PLAN-B

Tackling **light** and **noise** pollution

REVIEW OF LIGHT AND NOISE POLLUTION IMPACTS ON TERRESTRIAL BIODIVERSITY AND ECOSYSTEM SERVICES

DELIVERABLE 1.1

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List of Acronyms

AI	Artificial Intelligence
ALAN	Artificial Light at Night
BII	Biodiversity Intactness Index
CBD	Convention on Biological Diversity
dB	Decibel
h	Hour
Hz	Hertz
IPBES	International Platform on Biodiversity and Ecosystem Services
JND	Just Noticeable Differences
K	Kelvin
LED	Light-Emitting Diode
L_{eq}	Equivalent Noise Level
lm	Lumen
LP	Light pollution
LPI	Living Planet Index
lx	Lux
MA	Millennium Ecosystem Assessment
NLP	Nocturnal light pulses
nm	Nanometre
NP	Noise pollution
PIT	Passive Integrated Transponder
QC	Quality Control
s.d.	Standard Deviation
SEL	Sound Exposure Level
SEM	Scanning Electron Microscope
SMDH	Standard Mean Difference (Hedges' g)
SPL	Sound Pressure Level
µPa	Micropascal
USB	Universal Serial Bus
W	Watt
WWF	World Wildlife Fund

1 - Executive summary

The Earth is facing an unprecedented biodiversity crisis, characterised by rapid declines in species abundance and diversity. There are many drivers of biodiversity loss, but pollution has been identified as one of the most important. Understanding the impacts of all pollutants and preventing or appropriately mitigating those impacts is critical to combating biodiversity and ecosystem services loss. Two ubiquitous anthropogenic pollutants are light and noise pollution, which, despite over a century of research on their potential environmental impacts, have been largely overlooked in environmental regulations and decision-making.

This PLAN-B report collates and evaluates some of the available evidence for light and noise pollution impacts on terrestrial biodiversity and ecosystem services. The review demonstrates that: (i) both light an noise pollution impact terrestrial wildlife; (ii) synergistic effects can occur when organisms are exposed to both light and noise pollution in combination rather than individually; (iii) species differ in their response to these sensory pollutants based on the ways that they detect and use light and sound; (iv) although light and noise pollution impacts have been documented at levels within the range of normal background conditions, there is the potential that screening thresholds can be defined for population level impacts; (v) mechanisms of light and noise pollution impacts have been elucidated to varying degrees; (vi) laboratory studies can help to further define these mechanisms and help to explain patterns observed in field studies; (vii) there is evidence of both direct and indirect effects on ecosystem services. However, the review also highlights that studies on light and noise pollution across many taxa and geographic locations are limited. Mechanistic understanding of impacts is similarly limited, especially when extending from the individual to the ecosystem scale. Future work needs to prioritise addressing these limitations, using methods to quantify light and noise exposures in ecologically meaningful terms rather than relying on approaches and quantities that are specifically weighted towards human responses to these sensory pollutants.

2 - Related documents

PLAN-B D4.1 Restoring the night: A policy agenda for light pollution mitigation in Europe.

PLAN-B D4.2 Policy Agenda: Preventing the harmful effects of anthropogenic noise on biodiversity.

3 - Introduction

The Earth is facing an unprecedented biodiversity crisis, characterised by rapid declines in species abundance and diversity (WWF, 2024). The Living Planet Index (LPI), which uses the trends in population abundance of approximately 35,000 species to quantify the average change in relative abundance of species since 1970, provides a clear demonstration of the speed and extent of biodiversity loss that is occurring (WWF, 2024). Drawing on amphibian, bird, fish, mammal and reptile population data from around the world, the LPI shows that vertebrate populations have declined by 73% on average between 1970 and 2020. In terrestrial ecosystems alone, there has been a 69% decline over this period.

Other metrics demonstrate that this rapid loss of biodiversity is not restricted to the last five decades. For example, the Biodiversity Intactness Index (BII), which shows how much of the original terrestrial biodiversity in a region remains, demonstrates significant global decline since the 1800s and an acceleration of that decline from around the start of the 20th century (WWF, 2024). Similarly, data from as far back as the 1500s show that there was a significant rise in extinction rate from the early 1800s, with a notable acceleration in extinction rate since the early 20th century (IPBES, 2019).

Biodiversity loss results in the loss of ecosystem functions and resilience (Oliver et al., 2015), impacting the benefits that people derive from ecosystems. These benefits, referred to as ecosystem services, are essential for human existence (MA, 2005), although societies, especially in more developed regions, may not immediately recognise this level of dependence due to the decoupling effect of international trade, which geographically separates resource extraction from resource use (Reader et al. 2022). Given the level of human dependence on ecosystem services, major international initiatives, such as the International Platform on Biodiversity and Ecosystem Services (IPBES), have been established to facilitate global assessments of ecosystem services and accelerate global response to addressing biodiversity and ecosystem services loss (IPBES, 2019). National and international biodiversity targets have been set with the intention of putting nature on a path to recovery by 2030 (e.g. CBD, 2022), further catalysing international action to combat the loss of biodiversity and ecosystem services.

There are many drivers of biodiversity loss, but pollution has been identified as one of the most important (Jaureguiberry et al. 2022). Recognising this, the CBD Kunming-Montreal Global Biodiversity Framework adopted the target of reducing pollution risks and the negative impact of pollution from all sources by 2030, to levels that are not harmful to biodiversity and ecosystem functions and services (CBD, 2022). Target 7 makes specific mention of excess nutrients, pesticides, “highly hazardous chemicals”, and plastics in the environment, but the stated focus on “all sources” of pollutants ensures that it applies to all environmental pollutants resulting from anthropogenic activities. Understanding the impacts of all such pollutants and preventing or appropriately mitigating those impacts is critical to combating biodiversity and ecosystem services loss. Two ubiquitous anthropogenic pollutants are light and noise pollution, which, despite over a century of research on their potential environmental impacts (e.g. Allen, 1880), have been largely overlooked in environmental regulations and decision-making (House of Lords Science & Technology Committee, 2023; Van Hoorick et al., 2025; Yakushina et al., 2025).

3.1 - The evolution of light and noise pollution

Life has evolved over millions of years in an environment where the rotation of the Earth relative to the Sun governed the duration of day and night, and also seasonal changes. The physiology and behaviour of wildlife, therefore, evolved to align with diel and seasonal patterns. Similarly, over the millennia, natural soundscapes formed the sound environment in which life evolved.

Early humans (*Homo erectus*) began to change this, harnessing the power of fire to provide warmth and light after sunset and keep predators away (James, 1989). Fire enabled these early humans to socialise beyond dusk (Guarnieri, 2018). However, at this time, the resultant light and noise pollution from human activities would have been highly localised and likely of minimal environmental disturbance.

When modern humans (*Homo sapiens*) developed the ability to start fires, approximately 100-50 thousand years ago, this enabled humans to control the illumination of their nighttime environment and for communities and civilisations to develop (Guarnieri, 2018). The geographic clustering and activities of humans as these communities and civilisations developed would have increased both anthropogenic light and noise pollution in the environment.

Over the past century, there has been a rapid acceleration in the extent to which anthropogenic light and noise pollution have become a global challenge. The proliferation of electric lighting has enabled humans around the world to reliably extend their activities throughout the night. The fossil fuelled and, more recently, electric powered movement of goods and passengers by planes, trains and automobiles has introduced new sound sources throughout the global environment, making anthropogenic noise a feature of many previously undisturbed areas.

Given that most life on earth evolved in the absence of significant anthropogenic light and noise pollution, the dramatic increase in light and noise pollution sources since the 1800s, coupled with a notably rapid decline in biodiversity over this period, cannot be ignored. Whilst it is recognised that other factors, such as land use change and hunting, will also have driven biodiversity loss, understanding the role that light and noise pollution play in this process is crucial to managing human impact on the environment and shaping prevention and mitigation solutions.

3.2 - Aim of this report

This PLAN-B report collates and evaluates some of the available evidence for light and noise pollution impacts on terrestrial biodiversity and ecosystem services. This report focuses exclusively on the terrestrial environment, in line with the scope of PLAN-B, as aquatic systems are addressed separately by the European Commission-funded sister project, AquaPLAN.

Although the overall context is biodiversity and ecosystem services, the reality is that most scientific research is targeted at particular wildlife species. That said, healthy wildlife populations are the building blocks of diverse communities and, hence, resilient and well-functioning ecosystems. Therefore, understanding how anthropogenic light and noise pollution affect wildlife is critical to understanding the impacts of these pollutants on terrestrial biodiversity and ecosystem services.

Key questions that the report aims to address, based on review of currently available evidence, are:

1. Does light pollution impact terrestrial wildlife?

2. Does noise pollution impact terrestrial wildlife?
3. Do combined exposures to light and noise pollution elicit a different response in terrestrial wildlife than the individual stressor exposures?
4. Do species and/or organism groups differ in their responses to light and noise pollution?
5. Are there levels of light and noise exposure below which no response is observed?
6. Can thresholds of exposure be meaningfully defined?
7. Are mechanisms of light and noise pollution impacts on terrestrial wildlife clearly defined?
8. Is there direct/indirect evidence of light and noise pollution impacts on terrestrial ecosystem services?

3.3 - Approach and Report Structure

This report has been developed from an extensive review of evidence on the impacts of anthropogenic light and noise pollution on terrestrial biodiversity and ecosystem services.

The approach to evidence collation and the creation of a PLAN-B knowledgebase is detailed, along with the development and implementation of a bespoke Artificial Intelligence (AI) tool to facilitate knowledgebase population.

Although the knowledgebase is still in development, selected information has been drawn from it to provide overviews of evidence for major groups of terrestrial organisms:

- Amphibians and reptiles
- Birds
- Mammals
- Insects
- Molluscs
- Other invertebrates
- Plants

Evidence on the impacts of light and noise pollution on ecosystem services is also summarised.

Drawing on these summaries, other systematic reviews and meta-analyses that have been published, answers to each of the key questions and the strength of supporting evidence are discussed.

3.4 - Defining light and noise pollution

This report adopts the following definitions for anthropogenic light and noise pollution (i.e. light and noise produced as a result of human activities):

- Light pollution occurs when humans, other organisms, or the environment are exposed to unwanted or unnecessary lighting (Yakushina et al., 2025). This is sometimes referred to by the abbreviation LP and encompasses what is commonly termed Artificial Light at Night (ALAN).
- Noise pollution is unwanted sound that can impact humans and biodiversity (Van Hoorick et al., 2025). This is sometimes referred to by the abbreviation NP.

Where light and noise pollution are referred to in combination, these are often abbreviated to LNP.

4 - Developing the PLAN-B knowledgebase

4.1 - Overview

The PLAN-B T1.1 team (UKCEH, USAL, GDANSK Tech, MLU, UEMG, UGENT) have developed a systematic search and analysis workflow to identify data sources and collate information for incorporation into the PLAN-B knowledgebase (see MS1.1). This workflow involved bibliographic search term formulation and optimisation, knowledgebase design and the development and testing of AI, machine learning, and statistical approaches to assist with manual information extraction and analysis. Further details describing these activities are provided below.

4.2 - Literature review

A broad bibliographic search term (see box below) was developed by the PLAN-B T1.1 team in early 2024. The search term is structured around: (i) terrestrial biodiversity and associated broad organism groups, (ii) impact/response, and (iii) noise and/or light as a stressor.

The search term was initially used to search Web of Science, Scopus, Google Scholar and BASE. Multiple test searches were performed to identify the most suitable search term structure given the large number organism groups, potential responses. Following the discussion, the T1.1 team agreed that the most suitable search term structure was to use organism as the primary search term, response as the secondary and stressor as the tertiary, and to search the publication title only to focus the output. For the primary search all publication records returned must have one or more of the primary words/phrases in, then subsequent publication records identified must have one or more of the secondary words/phrases in and finally, subsequent publication records must have one or more of the tertiary words/phrases in. it was noted during search term testing that some potentially relevant publications for specific animals that PLAN-B T1.1 team were aware were not being identified by the searches. This was to be expected given that there are differences in the ways that publications refer to the animals/plants that have been studied, and, in general, the more unusual the organism, the more likely it is that it will be referred to by a specific name (e.g. capybara) rather than a more general descriptor. Adding some more specific animal names to the search term (otter* OR seal* OR "sea lion*" OR walrus* OR beaver* OR capybara* OR muskrat*) increased the total number of publications identified through the database searches by <1%, but did ensure that those papers would be within the final set used for further analysis. The final search term agreed had the following structure in Web of Science; it was necessary to make slight adjustments to the query to search other literature search engines due to differences in data fields or search categories. The outputs from each of the searches were downloaded into separate BibTeX files (.bib).

wildlife OR biota OR organism OR microorganism* OR micro-organism* OR taxa OR flora OR fauna OR biodivers* OR "ecosystem service*" OR environment* OR carnivore* OR herbivore* OR insectivor* OR omnivor* OR granivor* OR detritivor* OR animal* OR plant* OR shrub* OR tree* OR grass* OR herb* OR crop* OR lichen* OR bryophyte* OR moss* OR alga* OR fung* OR mushroom* OR bacteria* OR nematod* OR larv* OR mammal* OR bird* OR avia* OR aves OR amphibi* OR reptil* OR vertebrat* OR invertebrate* OR macro-invertebrate* OR macroinvertebrate* OR "macro *invertebrate*" OR arthropod* OR insect* OR mollusc* OR gastropod* OR primate* OR marsupial* OR lagomorph* OR rodent* OR arachnid* OR spider* OR lepidoptera OR moth* OR butterfl* OR annelid* OR worm* OR frog* OR toad* OR snake* OR lizard* OR mice OR mouse OR rat* OR rabbit* OR hare* OR bat* OR chiroptera OR newt* OR turtle* OR crab* OR salamander* OR alligator* OR crocodile* (Title) and effect* OR affect* OR impact* OR response* OR adapt* OR influenc* OR outcome* OR consequence* OR stress* OR multi-stress* OR sensitiv* OR exposure* OR behavio* OR reproduc* OR migrat* OR navigat* OR communicat* OR ecolog* OR diurnal* OR crepuscular* OR nocturnal* OR grow* OR social* OR develop* OR colo* OR DNA OR polari* (Title) and light* OR "ALAN" OR "sky glow" OR skyglow OR sky-glow OR "zeneth brightness" OR "night sky brightness" OR "night sk*" OR photopollution OR "photo pollution" OR photo-pollution OR "luminous pollution" OR noise* OR sound* OR *acoustic* OR resonan* OR audio (Title).

The aim was to create a literature search term that was as comprehensive as possible, that could be used during the PLAN-B project and beyond. Recognising that no single search term would enable all potentially relevant publications to be identified, the publications collated through each of Web Of Science, Scopus, Google Scholar and BASE searches were supplemented by publications from the ALAN Database (Barentine J. (Dark Sky Consulting, LLC) and Kyba C.), Sordello et al. (2020) and the personal publication libraries of some of the PLAN-B T1.1 team (MLU, UEMG, GDANSK Tech) together with specific publications identified by some PLAN-B stakeholders and from e.g. article alerts. The resulting separate .bib files were then merged by UKCEH into a single .bib file, which contained 78020 publication records. In order to remove the majority (~99%) of duplicate entries GDANSK Tech first repaired the .bib file (by fixing corrupted citation keys, missing commas or =, and unbalanced braces) to ensure parser acceptance, before a multistage deduplication process was followed: (1) normalization and exact title-based deduplication; (2) improved multiline title handling; (3) full-entry normalization + hashing to catch format/order variants; (4-5) strengthened title normalization (case, braces, punctuation). A final validation step compared the cleaned vs the original libraries to identify any missed duplicates. This process has resulted in the PLAN-B WP1 FINAL Publication library (.bib file), which contains citation information for 44196 publications. The resultant .bib file was included as part of MS01 and was also made available to all other PLAN-B WPs to support their activities. The .bib file format was chosen because it is compatible with many publication management software packages (e.g. Zotero, EndNote). The PLAN-B T1.1 team has chosen JabRef as the most suitable reference management software due to its ease of use and functionality.

To identify publications for prioritised entry into the PLAN-B knowledgebase (see below and MS01), publications related to a range of wildlife groups were identified by UKCEH using the following title and keywords search terms:

- bird* or avia* or aves

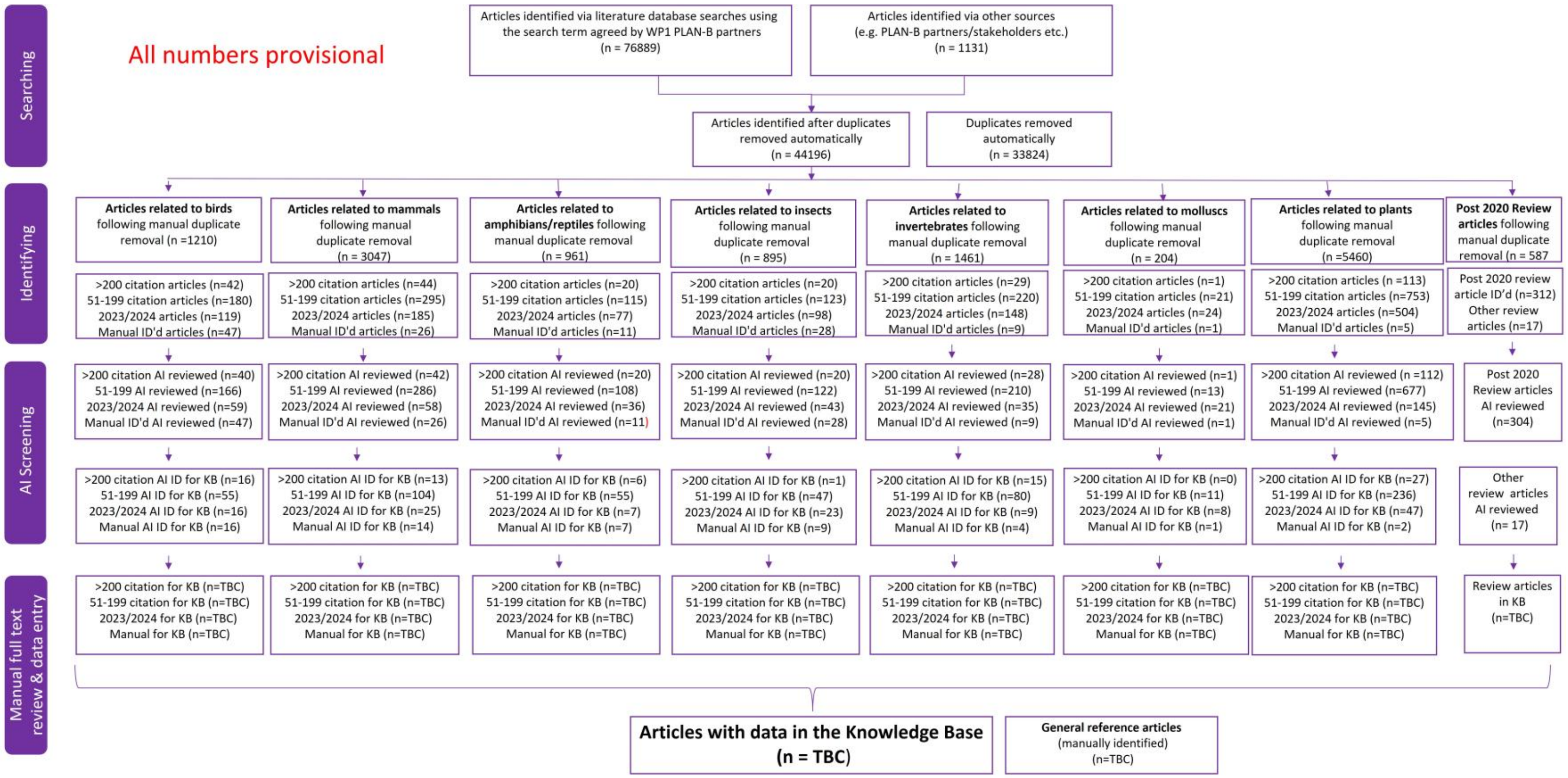
- mammal* or bat or chiroptera or rodent* or mice or mouse or rat* or primate* or marsupial or lagomorph or otter or seal or "sea lion*" or walrus* or beaver or capybara or muskrat*
- amphibian* or reptil* or frog* or toad* or anuran* or snake* or lizard* or newt* or turtle* or salamander* or alligator* or crocodile*
- plant* or shrub or tree or grass* or herb* or crop* or lichen* or bryophyte or moss or alga* or fung* or mushroom*
- lepidoptera or moth* or butterfl* or arachnid* or spider* or bee or wasp* or apoidea or insect*
- microorganism* or micro-organism* or bacteria or nematod or larv* or invertebrate* or macro-invertebrate* or macroinvertebrate or "macro invertebrate" or arthropod or annelid* or worm*
- mollusc* or gastropod* or crab*
- 'review' publications from 2020 onwards

The publications identified by each of these search terms were then extracted into separate .bib files. To identify suitable publications for data entry into the knowledgebase, the T1.1. team chose to base the selection on the number of citations each publication had. UKCEH identified this information (where it was available) in JabRef according to the following criteria:

- >200 citations = High priority publications
- 51-199 = Medium priority publications
- 5-50 = Low priority publications

It was unsurprisingly noted during this process that recent publications have fewer citations, so for publications from 2023 and 2024, suitable publications were identified by UKCEH based on their title and, in some cases, their abstract. Once this task was complete, the PDFs of all except the low-priority publications were obtained for subsequent review. Given the large number of publications collated, data entry by the PLAN-B T1.1 team is focusing on publications that are highly cited (>50 citations), recent publications (2023 onwards) and those already manually identified as likely to provide important information for a given wildlife group. The number (currently (January 2026) provisional) of publications identified at each stage of the literature review process is shown in *Figure 1*.

Figure 1: Diagram showing the number (currently (January 2026) provisional) of publications identified at each stage of the literature review process.



KB = Knowledge Base; Diagram based on: 10.6084/m9.figshare.5897389

4.4 - AI Tool development and testing

To facilitate screening the large volume of publications and expedite data extraction, the team developed an AI-based tool to automate the initial information extraction. The goal of this tool was to scan each publication's full text (PDF) and produce a draft entry for the knowledgebase, populating as many of the 130+ fields as possible with answers extracted from the paper. In essence, the AI acts as a first-pass curator: reading the paper and outputting structured data in the same format a human would enter the database. Additionally, the tool was designed to flag certain publications for priority relevance to Tasks 1.2 and 1.4. For example, if a paper explicitly studied the combined effects of light and noise together, or if it reported quantitative effect thresholds (which are key for risk analysis), the AI would mark those fields accordingly (e.g. an entry "Publication studies light and noise combined impacts: Yes" or "Biological effect levels stated: Yes – [description]"). This helps identify studies that are particularly informative for combined stressor impacts or dose-response relationships, which Task 1.2/1.4 are focusing on.

Pawel Tysiąc (Gdansk Tech) led the implementation of the AI tool. The solution leverages a large language model (LLM) to perform question-answering on the text of each paper. After experimenting with several models, the team selected Google DeepMind's Gemma 3 27B model, which is an open-access 27-billion-parameter transformer model, as the core of the system. Gemma 3 was chosen for its strong performance on knowledge and reasoning benchmarks and its ability to handle very long context windows (up to 128k tokens), which is essential for processing entire scientific papers. Being an open model, it could be run on local infrastructure, ensuring that potentially copyrighted PDF content was analysed internally without the need to send data to an external API. The model is multimodal, but in this application, only its text understanding was used (no images were processed by the AI tool, aside from any captions or text in the PDF itself).

The tool pipeline works as follows. First, each publication PDF is fed into a text extraction module. Using a library like PyMuPDF, the PDF is parsed page by page to obtain raw text. This text is then passed (potentially truncated or chunked if extremely long) to the LLM with a carefully crafted prompt. The prompt is structured as a series of questions corresponding to the knowledgebase fields, asking the model to provide specific details. To enforce consistency and brevity in answers, the model is instructed to output each answer in a strict JSON format, for example: {"answer": "Terrestrial"} for the *Ecosystem realm* field. The questions themselves are formulated to guide the model to the exact information and format needed. For instance, *"What is the DOI number of the text? The DOI number is the only answer; enter NA if not provided."* or *"Choose the most suitable IUCN Global Ecosystem Biome for the study from the provided list."* By providing allowed options in the prompt (for controlled vocabulary fields) and explicitly telling the model to answer "NA" when information is not available, the team attempted to minimise irrelevant or verbose outputs. The system cycles through all fields, sending each question (with the full paper text as context) to the model, and collects the answers into a structured JSON or spreadsheet row for that paper. Certain fields are populated with simple rules instead: for example, the "Publication Identifier (Citation Key)" was set to the PDF filename and did not require AI. The entire process is orchestrated by a Python script, which also handles exceptions (such as model timeouts or memory issues) – it will retry queries up to a few times if no answer is received and log any papers that fail for later manual attention.

The prompt and output format were tuned iteratively: early tests showed that the model might respond with unwieldy text if not constrained, so the final system prompt explicitly disallows extra commentary and limits the model to just output the answer in quotes. The use of an instruction-tuned variant of Gemma (the 27B-IT model) helped in following the instructions closely. Additionally, the pipeline took advantage of Gemma's multilingual capability. Although most papers are in English, if any were in other European languages, the model could still understand and extract answers, which added robustness. The outcome of this AI tool is that for each input paper, we obtain a draft data record: essentially, the AI suggests what should go into each knowledgebase field based on the paper content. These draft records greatly accelerate the subsequent human curation step, as a curator does not start from scratch; instead, they verify and edit the AI-proposed entries.

After extensive testing and refinement, the AI tool demonstrated excellent performance in many respects. In internal trials on a set of known papers, it successfully identified the key fields and even pinpointed which papers were most relevant for combined light and noise impacts or contained specific quantitative results. The AI's ability to mirror the structure of the knowledgebase means that it can populate a new entry in seconds, whereas manual extraction might take an hour per paper. This increases the throughput of literature processing. However, as described in the next section, the tool is not perfect, especially for certain detailed data points, and thus the workflow retains a necessary human review phase. The AI acts as an assistant, flagging priority information and filling in obvious facts, while the expert curator checks for accuracy and fills any gaps or corrects errors before finalising the database entry.

To quantify the AI tool's performance, the team conducted a detailed evaluation against manual curation for a sample of publications. A representative study was chosen and meticulously annotated by human experts for all 132 schema fields, yielding a ground-truth set of answers. The AI tool was then run on the same paper, and its outputs were compared to the human reference. Standard classification metrics was calculated, treating each field extraction as a binary decision (correct or incorrect). A field was marked True Positive (TP) if the AI provided the correct value as per the manual data; False Negative (FN) if the AI missed a piece of information that was present (e.g. output "NA" or blank when the paper did have a relevant detail); False Positive (FP) if the AI hallucination filled a field that should be blank (e.g. giving a specific value that the paper did not report); and True Negative (TN) if the AI correctly left a field blank (NA) when indeed the paper provided no information for that field.

Out of 132 fields, we observed: TP = 59, FP = 13, FN = 14, TN = 46. This corresponds to an overall accuracy of 79.5% in field-level extraction. More informatively, the Precision and Recall metrics were derived. Precision (the fraction of AI's filled answers that were correct) was 81.9%, meaning when the AI asserts a value, it is right about 4 out of 5 times. Recall (the fraction of the paper's facts that the AI successfully captured) was 80.8%, meaning the tool found roughly four-fifths of all available info. The F1 score (harmonic mean of precision and recall) came out to 81.4%, indicating a balanced performance. We also computed specific error rates: the false negative rate was ~19% (i.e. the AI failed to retrieve about one in five actual data points, leaving them as NA), and the false positive rate, which in this context is effectively the hallucination rate for fields that truly had no data, was ~22%. In other words, when a field had no information in the paper, the AI still invented an answer in about 22% of cases, whereas the other ~78% of the time it correctly abstained (left it NA). Put plainly: *when information is present, the AI catches it about 81% of the time; when the AI outputs a value, it's correct 82% of the time; and when a field should be empty, the AI properly leaves it empty about 78% of the time.* These are very solid numbers for an automated system reading complex scientific text. They show that the tool can significantly lighten the workload, since most fields do not need manual correction, but also that in every paper, there will likely be a handful of fields to double-check or fill in by a human (especially those ~19% missed or potentially 18% incorrect entries).

To further pinpoint strengths and weaknesses, performance by category of information was analysed. The schema fields were grouped into four broad categories and measured the proportion of fields correctly extracted in each:

- Species-Level Taxonomy and Traits: This includes fields like species Latin name, common name, taxonomic genus/family/order, as well as organism type (bird, mammal, insect, etc.) and feeding strategy. Here, the AI performed best, with roughly 89% accuracy. It correctly pulled out the scientific and common names of the study species and identified higher taxonomy, often even without explicit cues (likely leveraging both text and its internal knowledge). For example, in one test, the subject was the common nightingale; the AI accurately gave *Luscinia megarhynchos* as the Latin name and “nightingale” as the common name and placed it in the right genus and family. It also deduced traits like feeding strategy (“omnivore”) when mentioned or obvious from context, and noted if a detail was provided, such as the life stage (adult/juvenile) or sex of the animals. Only a couple of taxonomy-related fields tripped up the model: it struggled to identify the number of species studied when that was not explicitly stated (in one case, it mistakenly took the number of individual animals as if it were the count of species), and it misclassified one endpoint (a minor error in a categorical field). Overall, the high performance here suggests the model’s general reading comprehension and perhaps background knowledge in zoology were advantageous.
- Environmental Context Classifications: This covers fields about the study setting, e.g. broad ecosystem realm (terrestrial/freshwater/marine), biome and habitat type (using the IUCN and CORINE classifications), climate zone (Köppen class), and whether these descriptors were directly reported or inferred. The AI achieved around 72% accuracy on these. It usually got the broad context correct, for instance, if the study took place in a city park, the tool would correctly tag it as “Terrestrial” realm and likely identify “Urban” as the environmental lighting zone. It could also often infer if something was reported vs inferred (for example, if the paper explicitly stated, “temperate deciduous forest,” the AI marks a biome as reported; if not, it might still guess a biome from location but mark it inferred). The difficulties arose with finer, hierarchical classifications. The model sometimes picked an incorrect option from a predefined list, especially for biome or specific habitat classes, when the paper’s description was vague. In one case, the allowed list had many biome types, and the AI had to choose the closest match – the paper site was an urban woodland fragment, and the AI chose a “Temperate-boreal forests and woodlands” biome when actually “Urban & industrial ecosystems” might have been a better fit from the list. Such errors likely stem from the model’s uncertainty when no single category perfectly matches the description; it must make a best guess. These near misses highlight that while the AI grasps the general environment (natural vs urban, etc.), it may mislabel the precise category in a controlled ontology. Still, most of the environment fields were correctly filled or logically inferred.
- Measurement and Experimental Data: This category includes quantitative fields like the number of sampling points, exposure durations, measurement values and units, and statistical results (means, standard errors, etc.). Here, the AI’s performance was weakest,

roughly 57% accuracy, indicating a tendency to falter on numeric data extraction. It was found that the model often misinterpreted the question or the data. For example, one field asked for “Duration of measurements taken (in days)”. In our test paper, the study duration was not explicitly stated; the human curator marked it as NA, yet the AI answered, “28 days”. On examining the text, it appears the model latched onto a mention in the paper of a 28-day period (possibly the length of the entire study or an unrelated metric) and wrongly assumed that was the measurement duration. In another instance, where the paper provided a range of sound levels (60–80 dB) but no single “measurement value”, the AI still output “~70 dB” as a supposed representative value, essentially averaging or picking from the range – an incorrect approach since the schema expected NA or a clear indication of a range. Similarly, the AI gave a specific number for “number of species” by misreading the context and sometimes provided a full numeric answer where none was asked for. These errors suggest the model has difficulty with context-specific reasoning for numbers – it tends to produce some number rather than leave it blank, likely due to its training on always giving an answer. It highlights a need for caution and perhaps additional instructions or post-processing for numerical fields. Notably, if the model had very high “mathematical reasoning” abilities (as one might expect from its benchmark where Gemma scored ~89% on a math test), it didn’t directly translate to accurate data mining of numbers in text – because the challenge here is recognizing absence of data and aligning the correct figure with the correct concept, not solving a math problem.

- Temporal and Metadata Information: Fields such as the study start/end year, season of study, time of day of observations, and whether the study was in the field or lab. The AI did well here, with about 80% accuracy. It correctly gleaned the year(s) when the study took place or was published (except one case described below), identified the season (e.g. if the paper said “experiments were conducted in summer 2018”, the AI put Summer as the season), and noted if it was a field study or a laboratory experiment. One notable mistake was misidentifying the start year of the study: in a paper where the start year wasn’t explicitly mentioned, the AI guessed it to be the same as the publication year, which was incorrect. This error presumably arose from the model defaulting to a plausible year when unsure. Apart from that, temporal details were handled well, likely because dates and times are usually clearly stated in papers or can be inferred from context (and the model is good at parsing such patterns).

In summary, the AI tool showed strong abilities in extracting textual facts (names, categories, broad attributes) and moderate success with contextual inference, but it was less reliable for precise numerical or specific details that require careful reading or an understanding that “no info is given”. These observations reinforced the plan to keep a human in the loop – the AI significantly speeds up the process and gets most things right, but expert oversight is needed to correct the tricky bits.

Understanding the AI’s failure modes is important for improving the tool. Through error analysis, we identified several recurring patterns in the mistakes made:

- Misinterpreting the question’s intent: In some cases, the AI provided an answer that was correctly drawn from the text, but for a different question than what was asked. For instance, for the field “Number of species studied,” a paper might mention “15 individuals were tracked”, which refers to number of animals, not number of species (if all were the same species). A human would recognise the study had 1 species (15 individuals of it), but the AI saw “15” and answered 15 species, misunderstanding the intent. Similarly, for “Duration of measurements”, as noted earlier, the AI pulled a number related to something else (study length or count of measurements) instead of realising the question sought an explicit duration that wasn’t reported. These errors stem from the AI’s difficulty in mapping the question to the exact phrasing used in the paper. If the paper’s wording doesn’t closely match the question, the model sometimes answers a related concept. Improved prompt phrasing (or providing examples) might mitigate this, but it underlines that the model does not truly “know” the schema and relies on pattern matching and guesswork when unsure.

- Incorrect choice from a list of options: Many fields required the AI to select one entry from a controlled vocabulary (e.g. the specific biome type, or the type of biological response). When the paper did not explicitly use one of those terms, the AI had to infer the best fit. It was observed that in several instances the model picked an allowable but incorrect option. For example, a study’s outcome might clearly be about reproductive success, yet the AI chose “Growth” from the list of possible impact endpoints. The correct option (“Fecundity” or a similar reproduction-related endpoint) was in the list, but the model did not choose it. Possibly, it latched onto a growth-related detail elsewhere in the text or defaulted to a common category. This suggests some bias or default tendency in the model’s responses. Another example: determining the functional group for a species. If the species were an insectivorous bird, the AI should choose “Insectivore”, but if the text never outright says “this bird is insectivorous”, the model might incorrectly choose “Carnivore” or “Herbivore” based on partial information. These list-selection errors are understandable because they involve a degree of interpretation; however, from a database perspective, a “near miss” is still wrong (e.g. tagging a forest habitat as “shrubland” is a meaningful difference). This emphasises the need for a human to review such categorical fields. It also hints that a future iteration of the model could be fine-tuned specifically on our ontology to improve its exactitude.
- Inserting content where none exists (hallucinations): The model occasionally produced an answer that was not supported by the paper at all – a classic hallucination. This was especially evident in fields asking for some detail of mechanisms or background that the paper might not discuss. For instance, one field, “Main mechanism of ecosystem impact”, was often left blank by curators if the study focused on individual-level effects. In one test, the paper was about how birds change their singing behaviour under noise, with no mention of ecosystem-scale impacts. The AI, however, concocted an answer along the lines of “mechanism of impact is the Lombard effect leading to increased song amplitude and potential communication masking.” While the Lombard effect (animals increasing vocal volume in noisy environments) is indeed a real phenomenon and relevant to that study, the paper itself did not frame it as an ecosystem impact. The AI essentially over-generalised a known concept to fill the field. This is problematic because it introduces information that, while plausible, is not stated by the authors, thus misleading if taken at face value. Such hallucinations were not extremely frequent, but whenever an AI answer seems too elaborate or “extra,” it flags the need for verification. Often, the safest course for the AI when something is not mentioned is to return “NA”, and it was explicitly instructed to do so; these hallucination cases indicate that instruction did not always override the model’s training to *always provide an answer.*
- Over-detailed “NA” answers: A subtle but interesting pattern was that the AI sometimes gave unnecessarily verbose responses essentially to say, “not applicable.” Instead of

outputting a blank or "NA" for fields without data, the model occasionally generated a sentence or list of observations and then noted the absence. For example, for "Biological Response Standard Deviation (SD)," if the paper did not report any SD, the ideal output is just "NA." However, the AI might respond: *"The study measured several behavioural responses (flight initiation distance, foraging time, etc.), but it did not provide a standard deviation for these measures."* Technically, this is a true statement and, thus, was marked correct in evaluation (the model correctly identified that no SD was given). But from a database perspective, this answer is not in the expected format; a null entry was required, not a mini-summary. This tendency was seen across multiple statistical fields (standard error, median, min/max values): the AI was compelled to offer some explanation or related data from the paper, rather than a succinct "NA". This reflects the model's training on natural language, where elaboration is rewarded, conflicting with the requirement for terse, standardised outputs. It suggests the prompt may need to be adjusted (e.g. explicitly say "if not provided, just output NA and nothing else") or post-process the answers to strip out any extra verbiage. While these verbose answers did not mislead (they still conveyed "not provided"), they could clutter the data and make it less consistent. This was considered a format compliance issue more than a knowledge gap.

By examining these errors, the team has been able to iteratively refine the AI tool. For example, knowing the model often guesses a number rather than outputting NA, the prompt was adjusted to reinforce the option of "NA if not stated." Also, now any non-conforming answers are treated (like sentences) as NA in post-processing, unless the content clearly contains a value. The patterns of mistakes also highlight where a human should focus their attention during review, e.g. double-check any numeric entries and any list-based categorical fields, since those have a higher chance of AI error. It is essentially a form of quality control: the AI does the bulk of easy lifting, and the curator is alerted to the likely pitfalls.

It is worth reflecting on the choice of the Gemma 3 (27B) model and how its general benchmark performance translated (or did not fully translate) to this specialised task. Gemma 3 is a state-of-the-art open model, and according to its technical report, it achieves very high scores on a range of standard benchmarks. For instance, it excels in mathematical problem solving (MATH benchmark ~89%${}^{}$), demonstrates strong world knowledge and reasoning on MMLU-Pro (~67.5%), and has decent capabilities in following instructions to retrieve facts and even generating code or SQL (e.g. Bird-SQL benchmark ~54.4%), all on par with or better than many models of similar size. These figures suggested that Gemma had the right mix of abilities: numerical reasoning, broad domain knowledge (including scientific topics), and understanding of structured queries. Indeed, our experience confirmed some of these strengths (taxonomy extraction likely benefited from its broad knowledge; the structured output format was generally followed). However, it was also seen that high benchmark scores do not guarantee proficiency in every real-world task.

For example, Gemma's excellent MATH score did not prevent it from misreading numeric data in context. The discrepancy arises because solving a self-contained math puzzle (the nature of the MATH benchmark) is a different skill than information extraction from running text. Our task demands *precision and caution*; often, the correct action is to output "no data" if the paper does not report something. But most AI benchmarks reward coming up with an answer, not abstaining. This task framing mismatch meant the model's strength in always producing a plausible answer became a weakness in cases where the correct action was to say nothing. Similarly, a benchmark like GPQA (a measure of complex question answering under ambiguity) might correlate with some inference skill, but it does not punish a "nearly right" answer as harshly as our schema does. In our ontology, choosing "Growth" vs "Reproduction" is binary right/wrong, whereas an open-ended QA might consider an answer that is somewhat related as partially correct. Thus, the model's moderate score on GPQA (around 42%) and strong score on general knowledge (MMLU 67.5%) still left it struggling with fine-grained category distinctions in our evaluation.

Another point is ambiguity with multiple numbers in the text. Our scientific papers are full of various numbers: sample sizes, p-values, measurement values, time spans, etc. The model must link the right number to the right field. This is more akin to a slot-filling task in information extraction/NLP than the straightforward math word problems it was benchmarked on. The AI occasionally latched onto an irrelevant number simply because it was near a keyword. Tackling this might require model fine-tuning or additional context in the prompt to help it differentiate, which plain pre-training doesn't guarantee.

It was also noted that format sensitivity issues align with benchmarks that test structured output. Gemma's relatively lower performance on something like the LiveCode or Bird-SQL benchmarks hinted that it might not always rigidly adhere to a required format, since those tasks involve producing precise code or queries. Indeed, our AI sometimes gave those verbose NA answers or minor format deviations, showing a bit of "format drift." This is in line with the model not being explicitly trained to always give one-word or one-phrase answers. It was mitigated by prompt design to some extent, but it reinforces that an off-the-shelf model will behave according to its general training. In future, fine-tuning Gemma on a few examples of our Q&A pairs could further improve its format obedience.

Finally, a practical observation was the output variability. During development, it was found that the AI's answers could vary slightly across runs or depending on decoding settings and infrastructure. For consistency in the pipeline, a deterministic setting was used (e.g. temperature 0, fixed random seed) so that the output is the same each time for a given input. This eliminated randomness. However, differences in the runtime, for example, running the model on different hardware or via different libraries, could still cause subtle changes – a known quirk when using quantised models or different backends. Ensuring all extractions were done in one controlled environment solved this for our use case. It is a reminder that large LLMs are not inherently consistent unless you enforce it; something as small as an updated model version could change an answer. The team's approach is to lock down the model and settings once validated, and if an update is needed, re-validate a sample to ensure consistency.

In summary, the Gemma 3 model proved to be a powerful component of our workflow, confirming that an open, high-performing LLM can indeed handle the heavy text of scientific articles and pull-out relevant information. Its generalist strengths (language understanding and reasoning) were evident in the high accuracy for many fields. But the evaluation also taught us the limits of those benchmarks. Our specialised task required a blend of abilities and a cautious style that is not fully captured by standard evaluations. The AI's tendency to "always answer" had to be reined in for a task where sometimes the correct answer is *no answer*. This insight is valuable not just for our project but for any similar endeavour: one must align the AI's behaviour with the end-goals through careful prompt engineering or fine-tuning, rather than assuming a top-scoring model on academic benchmarks will automatically excel at the application without adaptation.

The development of this AI-assisted literature analysis workflow has significantly enhanced the PLAN-B team's capacity to build the knowledgebase of light and noise impacts on biodiversity. By combining an exhaustive literature search and curation process with a cutting-edge AI extraction tool, we created a pipeline that can handle the breadth (tens of thousands of papers) and still dive into the depth (dozens of data points per paper) in an efficient manner. The systematic search ensured we left no stone unturned in finding relevant studies, and the prioritisation scheme allowed us to focus on the most important sources first. The knowledgebase schema provides a clear blueprint of what information to extract, and the AI tool accelerates filling in that blueprint by supplying initial answers for ~80% of the entries correctly.

We found that the AI is especially useful for quickly identifying which studies are most relevant to specific questions (like combined stressor effects or threshold values) – something that would be very tedious manually. It essentially surfaces the "signal" from each paper (e.g., *"this study has data on how bird reproduction is affected by urban light at night"*), enabling experts to then verify and incorporate that signal into the database. The performance evaluation confirmed that while the tool is not infallible, its accuracy is high enough to save substantial time: a curator can trust most of the fields it fills and just focus on the few likely errors. This man–machine synergy yields a higher throughput without sacrificing rigour. Every AI-generated entry is still reviewed, but the human effort is reduced and can be concentrated where judgment is truly needed.

From a scientific perspective, this approach also standardises data collection. The AI, following the same prompt each time, is quite consistent in what it looks for, whereas individual human curators might interpret things differently or overlook details when fatigued. The AI does not tire or get distracted, so it scans the paper thoroughly for each question. This consistency can improve the overall quality of the knowledgebase if the AI's outputs are vetted. It also means that as we update the database in the future, the same tool can be run on new batches of literature, ensuring continuity in how information is extracted.

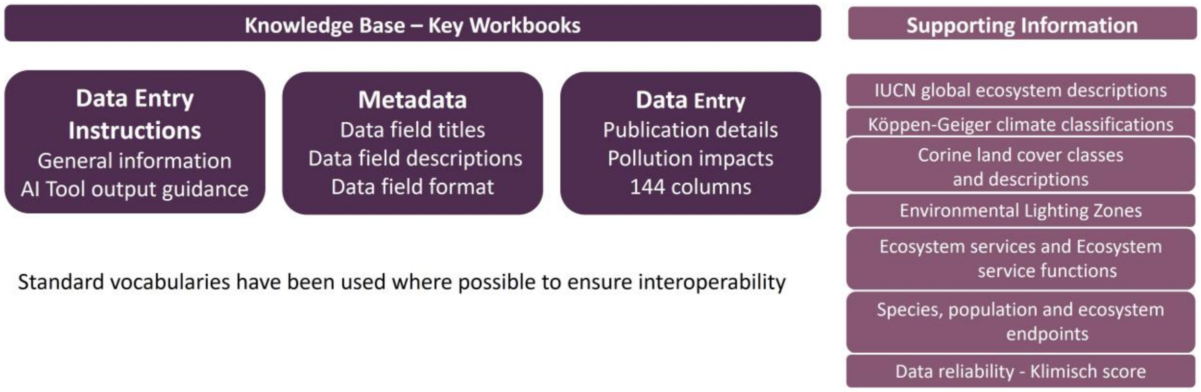
Looking ahead, there are a few avenues for improvement. We plan to refine the prompts and possibly fine-tune the LLM on a small set of manually curated Q&A examples from our domain. This could teach it to be more conservative (output "NA" more readily when appropriate) and better at the specific ontologies we use. We also foresee incorporating a secondary model or rules to double-check certain fields, for instance, a validation script that flags if an AI-proposed numeric value is outside a reasonable range or not found verbatim in the text. Another possible enhancement is using the AI to not only extract data but also to summarise key findings of each paper for qualitative insights (though that is beyond the strict needs of the database, it could be a useful context for researchers).

In conclusion, the integration of AI into our literature review and database population workflow has proven to be a valuable innovation. It exemplifies how modern AI tools can assist environmental science by handling tedious information processing tasks and allowing researchers to focus on interpretation and decision-making. The knowledgebase resulting from this work will underpin analyses of how LNP affect biodiversity, and thanks to this workflow, it will be populated more quickly and comprehensively than would have been possible with manual effort alone. As we complete Task 1.1 and transition to deeper analyses in Tasks 1.2 and 1.4, we are confident that the combination of a well-curated literature repository and an AI-assisted extraction mechanism will provide a strong foundation for new insights into anthropogenic light and noise impacts on wildlife.

4.5 - Structure and population of the PLAN-B knowledgebase

The PLAN-B knowledgebase was iteratively developed by the T1.1 team concurrently with the literature review process. It has been prepared as an MS Excel spreadsheet with multiple workbooks to facilitate ease of sharing, collation and subsequent dissemination. The overall structure, data entry instructions and all supporting metadata have been provided as MS1.1; example data from Morelli et al. (2023) was pre-entered. The fully populated knowledgebase and all associated metadata will be submitted following Quality Control (QC) checks as D1.2 in Aug 2026 as a .csv file via an open-access data repository (likely https://eidc.ac.uk/deposit). The .csv format was chosen as it is widely used, compatible with many software applications and can be machine-read by many different applications and programming languages.

Figure 2: General structure and key workbooks included in the PLAN-B knowledgebase.



Following the completion of the literature review, a search and analysis workflow was developed to collate information from publications that may be incorporated into the knowledgebase. This workflow integrates AI, machine learning and statistical approaches into query formulation, search optimisation and bibliographic information extraction and analysis. Several tests of the workflow were undertaken by Gdansk Tech, UKCEH and USAL. A workshop for the T1.1 team was then held in early July 2025 to review these tests and finalise the workflow. Following the workshop, members of the T1.1 team independently tested the guidance and data entry process. This testing highlighted some differences in how the guidance was interpreted and, hence, how data was entered into the knowledgebase. The guidance was amended, and a follow-up workshop was held to present the revised guidance to ensure any potential variability in approach during subsequent data entry was minimised.

The knowledgebase workbook contains 144 data entry fields and multiple workbooks containing supporting information to aid data entry (*see Figure 2*). The data entry fields and their respective data entry format (free text (in black text) or menu-driven (in red text)) are provided below. The menu-driven fields are provided to ensure data consistency, and most data entry options should be available from the menu provided. If this is not the case, then a free text field with the same field title but ending in ‘other’ (e.g. Species_Or_Organism_Feeding_Strategy_Other) is provided.

Publication_Identifier_Citation_Key
Publication_DOI_Or_Weblink
IUCN_Global_Ecosystem_Realm

IUCN_Global_Ecosystem_Biome
Reported_Or_Inferred_Global_Ecosystem_Biome
IUCN_Global_Ecosystem_Functional_Group
Reported_or_Inferred_Global_Ecosystem_Functional_Group
Study_Location
Latitude_Where_Study_conducted_Decimal_Degrees
Longitude_Where_Study_conducted_Decimal_Degrees
Köppen_Geiger_Climate_Classification
Environment_Type
Environmental_Lighting_Zone
Reported_or_Inferred_Environmental_Lighting_Zone
CORINE_Land_Cover_Class_1
CORINE_Land_Cover_Class_2
CORINE_Land_Cover_Class_3
Reported_or_Inferred_CORINE_Land_Cover_Class_1
Reported_or_Inferred_CORINE_Land_Cover_Class_2
Reported_or_Inferred_CORINE_Land_Cover_Class_3
Number_Of_Sampling_Points
Study_Type
Study_Exposure_Type
Start_Year_Of_Study
Start_Month_Of_Study
End_Year_Of_Study
End_Month_Of_Study
Season_Of_Study
Weather_Conditions_If_Stated
Time_Of_Study
Topic_Of_Study
Publication_Studies_Light_And_Noise_Combined_Impacts
Other_Stressors_Present
Other_Stressor_Detail
Is_Noise_Or-Light_The_Dominant_Stressor?
Organism_Details_If_No_Species_Details_Provided
Species_Latin_Name
Species_Common_Name
Species_Genus
Species_Family
Species_Order
Species_Class
Organism_General_Classification
Species_Or_Organism_Feeding_Strategy
Species_Or_Organism_Feeding_Strategy_Other
Organism_Lifestage
Organism_Sex
Number_Of_Species_Studied
Number_Of_individuals_Studied
Exposure_Modelled_Or_Measured
Name_Of_Model_Or_Device
Calibration_Details_Of_Model_Or_Device
Opperating_Frequency_Band_Of_Device
Duration_Of_Measurements_Taken
Units_Of_Duration_Of_Measurements_Taken
Measurement_Name_Or_Exposure_Indicator

Measurement_Name_Or_Exposure_Indicator_Other
Measurement_Units_As_Reported
Measurement_Units_SI
Measurement_Units_SI_Other
Have_Measurements_Been_Converted_For_Entry_From_As_Reported
Number_Of_Measurements
Location_Of_Measurement
Location_Of_Measurement_Other
Distance_Between_Measurement_Location_And_Receptor_Metres
Distance_To_Receptor_Stated_Or_Estimated
Measurement_Value_Qualifier
Measurement_Value
Measurement_SE
Measurement_SD
Measurement_Median
Measurement_Minimum_Value_Qualifier
Measurement_Minimum_Value
Measurement_Maximum_Value_Qualifier
Measurement_Maximum_Value
Does_Measurement_Value_Include_Background_Measurements
Source_Of_Background_Exposure
Exposure_Type
Source_Of_Exposure
Source_Of_Exposure_Other
Impact_On-Species_Endpoint
Impact_On_Population_Endpoint
Impact_On_Ecosystem_Habitat_Or_Community_Endpoint
Biological_Response_Exhibited_By_Species
Biological_Response_Exhibited_By_Species_Other
Reported_Or_Inferred_Biological_Response_Exhibited_By_Species
Details_Of_Biological_Response_Exhibited_By_Species
Biological_Response_N_Observed
Biological_Response_Value
Biological_Response_SE
Biological_Response_SD
Biological_Response_Median
Biological_Response_Minimum
Biological_Response_Maximum
Biological_Response_Observed_How_Measured
Biological_Response_Effect_How_Measured_Other
Biological_Response_Effect_Size
Biological_Response_Power_Value
Biological_Response_Power_Value_Reported_Or_Calculated
Main_Mechanism_Of_Biological_Impact
Main_Mechanism_Of_Biological_Impact_Other
Biological_Impact_NOAEL
Biological_Impact_LOAEL
Ecosystem_Response_Impact_Observed
Ecosystem_Response_Impact_Observed_Other
Reported_or_Inferred_Ecosystem_Response
Ecosystem_Response_N_Observed
Ecosystem_Response_Value
Ecosystem_Response_SE

Ecosystem_Response_SD
Ecosystem_Response_Median
Ecosystem_Response_Minimum
Ecosystem_Response_Maximum
How_Ecosystem_Response_Effect_Measured
How_Ecosystem_Response_Effect_Measured_Other
Ecosystem_Response_Effect_Size
Ecosystem_Response_Power_Value_Reported_Or_Calculated
Ecosystem_Response_Power_Value
Main_Mechanism_Of_Ecosystem_Impact
Ecosystem_Impact_NOAEL
Ecosystem_Impact_LOAEL
Ecosystem_Service_Impacted
Ecoysystem_Service_Impacted_Other
Reported_or_Inferred_Ecosystem_Service
Ecosystem_Service_Component
Ecosystem_Service_Component_Other
Reported_or_Inferred_Ecosystem_Service_Component
Data_Provenance
General_Notes
Numerical_Notes
Publication_Data_Reliability_Klimisch_Score
Peer_Reviewed?
Is_Study_A_Review?
Publication_Open_Access?
Is_Exposure_Level_Stated
Data_On_Biological_Responses?
Are_Biological_Effect_Levels_Stated?
Are_Ecosystem_Effect_Levels_Stated?
Comments_For_Database_Manager
Data_Entered_By_Initials
Species_IUCN_Status
Data_QC'd_By_Initials
Data_Excluded
Data_Exclusion_Criteria

Data related to a particular organism group(s) is currently (January 2026) being manually entered into the knowledgebase by members of the T1.1 team (see *Table 1*).

Table 1: Organisation leading on data entry for major organism groups.

Organism group	Organisation responsible for manual data entry
Amphibians and reptiles	UEMG
Birds	USAL
Insects	USAL
Mammals	MLU
Molluscs	USAL
Other invertebrates	USAL
Plants	MLU & GDANSK TECH (LP)

The AI Tool output is being used as a guide to identify publications that are most likely to contain useful biological data related to exposure, responses and effects based on the AI Tool's 'Yes' answers to the following queries: 1. Is_Exposure_Level_Stated?; 2. Data_On_Biological_Responses? and 3. Are_Biological_Effect_Levels_Stated?. Review publications (from post 2020), which often cover multiple organism groups, are also being evaluated (by UEMG), but the focus is on using those review publications to identify key primary research publications for entry into the knowledgebase that may not have been identified through the initial screening processes. The intention is to minimise data entry from review publications so that the data provenance and transparency can be maximised.

The remainder of this report presents and discusses some of the key elements emerging from the knowledgebase development. Although the fully QC'd knowledgebase will not be completed until August 2026, the literature review and knowledgebase population work undertaken to date provides a solid basis for evaluating knowledge of light and noise impacts on different organism groups and on ecosystem services. It also enables responses to the key questions posed in Chapter 1 of this report.

4 - Impacts on different organism groups

This chapter summarises some of the available evidence on the impacts of LNP on wildlife. Many of the studies that have been undertaken to date use standard, predominantly anthropocentric, methods to quantify the light and noise conditions to which the wildlife response is related. For noise, this is commonly the decibel (dB) level weighted by the frequency range to which humans are most sensitive (i.e. A-weighted, dB(A)). For light, illuminance is commonly reported in lux (lx), which places emphasis on brightness as perceived by human vision. To help put the information in this chapter in context, some comparative data have been compiled for light (*Table 2*) and noise (*Table 3*) levels commonly encountered in different settings.

Table 2: Variation in levels of illuminance.

	Illuminance (lx)	
Example	from	to
Full sunlight	103000	120000
Partly sunny	50000	
Shade, illuminated by entire clear blue sky, Midday	20000	
Operating table	18000	
Cloudy day	1000	10000
Bright office	400	600
Most homes	100	300
Fully overcast, sunset/sunrise	40	
Main road street lighting (average street level illuminance)	15	
Lighted parking lot	10	
Residential side street (average street level illuminance)	5	
Urban skyglow	0.15	
Full moon under clear conditions	0.1	0.3
Quarter moon	0.01	0.03
Clear starry night, excluding air glow	0.001	0.0002
Overcast night sky	0.00003	0.0001

Data compiled by Gaston et al. (2013) from data in British Standards Institute (2003), Rich & Longcore (2006), Dick (2011), and extended with information from https://en.wikipedia.org/wiki/Daylight

Table 3: Examples of Sound Pressure Levels in dB(A).

Setting/source	Mean / Range
Shotgun[1]	170
Fireworks[1]	162
Thunder[1]	120
Ambulance siren[1]	120
Car horn[1]	110
Motorbike[1]	95 – 110
Electric drill[1]	95
Urban area[2]	50 (60 – 70+)
Quiet suburban area[2]	45 - 50
Quiet office/residential area[1]	40
Wilderness[3]	30 – 40
Quiet rural nighttime[2]	25

[1]Centre for Hearing & Communication (https://www.chchearing.org/common-environmental-noise-levels); [2]https://www.noisequest.psu.edu/noisebasics-basics.html; [3]https://www.engineeringtoolbox.com/outdoor-noise-d_62.html

4.1 - Amphibians and reptiles

4.1.1 - Light pollution impacts on amphibians and reptiles

Amphibians

Across amphibians, the most consolidated effect in the literature is that ALAN can disrupt circadian rhythms and nocturnal behaviour, with measurable consequences for reproduction and early life history performance. Experimental work demonstrates exposure-related reductions in reproductive performance, including altered mating behaviour and reduced fertilisation success under ecologically realistic nocturnal light levels (Touzot et al., 2020). Evidence also indicates that ALAN can affect development across life stages, including shorter larval periods and reduced juvenile growth, with potential carryover consequences after metamorphosis (Dananay & Benard, 2018). These findings support a direct pathway from ALAN exposure to changes in reproductive success, development, and physiological allocation.

Indirect effects also occur. Light can modify predator-prey dynamics and foraging performance by changing visual conditions and activity patterns at night. Classic experimental evidence shows that enhanced lighting can reduce prey detection and consumption efficiency in nocturnal frogs, a mechanism that can translate to energetic deficits and altered survival risk even when light does not immediately cause mortality (Buchanan, 1993). More recent work on salamanders indicates that ALAN can influence regeneration and prey activity, reinforcing the view that light can reshape ecological interactions and energy budgets rather than acting only through a single behavioural endpoint (Wise et al., 2022). Overall, the amphibian evidence base supports both direct impacts on reproduction and development, and indirect impacts via altered performance and species interactions.

Key gaps for amphibians remain substantial. Most studies test limited combinations of intensity and spectral composition, and few quantify response curves that allow reliable extrapolation for mitigation effects in lighting and impacts on natural habitats. There is also a persistent gap in linking individual-level endpoints (calling, endocrine change, growth) to demographic rates (recruitment, survival to maturity) under long term exposure regimes.

Reptiles

For reptiles, the most consolidated evidence concerns sea turtles, where ALAN disrupts orientation and nesting, producing strong and repeatable exposure impact relationships. Beach and nearshore lighting can misorient hatchlings and prolong their time in high-risk coastal zones, increasing vulnerability to predation, dehydration, and exhaustion (Thums et al., 2016; Witherington & Bjorndal, 1991). Controlled and field-based studies show that artificial lights can override natural cues and that interactions between artificial lights and natural illumination can affect orientation (Tuxbury & Salmon, 2005). At broader spatial scales, remotely sensed night light data have been linked to nesting distribution patterns, supporting population-relevant inference where darker coastlines tend to host higher nesting densities (Hu et al., 2018; Mazor et al., 2013).

Indirect effects for sea turtles include functional habitat loss when lighting deters nesting or compresses nesting activity into fewer dark refuges, as well as elevated mortality risk for hatchlings via increased exposure time and altered movement paths (Dimitriadis et al., 2018; Silva et al., 2017). Although it is not regarding the terrestrial wildlife, the knowledge base includes evidence where artificial lighting is deployed intentionally in fisheries to reduce bycatch, indicating strong behavioural sensitivity of marine fauna to light cues (Bielli et al., 2019).

Beyond sea turtles, the evidence base is weaker but supports the general conclusion that ALAN can shift behavioural allocation and physiology in terrestrial reptiles. Experimental work in a diurnal lizard shows that night lighting can increase nocturnal behaviour, with associated changes in physiological proxies linked to energy allocation and reproduction (Taylor et al., 2022). For nocturnal reptiles, night light levels can shift activity in ways consistent with trade-offs between prey capture and predation risk, as shown for a nocturnal gecko under natural and artificial night lighting (Nordberg & Schwarzkopf, 2022). These studies support the generalisation that ALAN can alter behaviour and physiology in reptiles, but the weight of evidence outside sea turtles remains limited.

4.1.2 - Noise impacts on amphibians and reptiles

Amphibians

The most consolidated concept for amphibians is that anthropogenic noise disrupts acoustic communication, a core reproductive and territorial mechanism in many species. It is well established that traffic noise and similar sources can mask calls, reduce effective communication distance, and elicit compensatory changes in call structure and calling effort. Experimental research demonstrates masking effects on anuran communication, where road noise interferes with signal detection and recognition (Bee, 2007). Field and experimental studies show that frogs adjust call parameters under traffic noise, including shifts in frequency or temporal structure, consistent with attempts to maintain detectability in degraded soundscapes (Caorsi et al., 2017; Cunnington, 2010; Lengagne, 2008; Parris, 2009).

Direct effects also include physiological stress responses. Field experimentation indicates that traffic noise can induce stress hormone responses and impair breeding-related movement, providing a mechanistic bridge between soundscape alteration and reduced reproductive opportunity (Tennessen et al., 2014). At larger spatial scales, the road effect zone literature shows threshold like reductions in anuran abundance and richness near major roads, consistent with noise and correlated stressors contributing to distribution shifts and population level impacts (Eigenbrod, 2009).

Indirect effects are observed. Reduced mate attraction and altered female choice can lower effective reproduction even when adults remain present; increased calling effort or altered call structure can impose energetic costs and change predation risk; and chronic avoidance of noisy habitats can fragment breeding habitat and reduce connectivity. Despite strong evidence for these pathways, the amphibian literature still has gaps in long term demographic studies and in separating noise from covarying factors (e.g., land use and pollutants) in field studies (Barber et al., 2010; Jerem & Mathews, 2021).

Reptiles

For terrestrial reptiles, studies investigating noise impacts are scarce, which should be considered as an evidence gap. Studies indicate that reptiles can respond behaviourally and physiologically to anthropogenic noise, but mostly for marine research. The knowledge is sparse compared with that of amphibians. In terrestrial reptiles, controlled exposure experiments show that acute industrial noise can alter behaviour and stress-related responses in lizards, indicating potential welfare and ecological consequences where noise is chronic or repeated (Mancera et al., 2017). However, most reptile studies still focus on short-term behavioural endpoints, and there remains a critical lack of threshold response relationships, population dynamics, and replication across different habitats (Jerem & Mathews, 2021).

4.1.3 - Combined impacts of light and noise pollution on amphibians and reptiles

Explicit tests of the interaction effects of LNP remain limited. The systematic review of combined noise and ALAN research shows that relatively few studies quantify statistical interactions, despite frequent spatial and temporal co-occurrence of these sensory stressors (Halfwerk & Jerem, 2021).

For amphibians, the strongest direct evidence of combined impacts comes from factorial field experiments showing that light and noise can interact to disrupt interspecific interactions, including host parasite dynamics at calling sites (McMahon et al., 2017). In addition, earlier work shows that ambient light and ambient noise can jointly shape calling site choice and predator avoidance behaviour in frogs, providing mechanistic plausibility for interaction effects, although this literature often involves natural background noise rather than anthropogenic sources (Tuttle & Ryan, 1982). The consolidated conclusion is that combined effects are plausible and empirically supported in amphibians but remain understudied. For reptiles, evidence of combined anthropogenic light and noise impacts is currently limited. Therefore, combined risk assessment for reptiles currently relies more on exposure assumptions and mechanistic plausibility than on demonstrated interaction.

In summary, for amphibians, the evidence base strongly supports significant relationships between noise exposure and communication-related endpoints, with additional evidence for stress physiology and distribution shifts near roads. For ALAN, direct evidence exists for impacts on reproduction and development, and indirect evidence supports altered foraging and interaction processes, but taxonomic and exposure regime coverage remain limited. For reptiles, the ALAN evidence base is strongest for sea turtles and is sufficiently mature to support impact assessment and mitigation design, while evidence for noise remains comparatively sparse and should be treated as an important uncertainty, particularly for terrestrial reptiles. Across both groups, there is a consistent gap in long term studies that connect exposure gradients to occupancy and population viability, and a clear lack of experiments that quantify combined effects.

4.2 - Birds

4.2.1 - Light pollution impacts on birds

With ~11,000 species (Lees et al., 2022; McTavish et al., 2025), birds (Class: Aves) are the most speciose group of land vertebrates. Birds have a global distribution, occurring on every continent and thriving in both urban and rural environments, where they frequently live alongside human populations. This close association has contributed to a long-standing human affinity for birds, rooted in ecological interdependence and aesthetic value (Butler, 2024; Delfino, 2024; Santangeli et al., 2023). They are also widely recognised as effective indicator species (Amat & Green, 2010; Lawler et al., 2003; Mattsson & Cooper, 2006) due to their well-documented sensitivity to environmental change (Fraixedas et al., 2020; Liang et al., 2020; Zhang & Ma, 2011).

In a study of the impacts of ALAN on western bluebirds, nestlings in 15 nestboxes were exposed to solar-powered lights (DINHAND, 54 LED, 400 lumen, blue-white spectra with 448nm peak wavelength), with nestlings in 11 without light serving as a control (Ozkan, 2024). Overall, ALAN did not affect the onset or cessation of adult daily activity, although nestlings had smaller wing chords and lower body mass, but conversely better overall body condition than nestlings in control nestboxes. In captive budgerigars (*Melopsittacus undulatus*), exposure to short-wavelength ALAN (200 lux, 400nm) from a high-efficiency fluorescent lamp increased body mass and suppressed melatonin (Itay & Haim, 2024). Conversely, it also suppressed melatonin (the primary circadian hormone that regulates sleep) and reduced egg and hatching success, with effects increasing with exposure time. Another study corroborated this, stating that exposure to ALAN makes birds highly susceptible to disturbances in behavioural rhythms and in physiological systems that depend on circadian and seasonal timing signals (Helm et al., 2024). Another review article highlights that ALAN alters bird brain functions and associated neuronal changes in songbirds and other bird groups, with studies on captive and wild birds showing negative impacts on daily timing, sleep and brain functions (Taufique, 2022). Additional studies provide further evidence of these impacts on great tits (*Parus major*), where ALAN advanced wake-up timing, indicating that exposure disrupts the circadian system (Dominoni et al., 2022). In free-ranging European blackbirds (Turdus merula), individuals in light-polluted areas perceived a longer subjective day than those in darker areas (Dominoni & Partecke, 2015), and they extend foraging activity during illuminated nights (Russ et al., 2015).

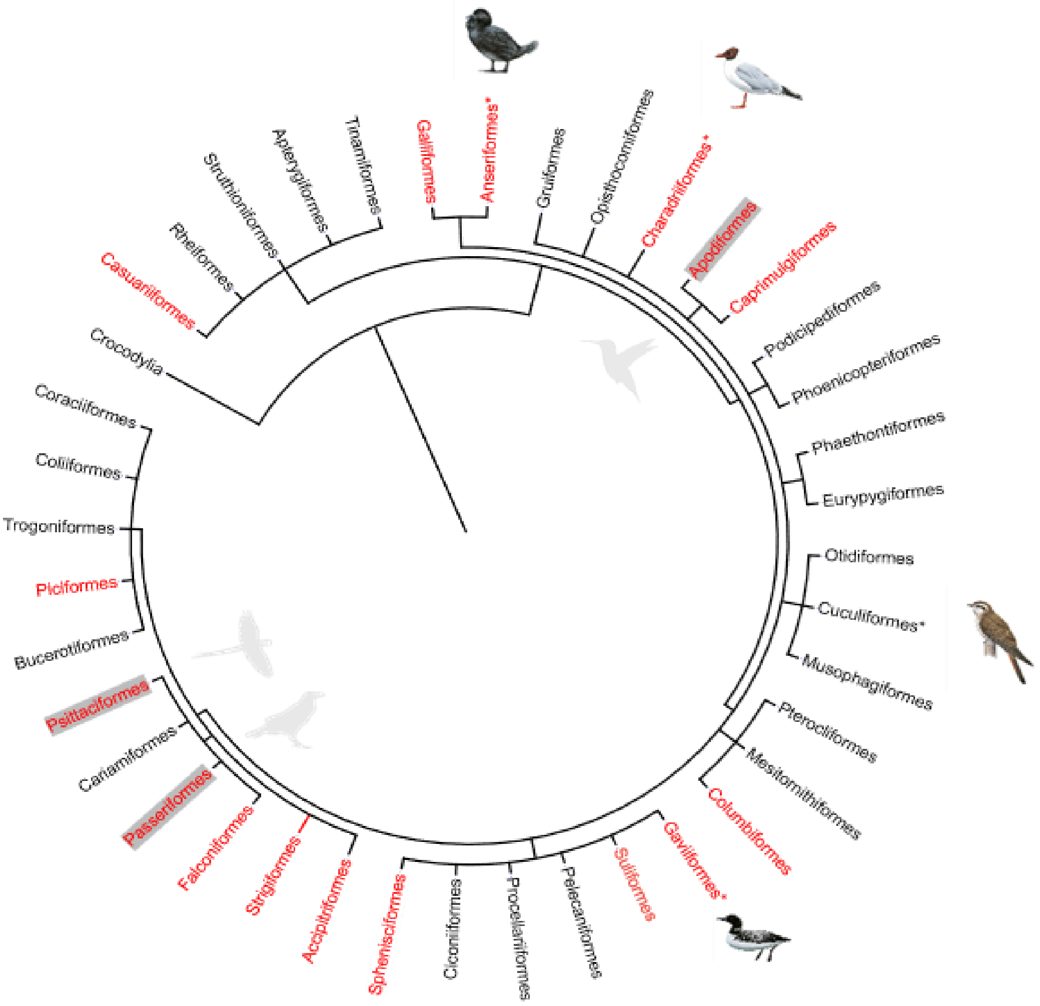
Across other groups, LP increased nocturnal vigilance in female Indian peafowl (*Pavo cristatus*), which resulted in less time sleeping (Yorzinski et al., 2015). In two crepuscular species: the common nighthawk (*Chordeiles minor*) and common poorwills (*Phalaenoptilus nuttallii*), there was an increase in relative abundance of extra-territorial common nighthawks in areas with more ALAN, but only in those areas with limited to no land cover. This association became negative in areas with 18% or more cover (Adams et al., 2024). There were also strong negative associations with ALAN across both species for the nest predation hypothesis that ground-nesting birds rely on camouflage to avoid predation, which is put at risk by illumination. There was limited support for foraging benefits, as Caprimulgiformes are insectivorous and can be attracted to ALAN due to the increased abundance of insect prey attracted to lights (Adams et al., 2024). A review of literature supports these impacts on altered species interactions (Seymoure et al., 2023).

This report highlights a range of negative impacts of ALAN on birds, particularly in regard to behaviour and physiological responses related to reproductive success and sleep quality, as well as some evidence for isolated potentially beneficial impacts. However, the taxonomic and phylogenetic breadth is limited, focusing mainly on songbirds. Future research should endeavour to fill gaps in the collective knowledge of ALAN across a wider range of avian groups.

4.2.2 - Noise impacts on birds

Growing evidence suggests that expanding urbanisation and the accompanying rise in anthropogenic noise are contributing to declines in avian biodiversity (Morelli et al., 2021; Morelli et al., 2023; Richardson et al., 2023; Yang et al., 2023). Anthropogenic noise can disrupt avian acoustic communication, alter predation rates, and influence how birds allocate time to behaviours such as parental care and foraging, ultimately affecting decision-making processes related to risk assessment (Lotinga et al., 2025a; Lotinga et al., 2025b). Because nearly all bird species rely on acoustic communication, and in oscines (songbirds, order *Passeriformes*), it serves as a primary channel for ecological and social interactions (Podos & Webster, 2022), such disturbances can have far-reaching effects. For example, black-capped chickadees (*Poecile atricapillus*) modify their alarm calls and reduce peak frequency in response to traffic noise (Courter et al., 2020), and similar frequency lowering has been documented in common chiffchaffs (*Phylloscopus collybita*) near airports (Wolfenden et al., 2019). This downward shift aligns with the acoustic adaptation hypothesis (Roca et al., 2016), although it contrasts with the more typical pattern of increased song frequencies recorded in many successful urban species (Slabbekoorn, 2013). In great tits (*Parus major*), however, one study found no frequency shift; instead, individuals increased call amplitude, a response known as the Lombard Effect (Templeton et al., 2016), emphasising that acoustic responses to anthropogenic noise are highly species-specific. Across these studies, birds also showed elevated aggression as well as heightened vigilance and altered predator perception (Klett-Mingo et al., 2016; Tilgar et al., 2022).

*Figure 3: Order-level bird phylogeny produced using the NCBI taxonomic database. Red marks orders with hearing data; grey shows widespread vocal learning; * indicates emerging evidence of vocal learning.*



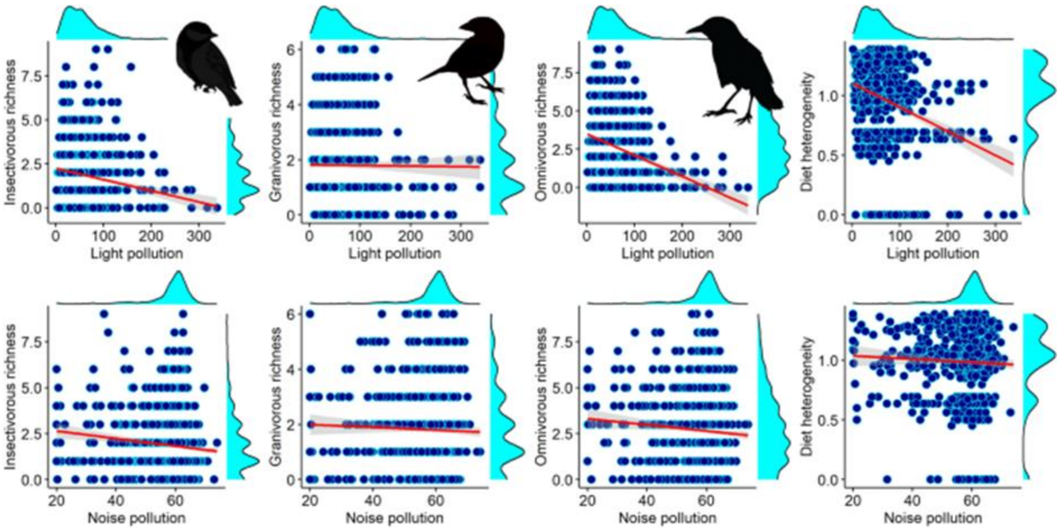
Not all bird species are capable of modulating their vocalisations (see *Figure 3*); this capacity is largely confined to vocal-learning lineages: songbirds (*Passeriformes*), parrots (*Psittaciformes*), and hummingbirds (*Apodiformes*), which possess the syringeal structures and neural motor control necessary for active call modulation (Riede & Olson, 2020; Ten Cate & Fullagar, 2021). In contrast, pigeons and doves exhibit a much more limited vocal flexibility, producing calls within a low frequency range of approximately ~0–1.5 kHz (Shieh et al., 2016).

There is even evidence for the impact of drone noise on birds, albeit limited. One study assessed the impact of drone noise on birds (Wilson et al., 2021) and found clear evidence of species-specific responses, particularly in calling rates and behaviour. The authors reported that detections of mangrove yellow warblers (*Setophaga petechia*) decreased in the presence of drones, whereas northern cardinals (*Cardinalis cardinalis*) increased their calling rate, especially alarm calls, when drones were overhead, which was interpreted as an agitated response to the drone noise. Drones are an already widespread and increasingly prevalent tool in ecological research, particularly ornithology (Vas et al., 2015), therefore, with emerging evidence of impacts on birds, future research should focus on the acoustic impacts of this novel source of noise disturbance on birds. In a review of the mechanistic pathways of anthropogenic noise impacts on birds, it was found that bird order was not a good predictor of bird hearing frequencies, but body dimensions were, particularly cranial height, which was the strongest predictor of peak hearing frequencies in birds (Engel et al., 2024a). The authors state that, in general, smaller birds have higher peak frequencies than larger birds, which was corroborated by an earlier study of body-mass and basilar papilla length and a review of bird audiograms, with owls being the outlier due to their unique ecology and specialized hearing capabilities (Gleich et al., 2005). In another review, anthropogenic noise was shown to negatively impact behavioural responses of birds that was mainly composed of negative and auditory perception and communication impacts. Anthropogenic noise, including traffic noise, was shown to negatively impact physiological outcomes (Engel et al., 2024b). This report highlights a range of behavioural and physiological impacts on birds and provides insights into species and physiology that could be key predictors of avian response to anthropogenic noise going forward.

4.2.3 - Combined impacts of light and noise pollution on birds

A pronounced phylogenetic signal underlies variation in avian tolerance to urban environments, and urbanisation consistently promotes biotic homogenisation. As a result, functional diversity—such as variation in dietary traits (see *Figure 4*), often declines, though the extent of these changes can vary depending on the metric used and the ecological context (Morelli et al., 2021; Morelli et al., 2023; Richardson et al., 2023; Yang et al., 2023).

Figure 4: Light (top) and noise (bottom) pollution across species diets and community dietary heterogeneity in fourteen European cities; margins show density distributions margins (Source: Morelli et al., 2023; http://creativecommons.org/licenses/by/4.0/).



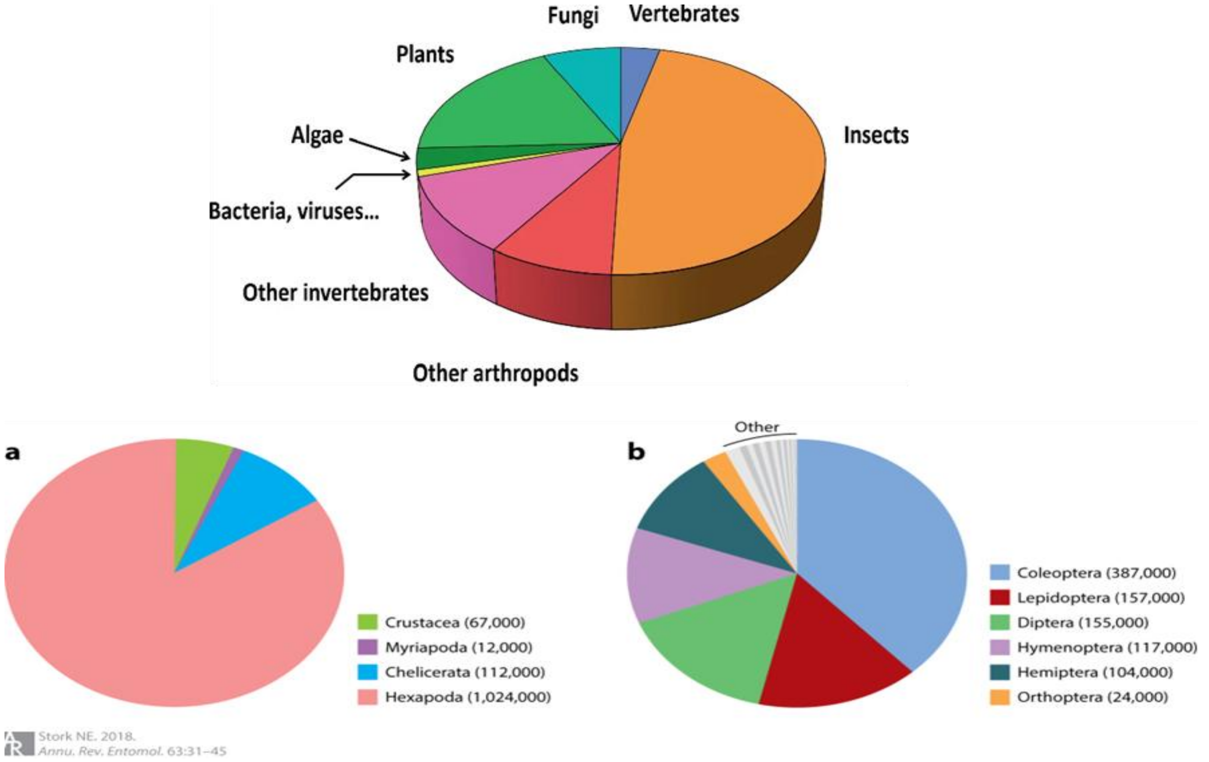
The synergistic impacts of these combined pollutants have been shown to affect both the physiology and behaviour of great tits (*Parus major*), a species that is widespread across European cities and among the most extensively studied urban birds, light and noise have a synergistic effect on nocturnal activity in great tits, but an antagonistic effect on diurnal activity yet the interactive effects of these increasingly prevalent pollutants are currently under appreciated (Dominoni et al., 2020). A review of the combined impacts of ALAN on organism groups found that 21 out of 28 studies addressed the combined impacts of anthropogenic noise and light pollution on birds (Halfwerk & Jerem, 2021), in particular the timing of the dawn chorus, but also on physiological and demographic traits, as well as stress, species richness and abundance, which has been highlighted in this report. Although there is some robust evidence for the synergistic impacts of these global and increasingly prevalent human sources of pollution on birds, more research needs to be done, with a particular focus on filling knowledge gaps across a wider range of species across avian phylogeny.

4.3 - Insects

4.3.1 - Light pollution impacts on insects

Insects constitute the largest class of all living terrestrial animals, comprised of ~1,000,000 described species (Hébert, 2023; Stork, 2018), with an estimated 80% of species that remain to be discovered (Stork, 2018); they account for 85% of the described arthropod species, 67% of animal species and ~50% of the total described eukaryotic species on the planet (Hébert, 2023; see *Figure 5*). they are the largest group within Arthropoda, with 5.5 million estimated terrestrial species (78.57% of the estimated 7.7 million arthropods), with 1.5 million of the mean estimates consisting of beetles alone (Order: Coleoptera), which account for about 40% (350,000–400,000 species) of all described arthropod species and ~25% of all described living animal species (∼1.5 million species), making them the most species rich order on Earth (Stork, 2018; Stork et al., 2015). The bulk of the rest of the class is formed of four other large orders of familiar insects (in descending order of species diversity): Lepidoptera (e.g. butterflies and moths), Diptera (e.g. flies and mosquitoes), Hymenoptera (e.g. ants, bees, wasps and sawflies), and Hemiptera (e.g. true bugs; cicadas, aphids, leafhoppers, bed bugs and assassin bugs), each consisting of >100,000 species and, together with the beetles, forming a total of at least 900,00 described species, which is ~90% of all living insects (Stork, 2018). The next largest: Orthoptera (e.g. grasshoppers, locusts and crickets), is comprised of >20,000 known species (Meena & Meena, 2021; Stork, 2018; see *Figure 5*).

Figure 5: Insect abundance compared to other organism groups (top) taken from Hébert, 2023. Lower panels: (a) arthropod subphyla and (b) insect classes taken from Stork, 2018 (Source: Hébert, 2023; Stork, 2018; http://creativecommons.org/licenses/by/4.0/).



Stork NE. 2018.
Annu. Rev. Entomol. 63:31–45

Many species of insects are nocturnal and rely on visual cues such as the position and illuminance of the moon to orientate themselves. A study in the United Kingdom looking at the distribution of diurnal/nocturnal aerial arthropods found that nocturnal aerial arthropods were most prevalent (Mungee et al., 2025). This is particularly true of the moths (i.e., a paraphyletic assemblage comprised of all non-Papilionoidea Lepidoptera; Mitter et al., 2017; Rota et al., 2022), which are predominantly nocturnal and rely on natural light and auditory cues for orientation and prey avoidance, having co-evolved as part of a notorious predator/prey "arms race" with one of their chief predators: the bats (Order: Chiroptera; Simon et al., 2023). Therefore, understanding the impacts of ALAN at both species and ecosystem levels is crucial for this group—the most taxonomically rich and biomass-dominant animals on Earth (see section: *Other invertebrates*).

As the human population increases, so too does global urban sprawl, resulting in increased ALAN, which spreads to the outskirts of cities and into peri-urban areas, eventually reaching protected areas(Gaston et al., 2015; Vaz et al., 2021b). ALAN can induce changes in traits that determine an organism's distribution, its ecological interactions and its abundance (Picchi et al., 2013). There is evidence of changes in the distribution and circadian habits of bioluminescent organisms because of ALAN (Cronin et al., 2000; Khattar et al., 2022; Owens et al., 2022; Viviani et al., 2010), as well as immature insects (Deacon et al., 2021).

Insects such as fireflies (Coleoptera) are particularly vulnerable to light pollution, with several studies highlighting the impacts of ALAN, as are moths, as they are often attracted to light due to a behaviour known as flight-to-light (Gaston et al., 2015; Owens et al., 2022; Vaz et al., 2021b). The presence of ALAN can impact the abundance (Picchi et al., 2013), range (Vaz et al., 2021a) and behaviour of fireflies, with light as low as 7 lux reducing the attractiveness of imitation female European glow-worms (*Lampyris noctiluca*)—a species where females continuously glow to attract mates—to males, with females not moving away from exposed light, but delaying or even refraining from glowing (Elgert et al., 2020). A review of literature on the impacts of ALAN on fireflies reports that <0.35 lux, and <0.025 lux can also reduce the approach of males to imitation females (Owens et al., 2022). It also reports that larvae of *Lamprigera sp*. Are less likely to forage under white LED of 3-4.5 lux streetlights and are more likely to move away or appear immobilized, and that less male courtship flash activity of *Photinus carolinus* occurs near ALAN of amber 150 lux LED lights in the field, and less courtship/foraging flash activity of *Photuris versicolor* under artificial lights in the field of 300 lux, another study reported accelerated weight gain of *Photuris sp.* larvae under chronic exposure of artificial light of 50 lux, among other effects. All the referenced firefly species are nocturnal, and these various studies highlight multiple effects of ALAN on their behaviour and physiology across various intensities and colour spectrums.

In the migratory moth *Helicoverpa armigera*, ALAN exposure in two forms: LED streetlighting (10-15 lux) and under high-pressure sodium lights (10-15 lux) effected peak activity, extending the perceived day length and preventing moths from starting their normal nocturnal behaviours (Meah et al., 2026). Skyglow causes decreased moth abundance, species richness and shifts species composition (Grenis et al., 2023), in another study using an experimental setup, male biased was reported for the flight-to-flight behaviour in two species: *Yponomeuta cagnagella* and *Ligdia adustata* (Altermatt et al., 2009), whereas one study reported a long-term reduction in this behaviour in reared *Y. cagnagella* moths from 10 different populations exposed to long-term urban LP, which the authors hypothesise may help moths to survive, but at the cost of reduced mobility (Altermatt & Ebert, 2016). These studies highlight different impacts across species and populations and at the ecosystem level.

In other taxa, interestingly, there is evidence for beneficial effects of ALAN, in the parasitoid wasp (Venturia canescens), exposure to control (0 lux), low (0.7 lux) and high (20) lux, LP increased nighttime activity, with increased foraging activity and egg laying at night, with a tendency for higher reproductive success under higher light intensity (Gomes et al., 2024). The authors note that ALAN also increased wasp lifespan, and modulated reproductive senescence, with offspring development influenced by LP and dependent on maternal age. A study exposing 19 caddisfly species across six families (Trichoptera) to light traps utilising LED, UV and mixed-white light sources found that a wavelength of 360-407 nm was most attractive to flies and corroborates cross-species evidence of this flight-to-light behaviour, and highlights this spectrum as a dangerous source of light pollution for caddisflies (Szanyi et al., 2022).

In the Australian black field cricket (*Teleogryllus commodus*), ALAN exposure of 10-100 lux influenced mate choice and mating efficiency in a sex-specific manner but did not affect the multivariate structure of male courtship calls (Botha et al., 2017). females engaged in less precopulatory mountings when provided with a stock male when reared under 10-100 lux, whereas males were mounted more often when reared under 100 lux before mating succeeded, indicating impacts on reproductive success. In the mantid species *Hierodula chinensis*, dim light (50) lux replicating dusk conditions found that successful predation rates were higher in both nymphs and adults when compared to simulated moonlight (0.1 lux) or complete darkness, suggesting that ALAN may affect the ecology of this typically diurnal predator (Kuang & Wang, 2024). Exposure to ALAN of 15-20 lux on barley (*Hordeum vulgare*) and the English grain aphid (*Sitobion avenae*) to study plant defence and plant-insect interactions recorded minimal impact on plant growth, but aphid colony growth and aphid maturation were reduced significantly (Heinen et al., 2023). These studies once again highlight both contrasting and corroborating effects of artificial light across phylogenetically diverse organisms at the species, population and ecosystem levels.

The results of these studies provide and support evidence that light pollution threatens insects globally (Lewis et al., 2020; Vaz et al., 2021a; Vaz et al., 2023), across multiple taxa and scales (Gaston et al., 2015; Manes et al., 2022). Habitat loss and the increase in ALAN associated with increased urbanisation have been linked to the worldwide decline in the diversity of insects (Merckx et al., 2023; Picchi et al., 2013). Therefore, it is imperative to understand the severity of impacts across species and to understand which taxa are particularly sensitive to ALAN so that focused conservation strategies can be developed. Studies capable of mapping and measuring risks to threatened species are pivotal for informing these strategies (Gaston et al., 2015). Identifying, reporting, and monitoring of these greatest threats could be crucial in halting losses caused by land-use change and maintaining higher ecosystem diversity, function and integrity (Vaz et al., 2023).

One study suggests that LED light may be a promising alternative to conventional streetlights as it was the least attractive lighting system across most groups of insects studied, which the authors suggest is likely due to the small amount of emitted short-wavelength light and lower light intensity (Martín et al., 2021), although LEDs had the strongest effects on moths when compared to high-pressure sodium lamps (Meah et al., 2026). Coleoptera and Lepidoptera were the most sensitive groups to light pollution in the study area, corroborating the wealth of evidence of ALAN impacts on moths and fireflies. These findings warrant further research into the potential of LED as an alternative system and highlight the need to focus on a more phylogenetically diverse range of insect taxa, to add to the breadth of evidence we have for these two orders.

4.3.2 - Noise impacts on insects

Anthropogenic noise appears to have a wide range of effects on insects, in the honey bee (*Apis mellifera*), individuals placed in an observational hive showed significant behavioural reactions to vibrational noise pollution produced by cargo train traffic (Chehaimi et al., 2025), with significant differences recorded in the worker population and pollen collecting foragers when exposed to substrate borne vibrational noise above their threshold sensitivity of up to 20m. Another study on the same species found that noise (and air) pollution resulted in reduced colony productivity, particularly brood development and pollen collection (Hussein et al., 205). Bursts of white noise (101 dB(A)) cause elevated movement speed and smaller foraging fragments in leafcutter ants (*Acromyrmex octospinosus*) (Byrne et al., 2022).

Among crickets and grasshoppers, field crickets (*Gryllus bimaculatus*) reduce chirps when exposed to traffic noise; however, long-term exposure seems to decrease sensitivity with a reduction of male chirp rate less in males closest to the road than in individuals further away (Gallego-Abenza et al., 2020). In the Pacific field cricket (*Teleogryllus oceanicus*), wild individuals exposed to traffic noise reduce reproductive investment. The spermatophore molds in crickets reared in masking noise were 29% lighter than in individuals reared in silence (Bowen et al., 2020). In the same species, crickets exposed to silence and simulated traffic noise of 50 dB(A), 60dB(A) and 70 dB(A); survival to adulthood was lower under noise treatments than silence, and the number of offspring hatched depended on the interaction between a female's exposure to traffic noise during the juvenile and adult life stages (Welsh et al., 2023). In *Oecanthus* tree crickets: *O. argentinus*, *O. celerinictus*, *O. forbesi*, *O. fultoni*, *O. quadripunctatus* and *O. texensis*, male individuals exposed to 116.4 dB, chosen due to it replicating the sound level crickets would experience 3m from a busy Ohio highway, were less likely to call in the presence of road noise (Costello & Symes, 2014). However, road noise did not impact the pulse rate, amplitude or frequency of calls, and it had no impact on females' response to male signal regardless of noise level, indicating that overall, tree crickets are still effective communicators in the presence of road noise. In wild individuals of the bladder grasshopper (*Bullacris unicolor*), individuals situated at a site close to road and railway traffic noise, peak frequency of male calls lowered, the interval between successive calls increased and the total number of calls detected by passive acoustic recorders decreased (Sathyan & Couldridge, 2020).

This research highlights a range of impacts of anthropogenic noise on a range of species, particularly in acoustic behaviour relating to reproduction, overall reproductive success, colony function and physiology, although predominantly among crickets. The main sources of anthropogenic noise exposure studies revolve around road and rail traffic, two increasingly prevalent and widespread sources of anthropogenic noise. As with other organism groups and even within insects, when comparing with light pollution, there is a bias for certain taxa, highlighting that broader studies need to be conducted that target impacts across phylogeny, particularly in such a speciose group. Previous studies of anthropogenic noise impacts have focused almost exclusively on vertebrates (Morley et al., 2014), and it is important that further studies focus on insects and other invertebrates to understand how anthropogenic noise impacts a group of organisms so widespread and essential to the health and function of ecosystems.

4.3.3 - Combined impacts of light and noise pollution on insects

Evidence for the synergistic impacts of light and noise is currently lacking; there is a wealth of evidence for the impacts of each in isolation, but limited studies exposing insects to both stimuli simultaneously. In a review investigating the combined ecological impact of ALAN and anthropogenic noise across organism groups, only 15 studies were identified as testing for possible interactive effects (Halfwerk & Jerem, 2021), and only one studied insects (McMahon et al., 2017), specifically the interactions between parasitic frog-biting midges (*Corethrella* spp.) and their host organism: the túngara frog (*Engystomops pustulosus*), which found that midges were sensitive to noise and light pollution. Exposure of 0.10-0.30 lux and 60-75 dB of simulated city noise and frog calls to test for attraction of the midges to frogs caused various effects, increased light significantly reduced abundance at low levels of noise, and at high noise intensity there was no midges regardless of light level, indicating a significant impact on the feeding ecology of this parasitic species and disruption of this interspecific host-parasite interaction (McMahon et al., 2017).

In later studies, it was found that traffic noise and ALAN each disrupted female field cricket (*Gryllus veletis*) development, mating behaviour, and reproductive output, delaying maturation, altering mating responses, and reducing fitness (Rebar et al., 2022). However, individuals reared under combined exposure did not result in decreased fitness relative to individuals reared under just one stimulus. Another study on the ground cricket (*Dianemobius fascipes nigrofasciatus*) investigating combined effects and comparing response of rural vs urban individuals found that both stimuli in isolation delayed development and prevented egg diapause (Ichikawa & Kuriwada, 2023), In rural individuals, noise and light alone did not significantly impact survival rates, however, the interaction of these stimuli did, thus their combined effect is detrimental, suggesting a synergistic effect (Hale et al., 2017). Whereas the survival rate of urban individuals was not significantly impacted by noise or ALAN, whether in isolation or synergistically.

Noise and light can have synergetic effects on the behaviour and physiology of insects, although the available literature is limited both in scope and taxonomic and phylogenetic breadth. Understanding the impacts of multiple stressors in synergy is essential, as they can have unexpected consequences at the species, population and ecosystem levels (Hale et al., 2017). Certain groups are common agricultural pests (e.g. Orthoptera), others are vital for ecosystem health and food security, particularly through pollination, although together, insects are considered vital indicators of ecosystem health and key ecosystem engineers that play a fundamental role in the food web, participating in multiple ecological processes such as pollination, nutrient recycling and pollination (Cornelissen et al., 2016; Johnson, 2024; Khalifa et al., 2021; Muinde & Katumo, 2024; Sanllorente et al., 2025; Sollai et al., 2024). With estimates suggesting that urbanization has resulted in a loss of insects in terms of a 42% decline in abundance, 40% in richness and 24% in trait effects when compared to conserved areas (Vaz et al., 2023), it is of paramount importance to conduct further research to understand the isolated and combined effects of these increasingly prevalent sources of anthropogenic pollution.

4.4 - Molluscs

4.4.1 - Light pollution impacts on molluscs

The available evidence for the impacts of ALAN on terrestrial molluscs is incredibly limited. A review of the knowledge base identified two papers (Moyse et al., 2023; Underwood et al., 2017) and two species of semi-terrestrial marine gastropods: the common flat periwinkle (*Littorina obtusata*) and the dog whelk (*Nucella lapillus*), respectively. Both studies exposed each species to experimental ALAN in the lab with LEDs and found that exposure to light can significantly impact predator-prey relationships, foraging and refuse-seeking behaviour.

In the study by Moyse et al. (2023), exposure of periwinkles (a polymorphic species occurring in a range of shell colours) and a common intertidal predator: the green shore crab (*Carcinus maenas*), to broad-spectrum and/or filtered ALAN altered predation rates and colour-based prey recognition. Exposure to broad-spectrum ALAN reduced overall predation rates by 55% compared to control conditions, with a 70% decrease for yellow snails. Under control conditions, yellow snails were 26% more likely to be attacked than brown snails. Under broad-spectrum ALAN, brown snails were 40% more likely to be attacked than yellow ones. Whereas filtered exposure removed significant colour-based differences in prey recognition.

The results of this study corroborate previous modelling work (McMahon et al., 2022) that found that broad-spectrum ALAN disproportionately increased the conspicuousness of yellow littorinid snails (*Littorina* spp.), which were consistently pushed above the detectability threshold (JND > 1) in comparison to brown and olive morphs which retain more effective camouflage against a fucoid algae background, implying risk is predator-independent mapped against three common intertidal predators with various visual spectrums: the herring gull (*Larus argentatus*), common blenny (*Lipophrys pholis*) and green shore crab (*Carcinus maenas*); tetrachromatic, trichromatic and dichromatic respectively. These results suggest a general ecological effect of light-exposure, decreasing the efficacy of camouflage at night, altering prey selection, which may drive changes in population demography and reduce polymorphism due to the advantages of morphological homogeneity in a genus of snails that rely on colour-polymorphism for survival (McMahon et al., 2022; Moyse et al., 2023).

In dog whelks, Underwood et al. (2017) divided individuals into two consorts, one was previously acclimated to artificial ALAN (22.3 ± 3.2) for 16 days, the other consort was not previously acclimated, while control individuals were never exposed to ALAN and only experienced natural dark nights under a standard 12:12 light-dark regime, with only intermittent exposure to dim red LED light (< 10 lx) during behavioural imaging. Behavioural responses were measured during assays conducted under white LED illumination (21.16 ± 3.05 lx), which included the presence and absence of olfactory cues from green shore crabs (*C. maenas*). ALAN reduced refuge-seeking at the waterline and increased foraging responses and prey handling. Risk evaluation was altered in non-acclimated individuals; the presence of light increased reliance on visual information rather than olfactory cues, indicating an opportunistic shift in sensory weighting toward vision as they may perceive it as more reliable than olfactory cues during risk-evaluation (Underwood et al., 2017).

The authors note that the red-light control is largely outside of the field of visual sensitivity of dogwhelks, aquatic gastropod eyes usually only possess a single visual pigment with a peak spectral sensitivity of 470-505 nm (Gillary, 1974; Hughes, 1970; Zhukov et al., 2006), outside of the spectral range of red light (620-750nm; Biological Insights, 2025). Although they state that if the red light had any residual effect on behaviour, this influence would have reduced the contrast between control and white-LED treatments, making their estimates of artificial light at night effects conservative and implying that real-world impacts may be stronger when comparing true darkness or moonlight with ALAN.

Another study found that the effects of LEDs of different wavelengths in a subtidal, fully aquatic abalone (cultivated in aquaculture as a food source) gastropod mollusc (*Haliotis discus*) varied (Xiaolong et al., 2016). The species exhibited a significant photophobic nature, under blue or green light survival, growth rates, and food conversion efficacy were lower when compared to groups exposed to red or orange lights; they lost more energy via excretion, faeces and respiration than they acquired from food (Falcon et al., 2020; Xiaolong et al., 2016). Under red and orange lights, *H. discus* acquired more energy from food and lost less energy via excretion and faeces, resulting in increased efficacy of food absorption and energy usage (Falcon et al., 2020). This provides species-specific evidence of strong colour-dependent effects on molluscs, albeit for one species, and is consistent with Underwood et al. (2017)'s suggestion that red light may be less disruptive for some molluscs and may even be beneficial.

A further literary search shows that ALAN attracts terrestrial slugs (family: Arionidae), over a 4 year period across a large field site with 24 streetlights (of an intensity of 119.4 and 119.6 lux 1.5 metres below the lamps; high-pressure sodium lamps and LEDs respectively) and one dark control site, the number of slugs increased strongly in the illuminated area but not in the dark site (van Grunsven et al., 2018), which the authors hypothesise could be due to reduced predation and increased food quality due to the abundance of insect carrion as a result of their attraction to the light. Slugs are an important component of ecosystems, as well as being a prevalent pest species, so the increase of their abundance under ALAN could have ecosystem and economic consequences. Conversely, another study found that ALAN can negatively impact the slug species *Deroceras reticulatum* and *Arion lusitanicus* when exposed to a 30-lux light bulb in the lab and a LED streetlamp (6800 lm), ALAN reduced survival rate of captive slugs and altered juvenile growth development, and fewer wild slugs fed at sites with ALAN than at unlit control sites (Grognuz et al., 2025). Plants at illuminated sites also showed less herbivory damage than at control sites. The authors note (corroborating the findings of this report) that the effects of artificial light at night (ALAN) on terrestrial gastropods are largely unexplored; however, the available evidence suggests substantial and sometimes contrasting impacts on slugs, with likely consequences for ecosystem functioning.

4.4.2 - Noise impacts on molluscs

No papers flagged for review were included in the knowledge base for noise impacts on molluscs. This is due to all the flagged papers either referring to completely aquatic species and/or life stages of organisms, e.g. the benthic larvae of the common blue mussel *Mytilus edulis* (Tidau et al., 2023) or involved sub-surface anthropogenic noise exposure.

In a meta-analysis of 108 experimental studies, including six studies involving five mollusc species (Pacific oyster, *Magallana gigas*; New Zealand scallop, *Pecten novaezelandiae*; common cuttlefish, *Sepia officinalis*; Chinese razor clam, *Sinovacula constricta* and striated sea hare, *Stylocheilus striatus*), Kunc and Schmidt (2019) found that molluscs exhibit a statistically significant and moderate-to-strong response to anthropogenic noise (SMDH = 0.84, 95% CI = 0.38–1.30), comparable to responses observed in other taxonomic groups. Species-level heterogeneity was modest (I^2_species = 12.07%), indicating broadly consistent responses among the studied species; however, the available data are insufficient to determine whether noise sensitivity exhibits a phylogenetic signal within Mollusca. Only 12.07% of the variation in mollusc responses is attributable to interspecific differences.

All five species included in the meta-analysis are essentially fully aquatic, with only brief exposure in the inter-tidal zone; they are functionally aquatic and cannot tolerate extended periods out of water. Another meta-analysis reported that amongst invertebrates, molluscs (and arthropods) exhibited the most pronounced physiological responses to anthropogenic and simulated (synthetic) noise (Davies et al., 2024). Both syntheses focused on aquatic marine and freshwater species and on underwater acoustics, highlighting a gap for semi-terrestrial and terrestrial taxa and the impacts of airborne anthropogenic noise.

4.4.3 - Combined impacts of light and noise pollution on molluscs

Despite the global expansion of the co-occurrence of artificial light and anthropogenic noise in urban environments and beyond (Dincel et al., 2025; Duarte et al., 2021; Falchi & Bara, 2023; Gaston et al., 2015; Kunc & Schmidt, 2019), empirical evidence examining their combined effects on terrestrial and semi-terrestrial molluscs remains extremely limited. Particularly regarding noise impacts on non-marine fully aquatic species of molluscs. This is likely due to a focus on underwater anthropogenic noise and light impacts, which have implications for fisheries, productivity and food security (Birch et al., 2025; Ferretti et al., 2024; Kunc & Schmidt, 2019; Ledoux et al., 2023; Solé, Kaifu, et al., 2023).

Although noise and artificial light have each been shown to affect invertebrates, no known studies to date have experimentally examined their combined effects in terrestrial/semi-terrestrial molluscs. This represents a clear gap in understanding cumulative sensory pollution impacts. Most studies investigate the impact of noise and light in isolation, and there is a major knowledge gap in the research of multi-stressor impacts in invertebrates (Halfwerk & Jerem, 2021; Solé, Kaifu, et al., 2023).

To summarise, although there is evidence for the effects of anthropogenic noise and, in particular, ALAN, on molluscs, this evidence base remains extremely limited, especially regarding terrestrial taxa. The available studies indicate strong species-specific responses, but the overall volume of research, and its taxonomic and phylogenetic diversity, is small. Currently, there is no robust synthesis addressing the co-occurrence of these stressors, and therefore, no clear understanding of whether noise and ALAN have additive, antagonistic, or synergistic effects on this ecologically and taxonomically diverse group.

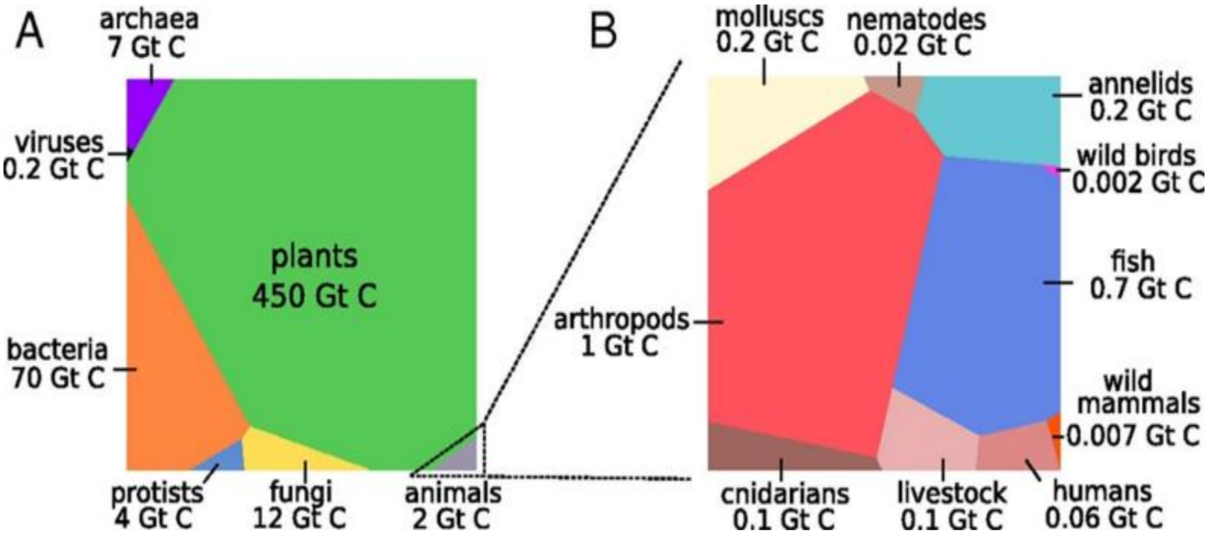
What we do know comes mainly from short-term experimental studies showing that both stressors can alter interspecific behaviours, especially predator–prey interactions and time allocation to foraging and predator avoidance, changes with potential consequences for trophic dynamics at the ecosystem level. Physiological effects are also evident, including increased metabolic stress and reduced growth. Exposure to ALAN can additionally disrupt circadian regulation and orientation mechanisms. Overall, the emerging picture suggests meaningful impacts, but the current evidence base is too sparse to generalise across molluscs and crustaceans.

4.5 - Other invertebrates

4.5.1 - Light pollution impacts on other invertebrates

Invertebrates are an incredibly diverse paraphyletic group defined by the absence of a vertebral column; the term simply includes all animals not placed within the subphylum Vertebrata (i.e. animals that possess a vertebral column and a cranium). As an informal taxonomic grouping, they constitute the largest group within the biodiversity of extant animal species. The group includes well-known predominantly terrestrial phyla such as the arthropods (e.g. insects, arachnids and crabs), which constitute the most speciose phylum of animals (an estimated ~7 million terrestrial species and over 80% of all known living species; Hébert, 2023; Sollai et al., 2024; Stork, 2018) and account for the largest proportion of global terrestrial animal biomass (Bar-On et al., 2018; see *Figure 6*), as well as the various worm phyla (Annelida, Nematoda, Platyhelminthes and Onychophora). It also encompasses several predominantly aquatic phyla, including Cnidaria (e.g. jellyfish and sea anemones), Echinodermata (e.g. starfish and brittle stars), and Porifera (sponges).

Figure 6: Global biomass distribution by taxa. (A) Biomass across kingdoms. (B) Biomass across animal taxa (Source: Bar-On et al., 2018; Deed - Attribution-NonCommercial-NoDerivatives 4.0 International - Creative Commons).



Although no global estimate exists for the proportion of terrestrial arthropods that are nocturnal, many major groups, such as woodlice, millipedes, centipedes, numerous spiders, and many insect taxa, are predominantly or facultatively nocturnal (Cloudsley-Thompson, 1933; Meah et al., 2026;

Mungee et al., 2025). This pattern is particularly attributed to arachnids (e.g. spiders, scorpions; Subphylum: Chelicerata), of which many species are cave dwellers, which is linked to desiccation prevention and a preference for cooler periods of the day. As such, many species have poor eyesight or lack eyes completely (e.g. *Stalita taenaria*; Mammola & Isaia, 2017) as a result of their cryptozoic (hidden), troglobitic (cave-dwelling) ecology. A subterranean lifestyle is also a characteristic trait of terrestrial species within the annelid, nematode and onychophoran phyla, particularly their soil-dwelling representatives (Baker et al., 2021; Cai et al., 2025; Chen et al., 2025). Both annelid and onychophoran worms are predominantly active under low-light conditions, with onychophorans being nocturnal and photonegative (Baker et al., 2021; Beckmann et al., 2015; Cai et al., 2025). Given the photophobic nature of many terrestrial invertebrates and their nocturnal and/or subterranean ecology, it is imperative that we understand how ALAN can impact this diverse group.

Spiders (Class: Arachnida) serve as a model organism group for studying the impacts of ALAN on invertebrates, as they are found globally across a range of habitats, and there is an extensive body of literature studying the impacts of ALAN on this group. Similar to the flight-to-light behaviour in flying insects (see section: Insects), two experiments showed that artificial light can attract arachnids, known as positive phototaxis (Graham et al., 2019). In a neotropical forest in French Guiana Light significantly increased the capture rate of all arachnids, particularly spiders of the order *Araneae*, when using lit pitfall taps compared to unlit traps (Lalagüe & Pétillon, 2023), a result corroborated by capture rates of camel spiders (order: Solifugae) in lit traps in the Mojave Desert (Graham et al., 2019). In central place (i.e. leaves its nest/burrow to forage for food, then returns – the central place) foraging spiders (*Drassodes* sp.), exposure to ALAN from both LED streetlights (10–15 lux) and high-pressure sodium (HPS) lamps (10–15 lux) suppressed peak nocturnal activity. This lighting effectively extended the perceived day length of spiders, preventing them from initiating their normal nighttime behaviours (Meah et al., 2026). LED lighting caused the strongest suppression, aligning with evidence that arthropods often display greater sensitivity to shorter wavelengths (Longcore, 2023), which the authors note likely resulted in the higher perceived brightness of spiders due to greater photoreceptor stimulation of LEDs than that of high-pressure sodium illumination (Meah et al., 2026).

ALAN can also impact wolf spiders (family: Lycosidae), a family comprised primarily of nocturnal hunters. In a study investigating the impacts of artificial light on the foraging and interactions of *Schizocosa myccooki* with red runner cockroach prey (*Blatta lateralis*), spiders were exposed to light conditions of 0, 0.01, 1 and 1000 lux. Spiders exhibited a stunted delay in first movements towards prey but increased detection distance (Amoroso, 2024). It can also impact wolf spiders' courtship displays. In another study of spiders of the genus *Schizocosa*, spiders were subjected to three light treatments described as bright, dim and dark. Responses were species-specific, and light impacted courtship and mating, as well as circadian activity patterns (McGinley et al., 2023). The authors note that their results suggest femur pigmentation evolved for diurnal signalling, whereas tibial brushes function to increase signal efficacy under dim light, which they state illustrates that acute changes in light intensity have potentially strong effects on sexual selection dynamics.

In orb-weaver spiders, exposure to short-term ALAN shrank the brains of the Australian orb-weaving spiders (*Hortophora biapicata*), with results showing a reduction in the volume of the brain structures in the primary eye visual pathway (Willmott et al., 2024), which the authors suggest is a potential consequence of plastic shifts in neural investment or oxidative stress. A study of the consequences of chronic night-time exposure to ecologically relevant levels of LED lighting on life history traits (specifically ontogeny; i.e. development of an organism from birth-adult, and mortality) of the nocturnal spider species: the Australian garden orb-web spider (*Eriophora biapicata*), results indicate that exposure to dim ALAN (~20 lux) accelerated juvenile growth and mortality and adult reproductive success and survival (Willmott et al., 2018). Spiders exhibited accelrated juvenile development, progressing through fewer moults and thus maturing earlier at a smaller size, there was also a significant increase in the daily mortality of juvenile spiders reared under 20 lux, although early maturation resulted in a comparable number of 0 lux and 20 lux reared spiders reaching maturity, females also produced significantly less eggs due to ALAN exposure (Willmott et al., 2018). A study by the same author on the same species found that exposure to juvenile spiders in the lab to cool white LED strip lighting set at daytime lighting of 2,000 lux and nighttime of 20 lux found that spiders were attracted to LEDs when choosing where to build their webs for foraging (Willmott et al., 2019). In the field, prey-capture rates were significantly higher for webs placed near LED lights, suggesting that the physiological costs of ALAN are offset by the abundance of prey, which the authors note is likely a partial explanation for the increased size, fecundity and abundance of orb-web spider species in urban areas, their results highlight the potential long-term consequences of ALAN in urban areas through the alteration of predator-prey dynamics of orb-weaver spiders predation on insect populations (Willmott et al., 2019).

In another study ALAN from USB mini LED bulbs of 450-600 nm (similar to the emission spectrum of Hong Kong street lamps; i.e. high-pressure sodium lamps) reduced the prey interception rates of *Nephila pilipes* orb weavers on moths, lowered interception efficiency and altered prey flight and visibility of webs (Yuen & Bonebrake, 2017), diminishing the functional value of spider visual lures and resulting in an overall reduction of prey captured and therefore potentially reducing fitness for spiders living in light polluted environments. The author hypothesised that chaotic and undirected flight towards light (the flight-to-light behaviour described in the section: Insects) may reduce the effectiveness of lit webs for prey capture.

In anecic (i.e. make vertical burrows and feed on organic matter from the surface) earthworms (*Lumbricus terrestris*) exposed to either 0 or 5 lux at night via greenhouse ceiling lights (fluorescent tubes, 36 W, 4000K), worms exposed to light showed a reduction in surface activity of 76%, as measured by casting activity and toothpick index, 85% of mating earthworms were observed in the absence of light, indicating that light pollution negatively effects earthworms due to reduced surface activity as it limits foraging and mating opportunities (Mittmannsgruber et al., 2024). A slightly later study on the same species found that ALAN (5 lux) reduced the removal of surface litter by 51% in earthworms when compared with those under dark conditions (Kavassilas et al., 2024), corroborating the suggestion that ALAN exposure could lead to less-well-fed earthworms and smaller populations due to limited mating opportunities. A later study corroborated these findings, across 7 ALAN light treatments (i.e. 0.1, 1, 10, 20, 50, 100 lx and a dark control) simulating levels that occur in the real world, found that *L. terrestris* earthworms significantly decreased their overall nighttime foraging in the presence of ALAN when compared to darkness (Cai et al., 2025a), a finding corroborated in the field, where 10 lux resulted in more risk exploration before surfacing and greatly reduced foraging activity, although this altered behaviour did not have a clear impact on the patterns of litter removal or soil respiration (Cai et al., 2025a). The authors report that their results confirm that 10 lux (or potentially even lower) is effective in disrupting L. terrestris nocturnal surfacing behaviour, but this may have short-term effects on carbon cycling.

Another study found that ALAN from long-established LED streetlights altered earthworm communities and soil structure in a nine-year field setting (Cai et al., 2025b). Ground-level illuminance ranged from 2.25–16.70 lux at brightly lit sites (mean 6.85 lux) and 0.13–3.71 lux at dimmer sites (mean 0.91 lux), with spectral differences (CCT ~5393 K vs ~5016 K). Bluer light (higher CCT) consistently reduced total earthworm abundance and biomass, while higher illuminance increased biomass, though this positive effect weakened under blue-rich spectra. The authors note that responses varied across ecological groups and age classes and were moderated by plant cover. These ALAN-driven community shifts partially propagated to soil function: via juvenile endogeic (i.e. shallow burrowing) earthworms, ALAN increased large macro-aggregates but reduced small macro-aggregates and micro-aggregates, demonstrating that night-time street lighting can restructure both earthworm assemblages and earthworm-mediated soil aggregation (Cai et al., 2025b).

Several studies investigate the impact of LP on crabs. As with the case of *Carcinus maenas* predation on *Littorina* snails (see section: Molluscs), ALAN has been shown to impact the predation rates of tufted ghost crabs (*Ocypode cursor*) on loggerhead sea turtle (*Caretta caretta*). In a study exposing turtles and crabs on a natural nesting beach over the course of 36 days, Silva et al. (2017) deployed high-pressure sodium vapour lamps of three colours: yellow, orange and red. They found that illumination increased the abundance of crabs, although only yellow light had a significant effect on aggression and prey-searching behaviours.

In total, 1146 nesting observation attempts were observed, with 96 individuals identified and Passive Integrated Transponder (PIT)-tagged for behavioural assays. They recorded a 20% reduction in nesting attempts, particularly in the centre of the observation sector, which received more light. Lighting also increased the time turtles spent on the nesting process and caused the turtles to perform more extensive beach crawls, although lighting had no perceived effect on the location of the final nesting site. Yellow and orange lights disrupted sea finding behaviour, and the authors noted that the turtles were often unable to orient themselves towards the sea under these colour lights; turtles spent several minutes crawling in circuitous paths (Silva et al., 2017). Red light had no observed significant effect on either species.

In a study of the impact of ALAN on Bernhard's hermit crabs (*Pagurus bernhardus*), male hermit crabs were collected and exposed to fluorescent white laboratory lighting (Velasque et al., 2023). The authors state that only male crabs were chosen to account for females potentially changing their shell preferences unpredictably during the breeding season. Crabs were split into two cohorts; constant light and a standard 12:12 light-dark regime. Crabs under constant light were consistently less bold than the control group, although there was no significant effect of light on individual consistency in behaviour. Crabs under constant light also exhibited a higher haemocyanin concentration, which Velasque et al. (2023) interpret as an increased oxygen demand due to an increased metabolic rate. Haemocyanin is analogous in function to haemoglobin in vertebrates (Manriquez et al., 2019).

This report highlights a multitude of impacts of LP on invertebrates, ranging from behaviour (particularly reproductive success, foraging efficiency and inter-specific interactions, especially predator-prey relationships) and physiological impacts. However, the breadth of available research is limited in taxonomic and phylogenetic scope, with a clear focus on spiders, earthworms and crabs, understandable considering the key role arachnids and earthworms play in ecosystem function, although more research needs to be conducted that focuses on exploring the impacts across a range of invertebrates that are currently unexplored.

4.5.2 - Noise impacts on other invertebrates

Many invertebrates, especially insects, rely on acoustic communication for mate attraction and predator perception through both airborne sounds and substrate-borne vibrations. Loud, continuous low-frequency noise from gas compressors dramatically reduces many sound- or vibration-sensitive insects and spiders, while increasing others less affected by noise or released from predators. This reshapes the entire arthropod community and may disrupt whole ecosystems (Bunkley et al., 2017; van Hoose, 2017). Compressor sites had 52% fewer froghoppers (Family: Cercopidae), 24% fewer grasshoppers (Family: Acrididae) and 95% fewer cave, camel and spider crickets (Family: Rhaphidophoridae) when compared to sites without compressors. For every 10-dB increase in noise, there was a reduction of velvet ant (Family: Mutillidae) populations by 56% and wolf spiders (Family: Lycosidae) by 44% and 53% for the genus *Pardosa*. Conversely, leafhopper (Family: Cicadellidae) numbers surged in response to noise, with a 44% increase in abundance for each 10-dB increase in noise. The author suggests that wolf spiders are likely to be negatively affected due to vibrations being one of their methods of prey detection, whereas noise could mask the sounds and movements of grasshoppers from their predators, such as birds and bats, whose activity patterns and distribution are altered by compressor noise pollution (Bunkley et al., 2017; van Hoose, 2017). A study of the impact of substrate-borne noise (via aeroplanes) found that *Schizocosa* wolf spider species increased their dominant frequency of courtship signals in noisier environments (Choi et al., 2024).

Another study shows that vibrational noise from wind turbines negatively impacts earthworm abundance. In Dutch crop fields, wind turbines produced low-frequency (<500 Hz) soil vibrations that declined with distance, on average by 23 ± 7 dB between 2 m and 256 m (site-specific attenuation 16–29 dB). Earthworms were sampled at 8, 32, 64, and 128 m; within that band, the maximum amplitude difference was ~13 dB (Velilla et al., 2021). When comparing nearest-furthest sampling points in proximity to the wind energy turbines, abundance dropped on average by 40% across all 7 different turbines across 7 different agricultural fields. In the funnel-weaving spider (*Agelenopsis pennsylvanica*), one study shows that environmental vibratory noise can impair information reception in web-building spiders (Pessman & Hebets, 2025). Under loud noise, urban spiders spun webs that dampen a broad range of near-distance vibrations (300–1,000 Hz), a likely defence against sensory overload, but one that could reduce detection of nearby prey or mates. Rural spiders exposed to loud noise tuned their webs to retain energy only in a narrow band (350–600 Hz), which may miss relevant cues outside that range. Overall, the study highlights that noise masks key signals and forces spiders to trade off sensitivity for filtering, indicating potential negative effects on foraging and reproduction despite their flexible, noise-responsive web designs (Pessman & Hebets, 2025).

In a study exposing red hermit crabs (*Dardanus calidus*) to anthropogenic noise in the lab, impacts on righting reflex and damage to the statocyst of crabs, as well as damage to the sensory epithelia of the tentacles of parasitic anemones (*Calliactis parasitica*) were evaluated (Solé, De Vreese, et al., 2023). Sound was calibrated to mimic a sinusoidal sweep (50–400 Hz) that occupies a frequency band commonly associated with shipping and offshore construction noise. Crabs were exposed to levels ranging from 157 ± 5 dB re 1 μPa^2 to 175 dB re 1 μPa^2. Acoustic exposure increased behavioural variability in red hermit crabs, with the variance in righting times widening over time and peaking 120 h post-exposure, driven by a subset of individuals exhibiting markedly delayed righting responses. SEM analyses revealed ultrastructural lesions in both the statocysts of hermit crabs and the tentacles of their parasitic anemones. Although these lesions were not strongly predictive of righting performance, the primary behavioural effect was an increased range of responses. Solé, De Vreese et al. (2023) highlight that acoustic-induced ultrastructural damage occurring simultaneously in symbiotic partners from different phyla is novel and suggest that such changes may reduce survival capacity and have broader interspecific consequences for semi-aquatic and aquatic invertebrate systems.

Although there is evidence for the impact of anthropogenic noise on invertebrates, it is limited in its taxonomic and phylogenetic breadth. A previous review stated that little research has focused on invertebrates and the acoustic channels they depend on, particularly near-field airborne cues and substrate-borne vibrations (Raboin & Elias, 2019). An earlier study states that while anthropogenic noise is widely recognised as harmful to wildlife, its impacts on invertebrates, which make up 97% of all animal species, have been vastly understudied, with only 4% of noise-impact research including them as of 2016 (Raboin, 2021). The author highlights that most invertebrates rely not on airborne pressure waves like vertebrates, but on particle motion and substrate-borne vibrations, sensory channels that humans cannot perceive but which underpin invertebrate survival, including mate attraction, predator avoidance, foraging, navigation, and social communication. Because human noise is dominated by low-frequency (<2,000 Hz) energy, it overlaps directly with the frequencies used by most terrestrial and marine invertebrates, making them highly vulnerable. Another publication also highlights the limit of anthropogenic noise impact studies on non-insect invertebrates (Mooney et al., 2025).

This report highlights a range of impacts of anthropogenic noise on a range of species, but predominantly crabs and earthworms, with some significant evidence reported for spiders, particularly in acoustic behaviour relating to reproduction, overall reproductive success, and physiology. Previous studies of anthropogenic noise impacts have focused almost exclusively on vertebrates (Morley et al., 2014), and it is important that further studies focus on insects and other invertebrates to understand how anthropogenic noise impacts a group of organisms so widespread and essential to the health and function of ecosystems. Physiological effects are also evident, including increased metabolic stress, reduced growth, and in some cases, physical tissue damage (e.g. sensory epithelia or statocyst lesions).

4.5.3 - Combined impacts of light and noise pollution on other invertebrates

In a study looking at shipping noise impacts on a terrestrial species of hermit crab: the Caribbean hermit crab (*Coenobita clypeatus*), wild individuals in the field were exposed to boat motor recordings of 98.1 + 2.6 (s.d.) dB (measured 1m from the speaker), to test for its impact on the crab's predator-risk assessment (Chan et al., 2010). The results show that approaching observers could get significantly closer under ship noise before they reacted than under silence. They were also able to get closer before the crabs hid (hiding initiation distance). These effects were exacerbated when flashing lights were added to the ship noise exposures, indicating anthropogenic noise and light can distract crabs and make them more vulnerable to predation. Other than this study, which was the only non-insect invertebrate study reported in a recent review of the available research on the synergetic ecological impacts of anthropogenic noise and ALAN on wildlife (Halfwerk & Jerem, 2021), no other research appears to explore the combined effects of these stressors on non-insect invertebrates, including molluscs (see section: Molluscs). Future research should focus on addressing these stressors on such a wide, diverse group of species, key to ecosystem health. Understanding the impacts of multiple stressors in synergy is essential, as they can have unexpected consequences at the species, population and ecosystem levels (Hale et al., 2017).

4.6 - Mammals

4.6.1 - Light pollution impacts on mammals

Mammals, including monotremes and marsupials, are the youngest class of vertebrates with special ecomorphological and physiological characteristics that are often accompanied by highly adaptable behaviour. Of all 5,488 mammal species, more than half (63.8%) are nocturnal (Hölker et al., 2010a). These include all 1,100 species (100%) of bats and 80% of all marsupials (Beier, 2006). Even among primates, a taxonomic order in which binocular vision is very important for orientation, almost one-third (31%) of the 432 species have a highly nocturnal lifestyle (Hölker et al., 2010a). Some species are also specialised to live in darkness underwater, underground in the soil, and in natural caves without any lighting.

However, the role and importance of light for mammals is not only related to their eyes, the sensors for optical perception of their environment, and orientation. It is also related to their physiology, in particular to a special organ found in vertebrates, the pineal gland (*Epiphysis Cerebri*), which has evolved from a light-sensitive organ in fish to a neuroendocrine organ in mammals (Ekström & Meissl, 2003; Zheng et al., 2024). While it is light-sensitive in fish and amphibians, in mammals it is indirectly influenced by photoperiodic information that passes through the retina of the eyes and triggers the release of the hormone melatonin, which synchronises the endogenous rhythm and protects against oxidative damage (Mano & Fukada, 2007; Falcón et al., 2009)

Types of effects

ALAN, therefore, has varying effects on the physiology, behaviour and ecology of mammal species and their role in ecosystems. It can (i) cause inflammations and destructive damage in the eye's tissues (Noell, 1980; Remé et al., 1996; Contín et al., 2016; Krigel et al., 2016), (ii) influence axial eye growth (Xu et al., 2023), (iii) disrupt the synchronisation of circadian rhythms (Grubisic et al., 2019), (iv) reduce the effectiveness of molecular repair processes (Anisimov, 2006; Ouyang et al., 2018), (v) change metabolism, immune function, endocrine balance (Nelson et al., 1995; Nelson & Drazen, 2000; Mustonen et al., 2002; Navara & Nelson, 2007; Ouyang et al., 2018; Grubisic et al., 2019), (vi) increase stress levels (Zubidat et al., 2007), (vii) alter individual behaviour (Ryddell, 1991; Daly et al., 1992; Beier, 1995; Bird et al., 2004; Kuijper et al., 2008; Stone et al., 2009; Sordello et al., 2025) and daily rhythms (Grubisic et al., 2019; Kramer & Birney, 2001; Rotics et al., 2011), (viii) reduce or increase hunting efficiency (Straka et al., 2019; Arlettaz et al., 2000), (ix) affect demographical parameters (Beier, 2006; Gaston & Bennie, 2014; Robert et al., 2015), (x) influence the risk of becoming prey (Morrison, 1978; Daly et al., 1992; Kramer & Birney, 2001), (xi) reduce habitat suitability (Beier, 1995), (xii) impede access to resources (Bird et al., 2004; Rotics et al., 2011; Straka et al., 2019), (xiii) affects photoperiod driven seasonality (Liu et al., 2022), (xiv) alter the composition of ecological networks (Sanders et al., 2023), and (xv) impacts the provision of ecosystem services (Lewanzik et al., 2014).

Physiology and health

Most of the conclusions related to tissue damage caused by high-intensity light or energy-intense blue light near the UV part of the spectrum, especially from LEDs, were drawn from experiments using either very sensitive breeds of animal species (albino rats *Rattus norvegicus* without eye pigments) or intentionally damaged eyes (removed eye lenses, rhesus monkeys *Macaca mulatta*). Levels and time of light exposure were partly very high (24h, 500lx, Krigel et al. 2016) and probably unrealistic under natural conditions. However, these investigations, mainly done under medical viewpoints of human welfare, have revealed the dangerous aspects of intense light and the underlying mechanisms, which can affect mainly the retina but also other tissues such as the lens of mammalian eyes.

Experiments with young, still developing guinea pigs (*Cavia porcellus*) under long term light treatment have shown significant prolongation in the axial eye grow compared to natural, blue filtered light, and E light (imitated natural light spectral composition with continuous wavelengths ranging from approximately 390 to 780 nm), if treated with low colour temperature light emitted from LEDs or Julia light (J light) with a spectrum profile similar to E light, except for a small peak at 430nm followed by a small valley at 450nm (Xu et al., 2023). Especially LEDs or other devices emitting light of higher intensity in the blue range have, therefore, not only a higher physiological footprint but also affect growth processes in the eye, leading to reduced functionality. A similar study, using coloured LEDs (red - λP 630 nm, amber - λP 601 nm, filtered warm white - λP 586 nm, and cool white - λP 457 nm) for studying the release levels and daily rhythm of melatonin sulphate in the nocturnal living Gould's wattled bat (*Chalinolobus gouldii*) under short-time (one night) exposure, could find no effects of such treatment (Dimovski et al. 2023).

However, not only the eye, but also in other tissues, and also deep inside the brain and in the pineal organ, one can find photoreceptors containing photosensitive opsins (G protein-coupled receptors; Grubisic et al. 2019, Moraes et al., 2021). Light, therefore, has different ways in which it can influence the mammal's organism in more subtle and also unexpected ways than mentioned above and with much less energy or longer lasting exposition.

Stress

Nocturnal light pulses (NLP) have been demonstrated to affect physiology and behaviour and may act as a stressor (Zubidat et al., 2007). This could be relevant, for instance, if one thinks about more adaptable techniques for illumination of foot- or cycle paths according to their low frequency of use in less populated areas as a measure for LP mitigation. Tests with the social vole (*Microtus socialis),* a rodent species of the family *Cricetidae* occurring in parts of Europe and Asia, using three 15 min 450 lx light pulses during each dark phase (scotophase) of the day have shown both thermoregulation and endocrine stress responses under short-day (SD; 8L:16D) acclimation. Resistance to cold was markedly lowered and also mean energy expenditure levels were lowest for voles exposed to NLP-treatment. Both mean total urinary adrenaline and serum cortisol levels were significantly elevated under this treatment compared to those of individuals in a control group. The authors conclude that NLP may negatively affect the winter acclimatisation of thermoregulatory mechanisms of *M. socialis*, probably by mimicking summer acclimatisation. NLP may, therefore, act as a stressor and correspondingly impose a major threat to the physiological homeostasis of this species, such that over-winter survival might be compromised (Zubidat et al., 2007).

Reproduction and desynchronisation of rhythms

On the other hand, masking of seasonal changes in ambient light cues, caused by artificial light of a naval base on Garden Island, Western Australia, has reportedly led to a suppression of melatonin levels and, as a result, to a significant delay in births in the urbanized tammar wallaby population *(Macropus eugenii)* living there and a poorly synchronization with the available food (Robert et al., 2015) compared to the population living under natural conditions in the bush 6.5 kilometres away. As reported by the authors, the wallabies on the base appear to behaviourally avoid night-time light but are limited in their capacity to do so. This increase in light at night compared with bush wallabies is sufficient to mask the cue of increased darkness that triggers blastocyst reactivation (Robert et al., 2015).

Bats

Various effects of LP related to hunting efficiency, microhabitat use and movement have been reported from studies on bat behaviour and bat foraging ecology. Arlettaz et al. (2000) found no differences in diet composition based on faeces analysed between two species of bats, the lesser horseshoe bat (*Rhinolophus hipposideros*) and the pipistrelle (*Pipistrellus pipistrellus*), using different foraging strategies but feeding on the same categories of prey (mainly moths and Diptera). Both species are hunting for food in the same or adjacent feeding grounds in south-west Switzerland, where the insects are attracted to street lamps, and both bat species are preferably hunting there. However, the population trends show a contrasting pattern, indicating potential competition for the same populations of prey. An attraction of bats by streetlights (125W Hg vapour lamps with white light) was also reported by Rydell (1991) for northern bats *Eptesicus nilssoni* in Sweden.

Similar effects on competition between species were observed in a remote village in a desert region, where two bat species (*Pipistrellus kuhlii, Eptesicus bottae*) hunt for prey in dark areas and, in some places, in areas illuminated by streetlights. The more synanthropic species *P. kuhlii,* used both dark and brightly lit areas, but flew at higher speeds and at lower altitudes above the ground under the streetlights. *E. bottae*, a species more adapted to the conditions of the desert, used both areas for commuting, but only searched for food in the dark, leaving the lit habitats to P. kuhlii (Polak et al. 2011). The conditions reported by Polak et al. (2011) were at 12.77±1.93 lx for light and at 0.27±0.058 lx for dark. The minimum sensitivity of the equipment used (Gossen GO 4068 Mavo-Monitor light meters, Gossen, Nürnberg, Germany) was 0.2 lx. The actual ambient light level in the dark was probably lower.

While some bat species use insect concentrations attracted by streetlamps for foraging, others seem to avoid or at least feel disturbed by ALAN. Pond bats (*Myotis dasycneme*) showed changes in flight patterns and a reduction in the percentage of feeding buzzes along their traditional commuting routes if a strong streetlamp (1000W) was placed along (Kuijper et al., 2008). Between 28% and 42% of pond bats turned before continuing on their normal commuting route. Virtually all individuals (96%) turned when the light was installed on an existing barrier, and, and they had to fly straight into the beam of light.

Information about more species and the interaction effect of tree vegetation on attraction or repellence of streetlamps with different UV intensities in their spectra and different bat species is reported by Straka et al., 2019 at 22 green open spaces in Berlin (Germany). The authors found a species-specific response of bats to streetlamps with and without UV light, providing a more detailed picture of ALAN impacts than simply total light radiance. Dense tree cover dampened the negative effect of streetlamps without UV for open-space foraging bats of the genera *Nyctalus*, *Eptesicus* and *Vespertilio*. On the other side, it amplified the already existing negative or positive effect of streetlamps with or without UV on *Pipistrellus pipistrellus*, *P. pygmaeus* and *Myotis spp*. Light levels are not reported, but the number of different street lamp types, such as mercury vapour (MV), metal halide (MH), and LED, within the radii 500 and 1,000 m.

A more complete overview about negative, neutral, and positive effects of ALAN on roosts, flight corridors, foraging areas, drinking sites, and migration with regard to geographic scale, habitat type, and foraging mode is given for 23 European bat species by Voigt et al. (2021).

Individual behaviour and predation avoidance

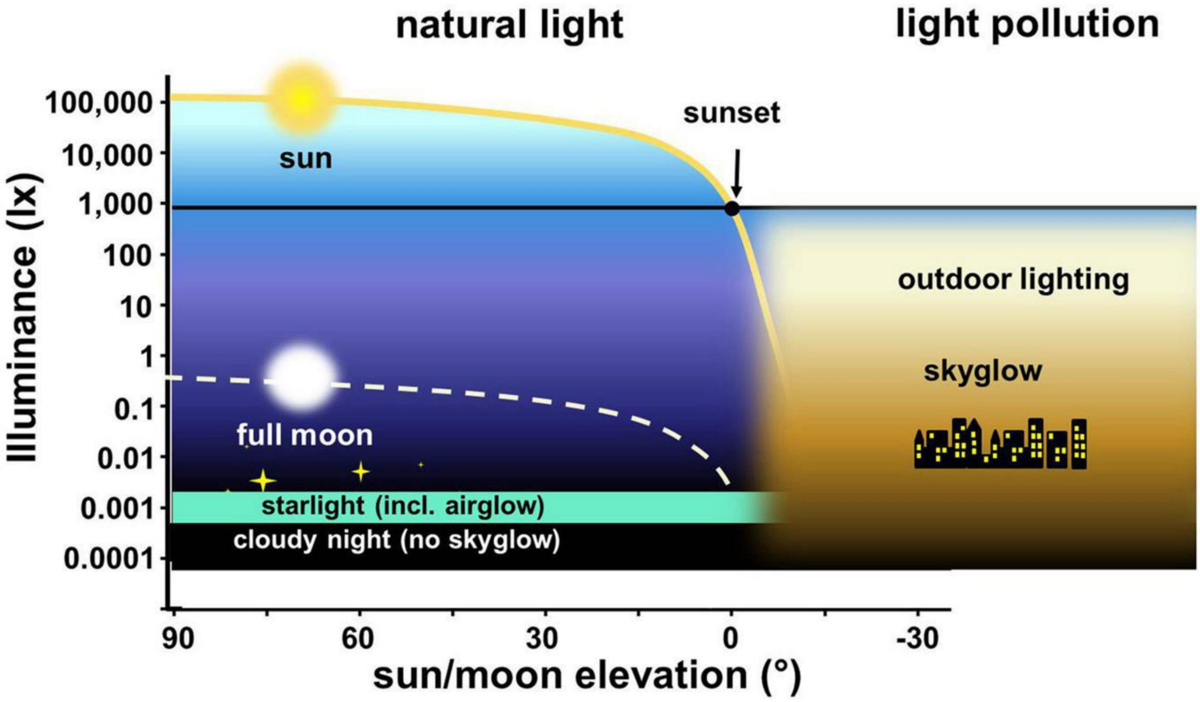
There are a few studies related to LP focusing on predation avoidance. Light can naturally increase the likelihood that nocturnal predators such as owls, felids, canids, or other species whose vision is specially adapted to dark conditions will catch their prey. Potential prey species that can adapt to this would definitely have an advantage. And indeed, such effects have already been observed in three species of rodents.

The effect of light intensity on activity and predation avoidance was investigated in a study of captive leaf-eared mice (*Phyllotis xanthopygus) by* Kramer & Birney (2001). Primary predators of this species are raptors and canids, all of which are expected to have increased hunting success under higher levels of moonlight. Because of the correlation between light intensity and predation risk, the authors predicted that increased light intensity during the dark period would result in decreased nocturnal activity. Three treatments were chosen to test for the effects of nocturnal light intensity on the activity of the mice: 0.0 lx (control), 1.5 lx, and 3.0 lx. Total activity of mice in middle (1.5 lx) and high (3.0 lx) light treatments was depressed, as evinced by significantly lower mesor and amplitude estimates compared with those of mice in control conditions (0.0 lx). The acrophase was also significantly different between the control and the 2 treatment groups.

Rotics et al. (2011) studied the effect of ecological LP on a rocky desert community, focusing on 2 spiny mouse congeners: nocturnal *Acomys cahirinus* (common spiny mouse) and diurnal *Acomys russatus* (golden spiny mouse). They hypothesised that in response to artificial illumination *A. cahirinus* would decrease its activity and *A. russatus* would increase its activity, and thus temporal overlap and interspecific competition could increase. Since illumination restricted both activity time and space, intraspecific encounters of *A. cahirinus* over foraging patches increased during and following the illuminated hours. However, diurnal *A. russatus* did not expand its activity into the illuminated hours, possibly due to the presence of competing *A. cahirinus*, or to non-favourable environmental conditions. Therefore, in opposition to the similar studies in bats (e.g. Arlettaz et al.. 2000), overt interspecific competition was not affected by experimental LP. LP had a negative influence by reducing overall activity and producing a relatively underexploited temporal niche, which may promote invasion of alien species that are less light-sensitive, and by increasing intraspecific overlap in foraging *A. cahirinus*. The reduction in foraging and activity under experimental lighting conditions in the study also probably reflects the increase in perceived predation pressure. The natural light level at this time was below 0.3 lx. Illumination levels were reasonably constant throughout the enclosures at an average intensity of approximately 2 lx. This low light intensity was similar to LP that measured about 40 m from an illuminated road junction in the study area. Enclosures were illuminated by 70-watt yellow metal halide lamps (Osram Ltd., Munich, Germany) on top of six 3-m-high poles. These lamps are similar in light colour to frequently used high-pressure sodium-vapour lamps, generating realistic ecological LP in terms of light intensities and spectrum.

Medical studies on model animals have often used very high light intensities to investigate the harmful effects on light-sensitive tissues in mammals. Exposure of organisms in the wild to such conditions is rather rare. However, animals that are attracted to lamps and feed on the insects attracted to them, such as Pipistrelle bats from streetlamps, may be exposed to such a risk. Especially nocturnal mammal species with few cones can be temporarily blinded by bright light because the rods become unresponsive (i.e. saturated) above 120 candela/m^2 (Perlman & Normann, 1998). Studies focusing on behavioural effects such as commuting, use of feeding habitats, or avoidance of predators have already found effects at very low levels of artificial light, comparable to nights with normal or bright moonlight. This suggests that even in habitats that naturally shield moonlight, such as forests, and/or when ALAN continuously increases levels to 0.3 lx and above, significant impacts of ALAN on mammalian species are to be expected (see *Figure 7*) from Hölker et al. (2021).

Figure 7: Ranges of exposure that animals experience and respond to with natural variation in light and light intensities observed with ALAN (here using human-centric metric lx). Illuminance during day, twilight, and night as a function of the elevation angle of sun and moon; yellow solid line – sun illuminance on a clear day; grey dashed line – moonlight full moon. Hölker et al. 2021 doi: 10.3389/fevo.2021.767177



4.6.2 - Noise impacts on mammals

In most groups of organisms discussed in the text above, sound is important for communication. This also applies to mammals. The mammalian ear is the most complex of all vertebrates as an organ for sound reception, and only mammals are able to hear very high frequencies in the range we call ultrasound (Watson 1953, Heffner & Heffner 1965, Manley 1972, Tucker 2017). In two orders of mammals, *Cetaceans* (dolphins and whales) and *Chiroptera* (bats), however, the vocal apparatus and the ear have also become the most important organs of orientation, with the eyes coming in second place. Both live in environments or at times of day when light intensity and visibility are reduced, have switched to ultrasound, and developed different but analogous orientation systems. No other group of vertebrates living in the dark has taken this path. Le Maître et al. (2020) assumed that "*the increased "evolvability" of the mammalian ear may have contributed to the evolutionary success and adaptive diversification of mammals in the vast diversity of ecological and behavioural niches observable today*".

Overviews about the existing knowledge in noise research were given by Kight & Swaddle (2011) and Erbe et al. (2022) for animals in general, with a focus on results from laboratory experiments, by Shannon et al. (2016a), with a focus on wildlife species, and by Slabbekorn et al. (2018), with a focus on mammals only. Among the 242 references about anthropogenic noise impact on wildlife published between 1990 and 2013 that were analysed by Shannon et al. (2016a), only 11% contained information about mammals, 126 studies focused on terrestrial wildlife only, 24% of them were done under laboratory conditions, 21% of the 126 studies were about wildlife in Europe.

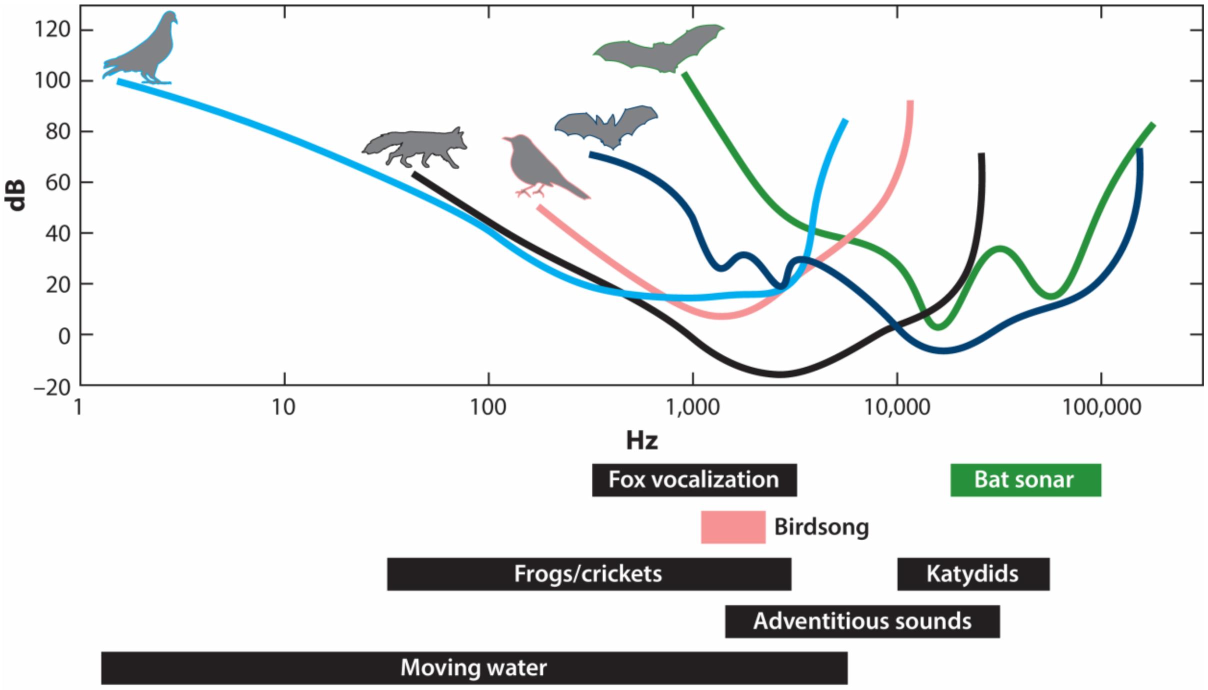
Several types of effects of anthropogenic noise on mammal species have been reported so far. It can have varying effects on the health, physiology, behaviour and ecology of mammal species and their role in ecosystems. Across various studies (e.g. Kight & Swaddle, 2011; Brown et al., 2012; Francis & Barber, 2013; Shannon et al., 2016a; Erbe et al., 2022), noise has been found to (i) harm audition and cochlear morphology, (ii) impact cardiovascular health, (iii) affect the neuroendocrine system, (iv) affect the immune system, (v) lead to imbalance of the metabolism, (vi) damage DNA integrity and genes, (vii) affect reproduction and development, (viii) disturb individual cognition and sleep, (ix) influence vigilance, (viii) influence movement, (ix) influence foraging, (x) affect mating, (xi) impact at the population level, and (xii) impact at the community level. A framework for understanding noise impacts on wildlife, with explanation of mechanisms and examples was proposed by Francis & Barber (2013). The authors explain, for instance, variation in responses to the same noise stimulus, discuss noise and the disturbance–interference continuum, and ask researchers for more awareness of bias introduced in monitoring and population studies by noise caused by themselves. Berkhout et al. (2023) also suggest noise affects wildlife diseases.

Sources of noise that were found impacting terrestrial wildlife or used in experiments on it could be related to the (i) general environment (urban and developed areas, no specific source identified), (ii) transportation (commercial (aircraft, train, bus) and private (general traffic, automobile, motorcycle, small boat) transport noise), (iii) industrial (general construction, machinery, energy (wind, oil and gas) development and operation, pile driving), (iv) military (gun fire, explosion, and aircraft noise), recreation (hunting, air tour, snowmobile, and race-track noise), other (simulated (white, pink, tones), human voice, alarm, and chainsaw noise) (Shannon et al., 2016a).

Important for the assessment of effects on mammals, or animals in general, is a good knowledge about the hearing sensitivity across the frequency spectrum documented in so-called audiograms and its comparison with the frequencies usually found in the different soundscapes, as was done for some examples by Francis et al. (2023, *Figure 8)*. In WP 03, we compiled a database of audiograms containing 490 data sets from 316 different species extracted from 170 research papers found in the Internet, which will be used in further analyses.

Figure 8: The auditory thresholds of animals are highly variable across the frequency spectrum.

Pigeons (Columba domestica) can sense ultrasound (aqua blue line), red foxes (Vulpes vulpes) have some of the lowest thresholds quantified (black line), and both vampire bats (Desmodus rotundus) (navy blue line) and big brown bats (Eptesicus fuscus) (green line) transduce ultrasound, yet vampire bats have markedly more sensitive low-frequency hearing (Heffner & Heffner 2018). Dooling & Popper (2007) compiled an average audiogram of 39 songbird species (pink line) showing the area of best sensitivity overlaps with the maximum power of their songs (pink bar). Bats, on the other hand, have their best hearing outside of their sonar ranges (green bar). Other sounds of nature (black bars) are likely also primary drivers of hearing sensitivity. This figure was published by Francis et al. (2023).



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Damages on audition and the cochlear system, leading to hearing impairment and deafness, are two of the most obvious effects of extreme environmental noise on sensory systems (Kight & Swaddle, 2011). The underlying mechanism is explained by Hu & Zheng (2008). Kight & Swaddle argue that in both terrestrial and aquatic animals, auditory injuries may stem from single, extreme acoustic traumas (e.g. noises occurring beyond the pain threshold), or from chronic exposure to dangerous levels of noise. An extended overview of this topic is given by Le Prell et al. (2019) and the special issue of the Journal of the Acoustic Society of America. Widely used mammal species for experiments are rodents (*Mus musculus*, *Rattus norvegicus*, *Cavia porcellus*, *Chinchilla lanigera)*, non-human primates (*M. fascicularis*, *M. mulatta, M. nemestrina; Papio papio; Saimiri spp.*, mainly *S. boliviensis* and *S. sciureus*), particularly also feral cats (*Felis catus*) and dogs (*Canis lupus familiaris*) were used (Burton et al., 2019; Le Prell et al., 2019; Trevino et al., 2019). The treatments were very variable, ranging from 40-50db SPL up to 155db SPL in such experiments.

Stress is an often-mentioned response to noise. Like effects caused by unnatural exposure to light, noise is affecting the neuroendocrine system via the hypothalamic–pituitary–adrenal (HPA) axis that is responsible for maintaining homeostasis (Kight & Swaddle, 2011). The increase of hormone production in this field can be interpreted as an indicator for stress and was found in rodents (*Mus* *musculus* – Jensen et al., 2010; R*attus norvegicus* – Pellegrini et al., 1997, Sobrian et al., 1997, Oliveira et al., 2009), cetaceans (D*elphinapterus leucas, Tursiops truncatus* - Romano et al., 2004), canids (*Canis lupus familiaris* – Gue et al., 1987), and primates (*Homo sapiens* - Evans et al., 2001). However, so far, no studies have investigated the long-term impacts of noise stress according to Kight & Swaddle (2011), although animals may habituate to stressors over time (Kight & Swaddle, 2011). Physiological experiments also suggest an impact of infrasound exposure of 100dB to 130dB on the immune system (Du et al., 2010; Ma et al., 2015).

Experimental results showed impacts on reproduction and development in pregnant *Rattus norvegicus* (Sobrian et al., 1997), which were exposed daily from day 15 to day 21 of gestation to an inescapable loud noise (an 85db- to 90db fire alarm bell) delivered randomly for 1 hr. Sound can be felt already early in the embryonic stage of the foetus physically, but also via physiological impacts on pregnant females. In humans, for example, excessive environmental noise (> 85 dB re 20 μPa) has been correlated with premature birth (American Academy of Pediatrics Committee on Environmental Health 1997). Studies in this field often use noise levels between 80dB and 100dB.

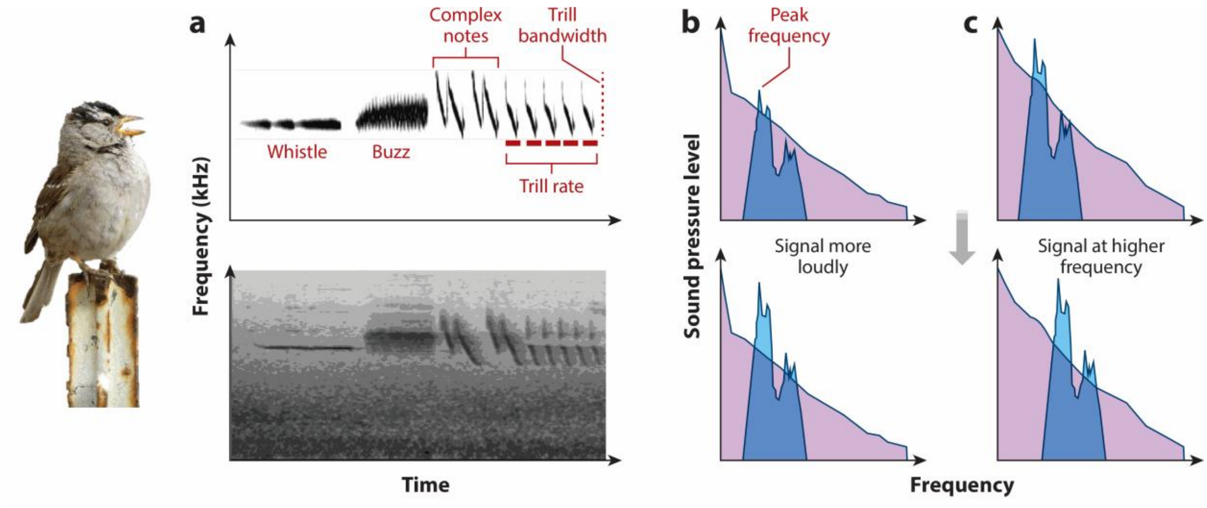
Various effects related to impacts on metabolism and cardiovascular health are reported reaching from decreasing weight gain, cellular leakage in the mesentery to damage in atria and ventricles or mitochondrial damage in myocardial cells (compiled in Kight & Swaddle, 2011). Also, loud Music does have an effect. Dogs that were exposed to 80dB to 90dB rock music showed reactions in the gastric motility (Gue et al. 1987). However, especially for music, ambiguous effects were reported related to stress and hormonal (serotonin) expression, which is one mechanism that may be responsible for psychological responses to noise (Kight & Swaddle, 2011). Kim et al. (2004) and Kim et al. (2006) reported contradictory effects in the neurotransmitter synthesis and expression (5-hydroxytryptamine, Tryptophan hydroxylase) and in spatial memory and neurogenesis of rats (*Rattus norvegicus*) exposed to noise (supersonic machine sound at 95dB) and music (comfortable music at 65dB) during pregnancy. While the developing offspring showed negative effects under noise treatment, the observed effects were positive under treatment with comfortable but also quieter music.

Ecological effects of noise are often related to disturbance, avoidance and resulting consequences. Disturbance in communication is often caused through masking of signals by noise. In this case, a broadband noise signal is overlaying the acoustic signal, e.g. a call, a song, or a warning, making it difficult to recognise and understand the message. There must be a difference in volume between both to keep them separated and understandable, which is called the critical ratio. The critical ratio is also frequency dependent; the higher the frequency of the signal, the higher the difference must be between the noise level and signal level. For most mammals studied, the critical ratio increases by approximately 3 dB for every increase of 1 octave, for example, from 2 to 4 kHz (Slabbekorn et al., 2018). Whether noise communication disturbs, therefore, depends on the ratio between the volume and frequency of the sender's signal and the distribution of volume across the frequency distribution of the noise, and the sensitivity of the species ears. Francis et al., (2023) provides an easy understandable explaining *Figure 9.*

Figure 9: White-crowned sparrow vocalisation.

(a) A white-crowned sparrow produces a song, visualised here via a spectrogram, which displays sound frequency over time. (Top) A band-pass-filtered song, where environmental noise has been filtered out of the recording. (Bottom) A white-crowned sparrow song vocalised in a noisy environment where the noise has

more energy at lower frequencies (darker shading). This pattern of declining energy toward higher frequencies is typical of noise from many natural and anthropogenic sources. Both subpanels display a song consisting of an introductory whistle, a buzz, complex notes, and a trill. One way to compare song or vocal performance among or within individuals singing in different contexts is to measure the trill rate (notes per second) and bandwidth of the trill (its maximum frequency minus its minimum frequency). There is a physical trade-off between the trill rate and the bandwidth such that fast trills typically have a narrow bandwidth, and trills with a broad bandwidth are sung more slowly. (b, c) White-crowned sparrow song (blue) and background noise (pink) via power spectra that indicate the sound pressure level across the frequency spectrum. (Top) Conditions where the song cannot be detected by a receiver because the signal-to-noise ratio is too small to be audible. (Bottom) Two documented responses by signalers to mitigate masking effects by noise. In panel b, the song is sung with greater intensity, and in panel c, the song is sung at a higher frequency. In both cases, the song adjustments improve the signal-to-noise ratio. White-crowned sparrow photo by Jennifer N. Phillips. Panels b and c were adapted by Francis et al. (2023) from Gomes et al. (2021a) with permission from Oxford University Press. This figure was published by Francis et al. (2023).



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Disturbance in behaviour resulting in physiological reactions, stress, escape, and wasting of energy is often caused by short noise events uncommon in the habitats where they are produced by humans or technical devices used by them. For mammals, based on former experience, it is often not the noise as such, but the combination with other traits of the disturbing source that makes them disturbed. Ungulates (elk *Cervus canadensis syn. Cervus elaphus*, pronghorn *Antilocapra americana*) showed reduced vigilance for tourists in cars but increased responsiveness if pedestrians or people on motorbikes appeared (Brown et al., 2012). This is an often-observed behaviour also in Europe. As Francis & Barber (2013) have discussed, the disturbance–interference continuum can range from acute or infrequent noise stimuli that will likely trigger startle or hide responses to frequent or chronic noises that interfere with cue detection, while the severity of an impact from a noise stimulus will depend on the temporal, intensity, and frequency features of the stimulus. However, road noise broadcast from a remote-controlled speaker (62 dBA Leq at 10 m) to black-tailed prairie dogs (*Cynomys ludovicianus*) in an area where the ambient sound levels were much lower (mean = 33 dBA Leq), with an increase of received noise levels at the end of the treatment (mean = 43 dBA Leq) showed different effects (Shannon et al., 2016b). As reported by the authors, the vigilance of the prairie dogs increased, and they responded already at greater distances to the approaching human “predator” and took flight more rapidly in noise than during the quieter control.

Avoidance behaviour is often related to noise that hinders activities or masks information. Greater mouse-eared bats (*Myotis myotis)* avoid noisy roads (Schaub et al., 2008) and have reduced foraging efficiency (Siemers & Schaub, 2010) because the noise masks the sound produced by their prey (Carabid beetles) while crawling through leaf litter and vegetation in forests and meadows. The methodological setting of the experiments of Schaub et al. (2008) and Siemers & Schaub (2010) used mealworms producing faint rustling noises with main energy between 3 and 20 kHz, with stronger clicks of up to 50 kHz and above. The loudest peaks of the mealworm sound ranged from approximately 45 to 62 dB SPL measured at a distance of 10 cm, which is similar to the sounds produced by a carabid beetle walking on soil, meadow or moist leaf-litter. The traffic noise was recorded at a distance of 7.5 m from the centre of the right lane of a highway and 1.5 m in height, normalised and played back digitally. Analyses of the energy density showed that traffic noise has its main energy clearly within the human audio range but does contain ultrasonic components up to 50 kHz (Schaub et al. 2008). For comparison, also sound produced by moving vegetation was simulated with dry reed bundles and recorded, which produced a series of broadband click-like and noise-like signals with energy ranging from 0 to frequencies higher than 85kHz. Additionally, broadband noise treatment was digitally generated using continuous white noise by these authors. The playback amplitude of the digitally generated broadband noise was adjusted in such a way that the incident sound measured 80 cm above the platforms had an SPL of 80 dB. This corresponds to the noise level 10–15 m next to a highway as a vehicle passes. The traffic playback files were digitally set at the same RMS sound pressure level for the loudest 500 ms window contained in the playback file. The playbacks of vegetation movement were set at 12 dB below the broadband noise and the traffic noise files, which are still unnaturally loud or at least corresponding to movement induced by very strong wind, as from a human perspective (Schaub et al., 2008).

To set it in relation, the information about the frequency and sound pressure level of the bats is needed. Calls of greater mouse-eared bats are broadband sweeps from between 120 and 70kHz down to approximately 27kHz. Any information about the sound level of the calls of this species was not found. Moreover, no information could be found in the literature about *Myotis myotis*. Related species call on a level between 109dB SPL to 119 SPL (*Myotis l. lucifugus*, Griffin, 1950; *Myotis albescence*, *Myotis nigricans*, Surlykke & Kalko, 2008). Since Myotis species reduce the call level while searching for food (Russo et al. 2007) and the distance to the prey, the masking effect of noise may change. The experimental setting is described in more detail here, compared to other parts of the document, because it is a rare case that such detailed information, covering most of the important aspects relevant for the evaluation of effects of noise is given in papers related to ecological research.

For a general evaluation, it is also necessary to give an overview of sound pressure and frequency ranges, that can be found in natural sounds or soundscapes (biophony, geophony) and compared to anthropogenic sound or mainly human-created soundscapes (anthropophony) (Pijanowski et al., 2011). In general, acoustic noise from abiotic sources, including anthropogenic noise, has energy mostly below 1kHz (Luther & Gentry, 2013). Kirk & Smith (2003) analysed ambient sounds from natural and biotic sources to show that protection from acoustic trauma is not a primary function of the medial olivocochlear efferent system because the sound level found in nature is, for the most part, far below 80dB. Even peaks are still below 100dB. However, most of the experimental settings to study noise effects start above these thresholds. Compared with this, anthropogenic noise is often louder than the sound levels in areas dominated by nature.

The loudest calls from terrestrial mammals we know are produced by lions (*Panthera leo,* 114dB SPL, https://www.audiology.org/the-loudest-animals-in-the-world/) and howler monkeys of the genus *Aluatta spp*. (90-140 dB SPL, https://www.audiology.org/the-loudest-animals-in-the-world/, https://www.discoverwildlife.com/animal-facts/mammals/why-do-howler-monkeys-scream), greater buldogg bats (*Noctilio leporinus*, 140dB SPL, https://www.ifaw.org/journal/loudest-animals-on-earth).

Most mammal species communicate at sound pressure levels well below 80 dB. In contrast, artificial soundscapes, especially in urban areas, near transport routes, far-reaching noises from machines in open fields or aircraft flying over rural areas and protected areas, have a broad frequency spectrum with comparatively high sound pressure levels. Loud biophonic or geophonic events, such as those caused by frog concerts, bird or seal colonies, crashing waves, strong winds, earthquakes or volcanic eruptions, are either limited to specific locations, habitats or short periods of time. Loud man-made technical noises often occur either suddenly and unexpectedly at irregular intervals or lay themselves over the landscape like a continuous soundscape (e.g. Pater et al., 2009).

For future studies, it is strongly recommended that all experimental procedures and necessary background information be documented more completely and concisely, as recommended by Pater et al. (2009) and McKenna et al. (2016).

4.6.3 - Combined impacts of light and noise pollution on mammals

Similar to Rydell (1981), Kuijper et al. (2008), Polak et al. (2011), and Stone et al. (2009) studied commuting behaviour and activity of lesser horseshoe bats (*Rhinolophus hipposideros*) along hedgerows illuminated with high-pressure sodium lamps to an average of 53.09 lx (SD = 2.73, range = 47.3–60.2, n = 36) compared to a control. At the unlit side, a mean of 4.17 lx (SD = 7.77, range = 0.07–24.28, n = 16) was recorded. This is still significantly higher than the mean light level recorded at the same locations on unlit nights (Mann-Whitney U test, W = 230.5, $p < 0.01$, mean 0.03, SD = 0.03, n = 62). The mean ambient light level in the middle of the fields on lit treatment nights was 0.04 lx (SD = 1.3, range = 0.02–5.46, n = 23). However, besides the light treatment, they also combined it with an investigation of the effects of the noise from the generators used for the illumination. Unfortunately, the noise level was not reported, only the combination of light and noise. However, there were significant effects in the number of bat passes acoustically recorded with bat detectors between areas treated with light (less) and those of noise (more), the control (highest) and lit areas (lowest), but no significant differences between noise treatment and the unlit control (Stone et al., 2009).

Selvakumar et al. (2025) did a combined study in an urban environment using communication and sound production of insects, amphibians, birds and bats as a response to assess the communication effectiveness and its change between low light, low noise, the combination of both and its counterpart conditions: high light, high noise, and high light and noise. Variables measured and used for the calculation of specific metrics (normalised communication performance, composite communication effectiveness, relative change in communication effectiveness) were sound pressure level and temporal variability for noise, intensity and time of exposure for light, call or signal rate, signal timing shift, signal structure and chorus synchronisation for communication. The effectiveness in communication was maximum for the reference (0.88) and minimum for isolated noise (0.63) and isolated ALAN (0.59). The greatest decrease was found for the combination of noise and ALAN exposure, with a reduction of the effectiveness to 0.31, which is more than 60 % of that under reference conditions. Combined exposure showed that amphibians (0.33) and insects (0.29) had low communication indices compared to birds (0.40) and bats (0.51). Temporal communication elements were also the most impacted across the taxa, with timing stability and synchronization exhibiting lower indices than call rate or signal clarity. The findings suggest that nocturnal noise and ALAN have a synergistic effect on the communication of wildlife, and that the issue of multisensory conservation and planning of biodiversity in cities must be considered simultaneously.

4.7 - Plants

4.7.1 - Light pollution impacts on vascular plants

Light is a key driver for the physiology and ecology of plants, serving both as an energy source for photosynthesis and as an environmental cue. ALAN is bright enough to influence plant phenology and physiology (Bennie et al., 2015, 2016; Lockett et al., 2022; Sanders et al., 2021). Much of the existing research has focused on light intensity, yet the colour of ALAN is also an important factor.

A five-point taxonomy of plants based on growth form/habitat was employed in the review of LP's impact on vegetation, comprising (1) herbs, (2) shrubs, (3) trees, (4) creepers and climbers, and (5) succulents and cacti. The most extensively studied plant category was trees, followed closely by herbs and succulents after herbaceous species.

Research observed effects on plant functioning and physiology, which are directly linked to primary productivity. Several studies have reported changes in plant biomass due to ALAN exposure (Bucher et al., 2023; Hey et al., 2020; Lockett et al., 2022). Moreover, research shown that ALAN affect stomatal dynamics and plant respiration (Kwak et al., 2017).

There is growing evidence that ALAN can significantly influence tree phenology, both as skyglow as well as via direct streetlights, and it has detrimental effects on trees (Friulla & Varone, 2025). In autumn, trees can retain their leaves longer (Massetti, 2018; Škvareninová et al., 2017), while in spring ALAN is linked to earlier budburst (Czaja & Kołton, 2022; ffrench-Constant et al., 2016; Zheng et al., 2021). Due to this, it lengthens the growing season of trees in cities (Wang et al., 2025).

The most considerable effect of LP on plants is the interference with their normal growth and development cycles (photoperiodism), which is how they react to the duration of the day and night. Their circadian rhythms may be altered by these conditions at night. Plants contain internal clocks that control how their leaves move, how they develop (growth), and how they store energy. These cycles may be disrupted by ALAN, which can impact their general health or stop their growth. Also, it may stop plants from blossoming and fruiting since many plants need darkness to start flowering or producing fruit. Too much light may also slow down, reduce, or completely stop these processes. ALAN may also affect dormancy and changes during the seasons. For example, certain plants require prolonged nights to become dormant or adapt to winter. LP can hinder this from happening, which makes them likely more vulnerable to frost or pests.

The reviews by Bennie et al. (2015, 2016), Briggs (2006), and Gaston et al. (2017) sum up and explain the findings of many experimental studies. Many types of trees, particularly those in cities, might have their buds burst sooner, and their leaves fall later when there is ALAN present nearby in the form of street lighting. This may make plants more likely to freeze and interfere with their seasonal cycles. Some studies suggest that longer photosynthesis could accelerate their development, but it can also cause stress, lower resilience, and make plants more likely to get pests (Grubisic et al. 2021). LP may change as shrubs bloom and bear fruit, which can sometimes cause problems with pollinators or seeds being dispersed. Shrubs that grow near streetlights may outcompete plants that can grow in the shadow, affecting the way plant communities are structured (Giavi et al. 2021).

A lot of herbaceous plants are affected by photoperiod. ALAN may stop or slow down blooming in short-day herbs and speed it up in long-day herbs. This can change how plants reproduce and how many of them there are (population dynamics). Outdoor lighting might disturb nocturnal pollinators, which can make it challenging for certain plants to be pollinated. Research indicates that grasses may undergo modified growth rates and competitive dynamics in the presence of ALAN, but these effects are often less significant than those seen in woody plants. Changes in how grass grows may affect the number of herbivores (Sanders et al. 2021).

ALAN can have an indirect impact when altering the environment or the behaviour of other organisms, subsequently impacting plants. Artificial light can change the way pollinators like bats, bees, and moths act, which could lead to less nighttime pollination. Plants that need bright areas to make fruit and seeds may not grow as well because of this. Depending on the type of LP, herbivorous insects may be more or less likely to eat certain plants. For example, some bugs may do better in bright places, while others may stay away from them. Some plants, like those that bloom year-round, may thrive in artificial light, while others may not. This may consequently modify the competitive dynamics and structure of plant communities (Gaston et al. 2017). ALAN, which is transmitted through soil, can change how bacteria and fungi behave, which can then affect how nutrients move through the soil and the health of plants. Some plants need nighttime animals to survive because they carry seeds and keep herbivores away. LP can mess up these interactions, which could hurt plants' chances of living and reproducing. Pollinators that operate during the night (Bennie et al., 2016).

The impacts of ALAN appear to extend to the community level, altering plant traits relevant for competition (Bennie et al., 2015; Liu et al., 2022; Murphy et al., 2021, 2022) and influencing interactions within food webs (Cieraad et al., 2022). The impacts extend all the way to ecosystem metabolism. A recent study in North America and Europe shows that ALAN indirectly decreases annual net ecosystem exchange by enhancing ecosystem respiration. Therefore, ALAN seems to disrupt the energetic constraints on ecosystem metabolism (Johnston et al., 2025). LP can impact plant functioning and physiology both at the individual plant level and on a larger scale, affecting ecosystem metabolism. Plants make up the base of our ecosystems, so they should be carefully considered by decision makers interested in the ecological impacts of ALAN.

4.7.2 - Noise impacts on plants

In contrast to the terrestrial animals discussed in previous sections, where the negative perception of sound is well established, it remains unclear whether plants are capable of experiencing comparable effects.

There is a growing body of research on “plant cognition” and the capacity of plants to perceive and respond to mechanical stimuli, including touch and sound (Mishra & Bae, 2019). Owing to their sessile lifestyle, plants have evolved a high degree of sensitivity to dynamic, tactile and acoustically complex environments. It is known that mechanosensitivity is not confined to well-known examples such as the carnivorous *Drosera species* (e.g. *D. rotundifolia, D. anglica, D. intermedia*) found in European bogs, or Mimosa pudica from tropical America. Rather, all plants, and indeed all living plant cells, are capable of sensing and responding to mechanical stimulation, whether arising from internal or external sources (Mishra & Bae, 2019).

While sensitivity to touch has long been recognised, plant responses to sound have only recently begun to receive sustained scientific attention. Emerging evidence suggests that plants are not only capable of detecting sound but can also discriminate between biologically relevant and irrelevant acoustic frequencies. For example, plants can distinguish the buzz of an effective pollinator from that of pollen thieves during buzz pollination; detect herbivore-associated sounds and activate defence responses; direct root growth towards the sound of flowing water; and increase nectar sugar concentration within minutes of sensing the sound of a bee near a flower (Mishra & Bae, 2019; Veits et al., 2019). A broader overview of experimentally observed plant responses to sound stimuli is provided by de Melo (2023). More generally, plants employ complex chemical, electrical and acoustic signalling mechanisms that enable them to perceive environmental cues and adapt to stressors (Ullah & Junjun, 2026).

Literature reviews addressing NP (Sordello et al., 2020; Guenat & Dallimer, 2023) include references to plants; however, the reported effects are largely indirect, arising from behavioural changes in animals directly affected by noise (e.g. Francis et al., 2012; Senzaki et al., 2020). In light of the emerging evidence outlined above, it is reasonable to consider whether plants may also be directly affected by anthropogenic noise. Empirical support for this proposition is provided by a long-term study conducted in New Mexico. Examining continuous noise from natural gas wells and its effects on seedling recruitment of foundational tree species – *Pinus edulis* and *Juniperus osteosperma* – as well as on overall vegetation diversity, Phillips et al. (2021) identified significant long-term negative impacts. These included reduced tree seedling recruitment, decreased evenness among woody plant species, and increasing dissimilarity in plant communities across sites with differing noise levels. Notably, seedling recruitment and plant community composition did not recover following the cessation of noise exposure. The authors suggest that this may partly reflect delayed recovery among animal species responsible for seed dispersal and pollination. Given the structural nature of these ecological changes, the effects are expected to be long-lasting, and the removal of noise may not result in immediate ecosystem recovery.

Further evidence of measurable impacts of NP on plants is provided by Velilla et al. (2025), who investigated vibrational noise associated with anthropogenic infrastructure, such as inland wind turbines commonly installed in agricultural landscapes. The expansion of renewable energy infrastructure over recent decades has led to a substantial increase in subterranean vibratory noise. In a controlled experiment, windmill-like vibrational noise was applied to *Pisum sativum* throughout its life cycle, from seed germination to seed production, in a full-factorial design that also included interaction with the generalist herbivore *Spodoptera exigua*. Plants were exposed to either high or low levels of vibrational noise. Germination time, flowering and fruiting phenology, and daily shoot growth were recorded. To assess potential indirect effects on plant–herbivore interactions, caterpillars of *S. exigua* were introduced to a subset of plants. Herbivory may increase, for instance, if vibrational exposure enhances leaf nutritional quality or weakens plant defence mechanisms. The results showed that plants exposed to higher levels of vibrational noise grew significantly faster and attained greater height than those in the low-noise treatment. There was also a marginally significant trend towards earlier flowering under high-noise conditions (Velilla et al., 2025). No statistically significant effect of vibrational noise on herbivory was detected. These findings suggest that subterranean vibrational noise can influence plant growth dynamics, with potential ecological and agricultural implications. Accelerated growth may alter interspecific competition and shift resource allocation trade-offs between growth and defence, as proposed by the authors. The experimental treatment consisted of low-frequency pink noise delivered via an MP3 player, stereo amplifier and vibration transducer, with a 12 dB difference between low and high treatments. This difference corresponded to soil vibration levels recorded at 8 metres compared with 128 metres from a wind turbine foundation.

Additional evidence of direct noise effects on plants is provided by Kafash, et al. (2022), who examined the impact of road traffic noise on growth, hormonal balance, oxidative stress, and antioxidant activity in two urban ornamental species, *Tagetes patula* and *Salvia splendens*. In the experiment, two groups of species were established. The treatment group was exposed to recorded traffic noise from peak hours in a highly congested urban area for 16 hours per day over a period of 15 days, while the control group was maintained under silent conditions. The average equivalent level of traffic noise was approximately 73 dB. Exposure to traffic noise resulted in a significant reduction in fresh biomass in both species, with decreases of 27% in *S. splendens* and 17% in *T. patula*. Biochemical analyses indicated a marked increase in hydrogen peroxide (H_2O_2) and malondialdehyde (MDA), both indicators of oxidative stress. This was accompanied by enhanced antioxidant responses, including increased DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity and elevated activity of key antioxidant enzymes such as catalase, peroxidase, and ascorbate peroxidase.

Traffic exposure also significantly altered phytohormonal balance. Concentrations of growth-related hormones, including zeatin, salicylic acid, indole-3-acetic acid, and gibberellic acid, were reduced, whereas levels of stress-associated hormones, notably abscisic acid and jasmonic acid, increased in both species. Taken together, these findings indicate that chronic exposure to daily traffic noise can adversely affect plant growth and physiology by inducing oxidative damage and disrupting hormonal regulation.

4.7.3 - Combined impacts of Light and Noise pollution on **plants**

At this time, it appears that there is a lack of research focused on quantifying the combined effects of light and noise pollution on plants. Nonetheless, there is an acknowledgement of the topic's significance and the indirect effects through altered plant-animal relationships (Dominoni et al., 2020).

5 - Impacts of light and noise on Ecosystem Services

ALAN and anthropogenic noise act as environmental stressors that can impair ecosystem services provision by impacting at the organism level and altering physiology, behaviour, phenology, and ecological interactions (Gaston et al., 2017; Shannon et al., 2016). Effects are often context-dependent because both stressors vary in intensity, timing, and spatial extent, and because responses differ across taxa and functional groups (Barber et al., 2010; Gaston et al., 2015).

Key mechanistic pathways relevant to ecosystem services include sensory masking and information loss, especially under noise, which can reduce detection of predators, prey, and social cues (Barber et al., 2010; Shannon et al., 2016). ALAN can disrupt circadian and seasonal timing, affecting activity windows, reproduction, and resource use (Gaston et al., 2015, 2017). Both stressors can also shift ecological interactions, with consequences for ecosystem functioning such as pollination, predation, and seed fate (Francis et al., 2012; Giavi et al., 2020; Knop et al., 2017).

5.1 - Representative ecosystem services influenced by artificial light and anthropogenic noise

5.1.1 - Pollination

Field evidence shows that ALAN can reduce nocturnal pollinator visitation and disrupt plant pollination networks, with measurable consequences for plant reproduction (Knop et al., 2017). Importantly, impacts can extend beyond the directly illuminated area due to redistribution of insects and altered interaction rates, implying that service changes may occur across illuminated and adjacent dark areas (Giavi et al., 2020). Noise can also affect pollination indirectly by reshaping predator and competitor dynamics and shifting pollinator behaviour and visitation patterns, with demonstrated community-level service changes in field systems (Francis et al., 2012).

5.1.2 - Seed dispersal, regeneration, and vegetation dynamics

Noise has been shown to disrupt seed dispersal and seedling recruitment through changes in the abundance and behaviour of key dispersers and seed predators, with cascading effects on habitat regeneration (Francis et al., 2012). These changes matter for ecosystem services tied to forest structure and renewal, including carbon storage and habitat provision, because recruitment bottlenecks can alter long-term vegetation composition.

5.1.3 - Biological control and pest regulation

Both ALAN and noise can alter predator-prey dynamics and the activity of key pest control agents such as bats and insectivorous birds. Light can deter light-averse bat taxa and act as a barrier to movement depending on spectrum and landscape context, potentially reducing pest consumption where bats avoid lit areas (Spoelstra et al., 2017). Since bats can provide economically relevant pest suppression in agricultural systems, any reduction in bat activity or connectivity can translate into reduced regulation services (Wanger et al., 2014). Noise can reduce foraging efficiency or cause habitat avoidance in many taxa, with effects that can scale up to community changes that modify regulation services (Shannon et al., 2016).

5.1.4 - Decomposition and nutrient cycling

ALAN can modify litter-layer communities and decomposition processes by changing invertebrate activity and trophic interactions, with experimental evidence of altered litter consumption and decomposition dynamics under artificial lighting (Czarnecka et al., 2021; Hey et al., 2021). This links ALAN to supporting services that maintain soil fertility and ecosystem functioning, which can indirectly influence provisioning and regulating services.

5.1.5 - Cultural ecosystem services

Dark skies and natural soundscapes are cultural services directly degraded by ALAN and noise at landscape scales. The global extent of skyglow documented by remote sensing-based products highlights that loss of natural night conditions is not confined to urban cores (Falchi et al., 2016). Similarly, noise mapping indicates widespread elevation of sound levels in protected areas, with implications for recreation, tourism, and perceived naturalness (Buxton et al., 2017).

5.2 - A Landscape-scale perspective

ALAN and noise operate as spatial gradients that frequently extend well beyond the immediate source, creating broad areas of altered sensory environments. For ALAN, LP can extend far beyond the footprint of direct illumination, affecting surrounding habitats and potentially shifting interaction rates and ecosystem functioning at larger scales than local lighting alone would predict (Falchi et al., 2016; Gaston et al., 2015; Giavi et al., 2020). For noise, propagation and topographic channelling can create heterogeneous soundscapes where transport corridors and industrial activity elevate background levels across extensive areas, including conservation units (Buxton et al., 2017).

At the landscape scale, impacts on ecosystem services can emerge through fragmentation of functional connectivity for service providers, such as pollinators and bats, via avoidance or barrier effects. Cumulative impacts are also likely where ALAN and noise co-occur and jointly modify behaviour and habitat use, potentially amplifying service losses in exposure hotspots. The knowledgebase systematise the body of scientific evidence by linking ALAN and noise exposures to biological responses and then to the ecosystem services they support. This provides a transparent bridge between literature and modelling choices by identifying priority service-providing taxa and processes per ecosystem service. Therefore, supporting the definition of the expected direction and relative strength of effects across exposure contexts. As a result, the translation of scientific evidence into weights and response functions becomes suitable for spatial modelling.

Combined with the LP Map and the Noise Map, the knowledgebase enables construction of a cost matrix (i.e., resistance surface) that represents how ALAN and noise constrain the movement, persistence, or functional performance of service providers across the landscape. This cost matrix can support scenario modelling of impacts on ecosystem services. For example, connectivity and flow-based analyses can be applied where service provision depends on movement, such as pollination and seed dispersal, and spatial prioritisation can identify areas where high ecosystem service potential overlaps with high exposure and thus higher expected service degradation. Comparative scenarios would also simulate mitigation actions, including shielding, spectral changes, curfews, and noise abatement, through modified pressure layers and updated costs.

Methodologically, the LP and Noise maps can be treated in the same way as any other spatial resistance layer used in ecological cost and connectivity modelling. In established least cost and circuit theory frameworks, resistance surfaces are constructed by translating environmental pressures or landscape attributes into spatially explicit costs that affect organism movement, survival, or functional performance (Adriaensen et al., 2003; McRae et al., 2008; Zeller et al., 2012). In this context, artificial light and anthropogenic noise represent pervasive and biologically meaningful forms of environmental resistance because they modify habitat permeability, alter behaviour, and constrain the effective use of space by key service-providing organisms. Therefore, it is possible to integrate sensory pollution into a unified cost matrix in a manner fully consistent with existing resistance modelling practices. This allows each ecosystem service or functional group to be represented by a resistance surface that reflects not only land cover or physical barriers, but also the sensory environment that shapes where organisms can forage, disperse, and persist.

This approach is conceptually aligned with ecosystem service matrix methods, which assign relative capacities or weights to land cover classes to represent the potential supply of different services (Burkhard et al., 2012; Jacobs et al., 2015) (Burkhard et al., 2012; Jacobs et al., 2015). Here, instead of using land cover alone, artificial light and noise are incorporated as additional spatial modifiers of service provision, enabling the cost matrix to capture how sensory pollution degrades the functional ability of landscapes to support pollination, pest control, seed dispersal, and other ecosystem services.

6 - Answering some 'key questions'

6.1 - Does light pollution impact terrestrial wildlife?

Global protected areas are increasingly exposed to LP (Mu et al., 2021). Based on the evidence collated as part of the PLAN-B knowledgebase development and the findings of numerous previous reviews (e.g. Longcore & Rich, 2004; Falcón et al., 2020; Sanders et al., 2020; Seymoure et al., 2019; Seymoure et al., 2023), it is clear that anthropogenic LP can significantly impact terrestrial wildlife across multiple scales (Bará & Falchi, 2023). The nature and mechanisms of impact can be varied, including behavioural changes (prolonged/time shifted activity due to the artificially extended photoperiod, e.g. Adams et al., 2026; Brent & Gilbert., 2025), impaired communication (for organisms that utilise bioluminescence for communication, e.g. Gardiner & Didham, 2020; Lewis et al., 2024; Moubarak et al., 2023; Owens et al., 2022), circadian clock disruption (e.g. Bloch et al., 2017; Fonken et al., 2010), interference with navigation (for nocturnally migrating species, e.g. Van Doren et al. (2021) and those that use the pattern of polarised celestial light to navigate (e.g. Dacke et al., 2003)), changes in reproductive physiology (Dominoni et al., 2013), and altered life history (Willmott et al., 2018). Although both continuous and flashing artificial light sources have been shown to impact wildlife, no definitive conclusion has been drawn on whether continuous or flashing lights are more impactful (Lafitte et al., 2023).

6.2 - Does noise pollution impact terrestrial wildlife?

For anthropogenic NP impacts on wildlife, there is a similarly extensive evidence base, from individual studies (e.g. Caufman & Sieving, 2025) to wide-ranging reviews and meta-analyses (e.g. Shannon et al., 2016; Nelson-Olivieri et al., 2024). Whilst some organisms, such as light-emitting fireflies (*Lampyridae*), use light to communicate, sound is more commonly used as a key means of communication within the animal kingdom (Ladich & Winkler, 2017). Therefore, NP that masks animal communication can be particularly impactful at the population level, as it can affect things like mate selection (and hence reproductive success) and obscure alarm calls that are used to alert other members of the population of a threat (e.g. a predator). Noise impact evidence is not restricted to individual species responses. There is also a growing evidence base of impacts on wildlife communities (Kok et al., 2023). There are notable differences in the responses to continuous noise versus intermittent (event-based) noise (Duquette et al., 2019), with greater levels of disturbance to wildlife being observed in the presence of intermittent noise (e.g. Caufman & Sieving, 2025; Sieving et al., 2024).

6.3 - Do combined exposures to light and noise pollution elicit a different response in terrestrial wildlife than the individual stressor exposures?

The use of stressor in this context may be interpreted as something that causes stress and therefore has a negative effect. However, responses can be positive as well as negative. Therefore, stressor is used here in the context of the definition proposed by Piggott et al. (2015): *"a variable that, as a result of human activity, exceeds its range of normal variation and affects (whether* *negatively or positively) individual taxa, community composition, or ecosystem functioning relative to a reference condition."*

When organisms are exposed to combined stressors (i.e. both light and noise pollution), their effects may be positive or negative overall, depending on whether the response to the individual stressors is positive or negative. If both light and noise elicit a negative response in the organism, the combined effect may be additive (both negative effects added together) or synergistic (producing a negative response that is greater than the sum of the negative responses to each stressor in isolation). For example, light and noise have been shown to reduce abundance (e.g. Mathiaparanam et al., 2024; Wilson et al., 2021), modify communication activity (e.g. Ritz-Radlinska et al., 2025) and alter selection pressures (e.g. Cronin et al., 2025). A recent study (Selvakumar et al., 2025) suggests that LNP have a synergistic effect on wildlife communication. Given the diverse sensitivities and responses of species to LNP, it is unlikely that synergistic effects will be observed in all cases. Advancing understanding of how wildlife respond to these combined exposures should be prioritised within future research programmes.

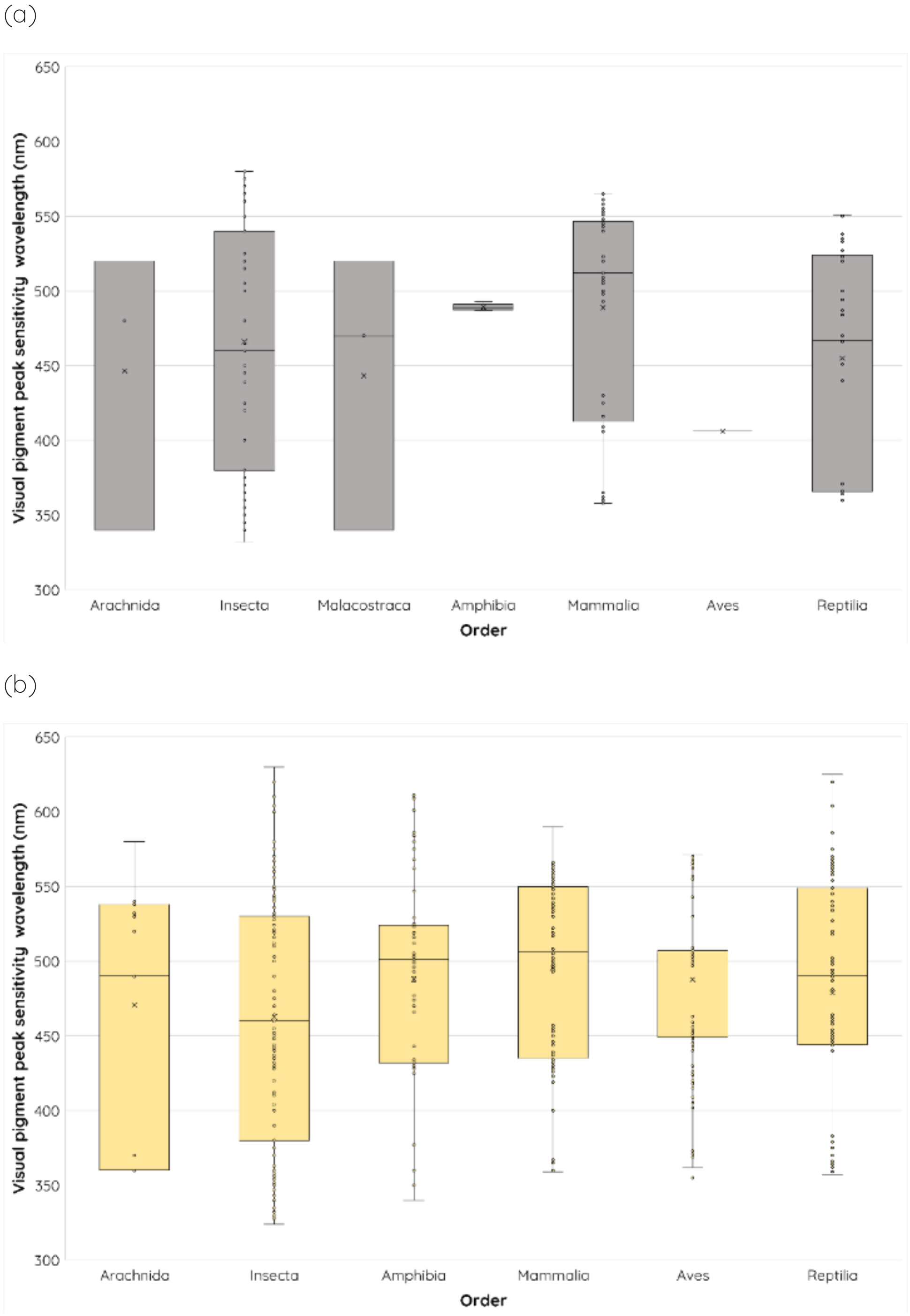
6.4 - Do species/organism groups differ in their responses to light and noise pollution?

Unsurprisingly, there are significant differences in the responses of different organisms to LNP. As these are sensory pollutants, their presence and characteristics are detected by sensory organs/cells of many organisms, eliciting some form of response. The nature of the response depends on the way(s) that the particular species/organism detects and uses light or sounds. There is a wide range of different approaches that have evolved to capture light information, including diverse visual pigments, rhabdomeric and ciliary photoreceptors, and compound and camera eyes (Falcón et al., 2020; Land & Nilsson, 2012). Similarly, sound sensing approaches extend from mechano-sensing of acoustic cues by plants (Appel & Cocroft, 2023; Demey et al., 2023), triggering defence mechanisms in response to the vibrations from insects checking on their leaves (Appel & Cockcroft, 2014), to the antennal and tympanal ears of insects (Albert & Kozlov, 2016) and the three-part (outer-middle-inner ear) hearing system of mammals.

Differences in hearing systems and the ways in which animals utilise sound are reflected in differences in audiograms and the peak hearing thresholds (Jäckel et al., 2022). In noise-polluted environments where noise masks communication within the peak hearing frequency range, animals can often adjust their calls to (for example, by changing frequency and/or amplitude) to still be heard (Duquette et al., 2021). However, depending on the characteristics of the NP exposure, significant communication interference may occur (Botteldooren et al., 2025). Masking is just one of the ways in which NP impacts terrestrial wildlife, but it clearly illustrates that species differ in their responses to noise. This can constrain their realised acoustic niche and influence their spatial ecology as a result (Habib et al., 2026).

Anthropogenic LP has been shown to alter spatio-temporal niches, modifying species interactions, from predator-prey dynamics to parasite-host interactions (Seymoure et al., 2023). Differences in light detection systems influence the spectral response of wildlife, and there are notable differences in photopigment peak sensitivities across taxa (Longcore, 2023). This is true for both nocturnal and diurnal wildlife (*Figure 10*).

Figure 10: Photopigment peak sensitivities across taxa for (a) nocturnal and (b) diurnal species. Data used to create figures were obtained from the database developed by Longcore (2023).



As well as differences between species in their response to LNP, differences between sexes have also been reported. For example, in twilight foraging sweet bee species (*Megalopta spp.*), males have increased retinal sensitivity to females (Jones et al., 2020). Studies of moths have found males to be more attracted to light than females (Altermatt et al., 2009), but males from light-polluted areas seem to have a modified response to light that results in a 'flight-to-light' response that is similar to that exhibited by females from areas with low levels of LP (Altermatt et al., 2016). Therefore, there are differences in the response to LNP from the species to the individual organism level.

6.5 - Are there levels of light and noise exposure below which no response is observed?

As is evident from Chapter 3, Sound Pressure Level (SPL) is often used to quantify 'noise' within studies and illuminance to quantify 'light'. For SPL, values are generally reported in dB or in dB(A) (the human-centric, i.e. A-weighted, measure of SPL). For illuminance, the unit of lux (lx) is commonly used. Although individual studies may report exposure levels below which no effect is observed, meta-analyses suggest that, when the various studies are viewed in totality, there is little clear evidence of light and noise exposure levels below which no response is observed. For example, the illuminance (lx) of the full moon in temperate latitudes is c. 0.05 – 0.1 lx during the summer (Kyba et al., 2017) and urban skyglow is c. 0.15 lx (Gaston et al., 2013). Within or below this illuminance range, animals have been shown to respond. For example, there is evidence of increased prey detection by the common toad (*Bufo bufo*) (0.0003 lx; Larsen & Pedersen, 1982), circadian rhythm alterations in Syrian hamsters (*Mesocricetus auratus*) (0.01 lx; Evans et al., 2007), and increased activity levels in fruit flies (*Drosophila melanogaster*) (0.03 lx; Bachleitner et al., 2007). For noise, the Leq (dB re 20 μPa) in a rural environment is c. 35–40 dB (Albert & Decato, 2017; EEA, 2014), yet modification of bird vocalisations has been reported from as low as 23dB (Nelson-Olivieri et a., 2024). It is clear from these examples alone that impacts from LNP are detectable within the normal background range for rural and natural nighttime environments. Given that there is the potential for any anthropogenic LNP to impact wildlife, the default position should be to minimise all such exposures.

6.6 - Can thresholds of exposure be meaningfully defined?

Whilst there is no single 'safe dose' or 'safe spectrum' (Czarnecka et al., 2025) due to the vast array of sensitivities to light and noise amongst different species, it is unrealistic to expect that human activities should only be approved if they do not generate increased anthropogenic light or noise in the environment. To help with decision-making, such as whether an environmental regulator should permit a particular activity to occur in a given area, it would be beneficial to have thresholds of exposure to screen out those situations where overall impact is likely to be minimal (i.e. would not be expected to impact significantly at the population level). This is different to the minimum level at which any response may be observed.

When defining thresholds, consideration needs to be given to how noise and light are commonly measured and reported, both in a regulatory context and also in research publications. Whilst it is recognised that the spectral composition of noise and light plays a significant role in the way that organisms respond, this information is seldom available within studies on the effects of these sensory pollutants on wildlife (Dincel et al., 2025). Similarly, most measurements that are reported in monitoring and regulatory contexts are done using instruments that are primarily designed for human-relevant monitoring and/or do not provide detailed spectral information. Therefore, for considering thresholds based on current knowledge and practice, the most pragmatic approach is to use the general measures of Sound Pressure Level and Illuminance, whilst acknowledging their limitations and the uncertainty that this introduces.

Values of 55 dB Lden and 50 dB Lnight are referenced in the Environmental Noise Directive (Directive 2002/49/EC) as levels to which noise from transportation and industry should be reduced to minimise impacts on human health. The European Environment Agency (2020) noted that these may not be the ideal thresholds (or indeed metrics) to use for wildlife, given that significant noise impacts in wildlife have been reported in the 40–50 dB LAeq range. For example, Reijnen et al. (1996) found, on average, that 47 dB(A) was the threshold for population reductions in coot, meadow pipit, shoveler, skylark, lapwing, black-tailed godwit and oyster catcher. This was used by Helldin et al. (2013) to propose 45–50 dB LAeq as an impact zone that would represent a 10% decrease in habitat quality. A relatively recent review of noise impacts on wildlife (Nelson-Olivieri et al., 2024) also noted that noise levels <50 dB can elicit population-level effects and that >95% of studies report significant biological responses at 90dB across various taxonomic groups. Therefore, for screening purposes when considering the potential for population-level impacts, a threshold of 45 dB LAeq may be appropriate.

For light, the identification of a potential threshold is more challenging. The reasons for this are two-fold: (i) low levels of illumination (<5 lx) have been found to induce biological and ecological effects with potential population consequences; and (ii) light pollution spreads over much greater distances from source than does noise pollution so, depending on the species considered, could enhance illumination over a significant part of a population's range. For example, illumination as low as 0.3 lx has been shown to modify reproductive physiology in the European blackbird (*Turdus merula*), advancing reproductive system development by up to one month (Dominoni et al., 2013). Such reproductive effects have a significant potential to lead to population effects.

6.7 - Are mechanisms of light and noise pollution impacts on terrestrial wildlife clearly defined?

There are various levels at which the mechanisms of LNP impacts on terrestrial wildlife, biodiversity and ecosystem services more broadly have been elucidated. Gaston et al. (2013) identified limited evidence for the mechanisms by which light impacts wildlife but proposed a framework for identifying the influence of LP across species and ecosystems. A key element of that framework is the distinction between light as a source of information and light as a resource. Viewed in this way, there is a clear fundamental difference between LNP in the sense that noise, or, more correctly, sound, is an important source of information for organisms, but is highly unlikely to act as a resource. More recent studies (e.g. Falcon et al, 2020) have advanced mechanistic understanding from the organism to the ecosystem level, but there are still many aspects of the mechanisms of impact that remain poorly understood. Laboratory studies can help to explain patterns observed in nature and mechanisms of impact (Slabbekoorn et al., 2018), but extrapolating from laboratory studies to field studies is not a straightforward process. Translating the findings from experiments into environmental management plans should be approached with caution (Roser & Koper, 2023).

6.8 - Is there direct/indirect evidence of light and noise pollution impacts on terrestrial ecosystem services?

Circadian clocks play an important role in synchronising pollination traits in bees and plants (Bloch et al., 2017). LP disruption to this synchronisation will directly impact the pollination ecosystem service. Similarly, ALAN sources can alter the night-time colour environment, causing some flowers to be more visible to pollinators than they would under normal night-time light spectra conditions (Macgregor et al., 2020). This artificially enhanced attractiveness of some plants relative to others may disrupt community level plant-pollinator interactions, impacting the pollination service as a result (Macgregor et al., 2019), and measurable impacts on plant reproduction have been reported (Knop et al., 2017). Similarly, seed dispersal has been shown to be impacted by noise due to changes in the abundance and behaviour of seed predators and dispersers (Francis et al., 2012). Whilst some evidence on the impacts of LNP on ecosystem services exists, the evidence to date is limited. As this area of research expands, and more is learned about the detailed mechanisms of impact, a more comprehensive picture of the ways in which anthropogenic light and noise pollution impact ecosystem services is expected to develop.

7 - Summary

The review demonstrates that: (i) both light an noise pollution impact terrestrial wildlife; (ii) synergistic effects can occur when organisms are exposed to both light and noise pollution in combination rather than individually; (iii) species differ in their response to these sensory pollutants based on the ways that they detect and use light and sound; (iv) although light and noise pollution impacts have been documented at levels within the range of normal background conditions, there is the potential that screening thresholds can be defined for population level impacts; (v) mechanisms of light and noise pollution impacts have been elucidated to varying degrees; (vi) laboratory studies can help to further define these mechanisms and help to explain patterns observed in field studies; (vii) there is evidence of both direct and indirect effects on ecosystem services. However, the review also highlights that studies on light and noise pollution across many taxa and geographic locations are limited. Mechanistic understanding of impacts is similarly limited, especially when extending from the individual to the ecosystem scale. Future work needs to prioritise addressing these limitations, using methods to quantify light and noise exposures in ecologically meaningful terms rather than relying on approaches and quantities that are specifically weighted towards human responses to these sensory pollutants.

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