columbidae and Pycnonotidae are bird families that play an essential role in seed dispersal in the forest (Corlett 2017). Some bird species, such as *Chalcophaps indica* and *Pycnonotus plumosus*, are also highly abundant. Both bird species prefer fruit and seeds, but *C. indica* is known to be rather terrestrial. They often pick up fruit that falls on the forest floor. Its presence on Nusa Barung Island is more recognizable by its sound than by direct sight.

Raptor species, such as eagle/falcon and pollinator birds, are keystone species that need more attention. Interestingly, Nusa Barung Island is a habitat for at least five species of raptors. The Javan hawk-eagle (*Nisaetus bartelsi*), an endangered species, is among them. Raptors are top predators and excellent indicators of the health status of the ecosystem. In this study, *Cinnyris jugularis* stands out as the sole pollinator bird. Usually, groups of nectarivore

**Table 5.** Ecological roles of bird in Nusa Barung Island.

No	Feeding Guild	Percentage (%)	Mainly Ecological Services	References
1	Insectivore	35.48	Controlling population of insects	Martínez-Núñez 2021; Mariyappan et al. 2023
2	Carnivore	16.13	Balancing ecosystem; controlling population of prey, scavenger	Mariyappan et al. 2023
3	Insectivore-Piscivore	16.13	Controlling population of insect and fish, nutrient cycling	Green & Elmberg 2014
4	Frugivore-Insectivore	9.69	Seed dispersal; controlling population of insects	Mariyappan et al. 2023
5	Granivore	9.68	Seed dispersal	Mariyappan et al. 2023
6	Omnivore	6.45	Prey for predator, controlling population of insect in forest floor	Setianto et al. 2017
7	Frugivore	3.23	Seed dispersal	Mariyappan et al. 2023
8	Nectarivore-Insectivore	3.23	Pollinator	Mariyappan et al. 2023

**Table 6.** Ecological roles of bats on the habitat in Nusa Barung.

No	Species	Mainly Ecological Services	Feeding Guilds	References
1	<i>Hipposideros ater</i>	Pest control	Insectivore	Prakarsa et al. 2023
2	<i>Hipposideros diadema</i>	Pest control	Insectivore	Prakarsa et al. 2023
3	<i>Megaderma spasma</i>	Pest control	Insectivore	Prakash et al. 2021
4	<i>Cynopterus brachyotis</i>	Seed dispersal, pollinators	Frugivore	Chan et al. 2021
5	<i>Cynopterus horsfieldi</i>	Seed dispersal, pollinators	Frugivore, Nectarivore	Chan et al. 2021
6	<i>Pteropus vampyrus</i>	Seed dispersal, pollinators	Frugivore, nectarivore	Duya et al. 2020
7	<i>Rousettus amplexicaudatus</i>	Seed Dispersers, pollinators	Frugivore	Sheherazade et al. 2017
8	<i>Rhinolophus creaghi</i>	Pest control	Insectivore	Taylor 2019
9	<i>Rhinolophus sedulus</i>	Pest control	Insectivore	Taylor 2019
10	<i>Philetor brachypterus</i>	Pest control	Insectivore	Taylor 2019
11	<i>Pipistrellus javanicus</i>	Pest control	Insectivore	Kruskop et al. 2019

birds like to visit flowers that are brightly coloured, do not have a striking odor, and have abundant nectar (Cronk & Ojeda 2008).

Since bats are the only mammals that can fly, they can search further for food. This makes them an important component at various trophic levels, influencing the population dynamics of species (Förster et al. 2019). Several species of bats that fly long distances can visit small islands, contributing to the transfer of energy and matter between ecosystems (Valido & Olesen 2023).

The study discovered at least four frugivorous and nectarivorous bats, which play crucial role in seed dispersal and pollination, particularly for plants that flower at night in locations that are challenging for other pollinators to access. Several tree species in the tropics depend highly on bats as the primary agents of their seed dispersal (Chan et al. 2021). Frugivorous bats play essential role in the dispersal of pioneer plant seeds on small islands, making them critical players in forest regeneration dynamics (Valido & Olesen 2023). Nectarivorous bats, especially from the Pteropodidae family, play role in pollinating various species of trees in tropical areas across islands (Fleming et al. 2009) that helps maintain plants' genetic diversity by spreading pollen between isolated islands.

Insectivorous bats, as biological agents, play an essential role in maintaining ecosystem balance by controlling the explosion of insect populations that have the potential to become pests for plants in tropical ecosystems (Prakash et al. 2021). Most of these species are very efficient at catching insects. Extrapolation results from the *Tadarida brasiliensis* colony in Texas, United States, showed that up to 20 million colonies can prey on more than 600 thousand tons of insects annually (Suyanto 2001). In addition, with their

ability to migrate long distances, even between islands, bats can play role in controlling the population of insect pests that often have no natural predators in small island ecosystems (Prakash et al. 2021). Some of the insect species have the potential to spread diseases, such as malaria or other zoonotic diseases.

Bats act as a link between habitats on and off the island. The long-distance movement of bats makes them important agents in connecting geographically isolated habitats or between fragmented habitats. The ability of bats to travel long distances allows them to function as essential vectors in the transfer of genetic material, nutrients, and energy between small and isolated islands (Moulistanos et al. 2023; Valido & Olesen 2023; Ciarle et al. 2024). Genetic exchange between isolated bat populations prevents genetic isolation, which has the potential to reduce genetic diversity. Bats that move long distances will bring new genes to isolated populations, helping to increase genetic diversity, which is essential for adaptation to environmental changes (Moulistanos et al. 2023).

## CONCLUSIONS

Winged vertebrates, such as birds and bats, can support ecosystem resilience on the Nusa Barung Island, which play essential roles in various ecological functions. Although the diversity of bird is moderate and bat species is relatively low, their role in maintaining ecology is essential. These roles potentially support plant regeneration and biodiversity, which are essential for maintaining ecosystem stability in the face of environmental disturbances. Bats and birds have similar ecological roles, synergizing at different times, day and night. All the bat species found in this study area are new records; ten bird species have also made their first record. Future research on bat species on this island still has potential; we have only explored one of the many caves, and the biodiversity of the land forest still holds mysteries that we have yet to unravel. Protecting the island from external disturbances and various human activities, such as bird hunting and guano harvesting, must be an important concern. The results of this study strengthen the species diversity database of Nusa Barung Island to improve the status of the area and its protection as the country's outermost border island—the border of state sovereignty.

## AUTHOR CONTRIBUTION

T.A. planned and developed study design, collected data, wrote the manuscript, supervised the study, and funding recipients; M developed study design, collected data, and wrote the manuscript; W collected data, did mapping, and wrote the manuscript; F.D.N.A., O.H., T.A.R., A.I.Z., B.S.S., B.S. collected data, wrote and edited the manuscript; I.P. supervised the study, edited, and proofread the manuscript.

## ETHICS CLEARANCE APPROVAL

Ethics clearance approved by Ethics Commission for Animal Care and Use, BRIN (No: 008/KE.02/SK/01/2024). The research permit has been approved by the Ministry of Environment and Forestry, Republic of Indonesia (No: SI.889/K.2/BIDTEK.1/KSA/5/2024).

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## CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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