Journal of Ornithology
https://doi.org/10.1007/s10336-026-02406-4

REVIEW

The impact of urban-related sensory and risk factors on owls: a systematic review

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Received: 26 May 2025 / Revised: 3 March 2026 / Accepted: 23 April 2026

Abstract

Urbanisation is a globally increasing phenomenon with diverse impacts on biodiversity. Interest in how urbanisation affects raptors is growing because, as top predators, they can be used as bioindicators for ecosystem functioning and sentinels for environmental change. However, a comprehensive synthesis detailing the global-scale impact of urban-related sensory and risk factors on nocturnal raptors (i.e. owls) is lacking. In this review, we examined the literature to identify such factors and to outline their association with behavioural and ecological traits of owls living in urban environments. Overall, we show that several urban-related sensory and risk factors affect owls, with vehicle collisions on roads being the most widely documented across species. Conversely, sensory pollution remains poorly investigated, which is surprising given that nocturnal and acoustic hunters, such as owls, might be severely impacted by artificial light at night (ALAN) and anthropogenic noise. We also highlight a research gap on this topic from the global south, where urbanisation is rapidly increasing. Importantly, we show that roads and sensory pollutants are associated in contrasting ways with many owl behavioural and ecological traits, such as hunting and habitat use. We argue that the interplay among roads, noise and ALAN influences how owls' prey species use roads, which may turn areas near roads into ecological traps. The severity of their impacts may depend on the intensity and type of anthropogenic noise and artificial lights along roads. Further research in this direction will have important implications for the conservation of owls in urban environments.

Keywords Nocturnal raptors · Sensory pollution · Urban ecology · Ecological traps · Roads · Vehicle collisions

Zusammenfassung

Sensorische Belastungen und Gefahren in Städten und ihre Auswirkungen auf Eulen (Strigiformes): eine systematische Übersicht

Die Urbanisierung schreitet weltweit dynamisch voran und zählt zu den zentralen anthropogenen Treibern des Biodiversitätsverlustes. Das wissenschaftliche Interesse an ihren Auswirkungen auf Greifvögel nimmt zu, da diese als Spitzenprädatoren sowohl wichtige Bioindikatoren der Ökosystemfunktion als auch Sentinelorganismen für Umweltveränderungen darstellen. Eine global angelegte Synthese zu den Effekten sensorischer Belastungen und urbaner

Communicated by O. Krüger.

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Gefahren auf nachtaktive Greifvögel, insbesondere Eulen (Strigiformes), fehlt bislang. In der vorliegenden Übersicht wurde die bisher publizierte Literatur ausgewertet, um relevante Belastungen und Gefahren zu identifizieren und ihre Zusammenhänge mit Verhaltensweisen sowie ökologischen Merkmalen urban lebender Eulen einzuordnen. Unsere Analyse zeigt, dass Eulen durch mehrere urbanen Belastungen und Gefahren beeinflusst werden, wobei Kollisionen mit Fahrzeugen im Straßenverkehr am häufigsten dokumentiert sind. Demgegenüber sind sensorische Umweltbelastungen bislang unzureichend untersucht – obwohl insbesondere nachtaktive und akustisch jagende Arten potenziell stark durch künstliches Licht in der Nacht (ALAN) und anthropogenen Lärm beeinträchtigt werden. Zudem zeigt sich eine deutliche Forschungslücke im Globalen Süden, wo die Urbanisierung besonders rasch voranschreitet. Weiterhin wird deutlich, dass Straßen und sensorische Belastungen in teils gegenläufiger Weise mit zentralen Verhaltens- und ökologischen Merkmalen assoziiert sind, darunter Jagdverhalten und Habitatnutzung. Wir argumentieren, dass das Zusammenwirken von Straßen, Lärm und ALAN die Raumnutzung von Beutetieren beeinflusst und dadurch straßennahe Bereiche zu ökologischen Fallen für Prädatoren werden können. Für ein mechanistisches Verständnis dieser Zusammenhänge sowie für den wirksamen Schutz von Eulen in urbanen Lebensräumen ist weitere Forschung unerlässlich.

Introduction

Urbanisation is increasingly recognised as a threat for biodiversity (McDonald et al. 2008; Theodorou 2022). The foremost detrimental effects induced by worldwide urban sprawl include habitat fragmentation and environmental pollution, which can directly alter species' distribution and lower their abundance and diversity (McKinney 2002; McDonald et al. 2008). Furthermore, the phenomenon of urbanisation does not only consist of physical land conversion and the spread of pollutants, but also involves growing human populations that interact with wildlife. The mere presence of people can affect wildlife behaviour (Ellis-Soto et al. 2023), for example by increasing stress-hormone levels (Almasi et al. 2015) and by causing animals to perceive humans as intruders and predators (Bötsch et al. 2018; Nyatanga et al. 2021), leading to wild animals avoiding urban environments. However, in some cases human presence and activities can attract animals by increasing the availability of limited resources, such as water and food, or alternative nest and roost sites (James Reynolds et al. 2019; Sumasgutner et al. 2023).

In this context, the response of birds to urbanisation has been widely explored, in part because they are relatively easy to observe and survey (Crooks et al. 2004; McDonald et al. 2008; Sol et al. 2014). Birds thus represent environmental indicators that can be used to investigate which type of interventions are required to better sustain biodiversity in urban environments (Sushinsky et al. 2013; Geschke et al. 2018). In particular, the response of birds of prey to urbanisation is receiving increasing attention (Natsukawa and Sergio 2022; Natsukawa et al. 2023). As predators, raptors are at the top of the food chain and thus play a crucial role for ecosystem functioning, making them good model systems to assess the impact of environmental change, including urbanisation (Sumasgutner et al. 2021; Natsukawa and Sergio 2022). Because the presence of breeding raptors in urban environments is correlated with higher biodiversity in some cases (Natsukawa et al. 2021), actions to improve their conservation might also provide protection for other species and help identify key hotspots for biodiversity conservation (Natsukawa et al. 2023).

The way raptors respond to urbanisation is not uniform across species due to different resource requirements (e.g. prey and nests, Kettel et al. 2018) and inter-individual variations in behaviour (e.g. some individuals being bolder than others, van den Brink et al. 2012). Highly territorial raptors may also occur in urban environments not due to attraction to urban spaces, but because their long-established territories may have undergone progressive urban transformation over time, requiring raptors to adapt their behaviours (e.g. changes in use of resources) to maintain territories and persist in urbanised landscapes (Palomino and Carrascal 2007). Moreover, recent findings suggest that smaller raptors are the most successful in urban environments (Cooper et al. 2022; Headland et al. 2023). Raptors may be drawn to urban environments due to the abundance of suitable prey species, such as pigeons, which are often characteristic of urban areas. Additional factors include the availability of alternative nesting sites on human-made structures or through nest box provisioning, reduced competition for resources, and lower predation risk (Kettel et al. 2018). Despite access to alternative nest sites, raptors sometimes experience low breeding success when main prey availability is low in urban environments (e.g. Eurasian Kestrel *Falco tinnunculus*, Sumasgutner et al. 2014a). In this case, lower breeding performance in urban environments is thought to result from raptors being less successful in hunting alternative prey (e.g. songbirds) compared to their usual prey in natural areas (e.g. small mammals) (Sumasgutner et al. 2014b). In addition, alternative nesting sites (e.g. nestboxes) are not suitable for all raptors, and urbanisation has led to the widespread reduction of natural breeding resources, such as hollow-bearing trees (Harper et al. 2005), especially the ones with large hollows (Treby and Castley 2015). For raptors that are obligate hollow-nesters, limited access to such nesting sites may be a constraint on breeding opportunities and further contribute to lower breeding success in urban populations compared to their rural conspecifics. Several anthropogenic factors related to urban environments also have a direct effect on both raptor mortality risk (Hager 2009) and behavioural and ecological traits (Senzaki et al. 2016). Collisions with vehicles on roads and contamination by rodenticides are typically considered the most impactful factors for raptors (Hager 2009; Panter et al. 2022; Šálek et al. 2023), but factors altering sensory perception and behaviour (e.g. noise pollution, Senzaki et al. 2016) may also ultimately influence their fitness. Because of the conflicts between the benefits of attraction to urban environments (e.g. prey availability) and potential costs, urban environments may act as ecological traps (Boal and Mannan 1999; Isaac et al. 2014).

Owls (order *Strigiformes*) have been studied to a lesser extent (Kettel et al. 2018; Headland et al. 2023) compared to diurnal raptors, especially in urban environments. This is likely because most species are highly nocturnal and cryptic, and have low population densities and detection rates (Wintle et al. 2005; Isaac et al. 2013), making their study more challenging. Some species cope well with urbanisation if suitable patches of natural habitat are preserved within the urban matrix (Pagaldai et al. 2021; Séchaud et al. 2021). However, in addition to the risks posed by collisions with vehicles on roads and rodenticides, owls occurring in urban environments are also exposed to factors affecting their environmental sensory perception (e.g. noise and light pollution, Fröhlich and Ciach 2019; Marín-Gómez et al. 2020). For example, areas with high levels of anthropogenic noise or areas close to roads are avoided by many species (Frey et al. 2011; Fröhlich and Ciach 2019; Milliet et al. 2024). Ultimately, the occurrence of owls in urban environments (including urban parks and gardens, Fröhlich and Ciach 2019; Marín-Gómez et al. 2020) is also affected by human presence (Cavalli et al. 2016; Moroni et al. 2017).

Here, we performed a systematic review of the literature with the purpose of: (i) providing a global synthesis on the anthropogenic factors that are a risk for owls' survival in urban environments and that affect their behavioural and ecological traits (hereafter called "urban-related sensory and risk factors"); (ii) identifying which of these factors may affect owls' behavioural and ecological traits, and determining whether they have positive, negative, or neutral associations with such traits; (iii) examining the potential problem of ecological traps; (iv) identifying future research needs.

Traditionally, only towns and cities have been recognised as urban environments. However, this is a limitation since urbanisation is a diffusion process whose effects extend beyond urban centres (Antrop 2000; Hoffmann et al. 2023). For our purposes, an urban environment can thus be defined as a geographic space characterized by the presence of urban-related sensory and risk factors which extend beyond cities (Antrop 2000; Hoffmann et al. 2023). Indeed, some of these factors occur also outside of city boundaries, such as roads, anthropogenic noise, and light pollution (Rheindt 2003; Francis et al. 2011; Rodríguez et al. 2017; Cox et al. 2020). For this review, we thus decided to include any urban-related sensory and risk factors in our review, even those that may not be exclusively associated with cities.

Literature search

We performed an advanced search on the Web of Science Core Collection Database (www.webofscience.com), covering all the available editions. We retrieved studies published from 1900 onwards, including all languages and document types. We used the following search strategy on the Web of Science Core Collection: *TS = [(owl* OR Strigiformes OR 'nocturnal raptor*' OR 'nocturnal avian predator*' OR 'nocturnal bird* of prey') AND (urban* OR 'urban environment*' OR town OR city OR 'urban development' OR 'urban* gradient*') AND (habitat* OR 'habitat loss' OR 'habitat fragmentation' OR 'habitat destruction' OR logging OR pollut* OR noise OR 'anthrop* noise' OR 'traffic noise' OR 'noise pollut*' OR ALAN OR 'artificial light* at night' OR 'artificial* illumination' OR 'light pollut*' OR 'chemical pollut*' OR roadkill* OR road* OR collision* OR 'vehicle collision*' OR electrocution OR 'wind* turbine' OR 'wind* blade' OR 'anthrop* stressor*' OR 'anthrop* disturb*' OR 'human disturb* OR 'human impact*')]*. This search strategy was built to be as comprehensive as possible to include all possible urban-related sensory and risk factors that could affect owls. The choice of keywords for the search strategy was verified and based on published books which describe owl species and information on their threats: Mikkola (2013), König and Weick (2008) and Cauli et al. (2022). We then reinforced our literature searchf using the same search strategy with the domain 'TITLE-ABS-KEY' on Scopus (www.scopus.com). The literature search was performed on both search engines on the 7th of November 2022 and included all records available that were published before this date. Moreover, we included studies retrieved from 'Urban raptors: ecology and conservation of birds of prey in cities' (Boal and Dykstra 2018), which covers the ecology of raptors in urban environments. Because it covers both diurnal and nocturnal raptors, we used the search term 'owl*' to recover as many references as possible from the reference lists throughout the book.

We found 271 studies on the Web of Science Core Collection, 240 studies on Scopus and 190 records from Boal and Dykstra (2018), comprising a total of 701 records. We removed duplicates and obtained a final list of 464 unique records (Supplementary Table S1).

Inclusion and exclusion criteria

There are 557 raptor species worldwide, 236 of which are owl species included in the order *Strigiformes* (McClure et al. 2018). We adopted a systematic approach to provide a global picture of the number of owls that are known to occur in urban environments. For the purpose of this study, in our search we included only records on urban-related sensory and risk factors that directly affect owls' survival or behavioural and ecological traits. Therefore, we did not consider natural factors that are indirectly affected by anthropogenic activities (e.g. food availability and abundance in cities, predation risk and competition with other species, natural habitat loss). We included studies conducted both within urban environments and along urban gradients. We included both correlational and experimental studies (e.g. an experiment testing the effects of noise pollution on owl behaviour). We then discarded the following: (i) studies concerning species other than owls; (ii) studies on owls but not involving any urban-related sensory and risk factors; (iii) studies in which the presence of owls has been used to study the behavioural response of other species (e.g. antipredator behaviours in passerines).

We then screened the remaining records by reading their title and abstract. If the title and/or abstract indicated that the study could fit our inclusion criteria, we read the study fully to assess its eligibility. We obtained a total of 89 eligible records, to which we added 70 further studies that we retrieved from selected records that consisted of either reviews or book chapters that were originally found in the search on Web of Science and Scopus. After the eligibility assessment, we obtained a final list of 133 records. Each step involved in the literature search process has been summarised in detail by following the PRISMA chart scheme (Supporting Online Information Table S1).

General trends

Patterns in the literature in relation to geographic regions and study species

Although early documents on owls exposed to urban-related sensory and risk factors trace back to the first half of the twentieth century, the number of studies has increased markedly from the 2000 s onward, and especially in the last decade (Fig. 1). This trend indicates a relatively recent rise in interest for this research area. Overall, the studies that we retrieved on the relationship between owls and urban-related sensory and risk factors ($n = 133$) were conducted in 28 countries. Most research has focused on owls in the northern hemisphere, especially the Nearctic region, followed by the Palearctic region (Fig. 1). North America led with the highest representation of studies (particularly in the USA $n = 38$; 28% of the studies), followed by Europe (especially Spain $n = 14$; 10% and Italy $n = 7$; 5%). In contrast, few studies

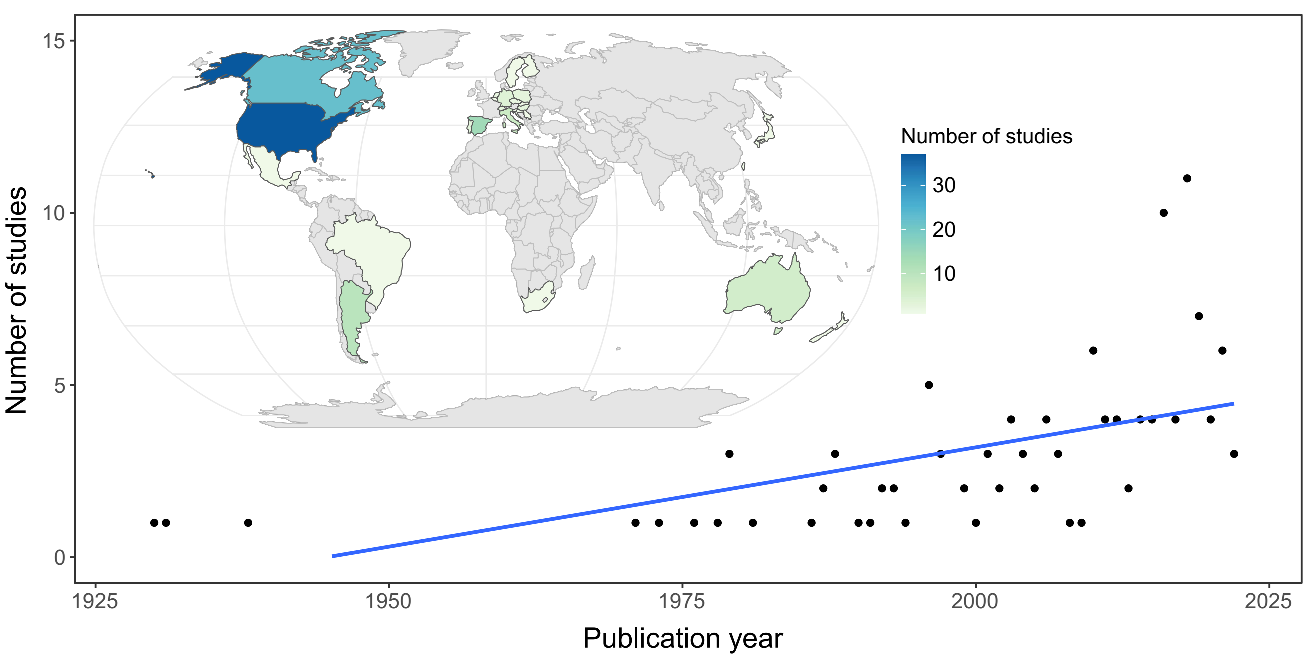

Fig. 1 Temporal trend showing the number of studies ($n = 133$) published in the period between 1930 and 2022 on owls exposed to urban-related sensory and risk factors. The world map illustrates the geographical distribution of the studies across the globe. The intensity of the colour scale indicates the number of studies by country

were conducted in the southern hemisphere, highlighting a clear difference in research contribution between the world's hemispheres (Fig. 1). The highest representation of studies from the southern hemisphere came from Argentina ($n=10$; 7%) and Australia ($n=6$; 4%), essentially the only contributors from South America and Oceania. The most striking research gap was for Asia and Africa (Fig. 1).

We identified a total of 30 species of owls that have been studied in relation to urban-related sensory and risk factors (Fig. 2). However, research was limited for most of them. We found more than 10 records for only six species (20% of the species; Fig. 2). Overall, the most studied owl species was the Burrowing Owl *Athene cunicularia* ($n=34$; 16% of the studies), and the highest number of owl species studied was in North America (Canada and USA, $n=18$ species studied, Fig. 2), followed by Europe (Italy, $n=7$ species studied). On the other hand, very few species have been studied across the southern hemisphere overall (Fig. 2) with Australia being the country with the greatest representation of species ($n=3$).

Urban-related sensory and risk factors affecting owls' behaviour and ecology

From our literature search, we identified several urban-related sensory and risk factors that affect owls. We classified them as: roads, collisions with obstacles, chemicals, noise, artificial light at night (ALAN), and reactions to human presence (Fig. 3). Most studies focused on the effects of roads ($n=81$; 49% of the studies; Fig. 3), and most of these ($n=52$; 64%) examined the impact of roads in terms of collisions with vehicles on roads, for a large number of owl species ($n=23$). Collisions with vehicles on roads may be one of the greatest causes of mortality for owls (Hager 2009; Šálek et al. 2023). The remaining studies ($n=29$; 36%) mostly investigated the effects of roads on owls' habitat use and selection.

Other than collisions with vehicles, we found studies showing that owls also collide with other anthropogenic obstacles ($n=26$; 16% of the studies). The most critical ones are power lines, which can cause mortalities and severe injuries through either collisions or death by electrocution when owls perch on the poles or come into contact with multiple conductors simultaneously (e.g. Eagle Owl *Bubo bubo*, Marchesi et al. 2002; Sergio et al. 2004; Schaub et al. 2010). This type of collision was documented in 20 studies based on our search and affected several species ($n=10$). According to one of these studies (Lehman et al. 2007), half of these species are often reported in electrocution incidents just in North America, suggesting that this threat might be broader and affect more species worldwide. Moreover, we also found a smaller body of research documenting owls' collisions with buildings and windows ($n=6$), fences ($n=1$, Martinez et al. 2006), trains ($n=4$) and aircrafts ($n=1$, Kitowski 2011). Despite the limited number of studies, these types of collisions affected a moderate number of species overall (Fig. 3).

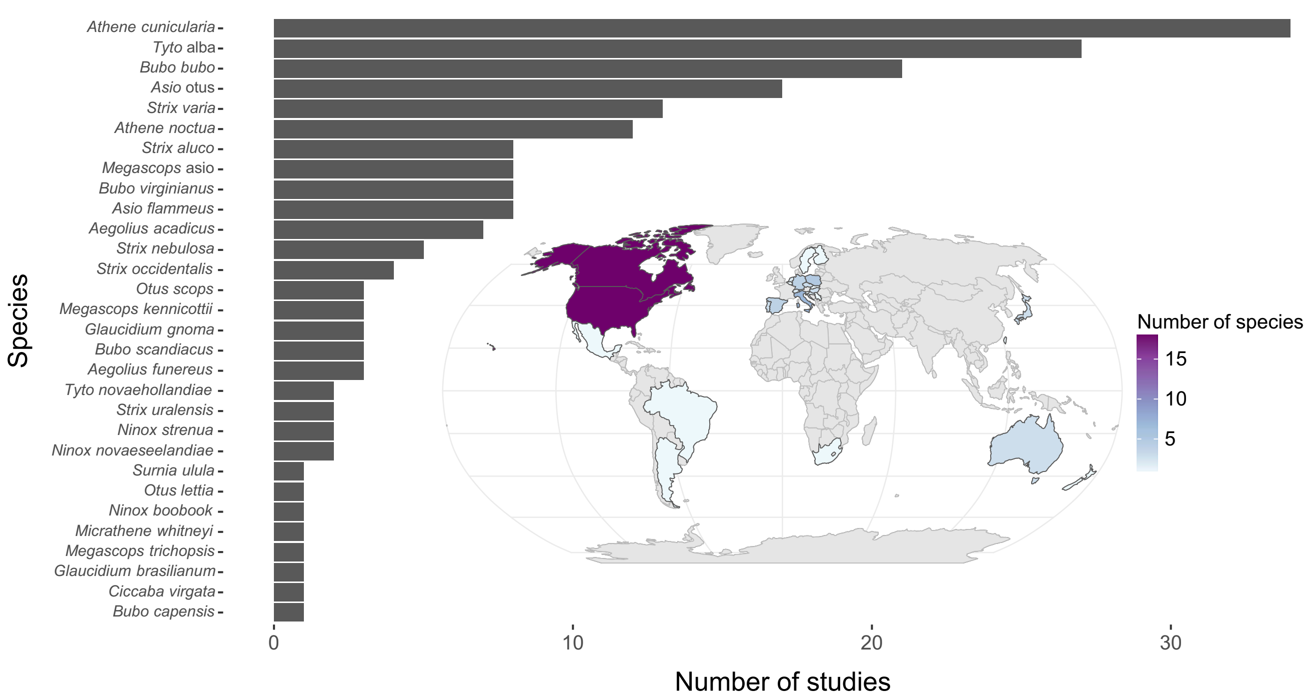

Fig. 2 Of the 236 owl species worldwide, 30 species were studied in relation to urban-related sensory and risk factors. The barplot shows the number of studies conducted for each studied species and the world map illustrates the geographical distribution of the owls studied across the globe. The intensity of the colour scale indicates the number of species by country

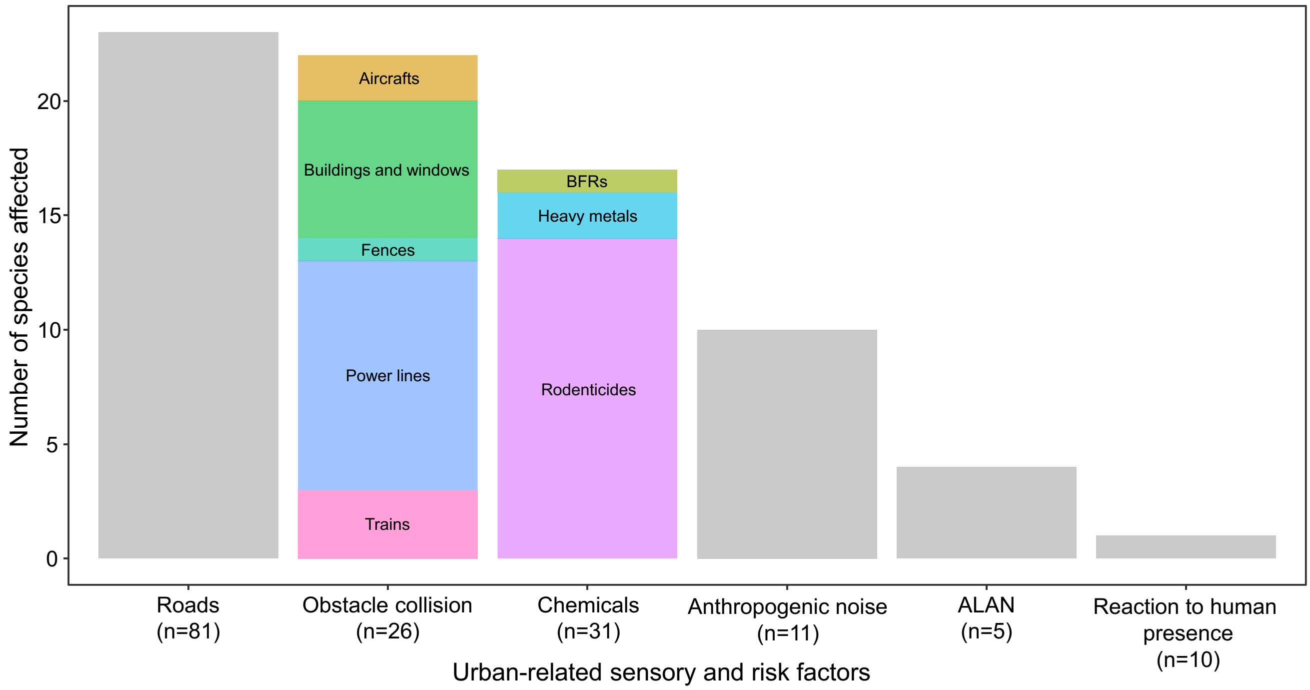

Fig. 3 Barplot showing all urban-related sensory and risk factors reviewed in this study that impact owls globally and the number of affected species per factor, with the number of studies per factor depicted in brackets (the total number of studies is greater than 133 since some studies included more than one urban-related sensory and risk factors). The acronym BFRs indicates brominated flame retardants, and ALAN indicates artificial light at night

Exposure to harmful anthropogenic chemicals was the second most documented factor based on our search ($n=31$; 19% of the studies, Fig. 3) and was recorded for many species (Fig. 3). Evidence on the impact of chemicals mostly came from studies investigating the effects of anticoagulant rodenticides (ARs), including second-generation anticoagulant rodenticides (SGARs), which are widely employed in urban environments to control rodent populations ($n=28$, covering 14 species). Because they can bioaccumulate in the ecosystem across food webs, they also threaten non-target predator species, such as owls (e.g. Barn Owl *Tyto alba*, Hindmarch et al. 2017; Southern Boobook *Ninox boobook*, Lohr 2018), and cause either sublethal effects or direct mortality. We found markedly fewer studies exploring the potential impact of other toxic chemicals ($n=2$ for heavy metals, Demajo et al. 2011; Espín et al. 2014; $n=1$ for brominated flame retardants, Eulaers et al. 2014).

Regarding the factors related to sensory pollution (i.e. anthropogenic noise and ALAN), we found a restricted body of research. Most studies focused on the impact of anthropogenic noise ($n=11$; 7% of the studies) and concerned 10 species (Fig. 3). The impact of ALAN has been investigated even less often ($n=5$; 3% of the studies; with only four species studied in total) (Fig. 3).

Finally, behavioural reactions of owls to human presence have been measured as risk perception and flight initiation distance (FID) in a few studies ($n=10$; 6% of the studies, Fig. 3), all using Burrowing Owls as a study system. For example, Cavalli et al. (2016) demonstrated a difference in boldness, with shorter FIDs in urban Burrowing Owls compared to rural conspecifics. Thus, it is possible that bolder behavioural traits are selected for in response to frequent exposure to humans in urban environments (Moroni et al. 2017), which may lead to more aggressive owls defending their nests from human intruders. For example, although studied in a rural non-urban area, reddish Tawny Owl females are bolder and more aggressive at defending their nests than colour-lighter conspecifics (Da Silva et al. 2013). Moreover, as argued by Carrete and Tella (2017), the consequences of fear of humans are not necessarily detectable by behavioural observations, as some individuals may show no behavioural response, but experience physiological effects that are undetected as yet.

Effects of urban-related sensory and risk factors on owl behaviour and ecology

Among the multiple urban-related sensory and risk factors that we found in our search, we identified three factors that can be associated with owls' behavioural and ecological traits: roads, noise, and ALAN. For each species and factor, we reported the measured behavioural and ecological traits, and recorded the association as positive, negative, or neutral based on the direction of the effect reported (Table 1). We assigned a positive association when the factor was associated with an increase, preference, or apparent benefit for the trait (e.g. higher habitat use, increased occurrence, or selection of that factor). Conversely, we assigned a negative association when the factor caused a reduction or impairment of the measured trait (e.g. decreased hunting success, reduced occupancy, avoidance behaviour), while a neutral association was assigned when the studies reported no significant effect of that factor.

We did not include the other urban-related sensory and risk factors, such as exposure to chemicals and collisions with obstacles, because they were instead associated with direct effects on mortality or physical and physiological impairment, rather than with behavioural or ecological traits. We further acknowledge that other factors not addressed in this review also affect the behaviour and ecology of owls.

Roads

We found that roads were documented in the most studies ($n = 29$ of 45 studies). Some owl species showed a positive association with roads, while others showed a negative association (Fig. 4). Based on the studies we found, six species showed attraction to roads, likely because they can be exploited as foraging and hunting grounds (de Bruijn 1994; Hager 2009). Small mammals often select roadside habitats for activities, such as foraging, refuge and movement (Bellamy et al. 2000; Hill et al. 2021), creating an attractive hunting ground for owls that eat such prey. Additionally, the abundance of perches along roads (e.g. trees, fences, streetlights, road signs) may signal that these areas are beneficial for hunting (Meunier et al. 2000). Road verges, since they are usually kept very short so as to increase visibility of wildlife for drivers, can also contribute to increased visibility and the ease with which prey can be captured (Ascensao et al. 2012). We also found evidence for an increase in space use near roads by a highly insectivorous species, the Burrowing Owl (Table 1), which selects these areas both to nest (Plumpton and Lutz 1993) and to forage (Griffin et al. 2018; Rodríguez et al. 2021).

However, road avoidance was identified for a greater number of species ($n = 8$), some of which were the same species that showed a positive association with roads (Fig. 4). For example, Burrowing Owls seem to avoid roads where vehicle speeds exceed 80 km/h (Scobie et al. 2014). This suggests that additional features rather than the mere presence of roads (e.g., intensity of anthropogenic noise or light) contribute to making roads more or less appealing to owls. Indeed, road density seems to affect the selection of both nesting and roosting sites, leading to lower site occupancy in areas with more roads (Frey et al. 2011; Bradsworth et al. 2021). Road type is another important factor, with major roads being most strongly avoided (Silva et al. 2012; van der Horst et al. 2019), likely due to their higher traffic volumes and associated noise. Because owls are acoustic hunters that rely on acoustic cues to locate prey (Konishi 1973; Knudsen and Konishi 1979), noise might mask these cues, and thus keep the owls away from major roads. However, effects of roads on owls' breeding productivity and demographic rates are rarely documented. A large body of research showed evidence of mortality due to vehicle collisions (Fig. 4), which can remove breeding or nonbreeding individuals from populations (Ramsden 2003). Conversely, another study showed a lack of a significant relationship between fledging success and major road density, specifically the length of highways within the home range of the owls (Hindmarch et al. 2014). Further research is thus needed to better quantify the long-term effects of roads and vehicle collisions on owls' breeding productivity at the population level.

We found only one study looking at the impact of roads on physiological measures (Fig. 4). By examining the levels of faecal corticosterone, Tempel and Gutiérrez (2004) tested whether road proximity increased stress levels in Spotted Owls *Strix occidentalis* and found no correlation between the two.

Noise

Anthropogenic noise was the second most documented factor ($n = 11$ studies), despite a markedly lower number of studies compared to roads (Table 1, Fig. 4). In this case, we identified a consistent and negative response of owls to noise, with no indication of positive association by any species (Fig. 4). Anthropogenic noise affected distribution in most species ($n = 7$, Fig. 4), as determined by acoustic monitoring surveys, which consistently revealed lower owl occurrence in sites with high noise pollution (Fröhlich and Ciach 2018a, 2018b, 2019). Owls rely mainly on their hearing to communicate and hunt (Knudsen and Konishi 1979; Martin 1986), so they are likely to select quieter areas to fulfil these vital activities. Regarding hunting, we found two studies that experimentally demonstrated how noise impairs hunting behaviour, in particular by lowering both prey detectability and capture probability (Mason et al. 2016; Senzaki et al. 2016). For example, when wild-caught Northern Saw-whet Owls *Aegolius acadius* were exposed to anthropogenic noise, the odds of them catching prey declined by 8% for each dB increase in noise (Mason et al. 2016). In the wild, populations of owls living in noisy urban environments or near noisy roads are likely to experience lower hunting success, affecting food supply to offspring and consequently breeding success. However, this prediction needs further investigation as we did not find any study relating noise pollution to breeding success.

Table 1 Owl species investigated with respect to roads, noise and ALAN. For each species, the behavioural and ecological traits (measured traits) that have been studied in relation to these urban-related sensory and risk factors are reported. Species have been reported by following the taxonomic alphabetical order References are shown in the rightmost column (see also Electronic Supplementary Material Table for the full reference list associated with this table)

Species	Factor	Association type	Measured trait	References
Northern Saw-whet Owl (*Aegolius acadicus*)	Noise	Negative	Hunting behaviour	Mason et al. (2016)
Burrowing Owl (*Athene cunicularia*)	Roads	Positive	Habitat use and selection	Plumpton and Lutz (1993), Poulin et al. (2005), Williford et al. (2009), Griffin et al. (2018), Bartok and Conway (2010), Wilkerson and Siegel (2010)
	Roads	Positive	Foraging	Plumpton (1992), Griffin et al. (2018), Rodríguez et al. (2021)
	Roads	Negative	Habitat use and selection	Scobie et al. (2014)
	Noise	Negative	Habitat use and selection	Scobie et al. (2014)
	Noise	Neutral	Habitat use and selection	Scobie et al. (2016)
	ALAN	Neutral	Habitat use and selection	Scobie et al. (2016)
	ALAN	Positive	Habitat use and selection	Rodríguez et al. (2021)
Little Owl (*Athene noctua*)	Roads	Negative	Habitat use and selection	Zabala et al. (2006), Silva et al. (2012)
	Noise	Negative	Presence and distribution	Fröhlich and Ciach (2019)
Short-eared Owl (*Asio flammeus*)	Roads	Positive	Foraging	Hager (2009)
	Noise	Negative	Presence and distribution	Patón et al. (2012)
	Noise	Negative	Hunting behaviour	Senzaki et al. (2016)
Long-eared Owl (*Asio otus*)	Roads	Positive	Habitat use and selection	Galeotti et al. (1997)
	Noise	Negative	Presence and distribution	Fröhlich and Ciach (2018a), Fröhlich and Ciach (2019)
	Noise	Negative	Hunting behaviour	Senzaki et al. (2016)
Eagle Owl (*Bubo bubo*)	Roads	Negative	Habitat use and selection	Van Nieuland et al. (2018)
Great Horned Owl (*Bubo virginianus*)	Roads	Positive	Habitat use and selection	Smith et al. (1999)
Southern Boobook (*Ninox boobook*)	Roads	Negative	Habitat use and selection	Weaving et al. (2011)
Morepork (*Ninox novaeseelandiae*)	ALAN	Neutral	Vocal behaviour	McNaughton et al. (2021)
Powerful Owl (*Ninox strenua*)	Roads	Negative	Habitat use and selection	Bradsworth et al. (2021)
Scops Owl (*Otus scops*)	Roads	Negative	Habitat use and selection	Klein et al. (2020)
Tawny Owl (*Strix aluco*)	Roads	Negative	Habitat use and selection	Silva et al. (2012)
	Roads	Negative	Abundance	van der Horst et al. (2019)
	Noise	Negative	Presence and distribution	Fröhlich and Ciach (2018b), Fröhlich and Ciach (2019)
	ALAN	Negative	Presence and distribution	Hanmer et al. (2021)
Great Grey Owl (*Strix nebulosa*)	Roads	Positive	Foraging	Hager (2009)
Spotted Owl (*Strix occidentalis*)	Roads	Neutral	Physiology	Tempel and Gutiérrez (2004)
	Noise	Neutral	Physiology	Tempel and Gutiérrez (2003)
Ural Owl (*Strix uralensis*)	Noise	Negative	Presence and distribution	Fröhlich and Ciach (2019)
Barred Owl (*Strix varia*)	Roads	Positive	Habitat use and selection	Dykstra et al. (2012), Gagné et al. (2015), Clément et al. (2021)
	Roads	Positive	Foraging	Hager (2009)
Mottled Owl (*Strix virgata*)	Noise	Negative	Presence and distribution	Marín-Gómez et al. (2020)
	Noise	Neutral	Vocal behaviour	Marín-Gómez et al. (2020)
	ALAN	Negative	Presence and distribution	Marín-Gómez et al. (2020)
	ALAN	Neutral	Vocal behaviour	Marín-Gómez et al. (2020)
Barn Owl (*Tyto alba*)	Roads	Positive	Habitat use and selection	de Bruijn (1994), Hindmarch et al. (2017)
	Roads	Negative	Habitat use and selection	Ramsden (2003), Frey et al. (2011), Hindmarch et al. (2012)
	Roads	Neutral	Breeding	Hindmarch et al. (2014)
	Roads	Negative	Breeding	Ramsden (2003)
	Noise	Negative	Presence and distribution	Regan et al. (2018), Fröhlich and Ciach (2019)
Masked Owl (*Tyto novaehollandiae*)	Roads	Positive	Habitat use and selection	Kavanagh and Murray (1996)

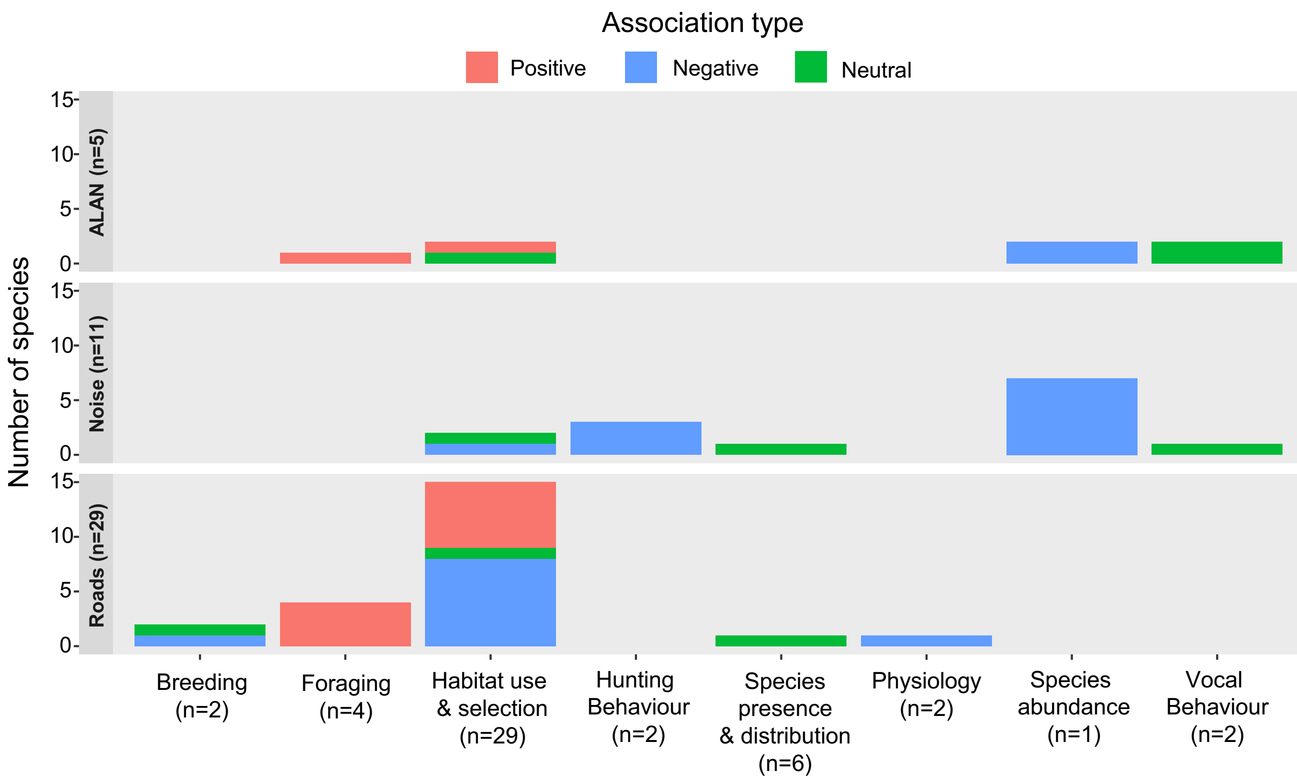

Fig. 4 Barplot showing the number of owl species affected by roads, noise and ALAN based on the type of association (positive, negative and neutral) and the measured behavioural and ecological traits. The number of studies for each factor and for each trait is shown in brackets

We found only one study (on Burrowing Owls, Scobie et al. 2016) showing a case of no effect of noise exposure on habitat use (Fig. 4). The unexpected result was likely due to the limited presence of areas in the study where owls could hear high-frequency sounds—those that may impair hearing by masking prey sounds (Scobie et al. 2016). This suggests that considering sound frequencies may be crucial when trying to assess the impact of noise pollution on owls' behaviour and habitat use. Also, given the variability in the hearing system structures across owl species (i.e. not all owls have the same degree of asymmetry in their ear placement, Mikkola 2013), responses to noise could be species-specific.

The impact of noise on owls' vocal behaviour ($n = 1$) and physiology ($n = 1$) was under-studied. In the two studies we found, the exposure to noise was not associated with significant variations in either vocal outputs (Marín-Gómez et al. 2020) or stress levels (Tempel and Gutiérrez 2003).

ALAN

The impact of artificial light at night (ALAN) on owls was the least documented ($n = 5$, Table 1). Unlike for noise, we did not identify a consistent type of association, probably due to the limited number of studies and the fact that those few studies focused on different traits (Fig. 4).

We found a negative association between ALAN and species presence for two owl species, Mottled Owl *Strix virgate* (Marín-Gómez et al. 2020) and Tawny Owl *Strix aluco* (Hanmer et al. 2021). This pattern is likely explained by altered prey activity patterns due to ALAN. Some small mammal species, such as Wood Mice, *Apodemus sylvaticus* tend to reduce their activity when experimentally exposed to ALAN, and, therefore, avoid lit areas (Spoelstra et al. 2015). In turn, this may encourage owls to move to non-lit areas to maximise hunting and foraging, especially small-mammal specialists, such as the Mottled Owl and the Tawny Owl. Conversely, other small mammal species, such as voles, increase their space use under ALAN (Hoffmann et al. 2018, 2019), exposing them to higher predation risk. These contrasting responses in small mammals could be species-specific, or could depend on the type and intensity of artificial light. Consequently, owls' response to ALAN may depend on how their prey species respond (Hanmer et al. 2021).

Interestingly, artificially illuminated sites appear to be attractive for Burrowing Owls, which increase their space use near streetlights to better find insects, whose availability and abundance are greater near artificial lights (Rodríguez et al. 2021). This suggests that owls' positive association with ALAN is strongly dependent on their prey type and foraging habits. However, a different result on the effects of ALAN was found by Scobie et al. (2016) on the same species (i.e. the Burrowing Owl); they did not detect any attraction to artificial lights compared to other features of the landscape. Further studies are needed to better understand the relationship between owls' habitat use, foraging habits, and exposure to ALAN, as these interactions may be influenced by prey availability and/or the type of artificial light in the environment. Regarding the latter, one study specifically examined the impact of updating streetlights from high-pressure sodium (HPS) to white light-emitting diode (LED) lights. The authors found no evidence that this change affected the vocal activity of the Morepork *Ninox novaeseelandiae* (McNaughton et al. 2021). The absence of an effect of ALAN on vocal behaviour was also supported by Marín-Gómez et al. (2020).

We did not find any studies assessing the impact of different types of ALAN on foraging habits or habitat use. In addition, similarly to noise, we point out the absence of research on the impact of ALAN on owls' breeding success. Further studies in this direction are needed to understand how sensory pollution affects owls' fitness, which would help to better address potential conservation measures.

Potential ecological traps for owls: current insights and future directions

Ecological traps occur when animals preferentially select habitats that appear suitable, but lead to lower fitness compared to other available options (Hale and Swearer 2016). Ecological traps are frequently linked to human-modified landscapes, such as urban or agricultural areas, where novel or misleading cues, such as artificial lighting or altered vegetation patterns, may attract animals to these suboptimal or hazardous habitats. The population-level implications of ecological traps can be severe, effectively turning affected habitats into habitat sinks, where mortality exceeds productivity (Robertson et al. 2013). By identifying the urban-related sensory and risk factors affecting owls, this review highlights that roads, along with associated features, such as ALAN and noise, are important factors that may create ecological traps near roads and in urban environments.

We found that many owls showed a positive association with roads, places where they may forage and nest (Plumpton and Lutz 1993; Hager 2009; Rodríguez et al. 2021). Roads may be perceived as ideal hunting grounds, both for the high availability of perching sites (Meunier et al. 2000; Dean and Milton 2003) and because roadside environments (e.g. road verges) are rich in small mammals (Meunier et al. 1999; Bellamy et al. 2000; Hill et al. 2021), the main prey for most owl species. The linear structure of road verges and the openness of the habitat further enhance the detectability of prey, and the reduced vegetation cover limits the ability of prey to hide, improving the success rate of owl hunting attempts (Dean and Milton 2003). These features are further enhanced in wider road verges, making them especially attractive for raptors (Meunier et al. 2000). Thus, perch site and small mammal abundance along verges significantly contribute to road usage by owls, even though this attraction increases their risk of vehicle collisions (Meunier et al. 2000; Ascensao et al. 2012). Indeed, we found that roads increase the risk of mortality for a large number of owl species ($n = 23$).

On the other hand, owls tend to avoid major roads in particular. Because these roads present higher levels of traffic volumes and thus higher traffic noise emissions, owls may use them sporadically to hunt but usually do not settle close to them (i.e. for nesting). High traffic noise likely impairs hunting success in owls (Silva et al. 2012; Senzaki et al. 2016). Intra-specific communication, which in owls is vital for claiming and defending territories, may also be negatively affected by traffic noise, further decreasing their attractiveness as habitats (Průchová et al. 2024).

Given their lower traffic volume, minor roads (i.e. secondary and tertiary roads) may be more attractive to owls. However, van der Horst et al. (2019) suggest that secondary roads could also function as ecological traps, posing a mortality risk by attracting individuals unable to establish territories in higher-quality habitats farther from major roads.

ALAN (from streetlights, artificially illuminated road signs and other traffic infrastructure) often coincides with noise pollution along roads. This combination likely influences the attractiveness of roadside habitats, either enhancing or diminishing their appeal to wildlife. The presence of ALAN can indeed attract prey such as insects, which, in turn, attract owls with an insect-based diet (Rodríguez et al. 2021). Owls that prey upon bats (e.g. Lesiński et al. 2009) may also exploit ALAN from streetlights to catch bats that in turn hunt insects near streetlights (Rydell 1992). This predator–prey dynamic influenced by ALAN needs further investigation on multiple trophic levels to better understand how sensory pollution shapes prey and predator behaviour.

Prey availability appears to play a crucial role in shaping the use of urban environments by owls. The abundance and behaviour of prey species are likely key factors influencing how strongly owls are attracted to roads, thereby impacting their risk of collisions with vehicles on roads. Changes in the activity or distribution of prey species (e.g. small mammals and insects) due to noise, ALAN or road design features can serve as valuable predictors of owl use of roadside areas. These changes could help anticipate areas of higher collision risk and inform mitigation strategies.

Future studies on prey response to urban factors, such as noise and ALAN, will contribute to our understanding of predator–prey dynamics in roadside environments. The mixed responses of owls to noise and ALAN suggest that the impact of roads may vary by species and depend on specific characteristics of these disturbances (e.g. noise frequency and amplitude, light type and intensity). The Burrowing Owl, with its attraction to roads and streetlights for nesting and foraging, but avoidance of noisy areas, provides an ideal model system to investigate how roads may act as ecological traps under varying levels of noise and ALAN. However, knowing whether a landscape is an ecological trap or not will require investigation of both mortality and reproduction/recruitment to the population.

In addition to prey availability, prey quality may also play a critical role in shaping ecological trap dynamics near roads. In our literature search, we found that rodenticides represent a relevant risk factor for owls, and rodenticides' widespread use in urban environments could result in poisoned prey being accessible to predators. Owls foraging in roadside habitats may, therefore, experience reduced fitness through secondary poisoning following prey consumption. Sublethal exposure to ARs can for example impair physiological function and behaviours (e.g. the ability to fly), but lethal exposure directly increases mortality risk (Lohr 2018). In some cases, owls killed along roads have tested positive for ARs, leading to the possibility that ARs-related effects may make owls less reactive and more likely to be hit by vehicles when hunting near roads (Hindmarch et al. 2017). Therefore, areas near roads may function as ecological traps despite apparently suitable foraging conditions.

Furthermore, the interplay between noise and ALAN might alter hunting strategies of owls in terms of switching prey type or using different sensory cues. For example, in noisy, but lit areas, owls may adapt by relying more on visual hunting to increase hunting success, especially towards prey types that expand their activity times into the night due to the presence of ALAN (e.g. passerines, Kempenaers et al. 2010; Dominoni et al. 2013). However, this shift to visual hunting strategies in the vicinity of roads might make owls less reliant on auditory cues in general and thus less aware of the surrounding environmental noise, such as vehicle traffic. This could expose them to higher collision risks with vehicles (Shonfield and Bayne 2017).

Finally, comparing the fitness of owls breeding near roads with those breeding at greater distances would provide a better understanding of whether road-adjacent environments function as ecological traps. Roads are usually considered ecological traps because of the frequent occurrence of collisions with vehicles, which can remove breeding individuals from populations, thus affecting population-level breeding success and adult survival (Bujoczek et al. 2011; Bishop and Brogan 2013). Collisions with vehicles on roads can also substantially reduce juvenile recruitment into populations (Hernandez 1988). However, it is largely unknown how the breeding productivity and demography of different owl populations may vary based on proximity to roads. In addition, to date no studies have conducted such a comparison accounting for the effect of sensory pollution. Such investigations would help researchers and conservation managers better mitigate when ecological traps are present (Hale and Swearer 2016).

Conclusions and new research avenues

In this review, we have synthesized the current knowledge on urban-related sensory and risk factors affecting owls on a global scale, focusing on how roads and sensory pollutants influence owls' behavioural and ecological traits. We found that this noise and ALAN can affect owl behaviour and ecology, potentially modulating prey use of roads, and possibly turning these areas near roads into ecological traps. The severity of impacts likely depends on the intensity and type of anthropogenic noise and artificial lights occurring alongside roads. However, most research has focused on the northern hemisphere, and more studies are needed from outside North America and the global south (McPherson et al. 2021), where urbanisation is rapidly expanding (Myers 2021). Promisingly, recent studies published after the timeframe of this review have started to fill this geographical gap, advancing our understanding of owl responses to urban-related sensory and risk factors globally. These include studies from Australia (e.g. exposure to rodenticide poisoning, Cooke et al. 2023; impacts of roads, Carter et al. 2025), South America (e.g. breeding performance in urban areas, Cavalli et al. 2023), eastern Asia (e.g. vehicle collision assessment, Gao et al. 2025), and southern Africa (e.g. human perceptions of owls, Buthelezi et al. 2025).

Despite growing interest, much remains unknown about the effects of urban-related sensory and risk factors on owls, and experimental studies are particularly scarce. Light pollution is the least explored urban factor in owl research. New research should focus on whether and how ALAN affects nocturnal predators, especially resident species exposed to continuous ALAN and how they adapt to this novel environmental change. Moreover, studies on human perceptions of owls and how they influence human-owl interactions in urban settings would benefit conservation efforts, especially in regions where superstitions still affect owl conservation (Ogada and Kibuthu 2008; Bontzorlos et al. 2023; Buthelezi et al. 2025).

Ultimately, roads and sensory pollutants are important factors affecting owl behaviour and ecology, primarily shaping their occurrence and habitat use patterns. Future research should explore the interactive effects of roads, noise, and ALAN on owl movements and prey use of roads, to determine how these sensory cues influence owls' foraging and the risks they face. Investigating how prey species respond to these factors will also be crucial in understanding the broader ecological dynamics. These new research avenues will help guide effective conservation strategies for owls in urban environments.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10336-026-02406-4.

Acknowledgements This work was supported by the UK Natural Environment Research Council via an IAPETUS2 PhD studentship held by GO (grant reference NE/S007431/1). We are also very grateful for the comments and suggestions provided by the anonymous reviewers that improved the quality of this article.

Author contributions GO and DMD contributed to the study conception and design. GO performed the literature search, processed the data and wrote the first draft of the article. All authors critically commented and revised the article. All authors approved all the sections of the article.

Funding This work was supported by the UK Natural Environment Research Council via an IAPETUS2 PhD studentship held by GO (grant reference NE/S007431/1).

Data availability The data collected from the literature review and used for this article can be accessed at https://github.com/beppe96/Owls-Review.git.

Code availability The R code used to process the data for this article can be accessed at https://github.com/beppe96/Owls-Review.git.

Declarations

Conflict of interest The authors declare that they have no competing interests that are relevant to the content of this article.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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