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Review

Acoustic detection and occupancy models: A systematic review with insights for future monitoring programs

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ABSTRACT

Wildlife management requires monitoring to infer spatiotemporal changes in the distribution or abundance of species and communities of organisms. Technological advancements have increasingly facilitated monitoring species through new data collection methods. Such technological advancements include small-sized acoustic recording devices that can record a wide range of sound frequencies, making them especially suitable for analysis by statistical tools such as occupancy models. We reviewed 188 publications that used acoustic methods and occupancy modelling published between 2002 and 2024 to synthesise and discuss the past usage and potential of combining these two methodologies in research studies in ecology and conservation. We examined the published articles' biogeographical focus, taxonomic group, study temporal design, and modelling choices. Additionally, we performed a text network analysis to understand the trends in the investigated topics of the articles. Our findings revealed that most studies were primarily implemented in the Nearctic region (61.7 %) and were concentrated on two taxonomic groups, birds and bats (42 % and 33 %, respectively). We found that nearly half of the studies limited their analysis to the simplest modelling solution, single-season and single-species models, even though many collected data for multiple species and sampled across several seasons. The text analysis revealed that the research primarily focuses on species monitoring and habitat use. Coupling low-cost passive acoustic monitoring with a diversified set of occupancy models is a scalable methodology that can help implement standardised protocols for regional and larger-scale monitoring programs, which are critical for animal conservation in an increasingly anthropogenic landscape.

1. Introduction

In a globally changing ecosystem scenario, monitoring wildlife is essential for understanding species distributions, assessing biodiversity trends, and informing conservation strategies. In wildlife monitoring, acoustic methods have had a determining role as sound can be highly informative and easily detectable compared to visual methods (Heinicke et al., 2015; Rosenthal & Ryan, 2000). Researchers can obtain various biological information from animal vocalisations, such as which species are communicating, sexual status, and the location and behaviour of the emitter (Wilkins et al., 2013). Traditionally, animal sounds have been sampled using methods of direct human hearing, such as transects and point counts, but methodological options have grown due to technological advancements. Autonomous recording units (ARUs) add flexibility with reduced survey effort by allowing unattended recording for more extended periods and on predefined schedules (Digby et al., 2013). Simultaneously, the costs of such devices have been decreasing, further democratising access to advanced acoustic surveys.

While these technological advancements offer numerous advantages, particularly in enhancing survey performance (Darras et al., 2019), they also present challenges, most notably in data analysis. The volume of data obtained from acoustic surveys can be considerably large, and acoustic data processing has been reported as a central concern for researchers (Speaker et al., 2021). Currently, many solutions are available to deal with the volume and complexity of acoustic data, such as automated classification of species (auto-ID) (Mac Aodha et al., 2018; Stowell et al., 2016). These processes not only enhance objectivity in species identification but are also rapidly advancing through the integration of machine-learning methods in the identification pipeline (Mutanu et al., 2022). Artificial intelligence (AI), particularly algorithms

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like Convolutional Neural Networks, has demonstrated significant potential in acoustic automated classification by processing and interpreting vast amounts of bioacoustic data (Sharma et al., 2023). Nevertheless, a significant gap remains in automated classification, with a continuous need for reference call libraries for most regions and taxa (Gibb et al., 2019).

Acoustic data can be leveraged to investigate various ecological parameters, including species richness, abundance, distribution, habitat suitability, and occurrence. When studying occurrence, researchers can create models incorporating focal habitat variables to explain the distribution of a species by recording its presence or absence. These are often called species distribution models, however, occupancy models allow the same inferences from occurrence data while considering that organisms may not always be detected during survey occasion (MacKenzie et al., 2018). This method involves the estimation of two key parameters: (i) Occupancy, denoted as Ψ (psi), is a biological quantity that indicates the probability of a unit being occupied by the target species during a single sampling season and; (ii) Detectability, denoted as P, is the result of the surveying protocol and is framed as the probability of detecting the species in a single survey of an occupied unit. This method requires surveyed sites to be repeatedly sampled in distinct periods or across space within a season to obtain estimates of detection probability (MacKenzie et al., 2002).

Beyond the single-season model, the dynamic or multi-season models add the capacity to predict the system's evolution by estimating the probability of local colonisation (γ) or extinction (ε) of the species (MacKenzie et al., 2003). These estimates have proven instrumental in monitoring wild populations and aiding management efforts (Eaton et al., 2014; Marcelli et al., 2012). Due to the development of occupancy model extensions, the applicability of occupancy goes beyond understanding species' distribution and habitat suitability. With multi-state occupancy models, researchers can incorporate the relative abundance of the species (high or low) or species breeding status (breeding or non-breeding), facilitating a finer understanding of habitat dynamics and species occurrence (Nichols et al., 2008). Occupancy models allow simultaneous modelling of habitat dynamics and species occurrence, providing a structured framework for long-term wild population management (Martin et al., 2010). Additionally, it is possible to account for false-positive detections on occupancy models, allowing to overcome problems of species' misclassification, hence avoiding biased occupancy estimates due to the models' assumption violation (Bailey et al., 2014). Multi-species occupancy models (MSOMs) further enrich this framework, enabling researchers to investigate community size and structure while inferring detectability and occurrence patterns among multiple species within the dataset (Guillera-Arroita et al., 2019). Finally, recent advancements in statistical frameworks, particularly multi-method or integrated models, have enhanced the ability to infer individual species and community parameters from diverse data sources, such as structured and citizen science data (Isaac et al., 2020). Acoustic data, particularly data collected by ARUs, is well suited for occupancy modelling. It is easy to increase the number of surveys, both revisits and new sites, at a lower cost. Due to the expanding ecological questions that occupancy models can answer, it is essential to know how these are incorporated with the acoustic methodology. Therefore, the specific aims of this review were: 1) to explore and describe the literature concerning the study period, the study site, and which organisms are being studied; 2) to investigate the methodologies and type of occupancy models being used in the research; 3) to understand which ecological questions are being asked when these methodologies are implemented together and; 4) to suggest recommendations to expand the application of acoustic methodology with occupancy models and fill the knowledge gaps on this type of research.

2. Methods

2.1. Literature search

In this review, we analysed the published applications of acoustic and occupancy modelling methods to detect past and current trends. We retrieved an extensive list of publications explicitly implementing the two methodologies. In November 2024, we searched peer-reviewed literature from 2002 to 2024, as site occupancy estimation was first developed and published in 2002 by Mackenzie et al. (2002). We used two search databases, Clarivate Web of Science (WoS) and Elsevier Scopus (Scopus), using the terms "occupancy model*" AND "acoustic" (Fig. 1). The output in WoS was filtered using the categories of the search database: ecology, biodiversity conservation, environmental sciences, zoology, ornithology, evolutionary biology and forestry. In Scopus, we filtered the output using agriculture, biological sciences and environmental science. We completed the search following a snowball approach, integrating those relevant studies referenced in the already identified literature into our results. Then, we extracted the required information from each article to characterise it and perform the exploratory analysis: publication year, study period, studied organisms, number of species, study site, type of occupancy model implemented, estimation method and acoustic detection method. To compare the publications' trend in our field of interest with other more broad but related topics, we performed similar searches in WoS during the same period and used the same filters. The term used was only "occupancy model", allowing us to evaluate the number of publications using this modelling methodology and its evolution through time.

2.2. Exploratory analysis

For our relevant pool of articles, we explored the number and timeline of publications to understand the trend in combining the two methodologies as well as the biogeographical region where the studies

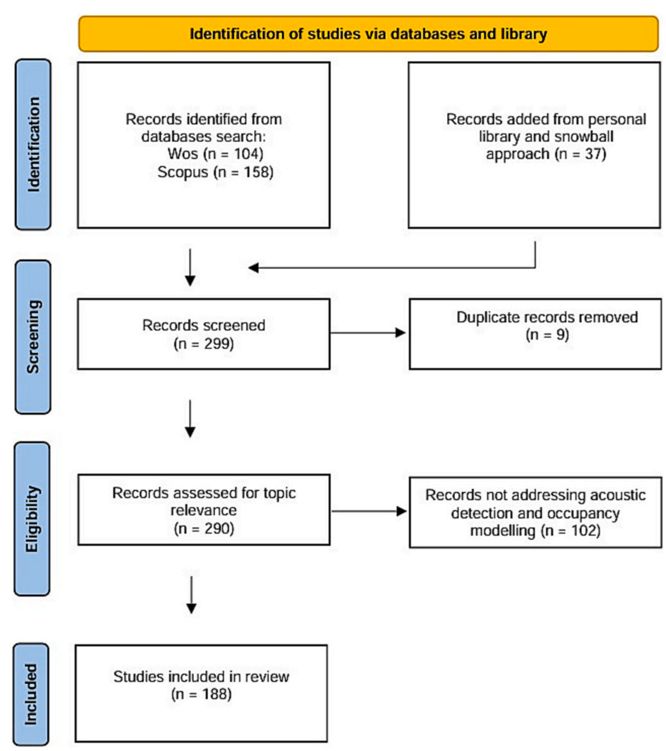

Fig. 1. PRISMA systematic review process, using the search 'occupancy model' AND 'acoustic' in SCOPUS and Web of Science databases, and the subsequent screening and selection process of publications.

were conducted. Next, we explored which were the targeted organisms of such studies by assigning them to one of five taxonomic groups: birds, bats, non-flying mammals, anuran, and insects. Bats were considered separately from other mammals due to their characteristic echolocation and the need to survey them with specific ultrasound detectors. To understand how occupancy models are used with acoustic data, we considered eight categories of occupancy models and counted the number of articles that used each category of models. Hence, we considered the following model variants: single-season single-species, multi-season (or dynamic models), multi-species, false-positive, time-to-first-detection, multi-scale, multi-state models and multi-method. It is worth noting that except for the single-species single-season model, each category is not exclusive since a study, for example, can use a multi-season model that also accounts for false-positive detections.

2.3. Text network analysis

We performed a text analysis to understand the topics and contents investigated in our pool of papers, extracting the author's keywords from the publication and all words from the title. We investigated these two components separately because keyword selection can purposefully exclude words from the title to avoid repetition. We standardised words so that similar words would be considered equal in the word frequency count, and plural words were reduced to singular. All special characters were removed from the title, and numbers were spelt. Words from the keywords were assembled and ranked in terms of frequency with a minimum occurrence of seven. In this rank, we did not consider the terms "occupancy", "model", and "acoustic" as they were the terms used in the database search. In addition to analysing keyword and title word frequency, we performed a network analysis of the keywords as indicators to understand the researched topics and uncover relationships between them, highlighting potential gaps in the existing research. The network defines words as nodes and the relationship between pairs of nodes as links. Following the word standardisation process outlined previously, we defined nodes as words appearing at least five times across the analysed titles and keywords and links as pairs of words that co-occurred twice across this dataset. Additionally, we associated each word with its year of publication to calculate the average publication year for each word, enabling us to identify temporal trends and shifts in researched topics over time.

3. Results

Our query returned 188 relevant publications (Appendix A). The number of publications per year that apply occupancy models to wildlife acoustic data has been gradually increasing until 2021, with a slight decrease in the upcoming years. While the first identified article was published in 2005, more than half of the articles were published in the last four years (2020–2024; N = 112; 59.6 %) (Fig. 2). Comparing the number of publications per year from searches using both "occupancy model" and "acoustic" terms with searches using only the "occupancy model" term, we could observe a similar trend with few published publications in the early years and a steady increase afterwards, followed by a decrease after 2021. There was a time difference of about five years between the growing usage of occupancy models and occupancy models with acoustic methods. Occupancy models started to be frequently used after 2008, whereas the application to acoustic data only started to increase in their number of publications after 2013 (Fig. 2).

3.1. Geographical distribution and organisms studied

The geographical analysis of the study sites highlights a geographical bias in research, predominantly favouring the Nearctic region. Among the study sites, the Nearctic region stands out with 116 publications out of 188 (61.7 %). The rest of the globe only accounted for a small fraction of the publications in this field, with the Neotropics accounting for 23

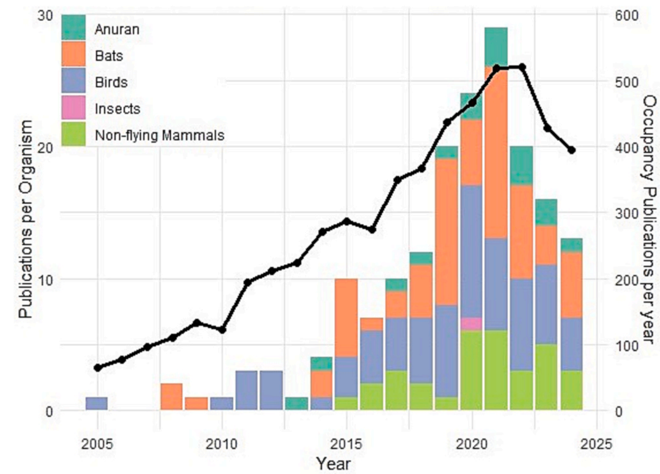

Fig. 2. Annual number of publications implementing acoustic methods and occupancy models in the research according to the studied organism (left bar plot), and comparison with the annual number of publications implementing occupancy models (right line plot).

publications (12.2 %), followed by Australasia with 21 (11.1 %), Palearctic with 11 (5.85 %), Indo-Malay with eight (4.3 %), and Afrotropic with just six publications (3.2 %) (Fig. 3).

The dominance of birds and bats in the investigated publications highlights their significance as the primary focus in research implementing acoustic methods and occupancy models, appearing in 79 and 62 publications (42 % and 33 %, respectively) (Figs. 2 & 3). At the same time, these two groups were heavily represented in the research effort in the Nearctic region, whereas in the remaining areas, there was a more even distribution across organisms (Fig. 3). The other studied organisms had more residual values, with non-flying mammals accounting for 32 research publications (17 %), anurans with 16 (8.5 %), and insects only having one publication that combines the two methodologies (0.5 %) (Fig. 2). Non-flying mammal studies were well-distributed across regions, with the highest number of publications in Australasia (N = 10). Despite the lower number of publications on anurans, the majority of them were conducted in the Neotropic (N = 7).

3.2. Modelling with occupancy

Our analysis shows that simple occupancy models prevail in the research literature, while more advanced models are underutilized, even when large species and years datasets are available. Regarding the categories of occupancy models used, the single-season single-species model accounted for half of the models used (53.7 %, N = 101) (Fig. 4). The multi-season model was the second most used when considering other types of models, appearing in 34 publications (18.1 %) (Fig. 4). Thus, approximately a fifth of the investigated publications modelled explicitly the variation in occupancy and detection over different seasons. It is important to highlight that while several studies spanned a study period of five years or more (N = 33), only about half of these (N = 15) opted to use multi-season models, indicating that many had the opportunity to implement such models but did not take this approach (Fig. 5).

Similarly, the results showed that multi-species occupancy models (MSOMs) were implemented in a few publications, while a distinctly higher number of publications studied several species simultaneously. We identified 25 articles implementing MSOMs models out of the 188 publications, translating it into 13 % (Fig. 4). Contrastingly, 112 publications collected acoustic data for more than one species and 79 for four or more species (Fig. 5). Thus, many publications could have applied MSOMs but did not do so in their analysis. Incorporating false positive detections into the analysis is highly relevant for species that

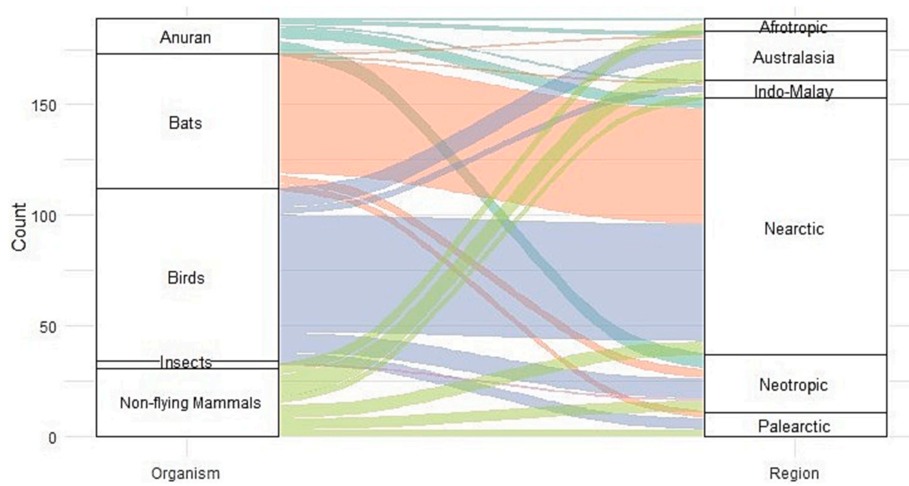

Fig. 3. Relationship between the studied organisms and global region where the study was conducted (N = 188 publications).

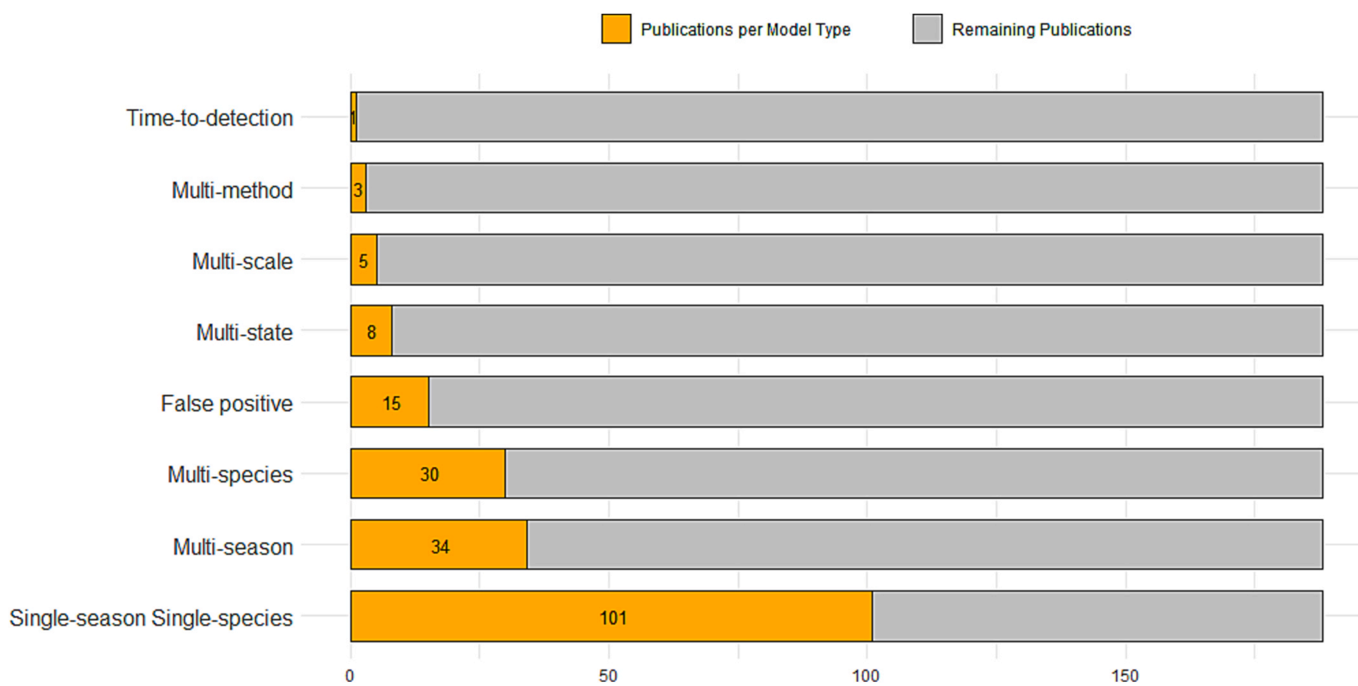

Fig. 4. Number of publications implementing each category of occupancy models in comparison with the remaining number of investigated articles (N = 188).

can be acoustically difficult to identify. Therefore, we expect these models to be generally used, but we only identified this model extension in 15 articles (13.8 %) (Fig. 4). The remaining categories of occupancy models had an overall reduced implementation: multi-state and multi-scale models were applied in just eight and five publications each. Multi-method models were applied in three publications, and the time-to-first-detection model was applied in only one publication (Fig. 4).

3.3. Researched topics

By extracting the frequency of each word in the titles and keywords of each article, we could investigate the topics being studied. Out of the 887 individual words in the title analysis (Appendix B), 88 had a frequency equal to or higher than five entries. The most frequent word was “bat”, with 48 entries; another highly mentioned organism was “bird”, with 24 entries. The other top-ranked words were “monitor” and “species”, with 37 and 30 entries, respectively, and “forest” and “using”, with 27 entries each. Hence, most research topics concerned monitoring species and investigating how species were using their habitat, with “forest” being the most researched habitat from the literature review.

When we analysed the keywords, we found similar patterns but with some differences in the vocabulary and frequency of the terms. There were 726 unique keywords (Appendix C), of which 27 accounted for seven or more entries (Fig. 6). This time, “passive acoustic monitor” was the most frequent word, with 34 entries. The keyword “detection” had a high count, with 30 occurrences demonstrating this feature of occupancy models. This time, “bat” shared the same number of occurrences as “bioacoustic” in the third position, with 23 entries. Words related to methodological aspects of the research had high counts, such as “acoustic monitor”, “ARU”, and “monitor”, with 18, 17 and 11, respectively, suggesting that a common goal of the research is to monitor species using Autonomous Recording Units. “Birds” was not a frequent keyword, but “barred owl” was chosen as a frequent keyword, occurring 10 times, and “Chiroptera” occurring 14 times (Fig. 6).

For the network analysis, we excluded the keywords “acoustic”, “occupancy”, and “occupancy model” to ensure a comprehensive

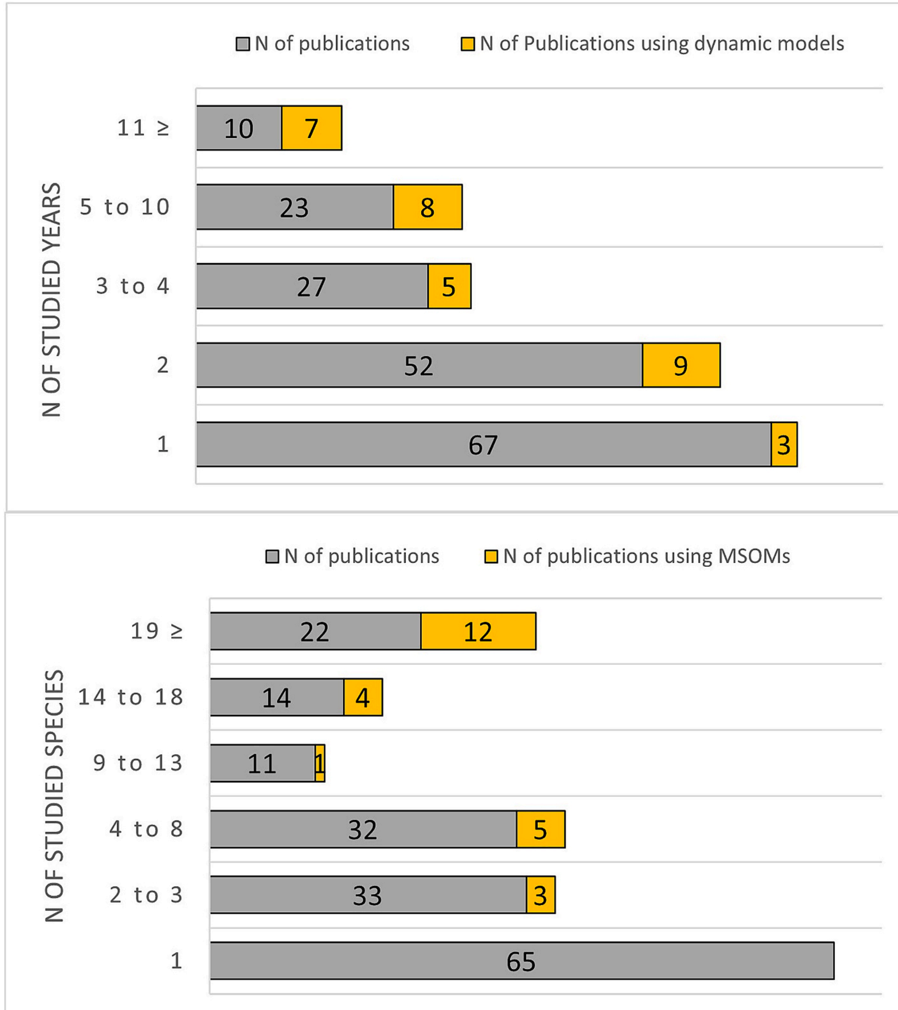

Fig. 5. Number of publications according to the number of studied years and number of publications according to the number of studied species. (A) Count of publications in relation to the number of years investigated and the number of publications using dynamic models in each category. (B) Count of publications in relation to the number of species investigated and the number of publications using multiple species occupancy models (MSOMs).

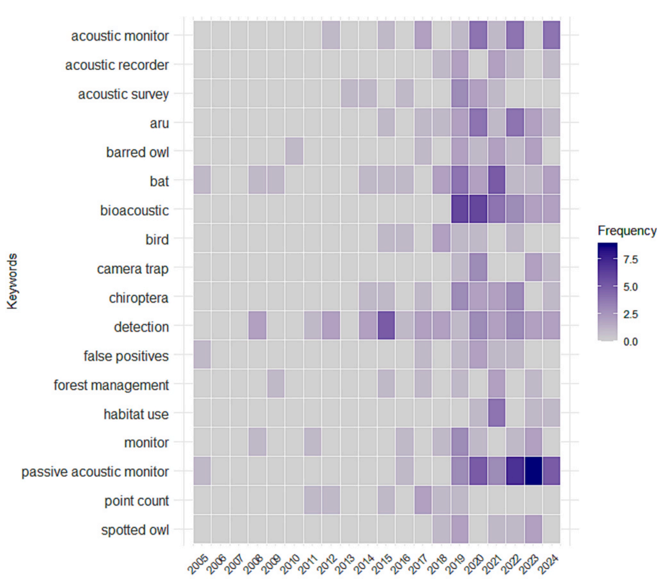

Fig. 6. Frequency of keywords over publication year *with a minimum frequency occurrence of seven across all publication years.*

understanding of the other relevant topics linking the publications. Hence, the resulting network for the title words contained 27 nodes and 502 edges. The words with a higher number of links were "bat" and "bird", with respectively 32 and 12 links with other words, demonstrating that they were the most important subject in the titles and respective publications (Fig. 7). The pairs of words with the higher number of links between them (link strength) were "passive" and "monitor" with 11 links, "using" and "monitor" with also 11 links and "habitat" and "use" with eight links. Considering the relation between words and publication year, it is worth noticing that "dynamic" or "multiple-season models" were prominent in earlier years. In contrast, in recent years, terms such as "endangered" and "range" have become more commonly researched according to the words in the titles (Fig. 7).

Regarding the network analysis for the keywords, the constructed network comprised 27 nodes and 142 edges. The keywords with the most connections were "passive acoustic monitor" and "detection," featuring 13 and 10 links with other keywords, respectively. This reiterates the focus on methodology process over the species being researched (Fig. 8). The keyword pairs exhibiting the strongest connections were "bioacoustic" and "passive acoustic monitor" with ten links, "barred owl" and "*Strix varia*" with six links, and "bioacoustic" and "spotted owl" with also six links (Fig. 8). When we consider the trend in keyword usage over time, it is evident that "colonization" was more frequent in earlier years, directly related to multi-season occupancy

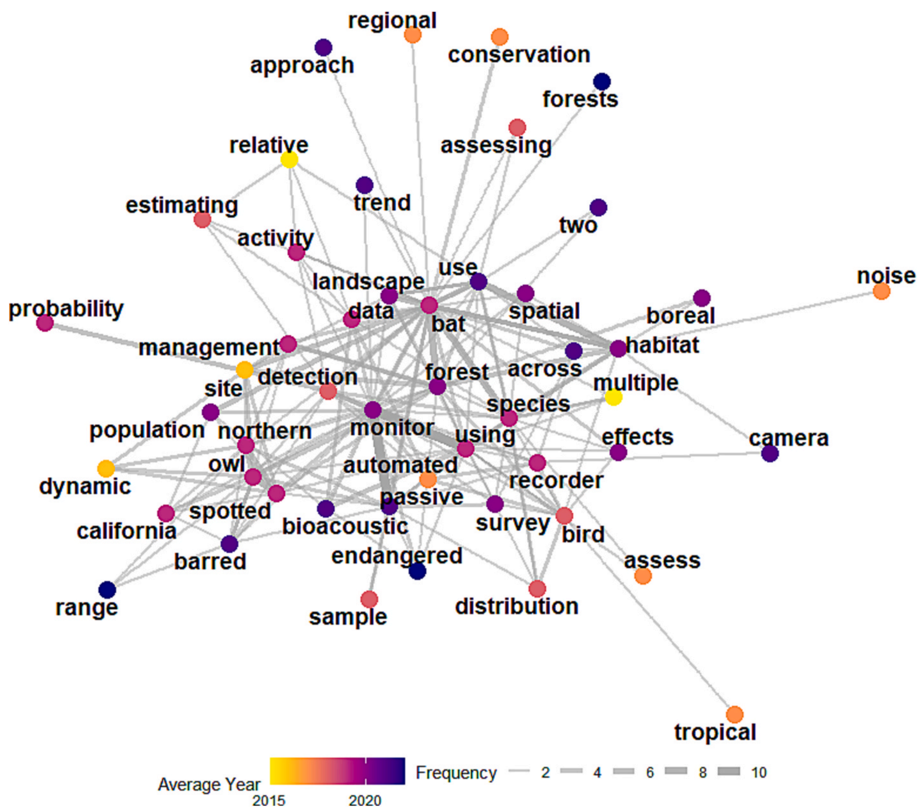

Fig. 7. Network of frequently co-occurring words in publications title. Nodes represent words that appeared at least five times across titles and edges representing word pair co-occurrence appearing in at least two titles. Node colour gradient corresponding to the average publication year.

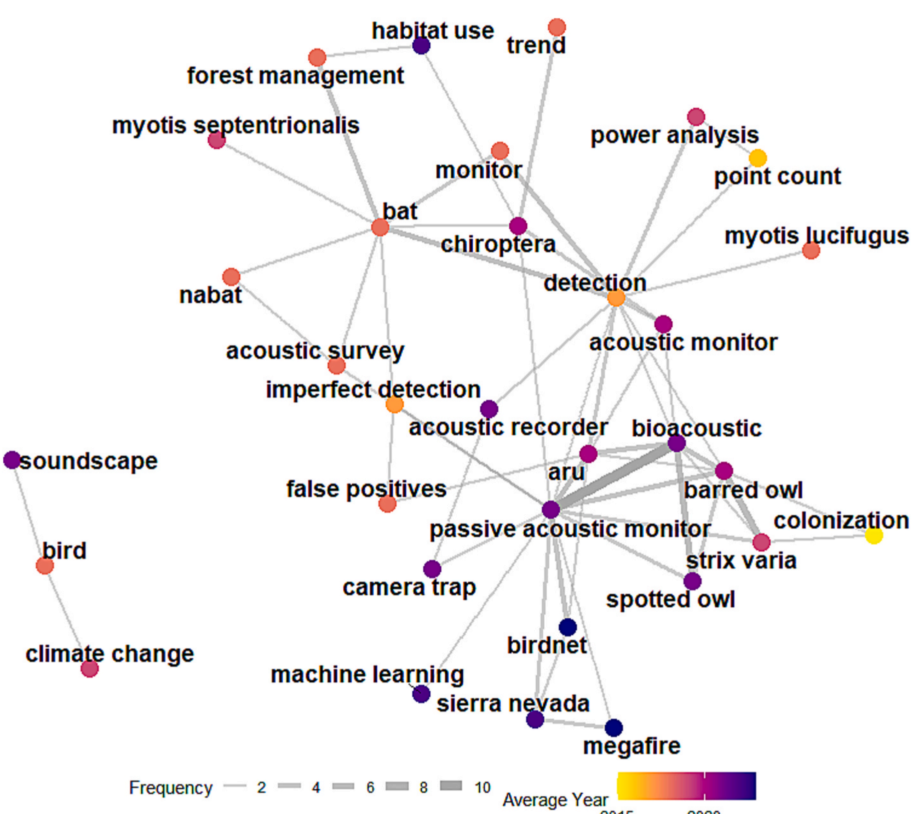

Fig. 8. Network of frequently co-occurring keywords. Nodes represent keywords used in at least five publications and edges representing keyword pair co-occurrence in at least two publications. Node colour gradient corresponding to the average publication year.

models. The keywords “megafire” and “birdnet” have been more prominent in recent years. This highlights the data becoming available from platforms like Birdnet and the research of extreme events related to climate change, like the mega-fires (Fig. 8).

4. Discussion

The analysis of peer-reviewed publications combining occupancy models with acoustic methods shows a steady increase over the years, revealing a growing interest and application of these methodological options in ecological research. This combination increased in parallel with the usage of occupancy models, showing the same trend and comparatively close to twenty times more publications each year (Fig. 2). The usage of occupancy models has been picked up since the late 2000s (Devarajan et al., 2020), but their use, coupled with acoustic methods, has mostly grown from 2014 until 2020. After 2020, there has been an atypical decline in the overall number of publications, potentially explained by the global pandemic, COVID-19 (Riccaboni & Verginer, 2022). In parallel, there was an increasing trend of published research papers in various scientific fields, of which occupancy and acoustic methods seem to follow the same trajectory (Lisón et al., 2020; Mutanu et al., 2022).

4.1. Studied taxa

Our results indicate robust research, mostly towards two vertebrate taxonomic groups, birds and bats. Generally, acoustic surveys were widely used in bird research due to call and song identification; therefore, it was expected that a large number of research papers were focused on these organisms (Shonfield & Bayne, 2017). Bats were the other organisms benefiting from coupling acoustic detection with occupancy models. A methodological component driving the high number of research articles investigating bats is the accessibility to ultrasound detectors and the capacity to record bat echolocation (Sugai et al., 2019). Alternative methods to study bats during their active period can be more expensive (e.g., infrared cameras) or less effective in detecting some species (e.g., mist nets). The two taxonomic groups were primarily studied in the Nearctic region, which comprises the majority of the publications. This denotes an opportunity to broaden the application of the combined methodologies in the Southern Hemisphere and Eurasian regions, even for these well-researched groups. The other taxonomic groups, such as non-flying mammals, did not benefit from the implementation of the two methodologies as they had a relatively low number of published studies. Terrestrial mammal communities are more commonly studied using camera traps (Srbek-Araujo and Chiarello, 2005; Pettorelli et al., 2010), therefore, most species studied using occupancy models and acoustic detectors were arboreal primates (Kalan et al., 2015; Vu & Doherty, 2021) and arboreal marsupials (Law et al., 2018; Lefoe et al., 2022), as these tend to live in habitats with denser vegetation and rely commonly on sound for communication. Amphibians also had a small number of studies applying the acoustic methodology with occupancy modelling (Fig. 2). This was unexpected as many species are vocal, and this is frequently used to detect amphibians (Čeirāns et al., 2020; Grafe & Meuche, 2005). Applying these methods could be crucial for their conservation, as they are one of the most threatened animal groups globally and would benefit from comprehensive and long-term monitoring programs. There is also the potential to apply these statistical methods in underwater environments, but we found only two research papers that studied marine animals, specifically belugas and manatees (de Souza et al., 2021; Small et al., 2017). Multiple acoustic techniques have been developed to study marine mammals, from mobile to fixed options and applied in various coordinated research efforts (Marques et al., 2013). Due to the favourable condition of sound propagation underwater, there is the potential to study many aquatic organisms using autonomous recording units. With the development of hardware and automated classification systems, occupancy models could be a viable approach for their application.

4.2. Occupancy models used

Approximately half of the research articles used the simplest method in occupancy modelling, where occupancy and detection are estimated over one species in one season, and these parameters were related to environmental covariates. Such a simple model is advantageous for investigating ecological processes such as species distribution (Guillera-Arroita et al., 2010; Royle et al., 2005) and species-habitat relationships (Ball et al., 2010). Bailey et al., (2014) noted that temporal dynamic models have also been generally used for native and invasive species and metapopulation studies (Ferraz et al., 2007; Yackulic et al., 2012). However, our research shows a high proportion of studies that collected data from multiple years, although only a fraction applied multiple-season occupancy models (Fig. 5). Therefore, temporal variation and dynamic parameters (colonisation and extinction) could be investigated but were not contemplated when applying single-season models. A primary bottleneck to the implementation of multiple-season models can be the research questions being addressed. Multiple-season models are specifically designed to predict the population’s evolution by estimating the probability of colonisation and extinction parameters (MacKenzie et al., 2003). When the focus of research is not on dynamics, implementing multiple-season models offers reduced advantage. On the other hand, a simpler approach that has been used is a single-season occupancy model that accounts for temporal variation by including year as a site-level covariate. This method, sometimes referred to as an ’implicit’ model of dynamics, allows for the investigation of trends over time without the added complexity of a full dynamic model (Coleman et al., 2014; Venier et al., 2017; Byerly et al., 2020). Additionally, the dynamic parameters from occupancy models can be analytically difficult to estimate due to the inherent modelling complexity to obtain robust estimation (Kelleher et al., 2025). Yet, detection/non-detection data can be relatively simple to collect, and recent technological advancements have resulted in massive increases in available data, thereby offering new opportunities for the broader application of multiple-season occupancy models. Addressing these thematic and analytical constraints presents an opportunity to fully leverage long-term data for more robust insights into species dynamics. Moreover, considering that long-term monitoring programs are essential to evaluate natural and anthropogenic oscillations in species distribution, multi-season occupancy models is an essential tool that helps to disentangle the origin of species temporal variation.

The pattern of multiple-species occupancy models published paralleled the multiple-season occupancy models. Many research papers collected data for more than one species, but only a fraction of them implement this category of models (Fig. 5). Multiple-species occupancy models can help investigate community ecology questions. One can infer detectability and occurrence patterns of one species using information from other more common species and, hence understand more precisely the community size and structure (Guillera-Arroita, 2017). These models are particularly relevant for rare or hardly detectable species, even being possible to infer about species that have not been recorded in the dataset (Dorazio et al., 2006). Therefore, multiple-species occupancy models are an essential instrument for enhancing our understanding of community dynamics and biodiversity. Similar to the challenges faced in multiple-season models, the underusage of multi-species models highlights significant opportunities for implementation. Many study designs are tailored to a focal species resulting in methodological constraints, even though non-target (bycatch) species are often recorded incidentally (Guillera-Arroita 2017; Steenweg et al., 2019). This results in valuable information on multiple species, yet these are seldom analysed together as a community. Multi-species occupancy models are highly informative when the community is analysed using random effects, where species respond similarly (though not identically) to environmental conditions, allowing for community parameter estimation (Guillera-Arroita 2017;

Kéry & Royle 2009). However, implementing multi-species models that investigate occupancy as a collection of fully independent species would still enable researchers to gain a more comprehensive understanding of community patterns and interspecific relationships, particularly benefiting conservation efforts for hard-to-detect and rare species.

Few research papers addressed false-positive detections in modelling, but ignoring type II errors can lead to significant biases in estimating occupancy and detection parameters (Chambert et al., 2015). Implementing false-positive occupancy models has been shown to enhance model support and improve the precision of estimators (Miller et al., 2011; Rojas et al., 2019). A necessary step of this method is quantifying false-positive rates in the species classification process. If species are classified through automated detection systems, a smaller subset of detections can be manually verified. This strategy is advantageous as acoustic methods usually produce extensive recordings, and complete human verification of the data set can become prohibitive. Artificial intelligence (AI) has emerged as a powerful tool to automate species classification, particularly, machine learning algorithms, as theyallow improvement over template-based automated detection by building adaptable classification models adjusted to the input data (Balantic & Donovan, 2020). AI tools have the potential to be widely implemented in ecological research and help process ever-bigger acoustic datasets. However, AI must be applied cautiously as significant knowledge gaps remain for underrepresented taxa and in optimizing it for diverse ecological contexts (Sharma et al., 2023).

The integration of multiple data collection methods represents an important step in the development of occupancy models. Multi-method strategies allow for model-based data integration to retain the strengths of each dataset (Isaac et al., 2020). This is achieved by establishing a joint likelihood framework synthesising multiple datasets into a unified ecological process model (Miller et al., 2019; Schaub & Kéry, 2021). By leveraging diverse datasets, integrated occupancy models also account for differences in detection probabilities between methods, enabling more precise estimates of occupancy and detection parameters (Robinson et al., 2020). Additionally, integrated models are valuable for extending inferences over broad spatiotemporal ranges from different datasets (Zipkin et al., 2021) and incorporating replicated and non-replicated data. But integration has its own set of challenges. Differences in data quality, sampling design, and methodological biases between datasets can difficult the integration process. Pre-processing steps, such as standardizing formats, handling missing data, and accounting for false positives, are essential but can be time-consuming. Moreover, integrating datasets with varying spatial and temporal resolutions requires careful consideration to avoid introducing additional uncertainties into the model. Despite these challenges, data integration holds great potential for advancing ecological research, especially as the availability of diverse datasets continues to grow, driven by technological advancement like remote sensing or data collection from citizen science.

4.3. Studied questions

The keyword analysis draws attention to an advantage of using occupancy models, demonstrated by the keywords “detection” and “detection probability”. They allow for incorporating observation error into the model, more precisely, imperfect detection. By accounting for this uncertainty, the models provide a more honest and precise representation of the system contained in the available data (Guillera-Arroita, 2017).

Other keywords that are central in the research are “monitor” and “acoustic monitor”, indicating that occupancy models and acoustic methods are of frequent use in monitoring studies (Shonfield & Bayne, 2017). Such monitoring schemes can be a practical approach to identifying population trends for rare and common species, particularly relevant for rare species as they can be hard to detect and their population estimates harder to obtain (McGrann & Furnas, 2016). If carefully planned, protocols can be successfully established and obtain valuable information for species assessment and management (Carlos Abrahams & Geary, 2020). The time and cost-effectiveness of the monitoring program can be enhanced by the implementation of automated species identification approaches, reducing manual verification by experts (Campos-Cerqueira and Aide 2016). Occupancy and acoustic are not only implemented exclusively to monitor species, as “habitat use” and “use” has been one of the most recent topics among keyword usage. The study of habitat use has been essential as many anthropogenic modifications can impact organisms and their habitat. These include light pollution (Mena, 2021), forest management and logging (Gallagher et al., 2021), controlled and uncontrolled fire (C. M. Blanco & Garrie, 2020; Burns et al., 2019; Starbuck, 2014), and climate change (Adams & Hayes, 2008), with these three topics present respectively as keywords “forest management”, “megafire” and “climate change”. Once conservation practitioners know how animals interact with the habitat, it is easier to implement mitigation measures that promote the resilience of communities. This is why “management” is a relevant topic, it can have conservation significance and positive ecological effects and well-informed management can prioritise specific monitoring strategies (J. Blanco et al., 2020).

Some words were not present in the keywords but were used in the titles. We could observe the difference in the network structure of the titles (Fig. 7). “Conservation” was a common word in the title in publications and had a high number of links, being therefore associated with multiple topics. Frequently, conservation efforts are targeted towards a rare focal species as management actions are more easily implemented when directed towards a few habitat characteristics affecting species’ occupancy. On the other hand, at larger geographical scopes, “species richness” can become an essential parameter to measure in management plans and is easily investigated through multiple species occupancy models (Devarajan et al., 2020). Interestingly, no keywords were associated with the study of metapopulations. Since the early development of multiple season occupancy models, metapopulation dynamics have been of particular interest due to the model capacity to estimate local extinction and colonization probability (MacKenzie et al., 2003). From a management perspective, this tool can be effective in investigating alternative conservation scenarios and their impact on occupancy (Wood et al., 2018), and specialised spatio-temporal models have been developed to predict metapopulation dynamics (Chandler et al., 2015). Endangered species are particularly susceptible to fragmentation and many have benefited from metapopulation studies implementing occupancy models including amphibian (Moor et al., 2024; Bertassello et al., 2022), mammals (Castle et al., 2020, Bauder et al., 2023), and insects (Laroche et al., 2018). However, acoustic methods have seldom been implemented to these taxa as a sampling methodology (Collier et al., 2012; Kelleher et al., 2025) suggesting that future studies could further benefit from exploring acoustic application in vocal species. Invasive species were also not mentioned in any of the 108 publications found, but it is highly relevant as biological invasions are one of the main drivers of species range shifts and biodiversity loss around the globe (Hoffmann et al., 2010). For some taxonomic groups, such as birds and mammals on islands, implementing mitigation methods to reduce the impact of invasive species can have considerable success (Jones et al., 2016; McMurdo Hamilton et al., 2023). Implementing multiple season occupancy models can help conservation practitioners understand the evolution of the invasive and native species distribution and lay the foundation for adaptive management, especially as occupancy and range dynamics are particularly important in the context of invasions (Guillera-Arroita 2017). For invasive species that are vocally active or sound producing, such as birds (Yackulic et al., 2012, Yackulic et al., 2013), fish (Higgs & Humphrey, 2020; Rountree & Juanes, 2017), and amphibians (Moss et al., 2021), acoustic methods hold significant application potential. When a high degree of certainty in acoustic identification is possible, these methods can be used to estimate species’ distribution areas and to assess competition between invasive and native species. The use of autonomous recording units, in particular, enhances the feasibility of data collection on a broader scale.

Increasing the scale of data collection can be facilitated by citizen science, but this topic had low relevance concerning our pool of publications, only with mention of platforms such as "Birdnet". Citizen science is increasingly important as a data source for large-scale monitoring projects. Such data has its challenges regarding analysis including the difficulty to account for observational uncertainty and to estimate occurrence rates, but there are multiple solutions, from survey design to statistical methods (Yackulic et al., 2014; Altwegg & Nichols, 2019). One of the options to improve parameter estimation for this data type is implementing false-positive occupancy models. To enhance this model framework, species identification uncertainty can be accounted using either binary detection/non-detection observations or by incorporating continuous-score data, which quantifies the model's confidence in its species classification (Ruiz-Gutierrez et al., 2016; Rhinehart, Turek, & Kitzes (2022). When implemented with an optimal design framework, for example by targeting data collection in specific regions of interest or areas with limited species information, citizen science projects can help to map large-scale species distribution while maintaining data reliability (Higa et al., 2015; Miller et al., 2019; Rodhouse et al., 2021) Adopting alternative strategies to collect data, such as citizen science projects, could mitigate logistic constraints frequently associated with large-scale monitoring programmes. Furthermore, the collection of data through citizen science projects can increase public engagement in conservation efforts and help close information gaps.

5. Conclusion

Acoustic recording methods allied to occupancy models are a natural and effective strategy to study the occurrence of wild populations. Their use has been growing steadily, but they have the potential to become even more widespread in the study of many sound-producing species. While acoustic methods are increasingly implemented to collect data, imperfect species detection should be thoughtfully considered when working with this type of ecological data. Importantly, it has been demonstrated how occupancy models and acoustics are established methods to monitor bats and birds; however, these are not generally applied to study other taxonomic groups. We recognise a necessity to further implement these methods to study non-flying animals and extend the research to the aquatic environment, for which very few studies have been reported. Additionally, it is reasonable to expect that beyond the Nearctic, where most studies are conducted, other regions of the globe would greatly benefit from more research coupling acoustic methods and occupancy models.

This review illustrates how most of the research is focused on studying one species or several species separately for short periods, applying the single-season single-species occupancy model. Occupancy models are still in active development, and several model extensions have the potential to become commonly implemented to investigate occurrence and a broader spectrum of ecological dynamics. This seems particularly true for multiple species occupancy models and multiple season occupancy models, as in many studies, data was collected but not thoroughly investigated. Finally, our review unveiled significant knowledge gaps as some topics are rarely investigated with occupancy models and acoustic methods. Therefore, priority should be given to expanding the research, such as invasion species ecology and metapopulation dynamics, and extending data collection to citizen science projects. Diversifying the studied subjects would likely yield novel insights into wild populations in less-studied habitats and inform the future of conservation and management efforts.

CRediT authorship contribution statement

Frederico Carvalho Martins: Writing – review & editing, Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis, Data curation. **Pedro Segurado:** Writing – review & editing, Supervision, Conceptualization. **João Tiago Marques:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Statement

All the data used in this manuscript is publicly available, and it was retrieved from the Web of Science web page (https://www.webofscience.com) and Scopus (https://www.scopus.com/).

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.114081.

Data availability

Data will be made available on request.

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