

Review

A narrative review of the impact of anthropogenic light and noise on owls

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Today, owls are exposed to increasingly brightly lit nights and noisy environments because of human activities. To understand the impacts of artificial light at night (ALAN) and anthropogenic noise we performed an evidence synthesis. We searched four literature databases and Google Scholar and we collected 39 relevant articles (1945–2024) providing 125 cases (64 on light pollution and 61 on noise pollution), targeting 25 species (c. 10% of owl species). We found harmful effects of both sensory pollutants on several outcomes. First, ALAN tends to reduce acoustic communication and to be associated with a lower occurrence of owl species, although it is difficult to confirm whether ALAN leads to silent or absent owls. Moreover, ALAN disturbs owl–prey interactions. Although light probably improves owl vision, the light-avoidance behaviour of small mammals could result in poorer hunting success of owls feeding on mammals. Conversely, ALAN enhances food provisioning and even breeding of owls feeding on insects that are attracted by light, to the detriment of these prey populations. Second, human-induced noise clearly tends to reduce owl vocalization, yet that vocalization may be essential to communication between individuals. The ability of owls to detect prey (hunting success) is also reduced under noise exposure (even at low amplitude), probably as the result of masking and distraction. Studies also demonstrate that anthropogenic noise can cause physiological and behavioural stress and disturbance to owls. Such adverse effects may contribute to declines in reproduction and occurrence of owls observed in noisy areas. As a result, we recommend reduction of both sensory stressors as much as possible, for owls and for ecosystem stability, for example by maintaining and restoring quiet and dark areas. We also recommend more consideration of owls in sensory ecology research to fill knowledge gaps.

Keywords: illumination, moonlight, sound, Strigidae, Tytonidae.

Human activities spread artificial light and sound throughout the environment (Halfwerk & Slabbekoorn 2015). The phenomenon of light pollution is increasing (Falchi *et al.* 2016) and expansion of light pollution is consistently higher in hotspots of

species richness, including for nocturnal species (e.g. bats, owls and geckos) (Koen *et al.* 2018). In Europe, the availability of dark areas will decline in the future for several owl species, including areas in the Natura 2000 network (Almpanidou *et al.* 2020). In parallel, artificial sounds are generated by many human activities such as traffic (roads, boats, aircraft), nocturnal recreation (e.g. tourism, events), military manoeuvres or industry.

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A significant increase in such anthropogenic noise disturbs natural soundscapes and this has become another global concern for life on Earth (Kunc & Schmidt 2019).

Adverse effects of light pollution have been widely documented across many taxa (Davies & Smyth 2018, Sanders *et al.* 2021, Pérez Vega *et al.* 2022). For birds, artificial light at night (ALAN) can alter physiology and body mass (Yadav *et al.* 2022), incubation behaviour (van Dis *et al.* 2021) and singing activity (Marín Gómez 2022), and can limit distributions (Sierro & Erhardt 2019). There is also evidence of numerous negative impacts of noise pollution on wildlife, including birds, regarding communication (Duquette *et al.* 2021, Gomes *et al.* 2022), space use (Nakano *et al.* 2018) and abundance (Keehn & Feldman 2018).

In this context, it is relevant to investigate the specific effects that light and noise pollution can have on owls (Strigiformes), an order that includes 244 mostly nocturnal species worldwide. Owls have good scotopic vision based on large, frontally implanted eyes (Potier *et al.* 2020) with rod-rich retinas (Martin 1982, Alix *et al.* 2017) that allow them to move in dim light environments (Martin 1986). Owls' hearing is also very acute (Krumm *et al.* 2017): auricular holes are located near the eyes inside the facial discs and some owls have asymmetrical ears which enable them to detect prey in dark environments (Knudsen & Konishi 1979). Nocturnal raptors are very sensitive to visual and acoustic stimuli, which they use to move, catch prey or find mates (Martin 1990), and some studies show that both artificial light and sounds disturb them (Orlando & Chamberlain 2023). For instance, the occurrence of Western Barn Owls *Tyto alba* in churches (nesting sites) is negatively correlated with light pollution levels (Zmihorski *et al.* 2020), traffic noise affects prey detection by Northern Saw-whet Owls *Aegolius acadicus* (Mason *et al.* 2016), urban noise reduces the vocal activity of Tawny Owls *Strix aluco* and Long-eared Owls *Asio otus* (Fröhlich & Ciach 2018a, 2018b), and attendance of Mottled Owls *Strix virgata* is negatively related with ALAN and daily noise in an urban context (Marín-Gómez *et al.* 2020).

The aim of this literature synthesis is to systematically map and review the effects of anthropogenic light and noise on owls. In 2022, McClure *et al.* (2002) published a review on the

effects of light and noise on raptors (both diurnal and nocturnal). They collected 32 articles up to 2020, including 10 on light pollution and 24 on noise pollution; they concluded that applied studies on sensory drivers on raptors remain rare. However, their search strategy was based on generic terms (such as raptor, bird of prey, owl) and on two literature sources (one academic database + Google scholar) which may partly explain the small number of articles found. Indeed, some relevant articles (Dice 1945, Hernandez 1988, Hathcock *et al.* 2010) were not included, suggesting either specific decisions during screening stages or limitations in the search strategy. Moreover, noise and light pollution have become a prolific research topic recently, so important new articles may have been published since 2020. Therefore, to better reflect the current state of knowledge we wished to update and complement this review, focusing on owls. We expected to retrieve more articles using taxonomic families and species names as search keywords and searching more literature databases. Moreover, beyond highlighting gaps in the literature, we also wish to provide an in-depth assessment of the evidence of the effects of noise and light pollution on owls.

Given that 18% of owl species were threatened in 2023, according to the IUCN Red List, conservation measures are needed. Thoroughly investigating the effects of light and noise pollution on these birds may help to identify appropriate mitigation strategies. Many stressors are already known to affect owl populations including road mortality, rodenticides, and habitat loss and fragmentation (Hinam & Clair 2008, Hindmarch *et al.* 2017, Wan *et al.* 2018, Cooke *et al.* 2022), but light and noise pollution could be involved too (Senzaki *et al.* 2020). In addition, ALAN and noise are similar disturbances (i.e. both are anthropogenic sensory pollutants that can disrupt animal perception, behaviour and habitat use) and may interact (Halfwerk & Jerem 2021). It is unknown whether any interaction is synergistic (more detrimental than the expected additive effect), antagonistic (less harmful than the expected additive effect) or emergent (individual exposure to noise and light has no impact, but their combined exposure does). This evidence synthesis is also designed to retrieve studies dealing with both anthropogenic light and noise pollution that may have assessed this interaction.

METHODS

To perform this literature review we followed as far as possible the guidelines of the *Collaboration for Environmental Evidence* (Collaboration for Environmental Evidence 2022), except as listed below. This method of conducting systematic maps and reviews in ecology allows for comprehensive, objective, rigorous and transparent syntheses used to inform researchers, practitioners and decision-makers (Pullin *et al.* 2022). Moreover, our review conforms to ROSES reporting standards (Haddaway *et al.* 2017) (Appendix S1).

The main question that we addressed was: What do we know about the effects of anthropogenic light and noise on owls? This question was developed through the following Population–Exposure–Comparator–Outcome (PECO) framework (Appendix S2; section 1).

The bibliographic search was performed on several sources to collect peer-reviewed and grey literature. First, four academic databases were searched several times until 29 November 2024. Web of Science Core Collection, Zoological Records, Biological Abstracts on the Web of Science platform (Clarivate, <https://www.webofscience.com>) and Scopus (Elsevier, <https://www.scopus.com/>) were requested using search strings based on the list of owl species (see Appendix S2; section 2 and Appendix S3). A test list of 21 articles was used to assess the comprehensiveness of the search strategy (see Appendix S4). Second, Google Scholar (<https://scholar.google.com/>) was searched until 30 November 2024 to complete the collection of grey literature using simplified search strings to meet the requirements of this search engine (see Appendix S2; section 3). Finally, we also screened an evidence synthesis known by the review team that focuses on artificial light and birds (Adams *et al.* 2021) and we exported citations that were not already retrieved.

The requests to the four academic databases provided 3378 citations. In addition, 151 citations were retrieved from Google Scholar and 10 additional articles came from the test list (McClure *et al.* 2022) or from Adams *et al.* (2021). All the citations from the different sources were merged and 981 duplicates were excluded. Citations were screened by one reviewer (R.S.) through three stages – on titles, on abstracts and on full-texts – according to predefined inclusion/exclusion criteria

(see Appendix S2; section 4). A flow diagram in Appendix S2 (section 4) provides details of the screening process of included/excluded articles at each stage, in accordance with ROSES guidelines. Appendix S2 (section 5) gives some examples of rejected articles with the reasons for their exclusion, and all inclusion/exclusion decisions are available in Appendix S5.

At the end of the three screening stages, 39 articles were included into a systematic map database detailing whether they deal with anthropogenic light, anthropogenic noise or both (see Appendices S6 & S7 (section 1) for further details). Metadata and data were extracted from each of these articles (for more details, see Appendix S2, section 6 and the ‘Code book’ sheets in Appendices S8 & S9). For this step, articles were split into ‘cases’, which considered only one species, one exposure (light or noise) and one outcome. Common variables were coded for all cases regarding populations, exposures and outcomes (based on eight categories of outcomes; see Appendix S2, section 6 for details). The results obtained by the authors, whether quantitative or qualitative, were also extracted and summarized as a positive, negative or no significant effect.

Metadata and results of articles were used to describe the characteristics of the available literature (bibliometric results; population, exposure and outcomes studied). As a result of the diversity of the outcomes reported and the limited number of studies with comprehensive quantitative data (sample size, mean, standard error), we could not perform a meta-analysis. We therefore developed a narrative synthesis in which data were described with tables, charts and texts to summarize the main findings of primary research on the effects of anthropogenic light and noise on owls, while avoiding any vote-counting (i.e. comparing the number of positive, neutral and negative studies, which is one of the pitfalls in evidence syntheses (Haddaway *et al.* 2015)). Data regarding study design (e.g. comparator, monitoring methods) were used to make recommendations to improve primary research.

Limitations of the review included (1) the screening process and data coding were conducted by a single reviewer and (2) no critical appraisal was performed to assess the risk of bias of the included studies, although information on quality of study design was coded for each study. In addition, we could not retrieve 22 papers (c.9%)

(Appendix S5), which led us to exclude these citations from the review process before full-text screening (because of the texts being behind a pay-wall or not published online). Finally, the articles we identified from other reviews suggest two limitations in our search strategy. First, more general studies that may include owl data were unlikely to be captured by our search strings (e.g. Alquezar *et al.* 2020). In this respect it would have been relevant to screen the 524 articles on birds included in the systematic map on noise pollution published by Sordello *et al.* (2020), but this was beyond our resources, knowing that 180 articles do not have an abstract and would have required full-text screening. Similarly, our searches may have missed articles that take artificial light or noise as a proxy to characterize urbanization and then do not include 'light' or 'noise' in their title, abstract or keywords. We are aware of these two restrictions but widening our search string to avifauna and urbanization would have broadened the scope substantially beyond the objectives of this review.

RESULTS

General trends

Among the 39 included articles published from 1945 to 2024 (Fig. 1), 21 focused on artificial light and 23 focused on anthropogenic noise, including five that dealt with both. Studies were mainly conducted in the USA (Fig. 2). Together, the articles provided 125 cases: 64 about artificial light (Appendix S8) and 61 about anthropogenic noise (Appendix S9). In total, 25 owl species (c.10% of Strigiformes) were studied from the perspective of artificial light ($n = 19$) or anthropogenic noise ($n = 16$), or both ($n = 10$) (Table 1). Western Barn Owl, Long-eared Owl and Spotted Owl *Strix occidentalis* account for most articles (respectively, seven, six and six) whereas Spotted Owllet *Athene brama* and Spotted Owl account for most cases (respectively, 15 and 13). All publications were journal articles except for a Masters thesis on noise pollution (Mason 2015) and a note from the U.S. Department of Agriculture on helicopter noise (Johnson & Reynolds 2002).

Artificial light effects

Two sets of articles clearly stand out (see Appendix S7, sections 2 and 3 for bibliometric

details): first, seven articles (1945–90) reported *ex situ* studies (conducted in outdoor aviaries or rooms/boxes in a laboratory) that mainly investigate hunting success and physiological outcomes, and secondly, 14 articles (2000–24) reported *in situ* studies that assess the effects of artificial light on diverse outcomes such as communication, occurrence, mortality or reproduction. The following summaries are derived from these two sets of articles.

Effects on occurrence

Six articles (16 cases, but only 6 of them have reported results), based on observational *in situ* studies, considered correlations between light pollution and owl occurrence, using several monitoring methods (e.g. acoustic, net capture, prospecting churches). Data all highlighted a negative relationship between ALAN and owl occurrence (Fig. 3). One study referred to Mottled Owls in a Mexican city (Marín-Gómez *et al.* 2020) and another came from an extensive survey of Western Barn Owls across Poland (based on nest counting in 2768 churches; Żmihorski *et al.* 2020). Another large study of Tawny Owls in the UK, based on citizen science, showed that ALAN decreased occupancy and colonization probability and increased the probability that a given occupied site became unoccupied in the following season (Hanmer *et al.* 2021). In an avian survey in Brazil, Tropical Screech Owls *Megascops choliba* avoided airports, which was attributed to light and noise pollution (Alquezar *et al.* 2020). Finally, one article reported an experimental study, manipulating light-emitting diode (LED) colours (red, yellow, green and blue) in migrating birds (Zhao *et al.* 2020). Collared Scops Owls *Otus lettia* were captured 11 times and data are provided but statistical results are reported for all bird species (number of birds trapped by different light colours, with short-wavelength blue light causing the strongest phototactic response while birds were rarely attracted to long-wavelength red light).

Effects on reproduction

Three cases reveal a positive relation between reproduction and ALAN (Fig. 3). Rodríguez *et al.* (2021) monitored 17 Burrowing Owls *Athene cunicularia* using global positioning system (GPS) loggers and showed a favourable effect of outdoor lighting on reproduction. Owls preferred to nest and fledged more young in lit areas. A study of

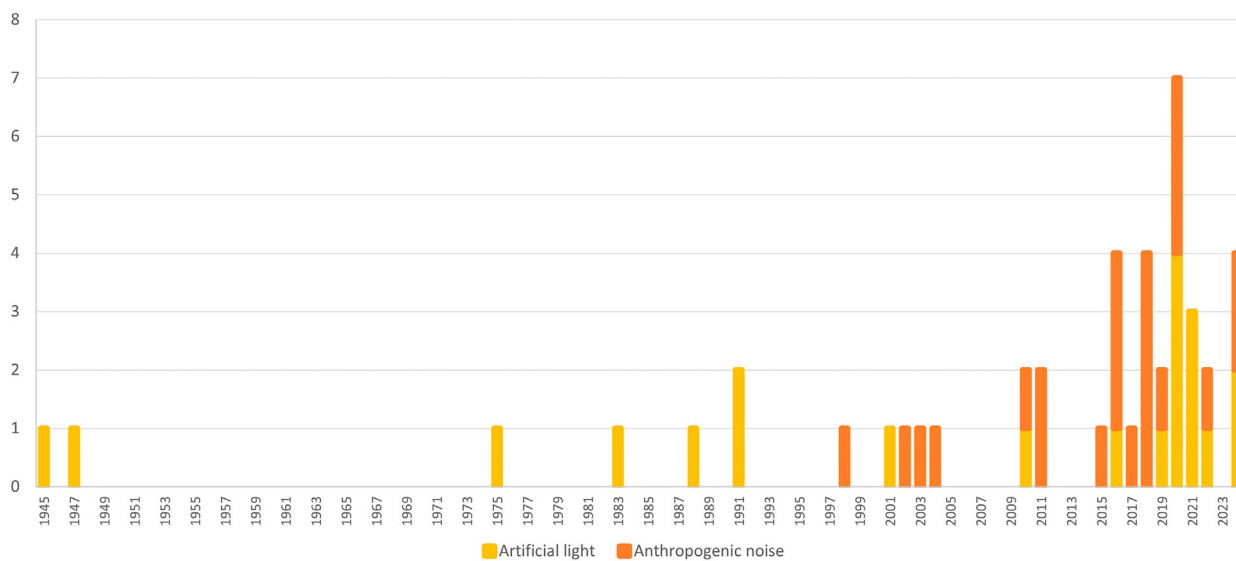


Figure 1. Number of articles per year on the effects of artificial light and anthropogenic noise on owls (Strigiformes) (total $n = 39$).

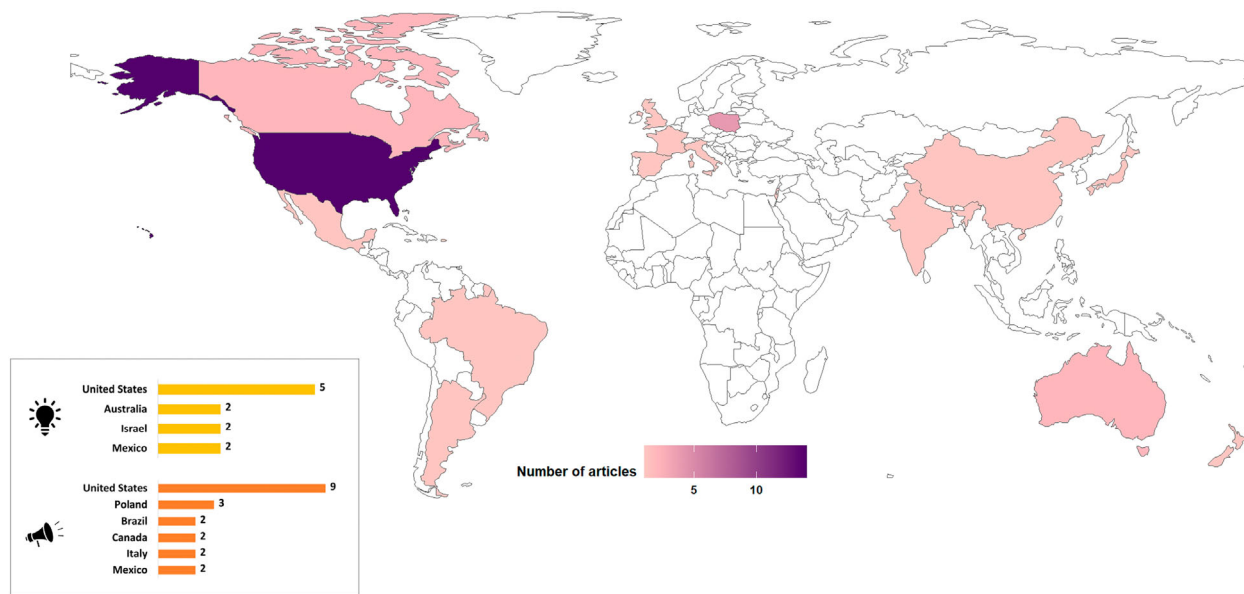


Figure 2. Geographical distribution of articles on the effects of artificial light and anthropogenic noise on owls (Strigiformes) (total $n = 39$). Box at the bottom left of the figure shows for each exposure (top: artificial light; bottom: anthropogenic noise) which countries supply two or more articles. In two articles, the location of the study was not reported; hence, we considered the country of the first author as the study location.

Long-eared Owls found that fledging was earlier when nests were exposed to higher levels of light pollution (Hadad *et al.* 2024).

Effects on space use

Two studies addressed space use by Burrowing Owls in relation to ALAN and showed nuanced

Table 1. List of species studied in the available literature concerning the effect of artificial light at night (ALAN) and anthropogenic noise on owls, sorted in descending order by total number of cases (in parentheses), number of articles and scientific names.

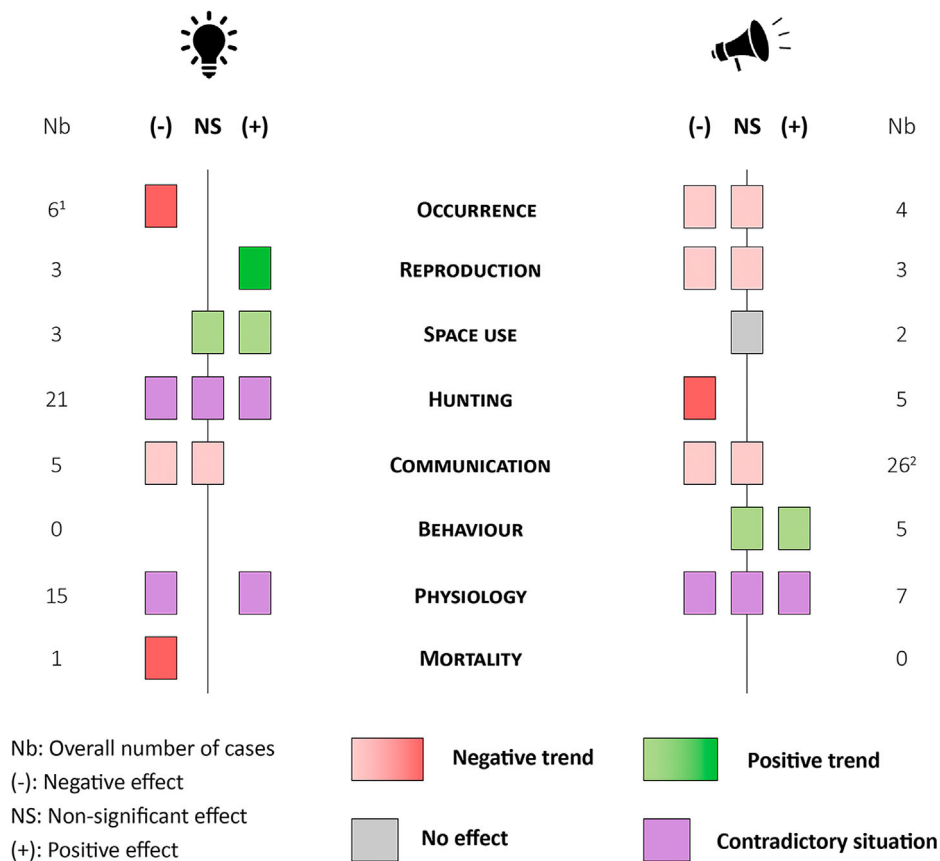
Family	Species	Vernacular name	RedList	Realm	ALAN	Noise	Total
Strigidae	<i>Athene brama</i>	Spotted Owllet	LC (s)	Indomalayan Palaearctic	1 (15)	0	1 (15)
Strigidae	<i>Strix occidentalis</i>	Spotted Owl	NT (-)	Nearctic Neotropical	0	6 (13)	6 (13)
Strigidae	<i>Athene cunicularia</i>	Burrowing Owl	LC (-)	Nearctic Neotropical	4 (8)	1 (2)	4 ^a (10)
Strigidae	<i>Bubo virginianus</i>	Great Horned Owl	LC (s)	Nearctic Neotropical	1 (6)	1 (4)	2 (10)
Tytonidae	<i>Tyto alba</i>	Western Barn Owl	LC (s)	Afrotropical Indomalayan Nearctic Neotropical Oceanian Palaearctic	5 (5)	2 (3)	7 (8)
Strigidae	<i>Strix aluco</i>	Tawny Owl	LC (s)	Indomalayan Palaearctic	2 (4)	3 (4)	4 ^a (8)
Strigidae	<i>Megascops choliba</i>	Tropical Screech Owl	LC (-)	Neotropical	1 (2)	2 (6)	2 ^a (8)
Strigidae	<i>Asio otus</i>	Long-eared Owl	LC (-)	Indomalayan Nearctic Palaearctic	3 (3)	3 (4)	6 (7)
Strigidae	<i>Asio flammeus</i>	Short-eared Owl	LC (-)	Afrotropical Indomalayan Nearctic Neotropical Oceanian Palaearctic	1 (6)	1 (1)	2 (7)
Strigidae	<i>Strix varia</i>	Barred Owl	LC (+)	Nearctic	1 (1)	2 (5)	3 (6)
Strigidae	<i>Aegolius acadicus</i>	Northern Saw-whet Owl	LC (-)	Nearctic Neotropical	0	2 (6)	2 (6)
Strigidae	<i>Strix virgata</i>	Mottled Owl	LC (-)	Nearctic Neotropical	2 (3)	2 (3)	2 ^b (6)
Strigidae	<i>Aegolius funereus</i>	Boreal Owl	LC (s)	Indomalayan Nearctic Palaearctic	0	1 (4)	1 (4)
Strigidae	<i>Athene noctua</i>	Little Owl	LC (s)	Afrotropical Indomalayan Palaearctic	1 (1)	2 (2)	3 (3)
Strigidae	<i>Ninox novaeseelandiae</i>	Morepork	LC (s)	Australasian	3 (3)	0	3 (3)
Strigidae	<i>Strix uralensis</i>	Ural Owl	LC (s)	Palaearctic	0	2 (2)	2 (2)
Strigidae	<i>Gymnasio nudipes</i>	Puerto Rican Owl	LC (s)	Neotropical	0	1 (1)	1 (1)
Strigidae	<i>Ninox connivens</i>	Barking Owl	LC (-)	Oceanian	1 (1)	0	1 (1)
Strigidae	<i>Ninox rufa</i>	Rufous Owl	LC (-)	Oceanian	1 (1)	0	1 (1)
Strigidae	<i>Ninox strenua</i>	Powerful Owl	LC (s)	Oceanian	1 (1)	0	1 (1)
Strigidae	<i>Otus lettia</i>	Collared Scops Owl	LC (s)	Indomalayan Palaearctic	1 (1)	0	1 (1)
Strigidae	<i>Otus scops</i>	Eurasian Scops Owl	LC (-)	Afrotropical Palaearctic	0	1 (1)	1 (1)
Tytonidae	<i>Tyto longimembris</i>	Eastern Grass Owl	LC (-)	Indomalayan Oceanian Palaearctic	1 (1)	0	1 (1)
Tytonidae	<i>Tyto novaehollandiae</i>	Australasian Masked Owl	LC (s)	Australasian	1 (1)	0	1 (1)
Tytonidae	<i>Tyto tenebricosa</i>	Greater Sooty Owl	LC (-)	Australasian	1 (1)	0	1 (1)
Total unique articles (cases)					21 ^c (64)	23 ^d (61)	39 (125)

Level of threat: LC = Least Concern, NT = Near Threatened, VU = Vulnerable, EN = Endangered, CR = Critically Endangered; Population trends in the world: (-) = decreasing, (+) = increasing, (s) = stable. ^aOne article focusing both on artificial light and anthropogenic noise. ^bTwo articles focusing both on artificial light and anthropogenic noise. ^cIncluding three articles focusing on several species. ^dIncluding four articles focusing on several species.

responses (Fig. 3). Rodriguez *et al.* (2021) observed that individuals occur more often and spend more time in lit areas than in control locations whereas Scobie *et al.* (2016) tracked 80 owls with GPS dataloggers in Canada and found no significant effect of ALAN on home-range size.

Effects on hunting

Hunting of rodents by owls was mainly addressed *ex situ* (six articles, 20 cases, seven species) resulting in heterogeneous information, while only Rodriguez *et al.* (2021) provided a clear positive effect of ALAN on feeding (insects) *in situ* (Fig. 3).



NB: The effects presented here are those observed on outcomes whether or not they are beneficial to the individual (e.g. an increase in physiological outcomes like fecal glucocorticoid metabolites may actually have negative consequences for individual health (stress markers)).

¹ For reliable reading, one result indicating an increase in extinction probability was transformed here into a negative effect (decrease in occurrence)

² One case reveals a positive effect (to avoid masking the general trend, this isolated case was not reported here)

Figure 3. Number of cases collected on the effects of artificial light and anthropogenic noise on owls (Strigiformes), for each outcome. Cases with no reported results and duplicate cases were not counted here.

Studies of the effect of an artificial light source on hunting behaviour or efficiency included those experimentally assessing the effect of moonlight by exposing owls to light from lamps, supposed to mimic moonlight (Clarke 1983, Kotler *et al.* 1991, Longland & Price 1991). However, artificial lighting cannot faithfully reproduce moonlight conditions, which include other aspects of light (e.g. spectrum, luminance, polarization) not accounted for in these studies, and the amount of light to which owls are exposed in these studies is much greater than that of a natural full moon (in particular Longland and Price (1991) tested 3 lx and Clarke (1983) experimented between 1.5 and 3.0 lx, whereas the full moon illuminance under

temperate latitudes in summer is about 0.2 lx (Kyba *et al.* 2017)). Hence, we considered that these studies have a valid exposure (ALAN) regarding the scope of the review.

Two of these, investigating Western Barn Owls and Short-eared Owls *Asio flammeus*, showed that more light significantly improved hunting efficiency (Clarke 1983, Longland & Price 1991). The time spent to locate, chase or catch rodents was reduced under artificial moonlight, and more rodents were captured. Even in a study where Short-eared Owls always caught their prey whatever the light condition tested, greater artificial moonlight intensity significantly increased the owls' hunting efficiency and, therefore, rodent

vulnerability (Clarke 1983). The third study, on Great Horned Owls *Bubo virginianus*, was more nuanced. It highlighted that light made attacks faster but there was no impact on attack probability (number of owl attacks on focal animals/rodent activity time) and the effect on capture probability (proportion of owl attacks resulting in captures) varied between rodent species (Kotler *et al.* 1991).

Other studies sought to measure the light level required by Long-eared Owls, Burrowing Owls, Western Barn Owls and Barred Owls *Strix varia* to better detect and catch prey (Dice 1945). Light favoured capture of rodents by owls, even for extremely low light levels (of the order of 10^{-8} foot-candles) (Dice 1945), whereas over a wide range of illumination conditions, from the lower level at which an owl can see its prey to the light intensity above which prey usually become inactive, Dice (1947) observed that Long-eared Owls and Western Barn Owls were able to see their prey even in very dim conditions, but that the best prey capture rate may occurred at intermediate illuminations.

Owings and Handa (1975) considered the role that shadow-casting could play in the detection of prey by Burrowing Owls. Their experiment showed that light conditions (at 0.01 foot-candles) with shadow-casting enhanced motion detection by owls over those without shadow projection. The authors concluded that moonlight could improve visual detection of prey not only for the level of light it provides but also because it generates cast shadows unlike twilight or starry sky.

In situ, pellet contents of Burrowing Owls, and insectivorous species, were compared with pitfall traps in lit areas and in control locations. These results led the authors to conclude that outdoor lighting provided easier access to food for this owl (Rodríguez *et al.* 2021).

Effects on communication

Five articles provided data on vocal activity (i.e. time or number of vocalizations) in relation to ALAN for three species. Two articles highlighted a negative correlation between ALAN and acoustic detection of Mottled Owls (San Martín-Cruz *et al.* 2024) and Tawny Owls (Orlando & Chamberlain 2023). However, three articles revealed no link. First, an *in situ* experiment found no effect of spotlighting on vocal activity of Morepork *Ninox novaeseelandiae* in a park in Australia (Weaving & Cooke 2010). Secondly, an observational study

found no association between lighting conversion from high-pressure sodium lights to LEDs (retrofitting) on the vocalization rate of Morepork (McNaughton *et al.* 2021). Finally, Marin Gomez *et al.* (2020) found no relationship between the onset or end of vocal activity and ALAN in Mottled Owls.

Effects on physiology

One article addressed *ex situ* the effect of manipulated photoperiod on the physiology of Spotted Owlets (Sudhakumari & Halder 2001). This study tested four artificial photoperiods (long photoperiod (LP), short photoperiod (SP), continuous light (CL) or continuous darkness (CD)) compared with the natural photoperiod, and showed that an extended daily photophase (LP, CL) tended to increase adrenal lipids and adrenal and gonadal weights and to decrease pineal weight, whereas the opposite was observed when shortening the photophase (SP, CD).

Effects on mortality

A single article counted owl roadkills and found significantly more Little Owl *Athene noctua* carcasses (97.6% of 378 total carcasses) on unlit than lit roads (Hernandez 1988).

Anthropogenic noise effects

Effects on occurrence

Seven cases referred to the occurrence of owls: two cases were based on owl captures (Alquezar *et al.* 2020), four cases came from passive recording of vocalizations (Herrera-Montes & Aide 2011, Duchac *et al.* 2020, Marín-Gómez *et al.* 2020) and the method remained unknown for one case. Whatever the method, one case found no significant correlation (Spotted Owl), and three found a negative correlation (Mottled Owl, Tropical Screech Owl and Puerto Rican Owl *Gymnasio nudipes*) between anthropogenic noise and owl occurrence (Fig. 3), whereas results were not reported for three cases.

Effects on reproduction

Two cases indicated a negative influence of noise on nest-site occurrence (Long-eared Owl) and number of young (Spotted Owl) (Hayward *et al.* 2011, Fröhlich & Ciach 2018a); the third case found no significant effect of noise on fecundity (Spotted Owl) (Hathcock *et al.* 2010) (Fig. 3).

Effects on space use

Two cases assessed the effect of urban noise on space use by Burrowing Owls (home-range, noise avoidance) in Canada and neither found any significant relationship (Scobie *et al.* 2016) (Fig. 3).

Effects on hunting

Five cases revealed that prey detection of three species was disturbed by anthropogenic noise (Fig. 3). Mason *et al.* (2016) found that the probability of mouse detection by Northern Saw-whet Owls decreased by 11% for each decibel increase in noise and that the probability of strike decreased by 5% for each decibel increase (Mason *et al.* 2016). Senzaki *et al.* (2016) found that the ability of Long-eared and Short-eared Owls to detect a prey was impacted even at the lowest level of traffic noise (40 dB[A]) and was approximately 17% lower than detections in ambient sound conditions (Senzaki *et al.* 2016).

Effects on communication

Nine articles based on passive or active (playback) to detect owl vocalizations provided a substantial set of 27 cases on the link between anthropogenic noise and vocal activity. A single case for Eurasian Scops Owl *Otus scops* in southern Italy indicated that male owls clustered around a human-inhabited area with significant noise and avoided the undisturbed forest (Grieco 2018). All other data revealed either no significant effect (12 cases, six species) or a negative effect (14 cases, seven species) (Fig. 3). For example, a multi-species study did not find any significant effect of industrial and road noise on Barred Owls, Great Horned Owls and Boreal Owls *Aegolius funereus* in a boreal forest in Canada (Shonfield & Bayne 2017). However, three studies in Poland found that vocal activity of various species (in particular Tawny and Long-eared Owls) was negatively correlated with anthropogenic noise (Fröhlich & Ciach 2018a, 2018b, 2019).

Effects on micro-behaviour

Six cases (one with no result) address the effect of chainsaw or helicopter noises during the day on various micro-behaviours (flushing or body movements – such as eye opening, limb movements, head rotation) of Spotted Owls. The results underlined that noise could either induce flushing or no reaction; this may be due to habituation to the disturbance when noise becomes chronic (Delaney

et al. 1999, Tempel & Gutiérrez 2003). Delaney *et al.* (1999) found that owl flushing started from a certain level of noise and this threshold was slightly lower during the nesting season.

Effects on physiology

Three articles (seven cases) assessed the effect of noise emitted by several human activities (e.g. chainsaws, voices) on physiological outcomes that are markers of stress (e.g. corticosterone level in faecal or blood samples, faecal glucocorticoid metabolites (GCMs)) on two species, Spotted Owls and Tropical Screech Owls. GCMs tended to increase when individuals were exposed to noise: Barbosa-Moyano *et al.* (2024) found a significant increase in GCM levels on the day of acoustic treatment; and Hayward *et al.* (2011) found a significant positive relationship between GCMs and recreational noise (off-road vehicles) but not road noise (Hayward *et al.* 2011). Corticosterone level seemed to be less sensitive to noise exposure as neither Barbosa-Moyano *et al.* (2024) nor Tempel and Gutierrez (2003) found any effect. Barbosa-Moyano *et al.* (2024) also assessed other physiological responses to stress such as concentration of leukocytes (heterophil/lymphocyte ratio) and plasma bacterial risk and found respectively no change and a significant increase in response to noise.

DISCUSSION

Although the number of available studies is relatively modest and their methods vary, the evidence base makes it possible to highlight clear trends for certain outcomes, whether for artificial light (Fig. 4) or anthropogenic noise (Fig. 5). Here, we discuss the best-documented effects to provide possible explanations for the results, to compare these findings with what is known about other taxa and to describe the carry-over effects for owl populations. Then, we compare whether the two stressors have similar or distinct effects and we describe some limitations of the primary studies (study design).

Artificial light makes owls silent and/or reduces their occurrence

It appears that ALAN either has no effect on the acoustic communication of owls (rate, time) (Weaving & Cooke 2010, Marín-Gómez

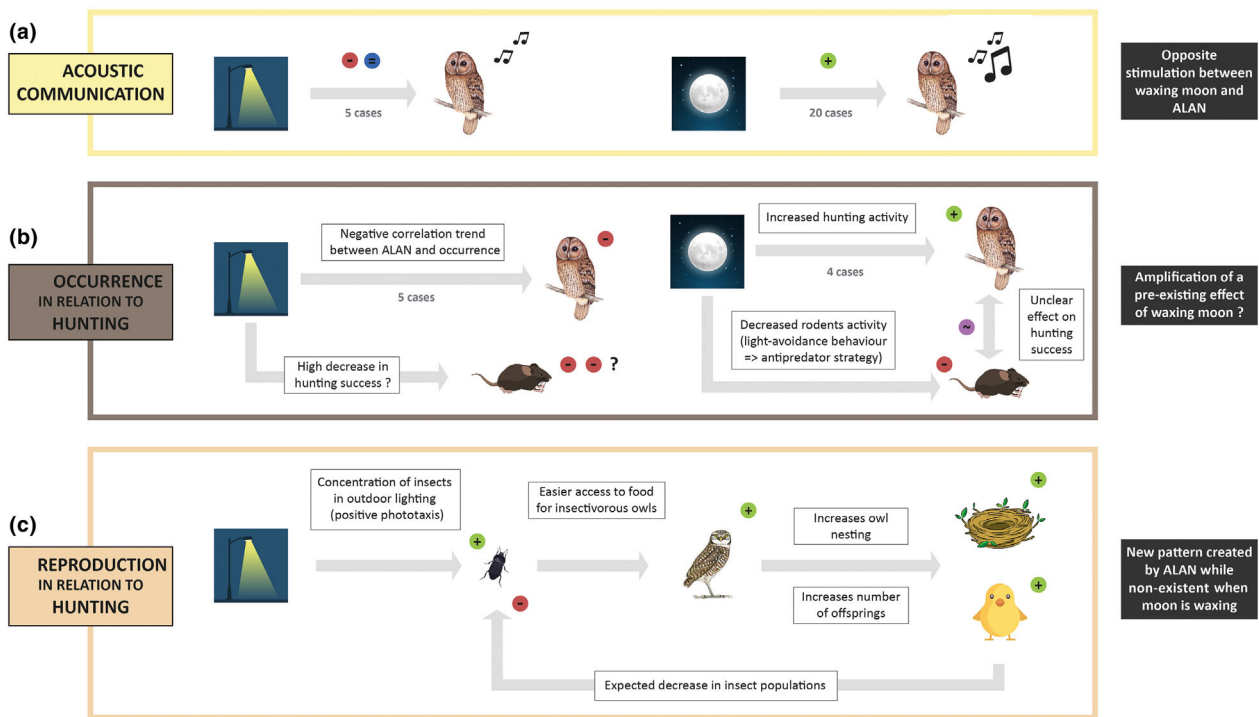


Figure 4. Illustration of the most obvious trends in the effects of artificial light on owls (Strigiformes) supported by the available literature (and comparison to moonlight effects).

et al. 2020, McNaughton *et al.* 2021) or reduces it (fewer vocalizations) (Orlando & Chamberlain 2023, San Martín-Cruz *et al.* 2024). As communication is essential between partners, between parents and offspring, or for territorial defence, its disruption is of particular concern for reproduction and therefore for the persistence of owl populations.

First, this result seems coherent because ALAN is known to stimulate singing behaviour in diurnal songbirds (Miller 2006, Marín Gómez 2022) and so the opposite effect (i.e. vocal inhibition under ALAN exposure) could be expected in nocturnal owls. Yet, vocal activity of owls is stimulated by moon illumination (Kroodsmá & Byers 1991). A systematic review of the influence of moonlight on acoustic communication shows that it is a global pattern in animals (Dickerson *et al.* 2023). Artificial and natural light may therefore have contrasting effects on owl behaviour (Fig. 4a). A similar pattern is observed in nightjars such as the Common Poorwill *Phalaenoptilus nuttallii* for which lunar illumination stimulates calling but artificial light is neutral or inhibits it (Preston & Brigham 2023).

However, it remains difficult to explain the mechanism by which moonlight influences owl vocalizations. Two opposite arguments exist. First, one might expect owls to have less need to vocalize when illumination enhances their vision. However, secondly, it could be argued that better visibility might increase the need for vocalization to defend territory if other individuals are more visible. In addition, a common explanation is that moonlight may accentuate visual cues such as flashing of the white throat feathers of some owls (Penteriani *et al.* 2010, Penteriani & Delgado 2017), which could stimulate sexual activity and therefore vocal activity. However, natural and artificial light differ in many aspects such as light spectrum, temporality or polarization. Moreover, the moon could also act through mechanisms other than light such as gravitational or geomagnetic effects (Grant *et al.* 2009). These differences between moonlight and anthropogenic light may result either in opposite effects (acoustic activity versus silent owls) or simply variations in the intensity of the response (more or fewer vocalizations).

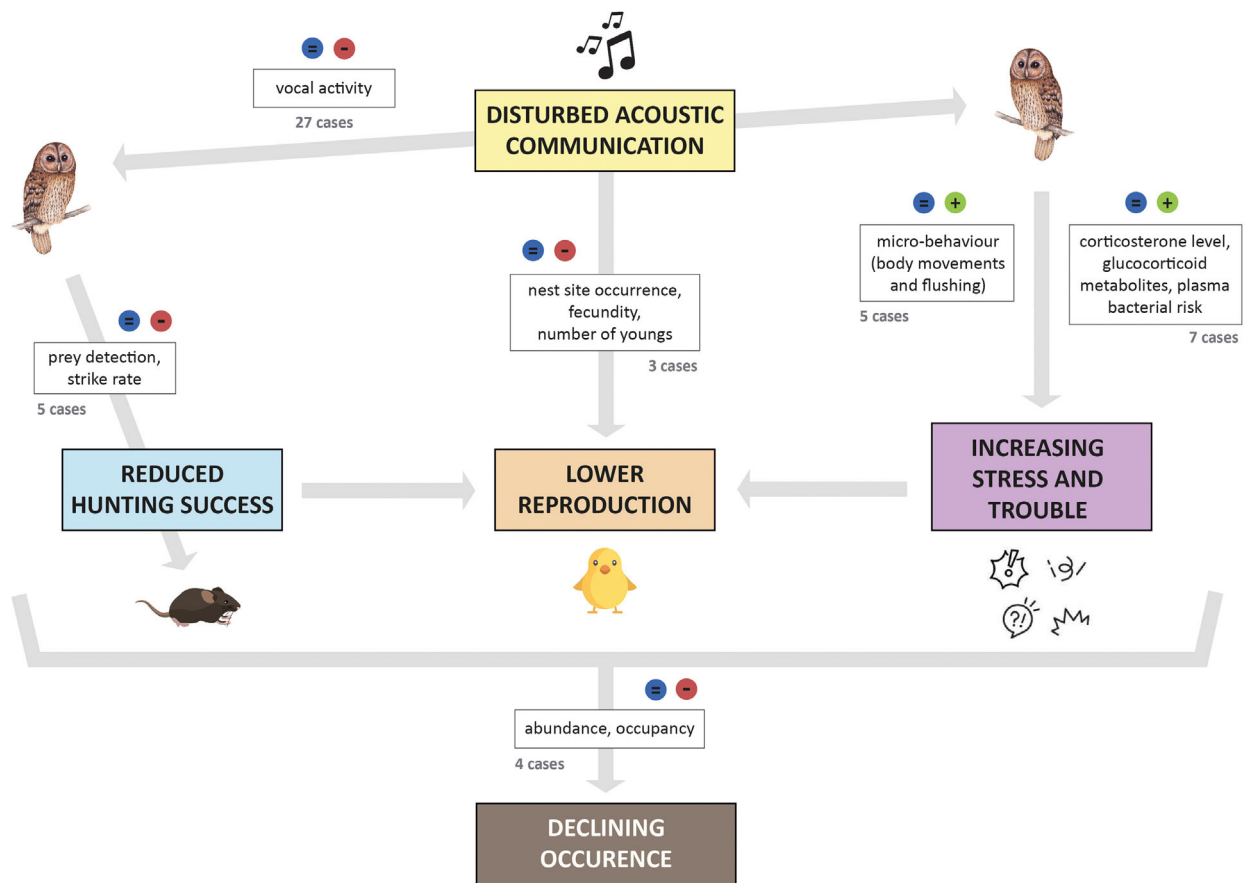


Figure 5. Illustration of the most obvious trends in the effects of anthropogenic noise on owls (Strigiformes) supported by the available literature.

In addition, it remains uncertain from studies based on acoustic surveys whether owls are silent or absent. Several studies conclude that light pollution leads to a decrease in owl occurrence (Alquezar *et al.* 2020, Marín-Gómez *et al.* 2020, Zmihorski *et al.* 2020, Hanmer *et al.* 2021). This negative influence of ALAN on occurrence of certain owls may be linked to prey–owl relationships as in Tawny Owls (Zalewski 1994) or Western Barn Owls (Bontzorlos *et al.* 2009). The decrease in owl occurrence under artificial light could also explain why Hernandez (1988) reported fewer mortalities of Little Owls on lit than unlit roads.

Artificial light disrupts prey–predator relationships according to owl diet

Studies on the effects of artificial light on owl hunting were mainly conducted *ex situ* and show

that artificial illumination tends to lead to better hunting efficiency (number of prey captured, less time needed to locate prey, faster attack velocities) (Clarke 1983, Kotler *et al.* 1991, Longland & Price 1991). These results contradict what we might expect from the documented effects of moonlight, which provide a relevant baseline. Lunar illumination does enhance hunting activity through more frequent attacks and longer hunting time per night (Bleicher *et al.* 2020) and more targeted attacks at prey location (Embar *et al.* 2014). However, it does not lead to a higher hunting success (number of prey captured per night, or number or prey brought to the nest) (Kaufman 1974a, Avilés *et al.* 2022). This apparent contradiction may result from moonlight improving owl vision while simultaneously increasing predation risk perception among small mammals (Abramsky *et al.* 1996, Bueno & Motta-Junior 2015,

Hernández *et al.* 2021), ultimately resulting in a lower hunting success. Indeed, brighter nights tend to reduce small mammal activity because animals are more concealed and wary. This inhibition by moonlight as an anti-predator strategy appears to be widespread among nocturnal mammals (Prugh & Golden 2014). Studies have also highlighted that hunting success of owls depends both on the colour of prey and on the colour of the ground (Kaufman 1974a, 1974b), which confirms that the underlying mechanism involves both owl vision and predation risk. As a result, *ex situ* studies on the effect of ALAN on owl hunting efficiency may not reflect what happens *in situ* because experimental space (including enclosures) is limited and rodents have less chance to hide or escape. Therefore, given the many studies showing that rodents usually respond to both artificial light and moonlight with a light-avoidance behaviour (Eilam 2004, Hemami *et al.* 2011, Dupont *et al.* 2019, Farnworth *et al.* 2019), it is most likely that ALAN has a negative effect on the success of hunting small mammals by owls. The results of Longland and Price (1991) suggest this, with a non-significant or a species-dependent effect of artificial light on owl hunting success, and a conclusion that artificial light gives owls an advantage, especially in open habitats where prey may not be able to compensate for increased predation risk. Moreover, light pollution is often permanent and may exceed full moon light levels (full moon illuminance under similar latitudes (temperate) in summer is about 0.2 lx (Kyba *et al.* 2017)), although the moon is cyclic, not always visible in the sky and species have evolved in this context. Overall, therefore, ALAN may have the effect of unbalancing the relationship between owls and small mammals by amplifying natural mechanisms (effect of moonlight), resulting in a complex outcome (Fig. 4b). Numerous long-term effects on owls can be expected from this situation, as a poorer diet can affect the survival of both adults and juveniles and therefore the maintenance of owl populations in lit environments. To our knowledge, there is no literature on the hunting success of other nocturnal predators that feed on small mammals (e.g. foxes, martens) to compare with the situation faced by owls.

A more obvious situation is observed for insectivorous owls with clear evidence of better food provisioning in lit areas for Burrowing Owls (Rodríguez *et al.* 2021), which have a diet of

which 80% is insects (items) (Sánchez *et al.* 2008, Cavalli *et al.* 2013). Insects are strongly attracted to light (Tielens *et al.* 2021) and this positive phototaxis concentrates these prey under lights, which then favours such owl species (Fig. 4c). This mechanism is well known for other insectivorous predators such as spiders (Gomes 2020), geckos (Nordberg & Schwarzkopf 2022) and bats (Li & Wilkins 2022). Diverse naturalist notes report observations of owls hunting in outdoor lighting to catch insects attracted to light (Walker 1943, Schwertner 2002), migrating birds trapped by an illuminated monument (Canário *et al.* 2012) or bats coming to hunt insects aggregated in lit areas (Dalery & Cugnasse 2016). ALAN seems to be an advantage for these species feeding on such insect prey with positive phototaxis. However, this mechanism may alter prey–predator relationships (Mcmunn *et al.* 2019). It leads to a decrease in insect populations (Davies *et al.* 2012) and may also impact the predators by enhancing interspecific competition (Schoeman 2016) and by modifying their spatial distribution (Nelson *et al.* 2022) or reproduction (Taylor *et al.* 2022).

Anthropogenic noise has several detrimental impacts on owls

One of the main findings from studies on the effects of anthropogenic noise is a reduction in vocal activity (Shonfield & Bayne 2017, Fröhlich & Ciach 2019, San Martín-Cruz *et al.* 2024) even if it is difficult to know from acoustic surveys whether owls are silent or absent. The impact of noise on animal acoustic communication is well documented, particularly in birds (Oden *et al.* 2020). However, a modulation of song parameters (e.g. frequency, amplitude) is observed in many taxa rather than a strict reduction in call rate (Gomes *et al.* 2022). Two major vocal adjustments are widespread in animals, including birds: (1) singing louder than background noise (Lombard effect) and (2) shifting song frequencies out of the noise range (Brumm & Slabbekoorn 2005, Patricelli & Blickley 2006). For instance, it has been demonstrated that free-ranging Common Nightingales *Luscinia megarhynchos* sing louder and White-crowned Sparrows *Zonotrichia leucophrys nuttalli* sing at higher minimum frequencies in noisy environments (Brumm 2004, Luther *et al.* 2016). Globally, birds tend to emphasize the low-frequency component of the song spectrum

and to increase their dominant frequencies when exposed to anthropogenic noise. However, smaller bird species seem to show broader shift capacity than bigger species (Roca *et al.* 2016). Fewer owl vocalizations in noisy areas would suggest that they may be less capable of vocal plasticity than other birds. As a result, wider consequences would be expected, because acoustic communication between owls is essential, particularly for breeding (Martin 1990).

A second marked effect is reduced hunting success under noise exposure (Mason *et al.* 2016, Senzaki *et al.* 2016). Noise affects food detection in other flying acoustic predators such as bats (Siemers & Schaub 2011, Bunkley & Barber 2015). The mechanism may be a masking effect of natural sounds by anthropogenic noise (Madliger 2012, Rosa & Koper 2018), especially birds (Blickley & Patricelli 2012, Grabarczyk & Gill 2020). Because hearing is a decisive sense in the hunting activity of owls in addition to vision, noise pollution may influence both adult and chick survival, with consequences at the population level.

An increase in owl stress is also a consequence of anthropogenic noise, as revealed by avoidance behaviours (i.e. flushing) (Delaney *et al.* 1999) and physiological markers (Barbosa-Moyano *et al.* 2024). There is a large literature, including for birds, showing that noise alters animal behaviour (e.g. flight pattern, movements, escape and micro-behavioural responses such as raising the head) (Arcangeli *et al.* 2022). Noise has been demonstrated to increase vigilance with the effect of reducing foraging efficiency (Merrall & Evans 2020, Sweet *et al.* 2022). Also, higher levels of stress markers such as GCMs, heterophil/lymphocyte ratio or corticosterone are known to be responses to noise for vertebrates, including birds, with consequences for immunity and fitness (Westlund *et al.* 2012, Troianowski *et al.* 2017, Kleist *et al.* 2018, Ribeiro *et al.* 2022). In the short term, the increase in physiological stress markers (e.g. glucocorticoids) enables individuals to react to a changing environment (e.g. by escaping a danger). However, repeated disturbances such as artificial lighting every night or continuous traffic noise generate chronic stress that affects the animal's health, survival and fitness (Martin 2009, Boonstra 2013, Wingfield 2013). In the same way, the increase in blood bactericidal risk (i.e. lower bacterial killing ability) observed in owls exposed to noise (Barbosa-Moyano *et al.* 2024), which could involve

a risk of infection for organisms, has already been observed in other taxa (Park & Do 2022).

Finally, our results also suggest an inverse relationship between anthropogenic noise and owl reproduction and occurrence, albeit based on fewer cases (Hayward *et al.* 2011, Herrera-Montes & Aide 2011, Frohlich & Ciach 2018). Although they need to be tested further, these results accord with available evidence for other animals, including other birds. Environmental pollution is known to affect reproduction in many ways (e.g. fecundity, incubation, parental care, young survival) (Aulsebrook *et al.* 2020) and we have several examples for diverse avian species in degraded soundscapes (Halfwerk *et al.* 2011, Bernat-Ponce *et al.* 2021, Williams *et al.* 2021). At ecosystem levels, anthropogenic noise may reduce bird abundance (Antonio Gonzalez-Oreja 2017) and can lead to a decrease in bird species richness (Proppé *et al.* 2013, Perillo *et al.* 2017).

In conclusion, these initial results on harmful effects of anthropogenic noise for owls that this literature review highlights are consistent with the impacts that could be expected from the available literature on other birds and, more generally, on animals.

Anthropogenic light and noise: interactions, similarities and differences

One of our review aims was to examine interactions between ALAN and noise impacts on owls. However, we retrieved only five articles that considered both anthropogenic light and noise and none considered interactions between the two stressors (Scobie *et al.* 2016, Alquezar *et al.* 2020, Marín-Gómez *et al.* 2020, Orlando & Chamberlain 2023, San Martín-Cruz *et al.* 2024). Hence, it is not possible to draw any conclusion about additive, synergistic, antagonistic or emergent effects between these two sensory disturbances on owls. Given that both stressors are common in urban environments, this is an important knowledge gap for owls. More studies are considering light and noise effects, but few are assessing whether or not they interact. In their systematic review, Halfwerk and Jerem (2021) collected 28 studies that simultaneously addressed the effects of noise and light pollution on animal species, 15 of which tested for possible interactions. It is known that ALAN and noise can act in synergy (i.e. when they are both present in the environment, the effects are greater

than their additive effects), including in birds. For instance, the distance to disturbance of traffic noise and light on the vocal and spatial behaviour of wild birds has been demonstrated to be greater when pollutants are combined (Hennigar *et al.* 2019) and nocturnal activity of urban birds is extended when they are exposed to both light and noise (Dominoni *et al.* 2020a). We therefore encourage researchers to address both anthropogenic light and noise and their interaction in further studies on owls, with specific study designs.

Although the interaction between artificial light and noise has not been studied for owls, we can compare our results obtained for artificial light with those obtained for noise, even though based on few articles. Anthropogenic light and noise belong to the same family of pressures (sensory pollutants), which is described as having similar types of effects such as masking, trapping, distraction and misleading, by creating attractive or aversive artificial stimuli in the sensory landscape (Dominoni *et al.* 2020b, Elmer *et al.* 2021). Nevertheless, in our review, few studies highlight similar impacts for both stress factors on owls, maybe because we collected studies with a wide range of outcomes. The most obvious common pattern concerns vocal activity, which tends to be inhibited by both ALAN and noise, although underlying mechanisms are more difficult to explain for ALAN. Moreover, we identified several differences between the impacts of both sensory pollutants. As a major difference, ALAN can act as a facilitating (vision) or even attractive (concentration of prey) factor whereas noise appears to be systematically detrimental for owls. For example, artificial lights attract insects, which in turn can enhance foraging conditions for insectivorous owls, whereas the masking and distracting effects of noise tend to reduce prey detectability, resulting in a lower hunting success. However, the advantage provided by ALAN must reach a limit beyond which the trade-offs become too great, for example through increasing risk of predation or disruption of circadian rhythms.

Limitations of the primary studies

In situ studies represent a large part of the collected data (45% for artificial light and 84% for artificial noise). Unlike *ex situ* studies (in cages or enclosures), they better reflect real conditions but at the same time they are more exposed to bias

because the environment is less controlled, especially in observational studies, which are the majority of *in situ* studies (93% for light pollution and 75% for noise pollution). In such studies, correlations between exposure and outcome are investigated. For instance, a large number of studies focus on owl vocalization in relation to light or noise (Mori *et al.* 2014, Fröhlich & Ciach 2019, Hanmer *et al.* 2021). During coding we extracted data from the studies, which inform the method used by the authors to monitor population and exposure (ALAN, noise) or the study designs. This knowledge enabled us to highlight some susceptibilities to bias and to make suggestions to improve future primary research; these are detailed in Appendix S7, section 4.

CONCLUSIONS

This literature review undertook a comprehensive and updated overview on the effects of light and noise pollution – two sensory pollutants that are widespread on Earth – on owls. We were able to collect 39 articles, which allowed us to identify several detrimental effects caused by both these sensory stressors. This reveals a modest amount of literature on the effects of anthropogenic light and noise on nocturnal raptors, although it enabled us to draw some initial conclusions.

Vocal activity tends to be inhibited by ALAN and more clearly by human-induced noise, which suggests an impairment of acoustic communication between partners and therefore on breeding. Hunting is clearly disturbed by both ALAN and noise. Masking and distracting effects of noise tend to reduce detectability of prey, resulting in a lower hunting success. ALAN unbalances prey–predator relationships both by increasing visibility for owls but at the same time the landscape of fear for rodents and by concentrating the availability of certain prey (e.g. insects) through prey phototactic responses. The result shows opposing effects on owls depending on their diet, with those that feed on rodents perhaps disadvantaged whereas insectivorous species may be favoured. It is also clear that anthropogenic noise increases stress and disturbance on owls, whether by causing avoidance behaviours (e.g. flushing) or physiological markers detectable in blood or faeces, which allows us to expect possible consequences for owl health and immunity. Overall, we suggest that knowledge is sufficient to recommend reducing artificial light

and anthropogenic noise as much as possible. These sensory pollutants should be integrated into conservation strategies, urban design, public policies and environmental impact assessments, to maintain and restore quiet and dark areas. At a local level, this means, for example, adapting (ideally removing) lighting or noisy activities near owl habitats or at certain critical times of the year (e.g. migration, reproduction).

However, the evidence base needs to be expanded by further primary research to fill knowledge gaps. Several meta-analyses and systematic reviews have underlined that birds are well studied in sensory ecology, both with respect to light (Falcón *et al.* 2020, Svechkina *et al.* 2020, Adams *et al.* 2021, Sanders *et al.* 2021, Pérez Vega *et al.* 2022) and noise pollution (Radford 2012, Kunc & Schmidt 2019, Sordello *et al.* 2020). However, it appears that owls do not benefit from this attention, perhaps because they are cryptic species with nocturnal habits. In fact, only 25 owl species have been considered in at least one article, which represents around 10% of the 244 owl species in the world. This makes it difficult to generalize conclusions for Strigiformes, a heterogeneous group with respect to mobility and activity patterns, home-range size and diet. In addition, many outcomes remain underexamined, such as circadian rhythm, dispersal or reproduction, even though they would be relevant to consider to better understand the effects of sensory stressors on population persistence. Finally, long-term impacts are expected but widely understudied. Indeed, local and short-term impacts (e.g. reduced vocalization, increased physiological stress, avoidance behaviours) may scale to population-level consequences over time, such as decreased reproductive success or survival rates. This lack of knowledge on long-term effects limits our ability to fully convey the ecological risks posed by anthropogenic light and noise. As a result, we encourage diversification of the studies in terms of species, outcomes (especially other than the probability of acoustic detection), types of noise studied (in particular other than traffic noise) and more operational studies (e.g. impacts of changing light spectra such as conversion from high-pressure sodium to LED or the duration of nocturnal lighting).

Furthermore, we identified potential biases in the available literature (mostly composed of *in situ* observational studies), related to the methods used to monitor population and exposure (ALAN,

noise) because of confounding factors or to the reliability of controls.

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AUTHOR CONTRIBUTIONS

Romain Sordello: Conceptualization; writing – original draft; methodology; investigation; writing – review and editing; data curation; formal analysis. **Aurelie Coulon:** Conceptualization; writing – review and editing; methodology; supervision. **Yorick Reyjol:** Conceptualization; writing – review and editing; methodology; supervision.

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CONFLICT OF INTEREST

The authors have no competing interests.

ETHICAL NOTE

None.

DATA AVAILABILITY STATEMENT

All the data that support the findings of this study are openly available within the article and its additional files.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. ROSES Form for systematic reviews.

Appendix S2. Search strategy.

Appendix S3. List of the 244 owl species living in the world.

Appendix S4. Test list and comprehensiveness.

Appendix S5. Decisions during the three screening stages.

Appendix S6. Systematic map database of included articles.

Appendix S7. Supplementary information.

Appendix S8. Coded cases about artificial light effect.

Appendix S9. Coded cases about anthropogenic noise effect.