Bats of Sicily: historical evidence, current knowledge, research biases and trends

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Abstract - Insular bat communities are a preeminent conservation taxon due to their ecological role and intriguing and unique species composition. Sicily is the largest island in the Mediterranean. However, research on Sicilian bats is still scattered, with substantial information being overlooked. Here we present a systematic review of all available bibliographic information from 1810 to 2022, including grey literature, archives, and peer-reviewed publications. The analyses of bibliographic sources permitted us to evaluate the status of research on bats using the Bat Research Efficiency (BRE) and Species-Research Effort Allocation (SREA) metrics. A total of 81 documents were obtained. Since 1955, an average of 1.2 contributions have been issued per year. Over half of the documents are in Italian. The studies are primarily conducted in north-western (40%) and south-eastern (28%) Sicily, mainly in the provinces of Palermo and Siracusa. Most of the contributions concern "Species records" (61%) and "Ecology" (21%). There were 28 species reported, but a significant bias exists towards *Myotis myotis*, *Miniopterus schreibersii*, *Rhinolophus ferrumequinum*, *Myotis capaccinii*, and *Rhinolophus euryale*. Around 31.5% of the studies focused on threatened species, while 68.5% concentrated on non-threatened species, with an overall preference for cave-dwelling species. Yet, SREA analysis demonstrates a lack of research efforts for all species. We encourage the use of a multidisciplinary approach towards under-studied species while covering geographical gaps and increasing public awareness of the functional role of bats in natural ecosystems.

Keywords: bats, checklist, conservation, history of fauna, Sicily.

Riassunto - Chirotteri di Sicilia: evidenze storiche, conoscenze attuali, limiti e tendenze della ricerca.

Le comunità di pipistrelli insulari sono un taxon preminente per la conservazione a causa del loro ruolo ecologico e della composizione interessante e unica delle specie. La Sicilia è l'isola più grande del Mediterraneo. Tuttavia, le ricerche sui pipistrelli siciliani sono ancora frammentarie e alcune informazioni importanti vengono trascurate. Qui presentiamo una revisione sistematica di tutte le informazioni bibliografiche disponibili dal 1810 al 2022, compresa la letteratura grigia, gli archivi e le pubblicazioni soggette a peer-review. L'analisi delle fonti bibliografiche ci ha permesso di valutare lo stato della ricerca sui pipistrelli utilizzando le metriche Bat Research Efficiency (BRE) (Efficienza della ricerca sui pipistrelli) e Species-Research Effort Allocation (SREA) (Ripartizione dello sforzo di ricerca per specie). In totale sono stati rinvenuti 81 documenti. Dal 1955 sono stati pubblicati in media 1,2 contributi all'anno. Oltre la metà dei documenti è in italiano. Gli studi sono stati condotti principalmente nella Sicilia nord-occidentale (40%) e sud-orientale (28%), soprattutto nelle province di Palermo e Siracusa. La maggior parte dei contributi riguarda la "segnalazione di specie" (61%) e "l'Ecologia" (21%). Sono state rinvenute 28 specie, ma esiste una significativa polarizzazione verso *Myotis myotis*, *Miniopterus schreibersii*, *Rhinolophus ferrumequinum*, *Myotis capaccinii* e *Rhinolophus euryale*. Circa il 31,5% degli studi si è concentrato su specie minacciate, mentre il 68,5% su specie non minacciate, con una preferenza generale per le specie che vivono nelle grotte. Tuttavia, l'analisi SREA dimostra la mancanza di sforzi di ricerca per tutte le specie. Incoraggiamo l'uso di un approccio multidisciplinare e verso le specie poco studiate, coprendo le lacune geografiche e aumentando la consapevolezza del pubblico sul ruolo funzionale dei pipistrelli negli ecosistemi naturali.

Parole chiave: pipistrelli, elenco delle specie, conservazione, Sicilia, storia della fauna.

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Received for publication: 18 March 2023
Accepted for publication: 18 July 2023
Online publication: 11 October 2023

INTRODUCTION

Islands are renowned for their intriguing patterns of bat species richness and endemism (Myres *et al.*, 2002; Conenna *et al.*, 2017). There are over 1456 species of bats worldwide, with 25% being insular endemics (Burgin *et al.*, 2018). They are considered more vulnerable to irregular conversions and threats (Jones *et al.*, 2009). This entails drastic habitat changes by urbanization, forest degradation, and cave disturbances (Frick *et al.*, 2020; Massaad *et al.*, 2022). Such factors have a downstream effect on insular bat population conservation in general and can influence bat foraging behaviour, diet availability, and ecological dynamics across islands (McCreless *et al.*, 2016).

Sicily is the largest island in the Mediterranean and is recognized as a hotspot for biodiversity conservation, given its unique biogeographical patterns, transitional position between Europe and Africa, and its wide range of natural habitats and protected areas (Médail &

Quézel, 1999). Currently, 26 insectivorous bat species occur in Sicily (Fichera *et al.*, 2022). They play essential ecosystem roles, particularly as natural suppressors of various pest insects (Williams-Guillén *et al.*, 2016; Puig-Montserrat *et al.*, 2020), and as bioindicators of environmental changes (Ancillotto *et al.*, 2016; Russo *et al.*, 2021). However, the rapid pace of anthropogenic and environmental disturbances, such as agricultural practices, habitat fragmentation, wind turbines, and climate change, are regarded as the primary threat factors affecting Mediterranean bats, including insular bats (Massaad *et al.*, 2022). Hence, an appropriate conservation plan must be implemented immediately to avert irreparable losses.

Research on Sicilian bats is scattered, and limited to brief notes, books, and predominantly Italian-language publications. Hence, relying solely on English or peer-reviewed literature can lead to overlooking important information, thus hampering future research and conservation efforts. In this sense, systematic methods for integrating historical and overlooked datasets can improve the quality of review syntheses and provide detailed insight, allowing us to develop a more comprehensive and less biased overview.

In this context, it is necessary to leverage all existing evidence and available literature to obtain a thorough and representative understanding of the current research status, priorities, and gaps. Hereafter, we intend to present a baseline and future research framework based on historical and current research status. Finally, we aim to provide an updated list of bat species currently represented and reported across the literature.

MATERIALS AND METHODS

Literature search and review

A systematic search was developed and implemented between March 10th and April 25th, 2022, following the PRISMA protocol (Fig. 1) as described by Moher *et al.* (2015). The systematic research aimed to summarize the evidence and available knowledge about Sicilian bats. Initial datasets were compiled from two types of research sources: (1) Primary dataset and (2) Secondary dataset documents. The dataset queries were not restricted to any time frame or language barrier.

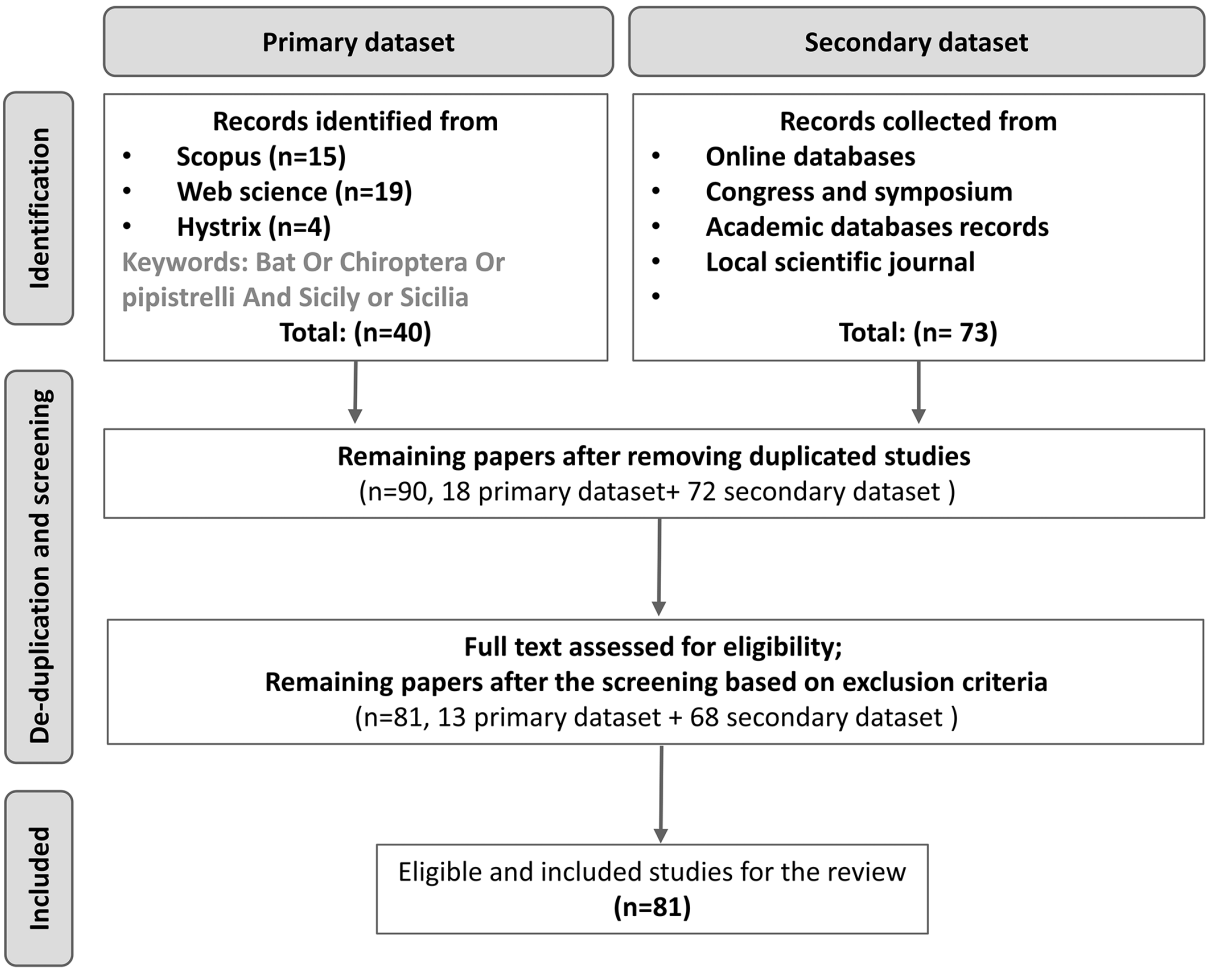

Fig. 1 - Flow diagram showing the selection steps of eligible documents obtained from primary and secondary datasets. / Diagramma di flusso che mostra le fasi di selezione dei documenti eligibili ottenuti dai dataset primario e secondario.

Primary dataset

Primary datasets were obtained from two different web databases: Scopus (www.scopus.com) and ISI Web of Science (www.webofknowledge.com). The following keywords combination "Bats or Chiroptera or Pipistrelli or Pipistrello" and "Sicily or Sicilia" were used. To cover a wider range of publications, a backward search of the bibliographic sources cited in each publication was performed (i.e. we used citations from one source to find other sources).

Secondary dataset

A bibliographic review of the bats in Sicily was carried out, including historical records, doctoral theses, regional reports, books, monographs, book chapters, webinars, conference papers, conference abstracts, and technical reports. Citations from online repositories such as Bibliografia Teriologica Siciliana - MAMMALIA and Ministero della Transizione Ecologica were also checked to collect additional datasets. Furthermore, a search string based on key author names (e.g., Zava, and Catalano) who have made significant contributions to the field of Sicilian bat research was used to include the highest possible number of publications.

Extracted information

After compiling all publications, a primary check was done by sequentially reviewing the titles and abstracts. Then, a detailed full-text evaluation was performed. Studies were excluded if they did not provide any relevant information or data on bat species within the geographical range of the study. When available, the following information was retrieved: author names, year of publication, language (English, Italian and French, and German), geographical location (categorized by province: Agrigento, Caltanissetta, Catania, Enna, Messina, Palermo, Ragusa, Siracusa, and Trapani), publication type (article, abstract, online blog), cited species, methodology used (acoustic monitoring, morphology, molecular, observations) and study habitats (forest, caves, laboratory or riparian areas). Eligible articles were then categorized into four main thematic research topics: "Conservation" (conservation status, threats, and anthropogenic pressure, legal protection), "Disease" (zoonotic disease, viruses, parasites, bacteria), "Ecology" (foraging, roosting, ecosystem role, niche modelling, paleoecology, behaviour) and "Species records" (status, distribution, preliminary survey, systematic survey, and new records).

We supplemented this literature search with a search of the IUCN Red List database (IUCN, 2022) to determine the trend status (decrease, increase, unknown, and stable) and IUCN Red List threat categories (least concern, near-threatened, data deficient, vulnerable) of the considered bat species. Then, based on the most recent IUCN Red List status assessment, bat species were subdivided into two subgroups. Species classified as data deficient (DD), vulnerable (VU), and endangered (EN) were grouped as "threatened", whereas species classified as least concern (LC) or near threatened (NT) were grouped as "non-threatened" (Massaad *et al.*, 2022). Scientific names of species were conformed to the name currently used by the IUCN Red List. For example, *Myotis oxygnathus* (Ragonese, 1991) = *Myotis blythii*; *Pipistrellus savii* (Krampitz, 1957) = *Hypusgo savii*; *Vespertilio schreibersii* (Lilford, 1862) = *Miniopterus schreibersii*; *Vespertilio kuhlii* (Lilford, 1862) = *Pipistrellus kuhlii*.

Data analysis

Due to the high heterogeneity of the secondary dataset, data extraction, integration, and analysis proved to be less straightforward. Studies with missing data were excluded from the statistical analysis. The distribution of publications per thematic research topics (Conservation, Ecology, Disease, and Species records), species, language of publications, family, province, and study area was evaluated using Pearson's Chi-square independence test (χ^2). Kendall's Tau-b coefficient was used to identify the presence of any publication trend over the years. Kruskal-Wallis test was performed to check any significant difference in the number of publications over three-decade intervals (1990-2000, 2001-2011, and 2012-2022). All descriptive statistical analyses and plots were generated using R studio packages (R Core Team, 2021).

Bat Research Efficiency (BRE)

The 'Bat Research Efficiency' metric function general idea was adapted from López-Bosch *et al.* (2021) and then adjusted based on the available parameters. Bat Research Efficiency represents the research efficiency and the accuracy of detection of bat species across different provinces. BRE was calculated using the following parameters: the number of studies conducted in each province (Z), the number of distinct recorded species per province (S), and the area of the province (A).

$$\mathbf{BRE}=\frac{Z+S}{A}$$

All the parameters were standardized and ranked as follows:

1. Z: number of studies per province was ranked between 0 and 1, where 0 indicated the province with 0 related publications and 1 for the province with the highest number of publications
2. S: number of species was also ranked between 0 and 1, with 0 indicating no species records and 1 representing the highest number of species recorded per province.
3. A: province area was ranked between 1 and 2, the number 1 represented the province with the smallest area, and 2 the province with a larger area.

The BRE index ranges between 0 and 1. Regions with a high BRE exhibit higher research efficiency, higher research publications, and greater taxonomic distinctiveness. Provinces with lower BRE showed less research effort, a higher research gap, and a shortage of publication and species identifications. Based on the results of BRE, a distribution map of the geographic pattern and research knowledge across Sicilian provinces was created using Qgis 3.0. We excluded publications with undefined geographical localities.

Species-Research Effort Allocation (SREA)

To identify research attention and effort received by each bat species in the period ranging from 1986 to 2022, we utilized an adapted version of the Species-Research Effort Allocation (SREA) metric (Tanalgo & Hughes, 2018). It is worth noting that we selected the period from 1986 onwards, as research on bats has been published consistently, with little variation in terms of the number of publication items. SREA was calculated using the following simplified metric formula:

$$\mathbf{SREA(X)}=\frac{R}{y}$$

Where (X) denotes the bat species, R represents the number of citations of the species across the studied publications, and *y* indicates a constant number of years (36 years, in our case). SREAs with a value of 1.00 refer to species receiving average research effort, SREAs higher than 1.00 refer to species receiving adequate research effort, and SREAs lower than 1.00 represent species receiving insufficient research effort.

RESULTS

Research trend, source, and language

A total of 81 studies, including 13 primary dataset and 68 secondary dataset documents, were retrieved, and analysed (Fig. 2). Since 1955 an average of 1.2 studies have been published per year, with 0.37 for primary dataset and 0.83 for secondary dataset documents. The years 1986 and 2005, with five documents each, stood out with the highest number of contributions. However, the number of contributions has steadily increased since 1994, with an annual average of 1.78 documents (tau-b coefficient= 0.557, $p< 0.05$). Though, no significant difference in the number of documents was observed over the last three decades (1990-2000, 2001-2011, and 2012-2022) (Kruskal-Wallis, H-value=2, p=0.391).

The most used language in the contributions was Italian (51%), followed by English in approximately 48% of all publications. Only two documents were written in French, and one in German. However, there was an asymmetrical distribution of languages. Only 10% of primary dataset articles were published in Italian, with the rest in English. The secondary dataset was equally partitioned between documents written in Italian (50%) and English (50%). It is worth noting that the number of documents written in Italian has significantly declined in the last 20 years, accounting for only 30% of total contributions, the rest being written in English.

Study areas distribution and BRE

Bat research studies spanned unevenly across the Sicilian provinces. Most of the research occurred in the north-western (40%) and south-eastern (28%) parts of the island. Palermo had the highest number of studies (32%), followed by Siracusa (28%), Catania (12%), and Agrigento (10%). Thus, only six studies focused on Trapani and Messina, respectively. Only two studies addressed bats in Ragusa and Caltanissetta, while only one document was devoted to Enna, and 21 contributions covered more than one region. The highest Bat Research Efficiency index (BRE) was accounted for by Siracusa (BRE=0.91),

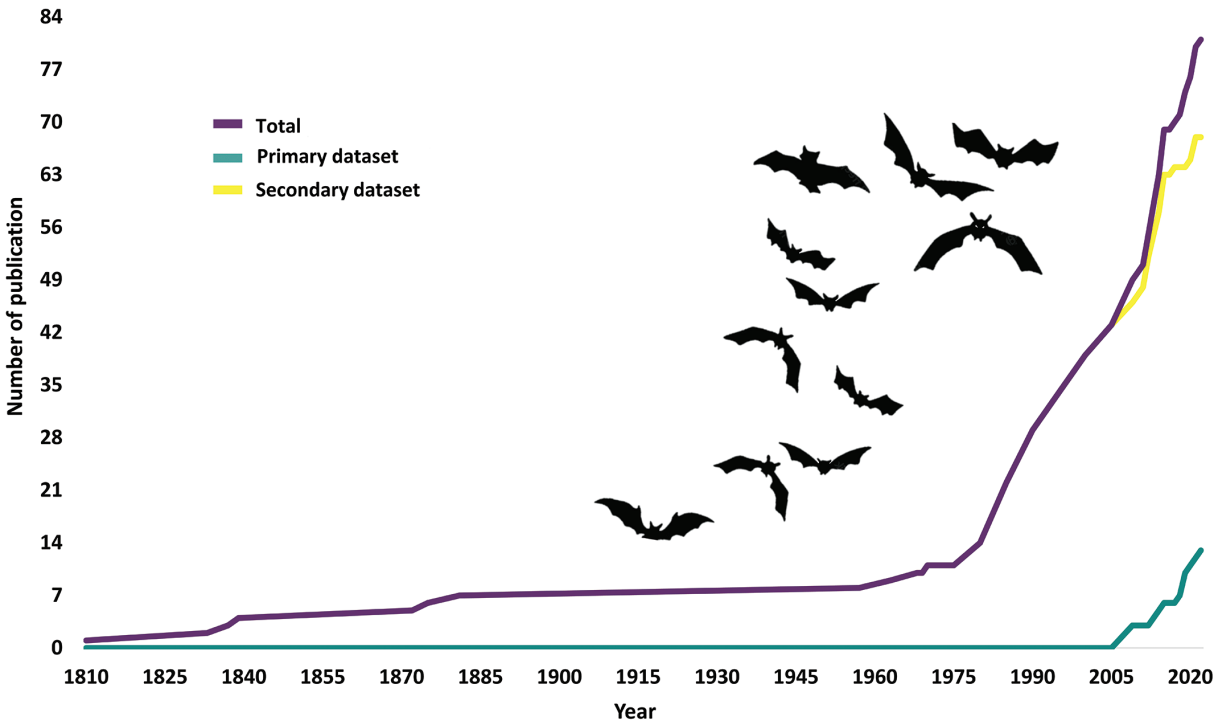

Fig. 2 - Documents in the primary and secondary datasets and the cumulative number of documents issued between 1810 and 2022. / Documenti nei dataset primario e secondario e numero cumulativo di documenti prodotti tra il 1810 e il 2022.

followed by Palermo (BRE=0.71), Catania (BRE=0.58), Trapani (BRE=0.51), Ragusa (BRE=0.48), Messina (BRE=0.41) and Agrigento (BRE=0.36). Caltanissetta and Enna provinces had the lowest BRE value with 0.22 and 0.15, respectively (Fig. 3). The contributions focused merely on four distinct study areas. There was also an unbalanced distribution of research studies across the study areas. Approximately 54% of the studies focused on caves, 17% on forests, 15% on riparian areas, and only 13% on urban areas (Fig. 4A).

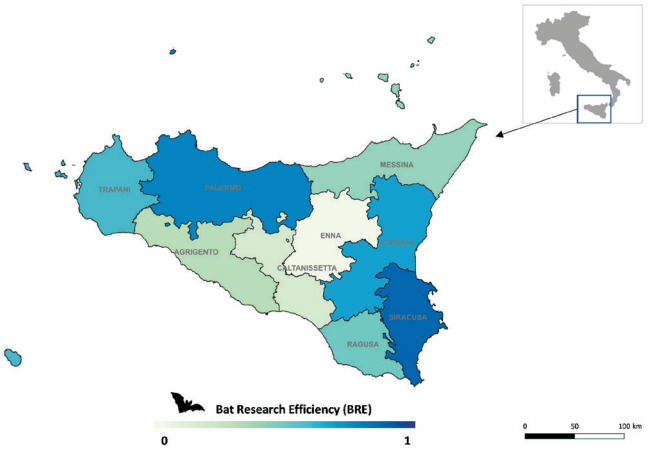

Fig. 3 - Variation of Bat Research Efficiency scores (BRE) in the nine Sicilian provinces. The colour gradient (darker to lighter) indicates a higher to lower BRE. / Variazione dei punteggi di efficienza della ricerca sui pipistrelli (BRE) nelle nove province siciliane. Il gradiente di colore (da più scuro a più chiaro) indica un BRE da più alto a più basso.

Species bias and SREA

A total of 28 bat species belonging to four families were cited across the 81 documents (Tab. 1). There was an average of 4.2 bat species cited per document, ranging from 1 to 24 species per document. Overall, 21% of the Sicilian bat species were classified as threatened (Fig. 4B). Around 31.5% of the contributions focused on threatened species, while 68.5% concentrated on non-threatened species, particularly species classified as least concern. Only 15% of the studies focused on a single species. The species of the family Vespertilionidae were the most prevalent among those mentioned (312 times), accounting for 54.5%, followed by Rhinolophidae (30.6%), Miniopteridae (9.9%), and Molossidae (4.8%).

A disproportionate SREA was observed across most of the species, with an overall SREA value below the threshold score of 1.00. The eight most studied species were *Myotis myotis* (n=38 citations, SREA=1.00), *Miniopterus schreibersii* (n=31, SREA=0.82), *Rhinolophus ferrumequinum* (n=26, SREA=0.68), *Myotis capaccinii* (n=21, SREA=0.55), *Rhinolophus euryale* (n=21, SREA=0.55), *Rhinolophus mehelyi* (n=19, SREA=0.5), *Myotis blythii* (n=17, SREA=0.44), and *Pipistrellus kuhlii* (n=16, SREA=0.42). On the other hand, for the following species, attention was scarce, with less than three citations across the 81 contributions: *Nyctalus noctula*, *Pipistrellus nathusii*, *Plecotus gaisleri, Rhinolophus blasii, Myotis mystacinus, Myotis punicus, Barbastella barbastellus*, *Myotis bechsteinii*, and *Pipistrellus pygmaeus.*

Likewise, primary and secondary dataset publications tended to skew towards the same few species (*Miniopterus schreibersi, Myotis myotis*, and *Hypsugo savii*).

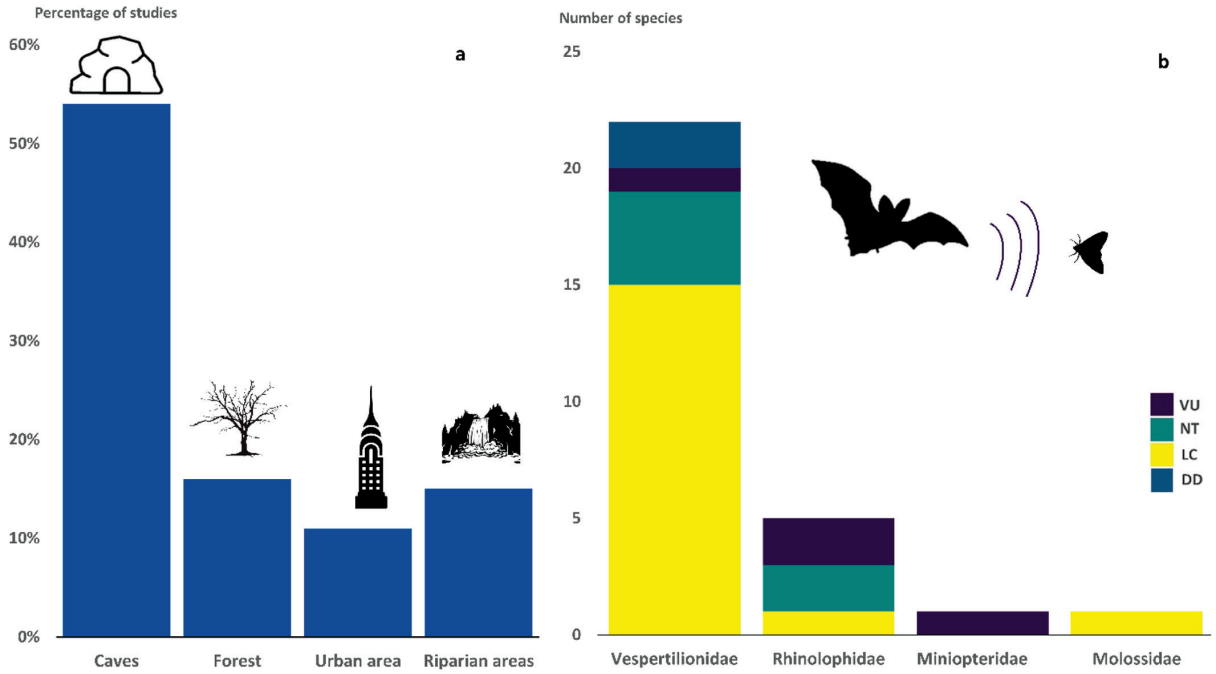

Fig. 4 - (A) Bar plot showing the distribution of studies across different habitats (caves, forest, urban area, riparian areas). (B) Species conservation status across Sicilian bat families classified according to the IUCN categories: Least Concern (LC), Vulnerable (VU), Near Threatened (NT), and Data Deficient (DD). / (A) Grafico a barre che mostra la distribuzione degli studi nei diversi habitat (grotte, foreste, aree urbane, aree ripariali). (B) Stato di conservazione delle specie delle famiglie di pipistrelli siciliani classificate secondo le categorie IUCN: Minima preoccupazione (LC), Vulnerabile (VU), Quasi minacciata (NT) e Carenza di dati (DD).

Twenty species were cited in primary dataset publications, whereas eight species were exclusively cited in the secondary dataset (*Rhinolophus blasii*, *Pipistrellus nathusii*, *Myotis emarginatus*, *Myotis bechsteinii*, *Myotis daubentonii*, *Myotis nattereri*, *Nyctalus noctula*, *Barbastella barbastellus*). Only *Plecotus gaisleri* was found in the primary dataset, but not in the secondary dataset documents.

Tab 1 - List of the 28 Sicilian bat species cited across the studied documents. Column headers indicate (left to right): scientific name, Species-Research Effort Allocation (SREA), total number of citations (TNC), citations in primary dataset (PD), citations in secondary dataset (SD), population trend and IUCN status. Population trend is categorized as decreasing (↓), unknown (?), and stable (-). The conservation status follows the IUCN red list criteria: Least Concern (LC), Vulnerable (VU), Near Threatened (NT), and Data Deficient (DD). / Elenco delle 28 specie di pipistrelli siciliani citate nei documenti studiati. Le intestazioni delle colonne indicano (da sinistra a destra): nome scientifico, Species-Research Effort Allocation (SREA), numero totale di citazioni (TNC), citazioni nel dataset primario (PD), citazioni nel dataset secondario (SD), trend della popolazione e status IUCN. La tendenza della popolazione è classificata come in diminuzione (↓), sconosciuta (?) e stabile (-). Lo stato di conservazione segue i criteri della lista rossa IUCN: Minima preoccupazione (LC), Vulnerabile (VU), Quasi minacciato (NT) e Dati insufficienti (DD).

Species name	**SREA**	**T.N.C**	**PD**	**SD**	**Population Trend**	**IUCN**
Rhinolophidae						
Rhinolophus hipposideros	0.5	19	3	16	↓	LC
Rhinolophus euryale	0.55	21	3	18	↓	VU
Rhinolophus ferrumequinum	0.68	26	3	23	↓	NT
Rhinolophus mehelyi	0.5	19	4	15	↓	VU
Rhinolophus blasii	0.02	1	0	1	↓	NT
Vespertilionidae						
Plecotus austriacus	0.21	8	1	7	↓	NT
Plecotus auritus	0.18	7	1	6	–	LC
Plecotus gaisleri	0.04	2	2	0	?	DD
Pipistrellus pygmaeus	0.07	3	1	2	?	LC
Pipistrellus kuhlii	0.42	16	3	13	?	LC
Pipistrellus pipistrellus	0.37	14	5	9	–	LC
Pipistrellus nathusii	0.04	2	0	2	?	LC
Myotis myotis	1	38	4	34	–	LC
Myotis capaccinii	0.55	21	2	19	↓	VU
Myotis emarginatus	0.26	10	0	10	?	LC
Myotis blythii	0.44	17	3	14	↓	LC
Myotis bechsteinii	0.07	3	0	3	↓	NT
Myotis daubentonii	0.10	4	0	4	–	LC
Myotis mystacinus	0.13	5	1	4	?	LC
Myotis nattereri	0.15	6	0	6	–	LC
Myotis punicus	0.07	3	2	1	?	DD
Nyctalus lasiopterus	0.07	3	1	2	↓	NT
Nyctalus noctula	0.02	1	0	1	?	LC
Barbastella barbastellus	0.07	3	0	3	↓	NT
Eptesicus serotinus	0.23	9	3	6	–	LC
Hypsugo savii	0.4	15	6	9	–	LC
Miniopteridae						
Miniopterus schreibersii	0.82	31	4	27	↓	VU
Molossidae						
Tadarida teniotis	0.4	15	3	12	?	LC
Mean	**0.3**	**8.5**	**2**	**6.5**		

Thematic focus

Studies revolved mainly around four topics. A significant bias was found across the documents. Studies on bats in Sicily focused mostly on "Species records" (61%), followed by "Ecology" (21%) and "Conservation" (13%), whereas studies on "Disease" were less represented, with only 5% of all publications. However, no statistical difference in research topic preference was observed between English and Italian articles ($\chi 2 = 3.486$, d.f. = 3, $p = 0.323$). The most frequently covered topics in the English and Italian language documents are 'Species records' and 'Ecology'. Similar findings were observed in primary and secondary dataset publications, with roughly 80% focusing on "Species records" and "Ecology" (Fig. 5).

Adopted methods

Various methods were adopted across the publications. Live capture of individuals and roost observation were the most employed methods, accounting for 26.5% of all publications, respectively. Echolocation was adopted in 20.4% of the total studies. Approximately, 10% of the contributions used fossil analysis, 2% used isotopic analysis, 6% used genetic analysis, and 4% used chemical analysis and modelling techniques. However, an uneven usage of the different methods was found between primary and secondary data (Fig. 5).

DISCUSSION

Early 19th century bat research

Bats have long captivated the attention of researchers in Sicily, as evidenced by the presence of historical research records. The first record was reported by Rafinesque (1810), who described and recorded bat species across the island, including the African bat species *Nycteris hispida*. Carlo Bonaparte (1833) provided some earliest evidence of bats on the island and noted the importance of Sicily as a hotspot in Europe, as it holds some unique bat species, especially those belonging to the genus *Vespertilio* (Sélys-Longchamps, 1839). Subsequently, Luigi Galvagni (1837) focused his efforts on the Etna massif and surrounding areas and noted the presence of six species inhabiting the caves of Pantalica-Siracusa and Grotta delle Colombe-Nicolosi. Three decades later, Lord Lilford (1862) reported the presence of seven species in the Siracusa caves. Minà-Palumbo's research (1868) can undoubtedly be described as pioneering, as he was the first to investigate the north-western provinces in 1868, focusing on the bat populations of the Madonie massif and different parts of Palermo and Caltanissetta provinces (Sarà, 1999). Doderlein (1872, 1881) reported Sicily Island as the most diverse area in Europe for bats, home to 15 to 16 common bat species including four to five rarely observed species, particularly those found in warmer climates. De Stefani (1895) reaffirmed this in his work on the identification of albinism in museum specimens.

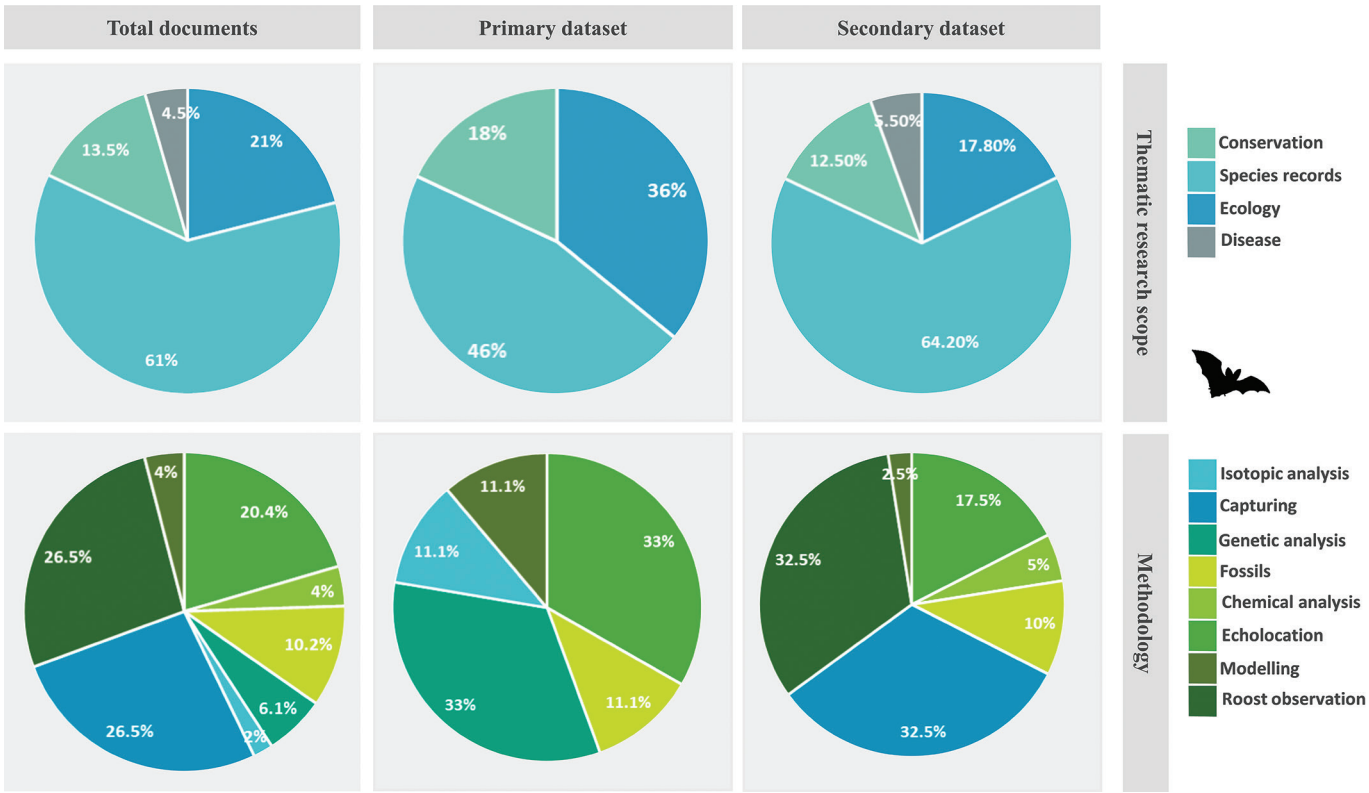

Fig. 5 - Distribution of the primary dataset, secondary dataset, and total documents according to research areas and used methods. / Distribuzione del dataset primario, del dataset secondario e del totale dei documenti in base alle aree di ricerca e ai metodi utilizzati.

Research temporal trend

Scientific research on bats in Sicily has improved in recent decades, with an increase in the number of documents both in the primary and secondary datasets. This rise, specifically for secondary dataset publications, can be attributed to different factors. Firstly, the many national or regional conferences and symposia periodically organized, such as the series "Italian Conference on Chiroptera" (Mucedda *et al.*, 2015; Fulco *et al.*, 2015a, 2015b; Fulco & Valvo, 2015), Congresso Italiano di Teriologia (Di Salvo *et al.*, 2012a, Russo *et al.*, 2014; Mucedda *et al.*, 2015; Fulco *et al.*, 2016), "Convegno Regionale di Speleologia della Sicilia" (Caruso, 1995; Sperlinga *et al.*, 2013). Furthermore, the creation of local and national interest groups on bats and the natural sciences in general, such as the Centro Speleologico Etneo or the Gruppo Italiano Ricerca Chirotteri (Italian Chiroptera Research Group), has had a significant impact on field research and collaboration between local researchers and academics, constituting a decisive factor in this expansion. Moreover, the availability of grants, access to local open-access journals, and the spread of social media platforms have paved the way for this obvious trend.

Languages and publication sources

The documents examined in the secondary dataset provided a more comprehensive view of taxonomic and historical evidence generally marginalised by publications in the primary dataset. Most of the documents in the secondary dataset were written in Italian as they were mostly published at local conferences and addressed mainly to the local stakeholders. This association between native languages and the type of documents we included in the secondary dataset was previously pointed out by Feijó *et al.* (2019) for Mandarin Chinese publications. Also, Preble *et al.* (2021) found a robust link between Japanese written documents and secondary dataset contributions. Although Italian language contributions may have an encouraging influence on local conservation, they may not be easily retrievable and accessible by non-Italian readers, hampering the dissemination of research results and datasets. To overcome this language barrier and facilitate the dissemination of local research, we endorse the inclusion of English extended abstracts in future Italian language contributions and vice versa. Also, we recommend the publication of scientific papers in international and local peer-reviewed journals.

Geographical and study area biases

Geographical bias is recognized as a prevalent problem in mammalian research (Guerrero-Casado & Monge-Nájera, 2021). This bias was evident in our review, with more than 70% of the studies carried out in the northwest (Palermo province) and southeast (Catania and Siracusa provinces) of the island. In part, this can be due to the fact that the north-western and south-eastern parts are home to the oldest universities, major academic research institutions, speleological associations, and museums, which tend to concentrate research efforts in their surroundings.

Another reason for this bias can also be elucidated by the presence of distinct ecological patterns and diverse ecosystems, as well as several protected areas that provide unique and facilitated conditions for research. This was also noticeable in the increase in the number of studies carried out in protected areas. One of the earliest confirmations was provided by Kahmann (1957), who discovered the presence of *Barbastella barbastellus*, one of the rarest bat species on the island, in the Ficuzza forest. Likewise, Mannino (1985) carried out extensive research on bat richness throughout the Monte Pellegrino Natural Reserve. Recently, Lo Nigro *et al.* (2021) detected the presence of 10 bat species identified through ultrasonic monitoring across the same area. Moreover, few recent studies described the bat populations across the Madonie natural reserve (López-Garcia *et al.*, 2013; Fulco *et al.*, 2015a). On the other hand, a substantial amount of bat research was carried out in the Nebrodi natural reserve, which encompasses the island's most extensive forested region (Zava *et al.*, 1986; Zava & Lo Valvo, 1991; Zava & Violani, 1992; Vergari *et al.*, 1998; Agnelli *et al.*, 2008; Salicini *et al.*, 2011, Di Salvo *et al.*, 2012a; Mucedda *et al.*, 2012; Fulco *et al.*, 2015a). To date, a total of 12 bat species have been observed in the Nebrodi mountains, including the recent rediscovery of *Myotis bechsteinii* by Di Salvo *et al.* (2012b) and *Barbastella barbastellus* by Mucedda *et al.* (2012).

As for our findings, Siracusa and Catania continue to receive considerable research attention, notably, research focusing on cave-dwelling bats, particularly in the Grotta dei Pipistrelli, Grotta Palombara, Grotta Immacolatella, Grotta di Pantalica, and in the Cave of Calafarina, which are famed sites for roosting, swarming, mating, maternity, and hibernation for poly-colonies of hundreds of bats (Ragonese 1968; Zava & Falzone, 1978; Caruso & Grasso, 1996). This was in line with the early findings by Ragonese (1967) who highlighted the role of these caves as a home for thousands of bats, *Rhinolophus ferrumequinum*, *Myotis myotis,* and *M. capaccinii*. Similar findings were also underlined by Caruso & Costa, (1978), Caruso (1982), Zava *et al.* (1986), Caruso (1995), and Caruso & Grasso, (1996). Moreover, Mucedda *et al.* (2009, 2015) recently discovered the presence of *Rhinolophus mehelyi,* and *Miniopterus schreibersii*, two previously undetected species in these caves.

These caves are now the subject of extensive research and periodic monitoring of different aspects, including palaeontology, species abundance, and conservation related (Kotsakis & Petronio, 1981; Ragonese & Contoli 1996; Agnelli *et al.*, 2004; Lanza 2012; Spena *et al.*, 2013; Audra *et al.*, 2019). The latest research by Fichera *et al.* (2021) rigorously described the current bat distribution across 31 different caves located in Mt. Etna and reported the presence of 19 bat species. Overall, all studies confirmed the key role of these caves, particularly as roosts for highly diverse groups of bats (Caruso 1999; Mucedda *et al.*, 2019).

Based on our review, we could pinpoint the current geographical gaps in research. For some provinces, only

a limited number of studies could be identified. These include Enna (known as Castrogiovanni until 1927), first investigated by Galvagni in 1837, and more recently by Fulco & Lo Valvo, (2015). Similarly, little information has been found on Agrigento (Kramptiz, 1957; Haberl, 2004) where studies mainly focused on islands pertaining to its jurisdiction, such as Lampedusa (Zava & Catalano, 1983; Lanza, 2012).

The Sicilian archipelago is formed by several smaller islands that cluster around the main island. Earlier evidence suggested that these islands are a promising hotspot for some bat species. However, these areas remain little studied, with most research dating back to the mid-to-late 20th century, except those carried out recently on the island of Pantelleria by Ancillotto *et al.* (2020) and Fichera *et al.* (2022). Complementary sampling methods combined with new approaches are therefore needed to extend previous results to all surrounding islands, including the Aeolian Islands (Kahmann, 1957; Fiore *et al.*, 1992; Zava *et al.*, 1994), Egadi Islands (Felten & Storch, 1970; Zava & Lo Valvo, 1991, Fornasari *et al.*, 1997, Masseti & Zava, 2021), Pelagie Islands (Felten & Storch, 1970; Zava & Catalano, 1983; Kock, 1989; Zava *et al.*, 1994; Fornasari *et al.*, 1997).

Our results reveal a significant bias in the studied area, with nearly 70% of the studies performed in caves. This disparity may have some implications on Sicilian research evidence particularly for species inhabiting less studied ecoregions and habitats. Hence, there is an urgent need for multifaceted and unbiased monitoring and surveillance programs that should address understudied habitats and provinces.

Taxonomic diversity

Taxonomy and species identification remain challenging across Sicilian bat populations. In line with these difficulties, several studies have delved into the occurrence of many previously undistinguished or suspected species. An early review by Agnelli *et al.* (2008) reported the presence of 20 species across the island. Regardless of being cited by Fornasari *et al.* (1997), *Myotis bechsteinii*, and *Barbastella barbastellus* were excluded from Agnelli's checklist due to doubts about their occurrence across the island.

Later, Sicilian bats underwent substantial taxonomic research, including the discovery of species new to the Sicilian fauna and the rediscovery of previously recorded ones. In 2015, Fulco & Lo Valvo highlighted the presence of 24 species after adding up the occurrence of *Hypsugo savii*, earlier confirmed by Harbel (2004) and Veith *et al.* (2011), *Myotis bechsteinii*, rediscovered by Di Salvo *et al.* (2012b), Soprano pipistrelle (*Pipistrellus pygmaeus*) by Fichera *et al.* (2013) and *Barbastella barbastellus* rediscovered by Mucedda *et al.* (2012). Elsewhere, Fulco *et al.* (2015a) reported the first record of *Plecotus auritus* for Sicily at an elevation of 1500 m.a.s.l. Recent research by Ancillotto *et al.* (2020), supported by Fichera *et al.* (2022), highlighted the presence of a newly detected species, Gaisler's long-eared bat (*Plecotus gaisleri*), in Pantelleria, bringing the total number of Sicilian bats to 26.

To our knowledge, three more species were present and mentioned in the literature but are missing from the last species checklist. It includes *Pipistrellus nathusii*, which was reported only twice by Fornasari *et al.* (1997) and Ragonese (1991), as well as *Rhinolophus blasii* and *Nyctalus noctula*, both of which were reported by Ragonese (1991). However, the presence of *Rhinolophus blasii* is highly doubtful, as it has been considered extinct since the 1960s (Bulgarini *et al.*, 1998; Rondinini *et al.*, 2013). *Pipistrellus nathusii*, on the other hand, was most likely confused with other species of the same genus.

In relation to other adjacent Mediterranean insular bat faunas, the Sicilian bat fauna stands out as the most diverse, the region hosting a total of at least 26 confirmed species compared to the 21 species of Cyprus (Benda *et al.*, 2018), the 22 species of Corsica (Corsican Fauna, 2022), the 19 of Minorca (Trujillo *et al.*, 2008) and the at least 21 species of Sardinia (Lecis *et al.*, 2018).

Among the 28 bat species cited, there was a clear research preference for cave dwelling species, particularly *Rhinolophus ferrumequinum* and *Miniopterus schreibersii*, which were estimated to account for at least 9000 individuals in some caves (Spena *et al.*, 2013), and *Rhinolophus mehelyi*, which is only known to occur in Sicily and Sardinia (Dondini *et al.*, 2014). Also, *Myotis myotis*, *M. blythii*, *M. capaccinii, and Rhinolophus euryale*, were widely reported and commonly identified through various museum specimens and fossil remains (Spena *et al.*, 2017; Salari *et al.*, 2019; Spena *et al.*, 2021). This bias toward cave species may be due to the ease of access of authorized researchers and local amateur naturalists to the protected caves, which coincides with the various ongoing cave monitoring programs. Today, however, most of the cave bat populations are in decline due to environmental and anthropogenic threats, particularly unregulated cave tourism and nearby foraging site loss caused by extensive logging (Rondinini *et al.*, 2013). Contrary to conservation priorities, another critical species preference is observed. As a matter of fact, a large portion of the contributions focused on non-threatened species, while only a few focused on threatened species, which account for 21% of all species.

Despite our findings being highly debatable, given the uncertain presence of some questionable species, our results show that the island's distinct biogeographical features may provide an important potential habitat for species found in the Mediterranean area, yet to be recorded in Sicily. Among the potentially overlooked bat guild, forest bats are the most elusive and least studied across the island. It is recommended that future field research and monitoring focus on these species to expand our knowledge of the status of bats throughout the island.

Species research priorities and future metrics

Research priorities have mainly focused on the status of species; however, there is a growing consensus that future research priorities and directions should be based on unbiased and holistic metrics. Through our review, we adapted SREA, chiefly employed in insular mammal studies as an evidence-based approach in re-

cent years; Japanese bat species (Preble *et al.*, 2021), Philippine bat species (Tanalgo & Hughes, 2018), insular bats (Conenna *et al.*, 2017) and marine mammals (Tiongson *et al.*, 2021). Based on numerical data metrics, all Sicilian bat species except for *Myotis myotis* received insufficient research effort. These findings corroborate our hypothesis that the island's research was largely inadequate and did not meet the effort required for each species. Tanalgo & Hughes, (2018) discovered a common lack of research allocation, where only 13% of Philippine bat species received adequate research attention. Preble *et al.* (2021) obtained similar results, emphasizing the lack of research effort, particularly for threatened Japanese bat species. On the other hand, we should avoid comparing our regional results with those obtained on a national basis data, as the research effort is necessarily greater in the national context than in the regional one.

Although in general, no species received sufficient research effort, our findings revealed a quasi-match between conservation needs and research attention. SREA was higher in four vulnerable species (*Miniopterus schreibersii, Myotis capaccinii, Rhinolophus mehelyi, and R. euryale*) than in the least-concern and near-threatened species. However, certain species, including the newly discovered *Plecotus gaisleri* and those prone to misidentification, like *Pipistrellus nathusii* and *Rhinolophus blasii*, had lower SREA scores. As a way to improve conservation, the inclusion of additional functional metrics can provide new insights and fill research gaps for understudied and newly discovered species.

Research topic preferences

Another research bias was evident throughout the study. The core studies focused on the thematic area of species records, while little information was available on bat conservation, ecology and diseases. Despite the complexity of studying species records, at least six species have been identified in the last 15 years using mist netting, acoustic monitoring, and molecular techniques. Discovered species were generally reported in short communications (Fichera *et al.*, 2013; Fulco *et al.*, 2015a) or in checklists (Agnelli *et al.*, 2008; Zava *et al.*, 1994). However, methodological advancements such as genetic tools, acoustic analysis, and interdisciplinary research have enabled the discovery and description of new species. Ancillotto *et al.* (2020), successfully demonstrated this assumption by predicting the geographical presence of *Plecotus gaisleri* by using modelling techniques. The species' presence was later confirmed by Fichera *et al.* (2022) using genetic and molecular methods. Unfortunately, the use of genetic techniques is still limited; even so, their adaptation may improve the scrutiny of the critical and isolated taxonomic complexes and the unique phylogenetic composition found across the island, previously described by Hulva *et al.* (2007), Salicini *et al.* (2013), Bogdanowicz *et al.* (2015) and Juste *et al.* (2018). Thus, further identification may lead to discoveries of new potential insular lineages and cryptic species distinct from those on the adjacent mainland.

In contrast, fewer studies focused on bats' ecological roles and conservation. As per ecological research, no detailed studies addressed the role of bats to date, and most of the research focused and bat behaviour and their interactions with adjacent habitats. For instance, Di Salvo *et al.* (2009) described bat habitat preference in a Sicilian rural landscape and compared bat activity and species richness across different habitats. Also, Fulco *et al.* (2016) published another relevant abstract in which they described the distress calls emitted by *Myotis myotis* species and the behavioural responses eventually resulting. We believe that the lack of ecological studies is directly related to the lack of funding for long-term studies. Urgent research on bat ecology is required, particularly on their role as insect suppressors, their importance in structuring trophic and spatial ecological networks in agricultural and forest areas (Bueno *et al.*, 2021) as well as how bats respond to spatiotemporal vegetation dynamics (Bueno *et al.*, 2020).

Although all Sicilian bats are legally protected under the Convention on the Conservation of Migratory Species of Wild Animals and EUROBATS, the EC Habitats Directive (92/43/EEC), and other joint environmental accords, few monothematic studies addressed conservation issues and threats faced by Sicilian bats. Corrao *et al.* (1985) conducted early research that claimed the fatal impact of pesticide residues in a colony of more than 600 bats. To date, bats continue to face many threats, including environmental pollution, such as metal accumulation, as recently highlighted by Ferrante *et al.* (2018), and extensive forestry logging by Rondinini *et al.* (2013). For better conservation, it is necessary to carry out additional research to identify the main threats jeopardizing bats in Sicily.

In a broad sense, research scarcity was also present in disease-related research and was only relevant in a few studies conducted across the island. The first publication by Krampitz (1957) described the presence of the protozoan *Trypanosoma vespertilionis* in *Miniopterus schreibersii* bat colonies. Histopathological and microscopic analyses revealed that three bat species inhabiting Grotte dei Pipistrelli, including *M. schreibersii*, resulted positive for pneumonia at the splenic level and showed hyperplasia of the white pulp (Salvaggio *et al.*, 2013). Moreover, Witsenburg *et al.* (2015) revealed the presence of a haemosporidian parasite in bat colonies in Marzamemi. The use of multiapproach techniques and additional regular monitoring can facilitate and serve as proactive steps to avert any future zoonotic outbreaks, such as those recently witnessed during the COVID-19 pandemic. More research is recommended to confront the lack of evidence in the main research topics, particularly ecology, and conservation, which will certainly improve future conservation plans.

Future perspectives

Research on bats in Sicily has seen an increase in the number of publications over the years. However, our review highlights the presence of numerous research gaps and biases in several aspects. To fill these gaps, we propose the following future research perspectives.

- We endorse additional research in understudied habitats, particularly in forest and urban areas while maintaining the ongoing monitoring in the caves. More research effort should also be put into the less studied provinces, Enna and Caltanissetta, in particular.
- Regardless of the number of studies reporting on species records and taxonomic analysis, more research is essential since the island may still have undiscovered bat species. Fundamental well-distributed research efforts and prioritization are necessary for responses to the uneven distribution of species research efforts. Several methodological approaches, such as molecular techniques and acoustic monitoring, should be employed to ensure effective species research, protection, and conservation. Furthermore, we recommend additional research on understudied, newly discovered, and threatened species.
- Further research is needed to fill the current research gaps in ecology and conservation. Special attention is required to cover bat ecosystem roles in agricultural and forest areas.
- Because the conservation status is still little understood, we strongly advocate for identifying the main threats and assisting in setting future conservation measures and guidelines.
- At the national level, improvements in research collaboration are also essential, particularly between the amateur naturalist and academic research sectors. As this database is likely to expand in the coming year, future local web-based databases and social media pages about Sicilian bats are strongly encouraged to facilitate research accessibility and promote local research works.

Acknowledgments

We thank Enrico Bellia and Bruno Massa for their invaluable help in bibliographic research. We thank all the authors for their contributions and research on Sicilian bats. We would also like to thank all the naturalists and people in charge for their efforts in the conservation of bats in Sicily. We express our gratitude to the editor and the two reviewers for their valuable comments and suggestions, which have greatly enhanced the quality of this manuscript.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online for this article.

S1 - Table of included primary dataset publications (listed in reverse chronological order).

S2 - Table of included secondary dataset publications (listed in reverse chronological order).