PLAN-B

Tackling light and noise pollution

EXISTING MEASURES FOR PRE-VENTING AND MITIGATING LP&NP IMPACTS ON TERRES-TRIAL BIODIVERSITY AND ECO-SYSTEM SERVICES

DELIVERABLE 5.1

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Author(s):	Pawel Tysiac (Gdansk Tech), Karolina Zielinska-Dabkowska (Gdansk Tech), Yana Yakushina (UGENT), Graeme Sherrif (USAL), Michael Lomas (USAL), Camilla P. Teixeira (UEMG), Vinícius Goulart (UEMG), Joanna Badach (Gdansk Tech), Catherine L. Barnett (UKCEH), Katarzyna Bobkowska (Gdansk Tech), Adam Inglot (Gdansk Tech), Reinhard Arnold Klenke (MLU), Geert Van Hoorick (UGENT), Michael D. Wood (USAL)
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List of Acronyms

AA	Appropriate Assessment
AI	Artificial Intelligence
ALAN	Artificial Light at Night
CCT	Correlated Colour Temperature
COP	Communities of Practice
CBD	Convention on Biological Diversity
CMS	Convention on the Conservation of Migratory Species of Wild Animals
D	Deliverable
dB	Decibel
EC	European Commission
END	Environmental Noise Directive
EAP	Environment Action Programme
EIA	Environmental Impact Assessment
ELIA	Environmental Lighting Impact Assessments
EU	European Union
GBF	Kunming-Montreal Global Biodiversity Framework
h	Hour
Hz	Hertz
K	Kelvin
Lden	Day- Evening- Night noise level
LED	Light-Emitting Diode
L_{eq}	Equivalent Noise Level
lm	Lumen
Lnight	Night-time noise level
LP	Light pollution
LNP	Light and noise pollution
LPI	Living Planet Index

lx	Lux
NBSAPs	National Biodiversity Strategies and Action Plans
NGO	Non-Governmental Organization
NRL	Nature Restoration Law
NP	Noise pollution
NLP	Nocturnal light pulses
nm	Nanometre
NP	Noise pollution
SEL	Sound Exposure Level
SEM	Scanning Electron Microscope
SMDH	Standard Mean Difference (Hedges' g)
SPL	Sound Pressure Level
T	Task
TBES	Terrestrial biodiversity and ecosystem services
ULP	Urban Lighting Plans
ULR	Upward Light Ratio
µPa	Micropascal
ZPAP	Zero Pollution Action Plan

Executive Summary

Artificial light at night (ALAN) and anthropogenic noise are increasingly recognised as important environmental pressures on terrestrial biodiversity and ecosystem services (TBES). This deliverable (D5.1) provides a structured review of existing measures for preventing and mitigating the impacts of light pollution and noise pollution (LNP) on TBES. The review is based on published scientific literature, PLAN-B evidence-mapping outputs, selected legal and policy instruments, technical guidance, reference documents and supporting implementation input from Communities of Practice (CoP).

The review groups existing mitigation measures into five practical families: regulatory, planning, technological, environmental and social measures. Regulatory measures create formal requirements, policy conditions and governance opportunities for mitigation. Planning measures identify where exposure should be avoided, reduced or spatially controlled, for example, through the protection of dark corridors, quiet areas, ecological networks and sensitive habitat edges. Technological measures reduce or modify emissions at source or along the exposure pathway, including through shielding, adaptive dimming, spectral control, low-noise surfaces, quieter equipment and sensor-based operation. Environmental measures provide species/taxon-specific protection through habitat buffers, screening vegetation, earth berms, refuges and restoration-oriented actions. Social measures, including awareness, citizen science, stewardship, codes of practice and stakeholder engagement, support acceptance, compliance, reporting and long-term maintenance.

A key finding is that evidence is generally stronger for exposure reduction than for documented biodiversity recovery or ecosystem-service improvement. The implementation of a measure does not automatically demonstrate ecological effectiveness. A measure is ecologically relevant when it reduces the exposure pathway that matters for sensitive species, organism groups, habitats, ecological processes or ecosystem-service functions, at the right place, time and spatial scale. Where feasible, this should be validated through taxon-specific monitoring, implementation checks and ecological response indicators.

The review also shows that light and noise pollution are still frequently overlooked or addressed inconsistently, despite the fact that both pressures often occur simultaneously within the same habitats, ecological corridors, protected area boundaries, transport networks, and recreational landscapes. Future mitigation efforts should ensure that both forms of pollution are systematically considered in planning and management processes. In addition, where feasible, opportunities for integrated mitigation should be explored. Where light and noise pollution affect the same receptors or exposure pathways, combined mitigation measures may offer a more effective approach than addressing each pressure separately.

The review concludes that mitigation should start from the ecological problem, not from the measure itself. The key question is what pressure affects which species, habitat or ecological function, and where this exposure occurs. Future work should develop practical tools for measuring light and noise from the point of view of species and habitats, improve monitoring, and support combined light-noise mitigation where both pressures occur together. Biodiversity-sensitive mitigation should also become part of planning, procurement, permitting, protected-area management and long-term maintenance.

1. Introduction

Artificial light at night (ALAN) and anthropogenic noise are increasingly recognised as sensory pressures that affect terrestrial biodiversity and ecosystem services (TBES). They represent concerns that pose various negative impacts, including on human comfort, urban quality and environmental management. ALAN has been described as a form of ecological light pollution because it alters natural light regimes that organise biological rhythms, movement, orientation, species interactions and ecosystem processes (Gaston et al., 2015; Gaston & Sánchez de Miguel, 2022; Hölker et al., 2010; Longcore & Rich, 2004). Similarly, anthropogenic noise is now recognised as a conservation-relevant sensory pollutant because it can interfere with acoustic information used by organisms to communicate, detect predators or prey, orientate, forage and reproduce (Francis & Barber, 2013; Halfwerk et al., 2011; Shannon, McKenna, Angeloni, Crooks, Fristrup, Brown, Warner, Nelson, White, Briggs, McFarland, et al., 2016). **In this sense, light pollution (LP) and noise pollution (NP) should be understood as ecological pressures that modify the sensory conditions through which organisms perceive habitats, detect resources and risks, communicate, move, reproduce and maintain daily or seasonal activity patterns** (Dominoni et al., 2020). Their relevance is also spatially extensive: artificial sky brightness affects large parts of the global night-time environment, satellite observations show continued growth in lit area and radiance, and anthropogenic noise can penetrate protected landscapes (Buxton et al., 2017; Falchi et al., 2016; Kyba et al., 2017).

The ecological effects of light and noise pollution (LNP) are not determined only by the overall level of exposure. For ALAN, intensity is important, but organisms also respond to **spectral composition, wavelength distribution, directionality, timing, duration and spatial context**. Artificial lighting may alter broader night-time sky-brightness regimes, while changes in lighting technology can shift the spectral signatures of illuminated habitats (Bennie, Duffy, et al., 2015; Davies, Bennie, Inger, De Ibarra, et al., 2013; Davies, Bennie, Inger, & Gaston, 2013). **A reduction in one spectral component, or a shift towards a visually "warmer" light source, should therefore not automatically be interpreted as ecologically harmless.** Different organisms perceive and respond to different parts of the spectrum, and the ecological significance of a lighting intervention depends on the full spectral distribution, the target species group, the timing of exposure and the surrounding habitat context (Davies, Bennie, Inger, De Ibarra, et al., 2013; Gaston & Sánchez De Miguel, 2022; Owens & Lewis, 2018; Spoelstra et al., 2017).

Similarly, the ecological relevance of anthropogenic noise cannot be assessed only through average sound-pressure level. Decibel-based indicators are useful, but they do not fully describe how organisms experience acoustic disturbance. **Frequency composition, masking potential, intermittency, temporal pattern, propagation conditions and the overlap between noise frequencies and biologically relevant communication or perception bands are also critical** (Brumm & Slabbekoorn, 2005; Francis & Barber, 2013; Shannon, McKenna, Angeloni, Crooks, Fristrup, Brown, Warner, Nelson, White, Briggs, McFarland, et al., 2016; Slabbekoorn & Ripmeester, 2008). A sound source may be ecologically important because it masks mating calls, alarm signals, predator or prey cues or other acoustic information used by organisms. Traffic and infrastructure noise, for example, may affect reproductive success, communication distance, habitat use and behavioural allocation even when the relevant mechanism is not only energetic stress but also acoustic masking or altered risk perception (Halfwerk et al., 2011; Kunc & Schmidt, 2019).

Different organism groups may respond to LNP in different ways. Artificial light can attract or disorientate insects, alter bat movement and foraging behaviour, affect bird activity and community abundance, and influence amphibian calling or breeding-site use (D. Dominoni et al., 2020; Lewanzik & Voigt, 2014; Owens et al., 2020;

Owens & Lewis, 2018; Smit et al., 2022; Spoelstra et al., 2015, 2017; Wilson et al., 2021). Noise can mask communication, warning signals or other sounds used by animals and may therefore affect behaviour, reproductive performance and habitat suitability (Francis & Barber, 2013; Kunc & Schmidt, 2019; Shannon, McKenna, Angeloni, Crooks, Fristrup, Brown, Warner, Nelson, White, Briggs, McFarland, et al., 2016; Slabbekoorn & Ripmeester, 2008). These responses may seem species-specific, but they can also affect wider ecological processes. This matters for TBES because changes in movement, communication, breeding, foraging and habitat use can influence pollination, seed dispersal, biological control, decomposition, nutrient cycling, ecological connectivity and the cultural value of dark and quiet landscapes (Bennie, Davies, et al., 2015; Bennie et al., 2016; Knop et al., 2017; Lewanzik & Voigt, 2014). **For this reason, mitigation measures should be assessed by whether they reduce ecologically relevant light and noise exposure for the species, habitats and processes that support TBES.**

This deliverable provides an overview of existing solutions for preventing and mitigating the impacts of LNP on TBES. In line with the PLAN-B task description, it examines existing methods and tools used in Europe and internationally at different governance levels. The review brings together published research, including empirical studies and monitoring-based assessments; binding and non-binding regulatory instruments such as guidelines, standards, legal and policy instruments; impact assessment frameworks; and feedback from Communities of Practice (CoP). This broad scope is necessary because mitigation measures are not all supported in the same way. Some have been tested in field studies, while others are mainly supported by guidance, regulation or practical experience. Many decisions that shape mitigation are made above the local level, through international, European, and national governance levels. However, their practical effect depends on how they are applied in regional planning, local management, site-specific decisions and stakeholder involvement (European Parliament and Council of the European Union, 2002; CMS, 2024).

This report does not aim to provide a universal ecological threshold for all species or places. Such a threshold would be scientifically unrealistic because responses vary among taxa, life stages, behaviours, habitats, seasons and exposure regimes (Gaston et al., 2015; Halfwerk & Jerem, 2021; Shannon, McKenna, Angeloni, Crooks, Fristrup, Brown, Warner, Nelson, White, Briggs, McFarland, et al., 2016). Instead, the report provides a structured review of available mitigation solutions and organises them according to **pressure type, family of the measure (regulatory, planning, environmental, technological, social), exposure pathway, implementation context and monitoring need**. This approach supports practical decision-making while recognising uncertainty and the need for ecological judgement.

A central assumption of the report is that mitigation should be evaluated by its capacity to reduce relevant exposure and, where feasible, to support measurable ecological response. Installing a shielded luminaire, a low-noise surface, a quiet zone or a dark corridor should not be treated as sufficient by itself. Where appropriate, each measure should be interpreted by asking whether it helps **avoid, reduce, redirect or manage the relevant light, noise or combined pressure in a way that fits the ecological objective, the organisms or habitats concerned, the timing, the spatial scale and the implementation context**. Monitoring is important for checking whether exposure has changed, whether the measure or measure package has been implemented as intended and, where feasible, whether ecological responses can be observed. In practice, measures should be selected and combined as complementary actions. The following ecological exposure dimensions are used throughout the report to interpret the relevance of mitigation measures for TBES. Examples of ecological exposure dimensions and their relevance to TBES are shown in *Table 1.1*.

Table 1.1. Examples of ecological exposure dimensions and their relevance to TBES.

Ecological exposure dimension	Why it matters for TBES
Level	Higher light or noise exposure can increase disturbance, avoidance, attraction, disorientation, masking, habitat displacement or changes in activity patterns.
Wavelength / spectrum	Different organisms respond differently to blue-rich, amber, red or broad-spectrum light. Reducing one spectral component does not necessarily remove risk for all species groups.
Frequency	Noise effects depend not only on sound-pressure level, but also on frequency composition, acoustic masking and overlap with biologically relevant communication, orientation or detection bands.
Timing and duration	Exposure during breeding, migration, dispersal, foraging, calling, roosting or nocturnal activity can be more harmful than exposure at less sensitive times.
Spatial scale	Effects depend on whether exposure occurs at a lamp, façade, road section, infrastructure corridor, habitat patch, breeding site, roost, ecological corridor, protected-area edge or landscape scale.

In summary, LNP affect TBES by altering the sensory conditions under which organisms interact with their environment. Effective mitigation therefore requires attention to level, wavelength, frequency, timing, duration and spatial scale, interpreted through habitat context and ecosystem-service relevance. **This report provides a practical basis for that task by reviewing existing mitigation measures and framing them as tools for reducing ecologically relevant exposure across governance and implementation contexts.**

2. Evidence base and analytical approach

This chapter explains how the evidence base for D5.1 was assembled and organised. The aim was to support a practical review of existing measures for preventing and mitigating the impacts of LNP on TBES.

The review builds on **interdisciplinary work conducted within the PLAN-B project.** The main research-trace layer was provided by **WP1 Task 1.1**, which collects and organises bibliographic evidence on the impacts of LNP on TBES. The curated bibliographic library was used to prepare outputs for D5.1 and to identify possible links between **publications, pressure domains, species groups, mitigation measures and monitoring needs (supplementary to this article).** This material was not treated as a structured evidence-mapping layer supporting the organisation of the review.

Earlier PLAN-B outputs and related task materials were used where relevant to provide **scientific, methodological and implementation context.** Selected reference documents, including guidance, technical and policy-oriented material, were used to support interpretation of existing measures, their practical meaning and their relevance for WP5. In this way, D5.1 uses previous project work as a foundation for **identifying and interpreting existing prevention and mitigation measures**, without repeating the full methodological detail of the underlying database or screening workflow. The evidence collected also included **an internal review of legal and policy instruments** directly and indirectly applicable to LNP. This review covered both **binding regulatory instruments**, such as laws, regulations and formal legal requirements, and n**on-binding instruments**, such as standards, guidelines, policy documents, strategies and good-practice recommendations.

Other PLAN-B and practice-oriented materials, including **CoP discussions, workshop notes and feedback from public authorities, environmental agencies, municipalities and related projects**, were used as contextual implementation input. Within the analytical workflow, this material supported qualitative interpretation of **stakeholder roles, feasibility, acceptance, governance barriers, monitoring needs and implementation conditions**. It was used to support **expert judgement, and consistency checks** but was not treated as independent evidence of ecological effectiveness or weighted in the same way as scientific evidence. This allowed the review to reflect **practical implementation experience** without reproducing the full stakeholder-analysis workflow in the report.

2.1 Evidence sources

The evidence base combined **scientific, technical, policy, legal and practice-oriented sources** because no single source category was sufficient to describe both **the ecological relevance and the practical implementation of existing LNP mitigation measures.** Scientific literature provided the principal evidence layer for **identifying ecological mechanisms, exposed species groups, taxa-specific responses, links with terrestrial biodiversity and ecosystem services, and examples of measures already discussed or tested in research**. It was also used to identify exposure variables, response indicators, study designs and areas in which evidence remains incomplete. **Guidelines, standards, handbooks, and technical reports** were used primarily to understand **how measures are described and applied in practice.** These sources supported the interpretation of technical specifications, monitoring expectations, operational requirements, implementation sequences, and common constraints. **Because many such documents were developed for human health, or engineering, their biodiversity relevance was assessed separately.** Policy and legal documents were used to **identify the governance of conditions under which measures may be required, permitted, funded, monitored, or enforced**. This layer included binding and non-binding instruments and supported the identification of regulatory competences, procurement requirements, permit conditions, implementation responsibilities, and potential conflicts between regulatory areas. CoP material was used as a **separate contextual layer**. It included discussions with public authorities and environmental agencies, municipal workshops, exchanges with related projects, and implementation-oriented meeting notes. Examples included discussions with climate-policy actors and city-level representatives, exchanges with environmental-agency practitioners, and feedback from organisations working in areas such as zoological management.

A curated bibliographic library in `.bib` format, containing **44,196** entries and developed as part of Task 1.1, was combined with a selected set of reference packages used in the screening. **Rule-based text matching** identified combinations of signals relevant to Deliverable 5.1 (D5.1). These included:

- **the pressure addressed** - light pollution, noise pollution, or both;
- **links to terrestrial biodiversity, organism groups or ecosystem-service pathways**;
- references to **mitigation, prevention, monitoring, implementation or governance**; and
- where available, information on **study design, indicators or stakeholder relevance**.

Entries showing several signals of a possible connection with existing mitigation measures were classified as being of **potential interest.** Materials useful for contextual interpretation, but not necessarily describing a measure directly, were assigned to the supporting-information category. In total, the screening **identified 23,742 entries of potential interest to D5.1 and 14,854 entries that could provide supporting information** (*Figure 2.1.1*). These counts should be understood as evidence-mapping outputs.

Other evidence components and interpretative layers used in the review are summarised in *Table 2.1.1*. The table indicates whether each source category contributed to **direct evidence, contextual interpretation, implementation understanding, filtering support or expert judgement.**

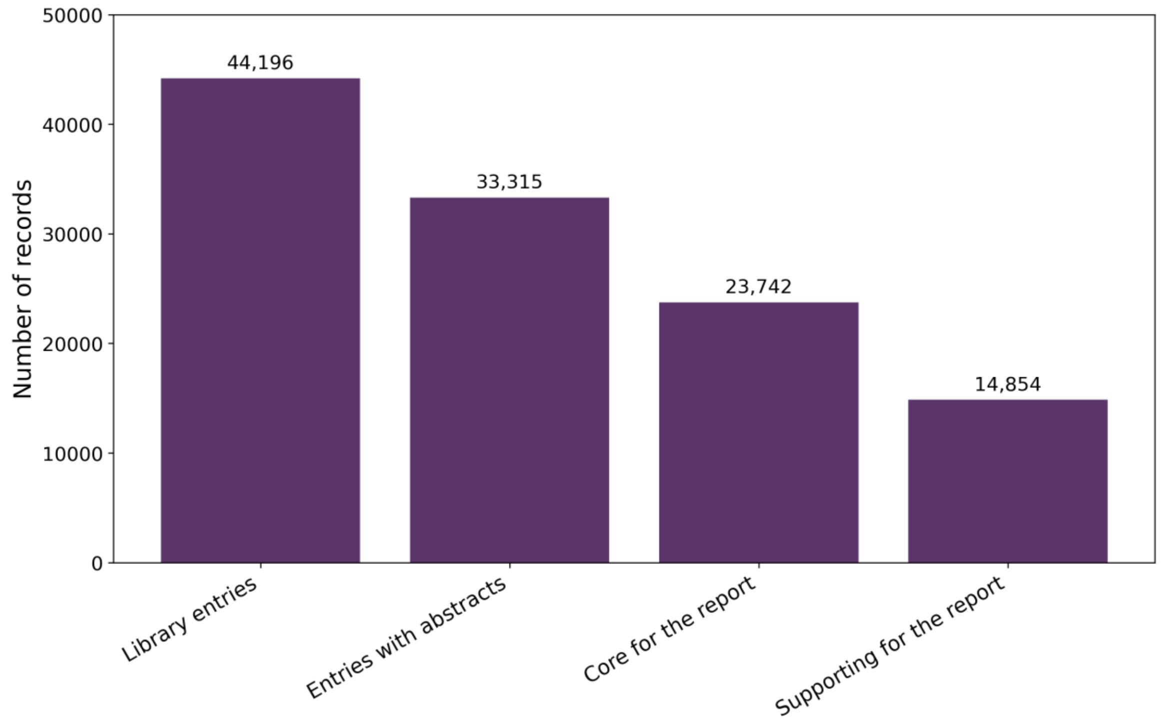


Figure 2.1.1 Bibliographic screening overview.

Table 2.1.1. Summary of evidence components and their role in D5.1.

Evidence component / source	Role in the review	How it was used
Curated bibliographic library developed under WP1 Task 1.1	Main research-trace layer	Used to prepare working outputs for D5.1 and to identify possible links between publications, pressure domains, pollution sources, measure families, organism groups, TBES relevance, evidence type, study design, threshold language and source-to-measure links.
D1.1 "Review of light and noise pollution impacts on terrestrial biodiversity and ecosystem services"	Scientific and methodological grounding	Used to link the measure review to the wider PLAN-B evidence base on LNP impacts on TBES.
Selected reference documents and other scientific literature	Supplementary evidence and contextual interpretation	Used to clarify measure definitions, ecological pathways, species relevance, implementation examples, monitoring approaches and evidence limitations.
Legal and policy instruments	Regulatory and governance context	Used to identify binding and non-binding instruments, governance dependencies, implementation obligations, planning opportunities, permit conditions, procurement links and potential legal or institutional barriers.
CoP input, stakeholder feedback and implementation materials	Supporting practical/ contextual input	Used to interpret stakeholder roles, feasibility, implementation barriers, acceptance and local management condi-

		tions. This material contributed to implementation appraisal and consistency checks but was not treated as independent evidence of ecological effectiveness.
TOP summaries by mapped source support	Evidence-mapping and filtering support	Used to identify measure classes most frequently linked to the reviewed material. These summaries were not interpreted as rankings of ecological effectiveness, implementation priority or transferability.
Expert judgement and consistency checks	Interpretative control layer	Used to distinguish between evidence of exposure reduction, plausible ecological relevance, implementation feasibility and demonstrated biodiversity or ecosystem-service response. Expert judgement was also used to avoid treating automated tags, source counts or general policy language as direct proof of effectiveness.

The evidence base was not geographically uniform. **The bibliographic layer** was broad and international, but many implementation examples, legal instruments, technical guidelines and practitioner-oriented materials were more strongly connected with European contexts and with countries and governance settings most relevant to PLAN-B. Some examples also reflect better-documented contexts, including the United Kingdom and Western or Central European practice. For this reason, the review does not assume that a measure described in one country, habitat or regulatory setting can be transferred directly to another. Geographic coverage, governance context, habitat type, species group, monitoring capacity and implementation conditions were therefore treated as important limitations when interpreting transferability.

The screening process identified **8,261 light-related publications, 10,471 noise-related publications and 1,374 publications tagged as addressing both light and noise impacts** (*Figure 2.1.2*). A large group of publications remained unspecified at the screening stage, which is expected because the bibliographic library used was created for broader use within PLAN-B. Taken together, these records identified in *Figure 2.2.2* were used as an evidence map for the review. The presence of a measure in the evidence base was not treated as proof that it is ecologically effective, ready for implementation or suitable for every context. Instead, **the publications were used to trace where measures were described, what type of evidence supported them, and where information was strong, partial or missing.** The following sections use this evidence base to classify and interpret existing measures according to pressure addressed, practical role, biodiversity and ecosystem-service relevance, monitoring information and implementation context.

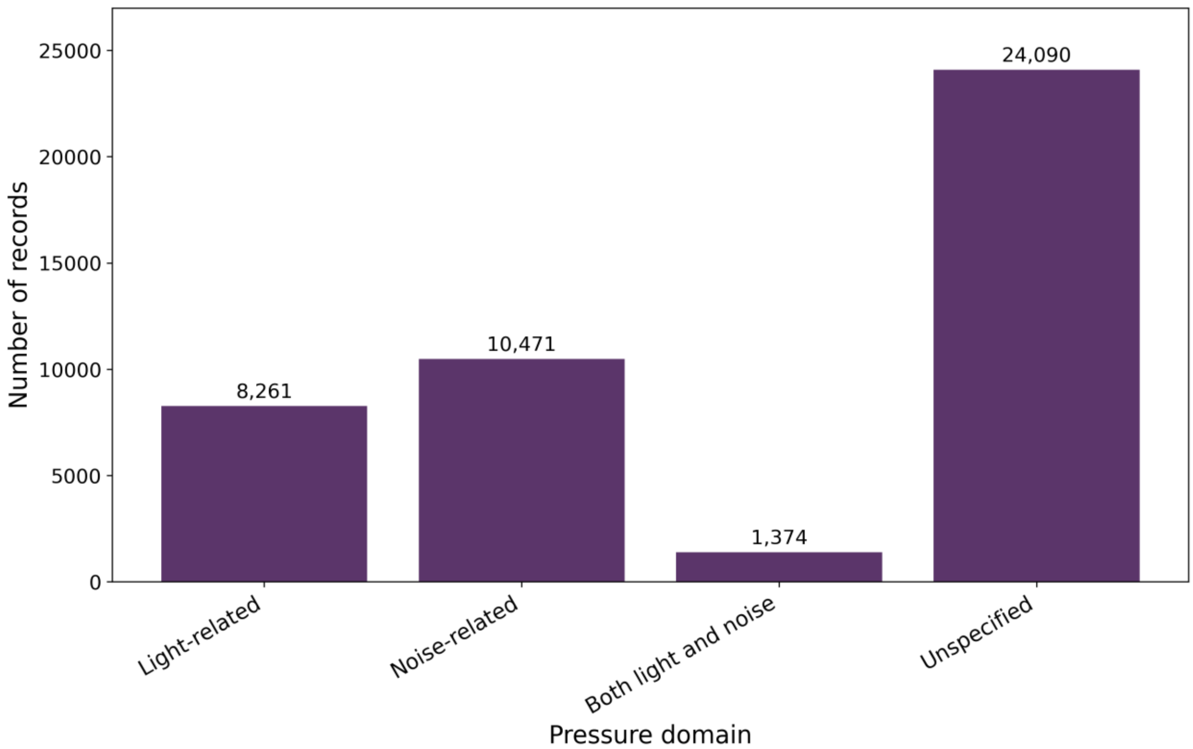


Figure 2.1.2 Distribution of data-mined entries by pollution source.

To prevent implementation-oriented material from being mistaken for ecological evidence, the analytical workflow used two related but separate assessment stages. First, a biodiversity-relevance **gate checked** whether a measure was sufficiently described, linked to taxa or terrestrial biodiversity and ecosystem services, measurable through exposure or response indicators, aligned with biodiversity-relevant outcomes, and supported by at least partial threshold or metric information. **Measures with incomplete ecological links were retained for review, where appropriate, but were not automatically presented as biodiversity-effective**. Second, **an implementation appraisal considered evidence of strength and diversity together with jurisdictional coverage, stakeholder readiness, maturity of engagement, feasibility, cost-effectiveness and implementation scale. CoP and stakeholder material contributed mainly to this second stage.** It helped clarify whether relevant actors had been identified, whether responsibility for implementation, monitoring, enforcement or coordination was plausible, and whether known acceptance or governance barriers could affect delivery.

The two stages were not interchangeable. Strong stakeholder support could not compensate for the absence of a credible biodiversity pathway, taxon-specific link, or monitoring logic. Conversely, a scientifically plausible measure could still be identified as implementation-limited where responsibilities, enforcement, resources, or local acceptance were weak. **The final interpretation, therefore, gave greater importance to ecological relevance while retaining implementation of readiness as a separate and necessary consideration.**

2.2 Identification of existing mitigation measures

The identification of mitigation measures followed a conservative review boundary. The aim was to retain measures that are already described in the **literature, regulatory instruments or practical implementation materials** (such as guidelines and standards). A measure was included when it represented **a recognisable action that could prevent, reduce, modify, redirect or manage ecologically relevant exposure** to artificial light, anthropogenic noise or combined light and noise pressure.

In practical terms, measures were identified in two steps. First, individual measures were detected in the reviewed material and stored in a **Relational Database Management System** (RDBMS). We chose the small and portable **RDBMS SQLite** (https://sqlite.org/), which is free and Open Source. The individual measures reported and found by our search could appear as **specific actions, tools, planning approaches, regulatory instruments, management practices or implementation recommendations**. Secondly, similar individual measures were combined into broader **measure classes when they had the same main function or ecological purpose**. For example, shielding, cut-off luminaires, spill-light reduction and directional lighting may appear as separate individual measures, but they can be combined into a broader measure class when their shared function is to reduce unwanted light exposure. Similarly, quiet areas, quiet zones, acoustic refuges and noise-sensitive zoning may differ in legal or planning context, but they can be grouped when their common purpose is to protect species from harmful noise exposure.

Three simple questions guided the inclusion and interpretation of measures. First, is the action already described in the reviewed material as an existing or usable measure? Secondly, does it address artificial light, anthropogenic noise or a clearly combined light and noise problem? Thirdly, can it help reduce or manage an exposure pathway that matters for biodiversity, such as intensity, spectrum, frequency, masking, timing, duration, directionality or spatial spread? **Measures that could be answered positively through the available material were retained as existing measures and then grouped where appropriate.**

The review also **distinguished between single-pressure and combined-pressure measures**. A measure was treated as addressing both light and noise only when it required joint planning, implementation or monitoring, or when it clearly addressed co-occurring light and noise exposure in the same ecological setting. Measures that simply mention light and noise side by side were treated more cautiously, because combined mitigation should not be reduced to two separate checklists placed next to each other.

The database was therefore used as a structured review tool. It helped identify **individual measures, group similar measures into broader classes, trace them back to source material and compare how much information was available for each measure**. However, the number of source links should not be read as a ranking of ecological effectiveness. A high count in *Figure 2.2.1* means that a measure or measure class was frequently found in the reviewed material, but it does not prove that it is the best option, that it will work everywhere, or that it is sufficient without local assessment and monitoring. **The interpretation of each measure therefore depends on the quality of the source material, its biodiversity relevance, available monitoring information, implementation context and possible contribution to ecosystem-service outcomes.**

Figure 2.2.1 Top measure classes by mapped source support.

2.3 Analytical organisation of the material

After the existing mitigation measures had been identified, the material was organised in the working database so that evidence from different sources could be compared in a consistent way. **The database role was to keep the information traceable and to show how each measure was linked to source material, ecological relevance, implementation context and monitoring information.** The organisation followed a simple logic (*Figure 2.3.1*). Source material first provided **evidence signals, such as the pressure addressed, the exposure pathway affected, the species group concerned, the implementation context and the monitoring information available.** These signals were then linked to individual measures and, where appropriate, to broader measure classes. This was useful because the reviewed material often used different names for similar actions. **The database therefore helped keep details of individual measures while allowing the report to present them in a clearer and more practical form.**

Each measure or measure class was described through four main groups of information. The first group described what the measure is, including **the pressure domain, measure family, setting and practical mechanism**. The second group described why the measure may matter ecologically, including the **exposure pathway, species relevance, habitat relevance and possible links to terrestrial biodiversity and ecosystem services**. The third group described how the measure may be implemented, including **responsible actors, governance needs, implementation setting and practical constraints**. The fourth group described how the measure may be checked, including **exposure monitoring, biodiversity monitoring, implementation checks, evidence limitations and remaining gaps**.

This structure was important because a measure can be strong in one respect and weak in another. A measure may be technically feasible but poorly monitored. It may reduce human exposure but have limited evidence for biodiversity. It may be ecologically relevant but difficult to enforce. It may also appear frequently in the evidence base without being proven to restore biodiversity or ecosystem-service functions. The analytical organisation therefore helped separate description, ecological interpretation, implementation context and evidence limitations.

Figure 2.3.1 summarises this organisation. **It shows how source material was translated into evidence signals, how these signals were linked to existing measures and measure classes, and how the resulting information was used in the review.** The figure should be read as an evidence-organisation model, not as a ranking system. It explains how the database supported the review by organising and tracing information, while t**he interpretation of ecological effectiveness still required judgement, monitoring information and consideration of local or sector-specific implementation conditions.** The summaries of measure classes by mapped source support are provided as supplementary material to this report. They present which measure classes were most frequently linked to the reviewed material in the working database. **These summaries should be interpreted as evidence-mapping outputs, not as rankings of ecological effectiveness, implementation priority or universal transferability.**

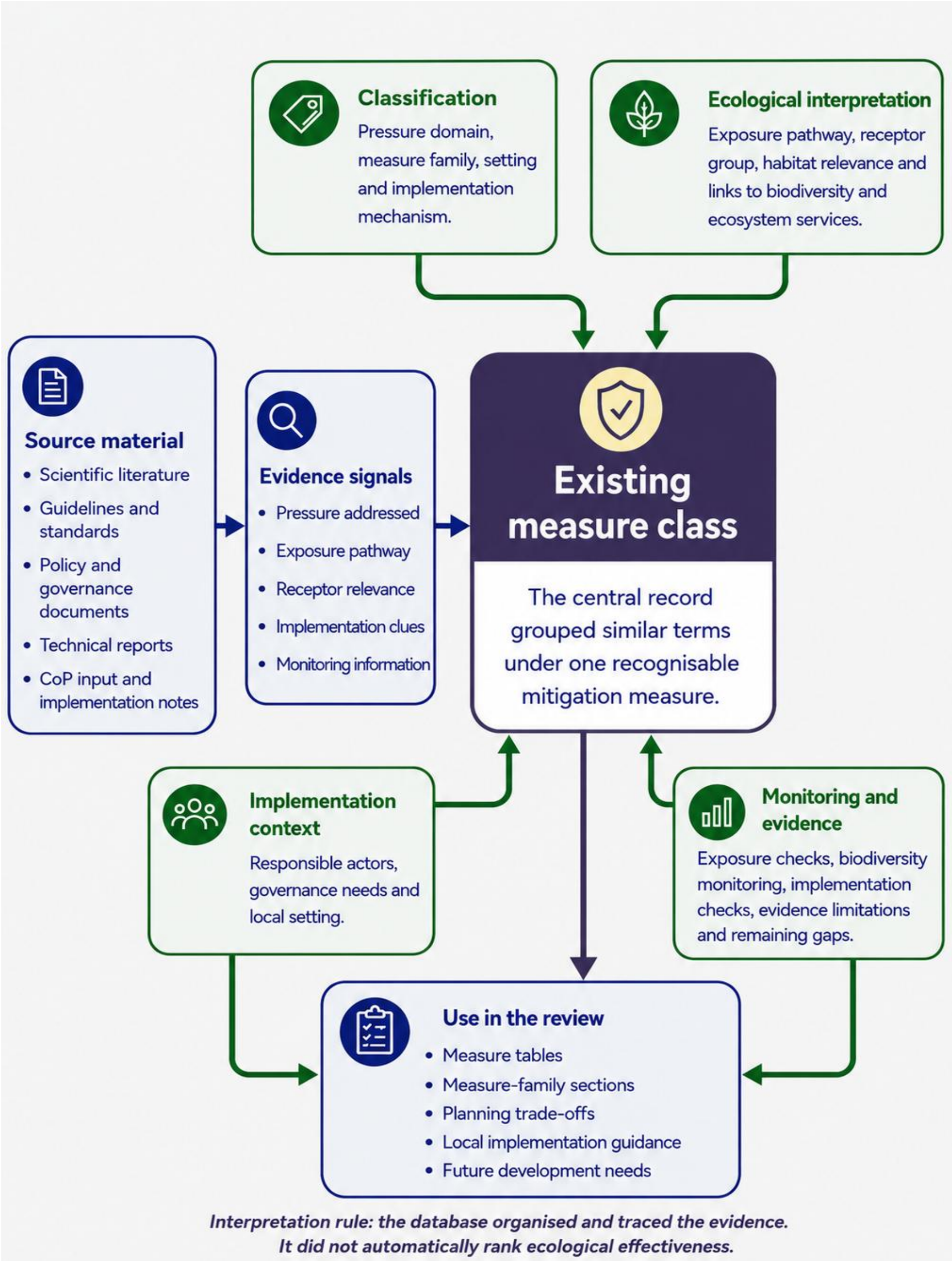


Figure 2.3.1 Evidence-mapping workflow for organising existing mitigation measure classes. Source material was screened through pressure, exposure-pathway, species group, implementation and monitoring signals, then grouped into recognisable measure classes and interpreted by classification, ecological relevance, implementation context and evidence needs.

2.4 Limitations and expert judgement

The review was designed to organise and compare evidence on existing mitigation measures. What is important, it was not designed to provide a final ranking of which measures are ecologically most effective. **The database helped identify, group and trace measures across different sources.** Its output shows where evidence exists, what kind of evidence is available and where important gaps remain. **A key limitation is that different sources support measures in different ways.** Some showed exposure reduction, some showed biological response, some described implementation feasibility, and others provided policy or stakeholder support. These forms of evidence are useful, but they are not equivalent. **Expert judgement was thus used to clarify what each source demonstrated.** The review distinguished between measures that are documented, measures that are feasible, measures that reduce exposure, and measures for which ecological or TBES benefits have been directly observed. **This distinction was especially important because reducing exposure is not the same as proving biodiversity recovery**. A measure may be well supported to reduce LNP, but less well supported to restore species, habitats, ecological functions or ecosystem services. **For this reason, the interpretation separated three levels of evidence: evidence that a measure can reduce the pressure, evidence that it supports a plausible ecological pathway, and evidence that it leads to a measurable biodiversity or ecosystem-service response.** Another limitation comes from rule-based screening. Broad terms such as light, noise, biodiversity, planning, policy, mitigation or monitoring can make a record appear relevant even when it does not describe a practical mitigation measure. **This risk was reduced by checking whether the record could be linked to a recognisable action, an exposure pathway, a pressure domain, a measure family and, where available, monitoring or implementation information.** Source counts were therefore treated as evidence-mapping indicators.

The strength of evidence also varied between measures. Some measures were supported by empirical studies, field observations, before-and-after assessments, monitoring results or systematic reviews. Others were mainly supported by guidelines, standards, legal instruments, expert judgement or stakeholder experience. **A legal requirement may show that a measure is institutionally relevant, but it does not by itself prove ecological effectiveness.** Similarly, an experimental study may show a response in one species group, but this does not automatically mean that the same response will occur in all taxa, habitats, seasons or governance settings.

Monitoring remained one of the main uncertainties. A measure was interpreted as stronger when the available material explained how exposure could be measured, how implementation or compliance could be checked, and how biodiversity or ecosystem-service responses could be observed. **Measures without clear monitoring information were treated as requiring local validation**. This was important because installing a measure does not prove that it works ecologically. It only creates the need to **check whether the expected exposure reduction or ecological response occurs**. Human-centred indicators were also treated with caution. Metrics such as lux, Correlated Colour Temperature (CCT), decibels (dB) are useful for comparison, are useful for comparison, regulation, and technical assessment, but they do not always describe the exposure that matters for sensitive species. **For LP, ecological interpretation may require attention to spectrum, wavelength, directionality, timing and spatial distribution. For NP, it may require attention to frequency composition, masking, intermittency, timing and propagation. Threshold values were therefore treated as contextual references or screening anchors, not as universal ecological limits.**

Combined light and noise measures required caution. A measure was treated as genuinely combined only when light and noise were considered together in planning, implementation, exposure reduction or monitoring. **Measures that simply mentioned both pressures were not treated as mature combined-pressure mitigation.**

This distinction was necessary because the evidence base for combined sensory pressures is less developed than for many single-pressure measures.

Transferability was another limitation. The same measure may perform differently depending on habitat type, species group, season, landscape structure, governance context, maintenance capacity, enforcement, public acceptance and available technical resources. **The review did not assume that a measure described in one country, habitat or regulatory setting can be transferred directly to another.**

Expert judgement was used throughout the review to interpret the outputs of the workflow. It was needed to decide **whether a source described a practical measure or only provided background context; whether a measure was existing or mainly speculative; whether the evidence supported exposure reduction or biodiversity response; whether a measure was single-pressure or genuinely combined; whether monitoring information was sufficient; and whether findings could be transferred across ecological and governance contexts**. This judgment was not used to fill in missing information artificially. Where the source material did not provide enough detail, the uncertainty was retained and reported as a limitation.

Overall, the main limitation of the review is the unevenness of information. Existing measures are described across many evidence streams, but the strength, ecological specificity and practical readiness of that evidence vary. The review treats each measure as part of an evidence-to-action chain: **source evidence, exposure pathway, species relevance, TBES link, implementation context, monitoring need and remaining uncertainty**. **For regulatory measures, the measures were treated rather by their existence and possible application to reduce LP, NP, or both, without assessing their direct effectiveness for the impact reduction.** This approach keeps the interpretation transparent and prevents the database from being read as automatic proof of ecological effectiveness.

3. Existing mitigation measures: practical families, functions and TBES relevance

Existing mitigation measures are organised into five general categories: **regulatory, planning, technological, environmental, and social measures.** This organisation helps to identify how measures can be implemented and in which field of action they can be applied.

3.1 Overview of mitigation families

The database is not a table, but **a system of related tables containing different groups of information, such as measures, evidence, settings, actors, and monitoring needs**. However, the report can give only a general overview about each of the above-mentioned, illustrated with selected examples, their potential value, and the issues that may occur during implementation.

The purpose of this overview is to show the broad fields of action.

- Regulatory measures create formal conditions for mitigation.
- Planning measures help decide where exposure should be avoided, reduced or spatially controlled.
- Technological measures reduce emissions at the source or along the exposure pathway.
- Environmental measures protect species, habitats and ecological functions.
- Social measures support acceptance, compliance, reporting and long-term stewardship.

These families should not be understood as separate solutions. In practice, mitigation measures are usually interconnected. A regulatory requirement may enable planning decisions and other mitigation actions; planning may identify where reduction is needed; technological measures may reduce light or noise exposure; environmental measures may protect species and habitats; and social measures may support acceptance, compliance and monitoring. The final package depends on the group of stakeholders and the taxon of species to be addressed, on ecological objectives, governance conditions, available material and human resources, financial budget, social acceptance and implementation constraints.

A general hierarchy can therefore be identified, but it should be understood as a practical way of thinking rather than a fixed procedure. **Mitigation usually starts from the problem and ecological context: what pressure, species, habitat or ecological function needs attention?** It then requires consideration of who can act, which rules apply and what resources are available. Only after this step, suitable measures families and measure types can be selected and adapted to the specific place, timing, spatial scale, technical requirements, maintenance, enforcement and monitoring needs (*Figure 3.1.1).*

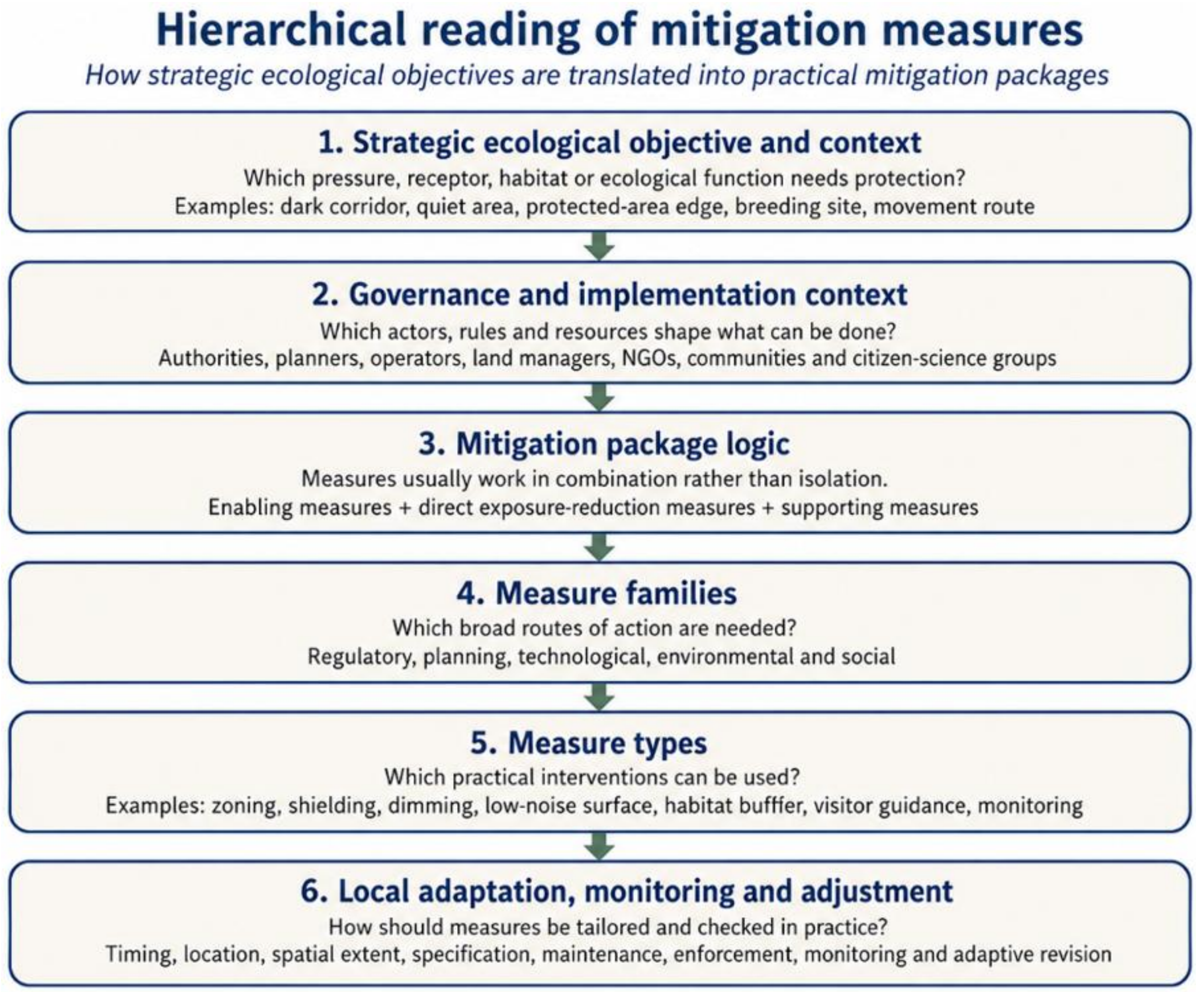


Figure 3.1.1 Hierarchical reading of mitigation measures. It shows how a strategic ecological objective can be translated into a practical mitigation package by considering governance context, measure combinations, measure families, measure types and implementation details.

3.2 Regulatory measures

Overall, regulatory measures provide both the **foundation and the driving force** for the adoption and implementation of **all other measures** aimed at addressing the impacts of LNP on TBES, including planning, biological, social, and technological measures. They are intrinsically interconnected with these approaches and help ensure their effective application. Regulatory measures can be found in both binding and non-binding regulatory instruments, including **legal acts, policies, guidelines, technical regulations, and standards**, and are intended to establish clear requirements for appropriate action to prevent, minimise, or mitigate potential and existing adverse impacts (for detailed explanation, see *Figure 3.2.1*).

LEGAL INSTRUMENTS	POLICY INSTRUMENTS	OTHER REGULATORY INSTRUMENTS
Legal instruments comprise **laws and other legally binding acts** adopted by competent legislative or regulatory bodies at the domestic or international level. Their primary function is to establish binding obligations, rights, procedures, and other regulatory requirements, which may be monitored and enforced by competent authorities.	Policy instruments are **strategic and governance tools** adopted by public authorities or other competent bodies to guide decision-making, **shape behaviour**, and promote the achievement of specific policy objectives. They typically **set out priorities, targets, recommendations, principles, or courses of action** and provide a framework for the development and implementation of regulatory, administrative, and practical measures.	Comprise a range of formal tools, such as **guidelines**, **technical regulations, standards, codes of practice, and certification schemes**, which are designed to support the implementation of regulatory and policy objectives. They typically **provide technical specifications, operational requirements, best practices, or performance criteria** that guide the actions of public authorities, businesses, and other stakeholders. Depending on their nature and legal basis, such instruments may be either binding or voluntary.

Figure 3.2.1. Classification of regulatory instruments.

Legal instruments play a crucial role in establishing binding measures and enabling effective enforcement mechanisms. By defining the responsibilities of relevant actors and the competencies of governmental authorities, they provide the basis for oversight and ensure compliance with the established regulatory frameworks.

In recent years, **increasing evidence of the adverse impacts** of LNP **has contributed to the growing recognition of these issues as environmental concerns** (European Environment Agency, 2026; Yakushina, 2025). This has led to the adoption of dedicated legislative measures or amendments to existing regulatory frameworks, aimed at preventing, reducing, or mitigating their impacts.

Legal acts addressing NP have a relatively long history, largely reflecting the perception of noise as a disturbance to human well-being and therefore primarily regulated as a form of nuisance (Garrard et al., 2025). Regulatory measures such as restrictions on noisy activities and curfews have existed for centuries. Prior to the 1970s, noise exposure was predominantly addressed as a nuisance issue; thereafter, it began to be increasingly reframed as an environmental concern (Lee, 2025). Legislation progressively **introduced requirements to limit noise emissions from a range of sources**, including aircraft, transport systems, industrial operations, entertainment venues, and outdoor machinery.

However, environmental considerations have historically been, and to a significant extent remain, **largely confined to impacts on human health and well-being**, rather than extending to broader ecological effects on biodiversity and ecosystems. Legislation establishes requirements to limit noise emissions from a range of sources, including aircraft, transport systems, industrial operations, entertainment venues, and outdoor machinery. **Key regulatory measures addressing noise pollution include** noise emission thresholds, urban and spatial planning measures (such as zoning and the designation of quiet areas), environmental noise assessment and mapping, monitoring, licensing and authorisation procedures, as well as enforcement mechanisms such as fines and the suspension of activities.

At the **national level**, several legislative frameworks illustrate these approaches. For example, in Norway, the Pollution Control Act (1981) recognises noise as a form of pollution and empowers competent authorities to establish limit values to reduce its impacts. In Germany, the Federal Immission Control Act (1974) aims to protect the population from harmful environmental effects of noise, with authorisations for industrial and commercial activities subject to requirements to mitigate adverse environmental impacts. Another example is Italy's Framework Law on Noise Pollution (1995), which provides, inter alia, for the limitation of noise levels in residential and sensitive areas and requires the development of noise maps and action plans in urban environments.

At the **EU level**, the ***Environmental Noise Directive*** (END) requires Member States to prepare strategic noise maps and noise management action plans every five years. However, it **does not set binding limit values, thresholds, nor does it set target levels for environmental noise**. Basically, the END lays down planning duties to Member States in order to combat noise for the benefit of human health.

Despite its anthropocentric approach, the END applies explicitly also to **quiet areas** in an agglomeration or in open country and by doing so, **noise mitigation measures will not only benefit human health but also biodiversity**. In particular, the designation of quiet areas offers significant opportunities for biodiversity conservation. This is illustrated by the example of Triglav National Park in Slovenia, where 134 quiet zones have recently been established, collectively covering approximately 10,000 hectares. These zones overlap with habitats important for rare and vulnerable species, as well as with areas protected under Natura 2000 to guarantee favourable conditions for species and habitats. The quiet zones are defined based on key habitats needed annually or in winter by various sensitive species (such as the Capercaillie) and habitats (such as raised bogs). Depending on the zone and its sensitivity, the **noise-related mitigation measures may include**: the **closure of certain** forest **roads** to public access, the **prohibition** or **(seasonal) restriction of activities** like hiking, ski-touring, cycling off-trail, paragliding, helicopter flights, logging, etc. The quiet zones are often marked in the field with signposts, roadblocks or notices to inform visitors.

A study for the European Commission (EC) (European Commission. Directorate General for Environment. et al., 2021) has proposed changes to improve the effectiveness of the END for its aim, protecting human health, that are also good for biodiversity preservation, like the adaptation of limit values. If the **END is revised**, its objective should also be broadened to **encompass** not only the protection of human health but also the **protection of the environment**, including biodiversity. A consequential amendment could be to extend the application of the END to quiet areas of importance for biodiversity conservation. In addition, stronger links could be established with the Natura 2000 network and with species protected under the Birds and Habitats Directives.

There are indirect, but meaningful links between **NP reduction** and the ***EU Nature Restoration Law*** (NRL), even though the NRL focuses on restoring ecosystems and does not explicitly regulate noise. Several restoration obligations and ecological outcome indicators clearly relate to reducing anthropogenic noise or its impacts. For protected habitats, Member States must bring degraded habitats closer to **"favourable reference conditions."** If noise is a source of degradation, e.g., in forests with capercaillie, bat corridors, coastal habitats with disturbance-sensitive seabirds, reducing noise is part of the required restoration measures. Restoration measures under the NRL must be consistent with the conservation objectives established under the Habitats Directive. Consequently, NP mitigation measures may be required where necessary to achieve those objectives. Furthermore, in urban areas, green spaces, green infrastructure, traffic-calming measures, and nature-based solutions can contribute both to noise reduction and to the achievement of the NRL's urban ecosystem restoration targets.

The **NRL also refers to LP** in its preamble. Although it does not impose any specific obligation to reduce LP, this recognition provides a basis for the development of restoration measures that incorporate actions to mitigate the impacts of ALAN. Furthermore, the concept of "favourable reference conditions" could be applied to LP in a similar manner, supporting the establishment of restoration objectives aimed at reducing ALAN-related pressures on ecosystems.

Unlike NP, the development of **legal frameworks** specifically addressing **light pollution** is relatively recent, reflecting the comparatively recent recognition of light pollution as a growing concern. The development of light pollution legislation has occurred through both **bottom-up and top-down approaches**. In some cases, local regulatory initiatives have prompted subsequent action at the national level, while in others, national governments have taken the lead in introducing dedicated legislation to address light pollution.

At the **local level**, many municipalities introduced **curfews and partial switch-off** or **dimming** of ALAN sources to reduce energy use, protect the environment, or protect the night sky for astronomy (Lichtverschmutzung Hessen, 2026). Across jurisdictions, curfews and other temporal restrictions on the use of ALAN are **typically imposed during periods of low activity**, most commonly between 1:00 a.m. and 5:00 a.m., when lighting demand is at its lowest., most commonly between 1:00 a.m. and 5:00 a.m., when lighting demand is at its lowest.

The past five years have marked a significant increase in the adoption of **nationwide legislation** addressing light pollution. Governments across Europe and other regions have either **amended existing environmental legislation to incorporate concerns related to ALAN** or **adopted dedicated legal frameworks** specifically aimed at reducing the wide-ranging impacts of light pollution. The latter approach has resulted in the development of foundational legislative instruments that establish comprehensive regulatory frameworks and contain measures specifically designed for light pollution mitigation. Current regulatory measures, however, are predominantly focused on reducing energy consumption, however, some examples of addressing environmental impacts could also be identified.

Croatia was the first European country to adopt dedicated nationwide legislation on light pollution. The *Croatian Act on Protection against Light Pollution* (Zakon o Zaštiti Od Svjetlosnog Onečišćenja, 2019), together with the ordinances adopted pursuant to it, establishes a comprehensive framework for the control and management of light pollution. Under this framework, the entire territory of the country is divided into **lighting zones**, ranging from dark zones in and around natural and environmentally sensitive areas to the brightest zones in commercial and highly urbanised areas. Each lighting zone is subject to **specific technical requirements and restrictions governing the use of ALAN**. These include limits on the **upward light ratio** (ULR), **curfews** and other temporal restrictions, **maximum correlated colour temperature** (CCT) thresholds (generally not exceeding 3000 K), and additional technical specifications designed to minimise light pollution and its associated environmental impacts. The law also requires **environmental impact assessment**, **monitoring** and **measurements** of ALAN exposure.

Germany has amended its environmental legislation to incorporate considerations of light pollution. These **regulatory measures** are specifically aimed at reducing environmental impacts and include, inter alia, prohibitions on directing ALAN sources towards water bodies, **restrictions on light sources harmful to insects**, such as ultraviolet radiation, and **limitations on illuminated advertising** within and in close proximity to protected areas.

Another example of a country with well-developed legislation addressing light pollution beyond energy efficiency considerations is **France**. France has adopted several legal instruments, including *Decree No. 2011-831 on the prevention and limitation of light pollution* (12 July 2011) and the *Decree on the prevention, reduction and* *limitation of light pollution* (27 December 2018) (Government of France, 2010, 2018). These provisions are designed to prevent, limit, and reduce the impacts of artificial light at night on, inter alia, wildlife, flora, and ecosystems. Regulatory measures for ALAN vary depending on location, distinguishing between urban and non-urban areas. In particular, in nature reserves and protected zones, lighting installations must comply with a range of restrictions, including a **maximum ULR of 0** and a **colour temperature not exceeding 2,400 K**, with an exception allowing up to 3,000 K in limited cases. Stricter requirements apply specifically to nature reserves and their buffer zones by local and regional government bodies. France's ambition to reduce light pollution is also evident in the **recent proposal for regulatory amendments** (French National Assembly, 2025) aimed at the protection and restoration of the nocturnal environment.

Nevertheless, specific legal provisions addressing LP, NP, or LNP remain relatively limited and often focus on particular concerns, such as energy efficiency, public safety, or nuisance, rather than on their broader environmental consequences. In the absence of dedicated legislation, more general regulatory measures embedded within existing environmental frameworks may provide an important basis for addressing these impacts. Such measures may include provisions relating to pollution prevention and control, environmental impact assessment, biodiversity conservation, protected areas, spatial planning, and ecosystem protection.

Regulatory measures addressing LP, NP, or both are also being developed across **policy documents at different governance levels**. The predominant form in which these pollutants receive attention is through the setting of targets to reduce pollution to levels that are not harmful to the environment.

At the **international level**, the most prominent framework addressing both pollutants is the ***Convention on Biological Diversity*** (CBD) (Secretariat of the Convention on Biological Diversity, 2022b). The recent ***Kunming-Montreal Global Biodiversity Framework*** (GBF) establishes global targets and goals to be achieved by 2030, with a longer-term ambition set for 2050. GBF **Target 7 aims to reduce pollution "from all sources"** to levels that are not harmful to biodiversity across all habitats and ecosystems. Although neither LP nor NP is explicitly mentioned in CBD Decision 15/4 (Secretariat of the Convention on Biological Diversity, 2022b), which adopted the GBF, accompanying guidance (Secretariat of the Convention on Biological Diversity, 2022a) suggests that "all sources" includes both light and noise impacts.

The global policy discourse on LP is evident in the ***Convention on the Conservation of Migratory Species of Wild Animals*** (CMS) (Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals, 1979), which has adopted several decisions as well as *International Light Pollution Guidelines* (Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals, 2024). These guidelines recommend the inclusion of **environmental impact assessment procedures for ALAN sources** in order to reduce the impacts of light pollution on species and their habitats. They also promote **adaptive management**, meaning that lighting practices should be modified if impacts emerge or become evident.

Other international frameworks, however, **consider NP impacts** predominantly from a marine or aquatic perspective, while their terrestrial impacts receive considerably less attention. As a result, **no specific international policy instruments or guidelines have been developed to address terrestrial** NP in a comprehensive manner.

The growing **policy attention** devoted to LNP did not bypass the **EU level**. The ***8th Environment Action Programme (EAP)* to 2030** establishes, under Article 2(d), the **objective** of pursuing a **zero-pollution ambition**, including the reduction of risks and adverse **impacts** associated with **LNP**. The EU's principal pollution policy framework, the ***Zero Pollution Action Plan*** (ZPAP), further reflects this commitment by setting a target to reduce by

30% the share of people chronically disturbed by transport noise. The actions envisaged under the ZPAP focus primarily on reducing NP through measures addressing transport-related noise and underwater noise, with the overarching aim of improving human health and well-being. LP, in turn, is acknowledged in the ZPAP as an emerging pollutant, and the intention is set to develop recommendations for its mitigation. However, **despite the EAP's explicit objective of addressing both LNP, the ZPAP does not establish specific targets or actions for reducing LP**. Furthermore, it provides only **limited consideration** of the measures required to mitigate the **impacts of NP on TBES**. As a result, the Action Plan does not fully reflect the broader ambition set out in the EAP to address the environmental impacts of both forms of pollution.

Policy development is also evident at the national level. A number of countries, in designing measures to reduce environmental pollution, have incorporated LNP considerations into policy documents such as *National Biodiversity Strategies and Action Plans* (NBSAPs), as well as other relevant strategic environmental policy frameworks. These typically include **ambitious targets to reduce LNP to levels that are not harmful to biodiversity**, as well as plans for the **development of appropriate guidelines or other regulatory instruments to address and monitor their impacts**. Such developments can be found, for example, in Austria, Belgium, France, Germany, Hungary, Luxembourg, Malta, Norway, and other European countries.

Table 3.2.1. Examples of regulatory measures developed in national policy documents.

Belgium, for example, recognises the environmental impacts of LNP and, among the operational objectives of its NBSAPs, includes the investigation, monitoring, and reduction of all pollutants, **LNP** included, to levels that do not harm biodiversity or ecosystem functions and services. It also explicitly identifies green areas as buffer zones as a means of mitigating noise pollution. Austria mentions **NP** under **Target 11**, which requires that biodiversity and ecosystem services be taken into account in spatial planning. It further highlights that while noise barriers can reduce NP, they may also fragment habitats and disrupt migratory routes, thereby recommending the creation of additional “green bridges” to restore ecological connectivity. **LP** is explicitly addressed under **Target 6**, “Energy Supply is Biodiversity-Friendly", which calls for lighting infrastructure to be adapted to biodiversity requirements. Measures include minimising LP through the **use of biodiversity-friendly lighting** systems with energy-efficient and long-lasting lamps, as well as **reducing illumination duration and intensity** via half-night switching and motion-detection systems. In Monaco, the Biodiversity Strategy introduces **Target 8**, which calls for the development of regulatory and technical measures to address **both LNP**. Hungary includes **specific targets addressing LP**, in particular Target 3.1, which promotes the development and **use of nocturnal insect-friendly outdoor lighting** techniques to reduce light pollution. It also includes Target 8.2, which calls for the **use of appropriately directed lighting fixtures and suitable colour temperatures** in the design and construction of artificial outdoor lighting, especially public street lighting, in order to further mitigate LP. Although regulatory measures and planned actions outlined in policy instruments vary across jurisdictions and governance levels, and not all policy frameworks address both forms of pollution, there is nonetheless a clear and growing recognition of the impacts of LNP.

Other regulatory instruments, including **guidelines, technical regulations, standards, and certification schemes**, can also play an important role in addressing LNP. Unlike legislation and policy, these instruments may be **developed not only by governmental bodies** but also **by non-governmental organisations, professional associations, and standardisation bodies**. Although **generally non-binding** in nature, they often have **significant practical value** and can strongly influence planning, design, and operational practices. Importantly, recommendations contained in standards or guidelines could be incorporated by reference into legislation or policy documents, thereby enhancing their practical authority and, in some cases, effectively making them mandatory.

Standards and certification schemes, for example, are frequently applied during the planning and design stages of projects and are often referred to in public procurement processes. In some cases, obtaining certification may be a prerequisite for the use of particular technologies in publicly funded projects. Within the lighting sector, several certification schemes have emerged that assess lighting technologies and systems against criteria extending beyond energy efficiency and product performance. Recently developed schemes, such as DarkSky Approved and the VDE Light Pollution Certification, award certification to technologies that align with responsible outdoor lighting principles, including the use of purposeful lighting, appropriate light direction, warm colour temperatures, and smart lighting controls, such as dimming and adaptive operation.

Other regulatory instruments **provide more detailed technical specifications and establish procedures that should be followed to minimise the impacts of LNP**. These technical measures are discussed further in *Section 3.4*.

In conclusion, **regulatory measures aimed at addressing the impacts of LNP on TBES** are **gradually emerging across different jurisdictions and governance levels**. **However**, their scope, ambition, and potential effectiveness in reducing these pollutants **vary considerably**. Despite this progress, regulatory action specifically targeting the environmental impacts of LNP remains relatively limited and is often concentrated within particular policy domains. In the case of LP, measures are frequently framed around energy efficiency objectives, while NP regulation tends to focus on human health concerns or specific issues such as underwater noise. Moreover, existing regulatory frameworks often lack effective enforceability, largely due to unclear allocation of responsibilities (undefined competences), as well as the absence of obligations for monitoring and measuring LNP. To strengthen both enforcement and the practical effectiveness of mitigation measures, regulatory instruments should incorporate more robust requirements for LNP monitoring and measurement. This would improve oversight, facilitate compliance assessment, and enable more effective control of pollution levels.

Regulatory measures are **crucial for the development and effective implementation of other mitigation measures**, owing to their significant **influence on decision-making and practice,** particularly by setting obligations to mitigate LNP. Their biodiversity relevance is mainly indirect but fundamental: they determine where exposure is avoided, reduced or controlled, and whether sensitive species, habitats and movement routes are considered before technical interventions are selected. To more effectively address the impacts of LNP on TBES, **future regulatory frameworks should incorporate more targeted and comprehensive measures**. Greater attention should be given to establishing scientifically informed thresholds and limit values at which LNP are recognised as harmful, thereby providing a clearer basis for regulatory intervention and enforcement.

Table 3.2.2. Summary of existing regulatory measures embedded in binding and non-binding instruments that are applicable to address LP, NP, or LNP impacts on TBES.

Regulatory measures	Commentary
Recognition of ALAN and/or noise as environmental pollutants	Legal and policy recognition of LNP as forms of environmental pollution facilitates the further development of obligations aimed at reducing their impacts on TBES.
Thresholds & technical limitations (maximum levels, curfews, ULR, CCT, etc.)	Setting maximum permissible parameters for ALAN and noise, as well as thresholds at which they exert significant pressure on TBES, in regulatory instruments is crucial for translating environmental objectives into measurable and enforceable standards, enabling effective monitoring and compliance, and ensuring that biodiversity and ecosystem integrity are protected from unacceptable levels of disturbance.
Urban planning (zoning)	The establishment of dedicated zones, such as dark sky areas and quiet areas, and the integration of LNP considerations into spatial planning are key to mitigating future impacts on TBES. These measures support a preventive and precautionary approach by protecting sensitive areas, managing cumulative pressures, and guiding sustainable development.
Authorisation & licensing (permits, certification, etc.)	Prevents harmful ALAN and noise emissions at the source by controlling activities before they occur. Permitting conditions, emission limits, certification schemes, and compliance requirements for lighting and noise-producing activities.
Environmental Impact Assessment (EIA) & Appropriate Assessment (AA)	Ensures early identification and avoidance of significant impacts on biodiversity and ecosystems. Impact prediction, assessment of LNP effects, mitigation hierarchy, and site-specific conditions for approval.
Adaptive Management	Enables ongoing adjustment of measures based on environmental outcomes and new evidence. Periodic review of mitigation effectiveness.
Monitoring, mapping & measurement requirements	Provides evidence base for enforcement and policy evaluation of LNP impacts. Requirements or recommendations for procedures, such as data collection, continuous monitoring, spatial mapping of LP/NP, reporting obligations, and indicators for TBES impacts.
Sanctions & incentives (enforcement mechanism)	Ensures compliance and encourages reduction of harmful emissions. Fines, penalties, liability rules, as well as tax incentives, subsidies, or rewards for best practices.
Reduction & mitigation targets	Sets measurable objectives to progressively reduce environmental pressures (e.g., halve LP by 2030 (France)). Binding/non-binding thresholds, emission reduction goals, time-bound targets for LNP reduction.
Public procurement criteria considerations	Drives market transformation towards low-impact ALAN and quieter technologies. Additional sustainability and environmental criteria in procurement, requiring light pollution/quiet-compliant products, services and practices.
Restriction of certain activities	Regulatory measures aimed at restricting or limiting certain activities (e.g. tourism, noisy activities, etc.) can help reduce environmental pressures associated with LNP during biodiversity-sensitive periods, such as migration and breeding seasons.
Requirements for responsible use of ALAN	Minimises unnecessary light emissions through operational best practices. Lighting design standards, curfews, shielding, directional lighting, intensity and spectral controls, "light only where and when needed" principles. Other recommendations for responsible use of ALAN, such as the Five Principles for Responsible Outdoor Lighting.

3.3 Planning measures: spatially targeting exposure reduction

Planning measures shape the spatial relationship between human activities that generate ecological pressures and species and/or ecosystem services. Planning is particularly important because many LP and NP impacts are determined not only by the characteristics of individual sources, but also by how exposure is distributed across landscapes and where it intersects with habitats, breeding sites, roosting areas, movement routes and ecological networks. Its primary role is to regulate spatial organisation in ways that prevent, reduce or manage exposure conflicts as part of land-use patterns and infrastructure development. This can include protecting environmentally sensitive areas, maintaining or improving ecological connectivity, increasing separation between LP and NP sources and habitats, and incorporating biodiversity considerations into planning and development processes.

The ecological evidence reviewed in this report points to several considerations that are particularly relevant for planning. First, **exposure is spatially structured**. Ecological impacts depend on exposure levels as well as the location of exposure relative to habitats, breeding sites, roosting areas, movement routes, and ecological networks. Second, **prevention is generally more effective than retrofitting**. Avoiding exposure conflicts during planning and development processes is often more feasible and cost-effective than mitigating impacts once infrastructure and land-use patterns are already established. Third, **ecological connectivity emerges as one of the dominant rationales for planning intervention**. Many species are affected through habitat disturbance, disrupted movement pathways, and degraded ecological connectivity. Finally, **integrated approaches to sensory pollution management** are increasingly recognised as important yet remain at an early stage of development in planning practice. Many ecological receptors are exposed to both pressures simultaneously, while planning systems typically address light and noise through separate policies, assessment procedures and management approaches.

The following sections examine how ecological evidence on LP and NP can inform planning decisions and how existing planning practices and instruments can support biodiversity-sensitive management. Particular attention is given to areas where ecological research challenges common planning assumptions, highlights ecological considerations that are often overlooked in planning practice, or identifies planning approaches supported by the available ecological evidence. The section also considers the practical limitations, implementation challenges and trade-offs associated with translating ecological evidence into planning and development processes. The key limitation is that planning interventions rarely focus on biodiversity objectives alone. Decisions concerning lighting, transport, land use and public space management must simultaneously address public safety, accessibility, mobility, aesthetics, heritage values, economic activity, energy efficiency and social acceptance. Consequently, **biodiversity-sensitive planning requires balancing ecological objectives with a wider range of societal considerations rather than maximising exposure reduction alone**.

3.3.1 Main pathways of reduction or support

Figure 3.3.1.1 presents a conceptual framework that organises the identified planning measures into three complementary pathways: (1) protecting ecological connectivity and low-disturbance networks, (2) identifying and managing ecological exposure conflicts, and (3) integrating ecological evidence into planning and development decisions. Rather than treating planning measures as a collection of individual tools, the framework classifies them according to the mitigation functions they perform. These functions range from maintaining the ecological quality and continuity of dark and quiet spaces, through managing spatial relationships between pollution sources, exposure pathways and biodiversity receptors, to strengthening the ecological evidence used in planning, assessment and monitoring. Together, the three pathways support a more coherent, place-based and biodiversity-sensitive approach to mitigating light pollution and noise pollution.

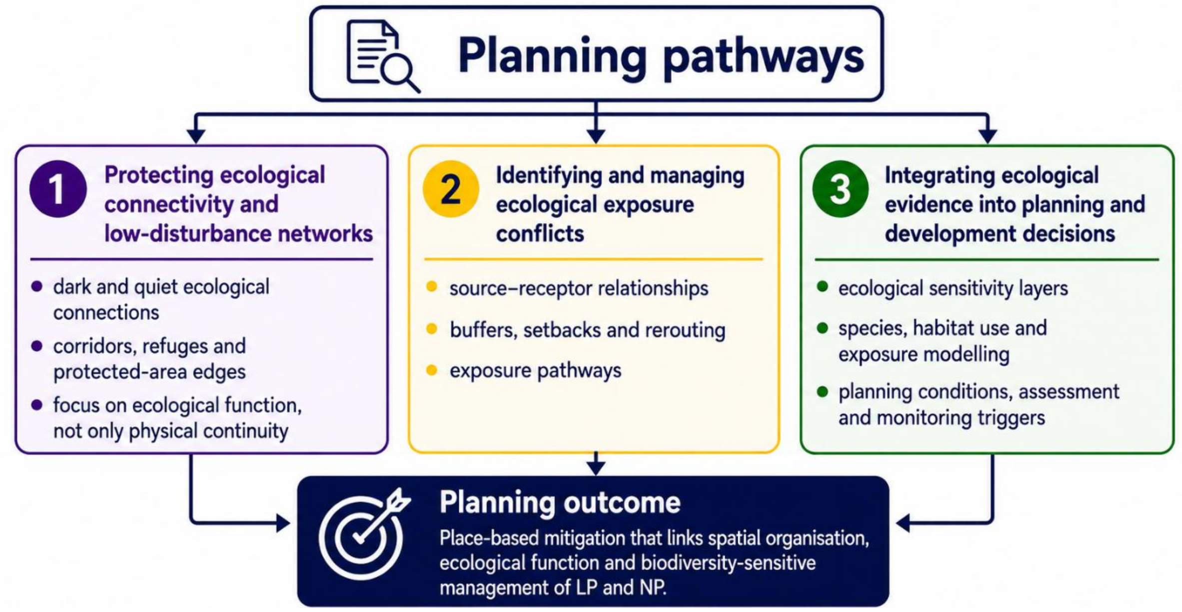


Figure. 3.3.1.1 The planning measures identified in the evidence base, organised into three main pathways.

- **Pathway 1**

Traditional planning practice already uses concepts such as green and blue infrastructure, ecological corridors, and habitat networks, but these approaches often focus on physical or vegetation-based continuity. However, not only can terrestrial habitats be fragmented or connected again by different kinds of measures. The open continuous space above the ground and between habitat elements can be fragmented, in our case by electromagnetic radiation, particularly light, and by noise. The evidence base suggests that ecological connectivity may also depend on environmental quality (Sordello, 2017; Sordello et al., 2022). A corridor or movement route that appears connected in spatial plans may function poorly for disturbance-sensitive species if it is exposed to ALAN or chronic anthropogenic noise (Azam et al., 2018; Jiang et al., 2023; Zeale et al., 2018). Planning for biodiversity-sensitive LP and NP mitigation requires more than standard green connectivity mapping. It may require **mapping the quality of dark and quiet connections**, **species activity detection and distribution modelling**, and **assessing whether existing corridors meet the biodiversity sensitivity thresholds to support movement, foraging, breeding, roosting or refuge functions** (Barber et al., 2011; Sordello et al., 2022; Stanley et al., 2023).

"Ecological connectivity depends on habitat quality, not only on spatial continuity"

For LP, this pathway supports the protection or restoration of **low-light and dark movement networks**. Dark corridor approaches aim to reduce the **spatial overlap between lighting sources and routes and/or habitats used by nocturnal or light-sensitive species** (Sordello et al., 2022; Azam et al., 2018). Evidence on bat activity suggests that dimming may not always be sufficient on its own. In urban settings, vegetation continuity and local ecological context may remain necessary for supporting bat movement (Stanley et al., 2023). Part-night lighting schemes may also be required, and may need to begin earlier in the night, to benefit light-sensitive species (Azam et al., 2015). In some cases, spatial measures such as keeping lighting away from ecological corridors may therefore also be needed (Azam et al., 2018).

For NP, the same connectivity logic applies to acoustic conditions. **Quiet and low-disturbance routes** can support habitats where noise-sensitive species depend on acoustic communication, breeding behaviour, occupancy, or movement. Evidence on **road-effect zones, traffic disturbance and wildlife responses to anthropogenic noise** indicates that noise exposure can influence habitat quality and ecological use beyond the immediate source location (Forman & Deblinger, 2000; Reijnen et al., 1997). One approach is to map noise propagation in order to identify where anthropogenic noise reaches habitats, corridors or breeding areas, and to compare exposure with available species-relevant thresholds or sensitivity information (Barber et al., 2011). Such noise mapping and monitoring can also help planners design targeted control measures. A more comprehensive approach would also map species activity, such as amphibian calling, breeding or population data, so that quiet connections contribute to **preserving acoustic conditions within habitats and movement networks** (Jiang et al., 2023).

"**Planning implication:** planning for ecological connectivity should check whether dark and quiet conditions support the ecological functions for which the ecological networks are intended for."

Where LP and NP affect the same habitats, corridors or protected-area edges, **integrated dark-quiet approaches** may be needed. These approaches are particularly relevant when ecological movement or habitat use depends on both darkness and acoustic quality. The evidence base includes support for **planning approaches that align land-use, lighting and noise rules within the same corridor or sensitive area** (Jiang et al., 2023). However, combined approaches should only be treated as genuinely integrated where light and noise are addressed through joint reasoning, joint implementation or joint monitoring, rather than simply being mentioned together in the same plan.

- ### Pathway 2

Conventional planning often separates functions, activities and land uses, but **ecological exposure conflicts** are not always visible within those categories. A recreational route, riverside promenade, cycling path, road edge or illuminated public space may appear compatible with green infrastructure or open-space planning, while still creating LP or NP exposure that affects sensitive habitats, species movement or breeding areas. The role of planning is therefore not only to assess whether land uses are compatible in functional terms, but whether **sensory exposure pathways are understood in relation to biodiversity and ecosystem services** (Buxton et al., 2020).

This pathway includes planning approaches that **reduce spatial overlap between exposure sources and sensitive habitats**. Examples include **locating illuminated or noisy infrastructure away from ecologically sensitive areas, using buffers to reduce edge effects, and applying setbacks where development or infrastructure would otherwise create light or noise exposure gradients**. The added value for planning is that these measures should be based on ecological exposure pathways rather than generic distance rules (Azam et al., 2018). Their effectiveness depends on whether they reduce relevant exposure at the of impacted species, habitats and ecosystem services as well as during biologically important periods (Shannon et al., 2016).

“Exposure conflicts often occur across conventional land-use categories”

For LP, this means considering where ALAN actually reaches, how it interacts with vegetation, urban built settings and movement routes, and whether the exposure affects species behaviour or habitat use. Evidence on illuminance thresholds, species activity and lighting impacts on urban habitats and species using or inhabiting them indicates that proximity to **lighting sources, light intensity and site conditions** can influence ecological response (Azam et al., 2018; Mammola et al., 2018; Stanley et al., 2023). Evidence from semi-natural and protected-area contexts further shows that light spillover onto hedges and forest edges can reduce habitat quality or alter activity along potential bat foraging and commuting routes (Pauwels et al., 2021). This suggests that **spatial planning should not treat lighting conflicts only as a matter of fixture design, but also as a question of where illuminated activities are located in relation to ecological functions**.

For NP, exposure conflicts are shaped by how noise propagates across space and by the timing, frequency, and intensity of the source. Planning measures such as **separating noisy activities from sensitive habitats, protecting quiet areas, and rerouting or separating traffic** can reduce exposure, but only where they actually change the acoustic conditions experienced by light and noise sensitive species (Forman & Deblinger, 2000; Reijnen et al., 1997; Shannon et al., 2016). This is particularly relevant for species that depend on acoustic or vibrational communication, because anthropogenic noise can interfere with calling behaviour, signal detection or species-specific communication systems (Narins, 2013; Shier et al., 2012).

Traffic-related measures are particularly important because they can shift both noise and, in some contexts, vehicle-light exposure away from sensitive habitats. However, rerouting should be assessed carefully to avoid transferring exposure to other species groups or sensitive habitats and therefore creating equivalent impacts elsewhere (Forman & Deblinger, 2000).

“**Planning implication:** LP and NP conflicts should be assessed as spatial exposure problems, not only as source-design problems. Planning should identify where light and noise actually reach sensitive species, habitats and ecological functions, and use this evidence to guide the location, separation or rerouting of illuminated and noisy activities.

The main planning lesson is that **spatial separation is most useful when it is ecologically informed**. Distance, buffers and rerouting are not automatically effective because exposure does not stop at planning boundaries and the strength of the impact varies by species, habitat, and time. Planning, therefore, needs to **identify where exposure reaches sensitive ecological functions, compare affected and less-affected areas, and consider whether mitigation changes both the exposure pathway and the ecological response** (Rutherford et al., 2023; Pauwels et al., 2021).

- ### Pathway 3

The third pathway concerns the **integration of ecological evidence into planning and development decisions**. Standard land-use considerations often identify protected areas, green spaces or broad habitat categories, but they may not capture ecological functions such as nocturnal movement routes, bat commuting paths, acoustic communication areas, roosting sites, breeding territories or seasonal habitat use. **Biodiversity-sensitive planning therefore needs to move from a land-use view of ecology towards an ecosystem-function view** (Sordello, 2017; Sordello et al., 2022; Shannon et al., 2016).

“Planning should move beyond habitat maps and make ecological functions visible in decisions.”

This pathway is particularly relevant where planning instruments use ecological sensitivity layers, overlays, development guidance or assessment requirements to shape decisions before projects are approved. For LP, this can include **mapped sensitive zones where lighting design, intensity, direction, spectrum, timing, or monitoring requirements are stricter than in surrounding areas** (Stanley et al., 2023). For NP, it can include **assessment of acoustic conditions near sensitive habitats, route-planning decisions, quiet-area designations or requirements** to demonstrate that noise exposure has been reduced at the relevant scale Barber et al., 2011).

The key planning shift is that **mitigation should begin with ecological assessment rather than with a predefined technical solution**. In practice, this means identifying which ecological functions require protection, which species, taxons or habitats are relevant, when exposure is biologically important, and which planning or design conditions are likely to reduce the pressure. This is especially important for measures such as lighting overlays, dark corridors, quiet areas or development conditions near sensitive habitats, because their ecological value depends on whether they reflect actual species use and ecological function (Azam et al., 2018; Barber et al., 2011; Sordello et al., 2022; Zeale et al., 2018).

Evidence-based planning can add value by determining where, when and for which ecological receptors technical interventions are needed. **Measures such as dimming, LED replacement, adaptive lighting or traffic management may reduce emissions or improve energy efficiency, but this does not automatically demonstrate biodiversity benefit.** Evidence from LP studies shows that ecological responses can vary according to species, habitat context, vegetation structure, timing, and the ecological function affected (Azam et al., 2015; Stanley et al., 2023). LP may also affect vegetation directly, including tree phenology (Škvareninová et al., 2017), which means that plants and habitat structure can themselves be relevant ecological receptors rather than only background context. Similar caution applies to NP, where average exposure reduction may not address frequency, masking, event timing, duration, or species relevance (Narins, 2013; Shannon et al., 2016; Shier et al., 2012).

“**Planning implication:** Planning should make ecological functions visible before decisions are made. Sensitivity layers, assessment requirements and permit conditions should be based on evidence of species use, exposure pathways and biologically relevant timing, not only on broad land-use or habitat categories.”

For planners, the practical implication is that ecological evidence should inform both the location and the conditions of development. This can include GIS-ready sensitivity maps, corridor or habitat-use data, exposure modelling, and monitoring triggers. Such tools do not replace planning judgement, but they **make ecological functions more visible within routine planning decisions and help ensure that mitigation measures address the right species, in the right places and at the relevant times**.

3.3.2 Representative examples

Several planning approaches already contribute to the management of LP and NP by shaping how lighting and acoustic environments are planned, regulated and maintained. The examples below illustrate different ways in which planning instruments can support exposure reduction, ecological diagnosis or environmental co-benefits, even where biodiversity was not the original purpose of the instrument.

Urban Lighting Plans (ULPs) and Urban **Lighting Masterplans** (Zielinska-Dabkowska, 2019) increasingly provide strategic guidance on lighting design, operation and investment priorities. The revised **Geneva Lighting Master Plan**, for example, seek to balance lighting quality, urban identity, energy efficiency and environmental objectives within a city-wide planning framework (City of Geneva, 2024). Lighting masterplans can also operate at district or site scale. **The King's Cross Lighting Masterplan in London**, developed for a major mixed-use redevelopment area, shows how lighting strategy can be used to integrate a site into its surrounding context after dark, while balancing public safety, heritage, public realm quality and potential impacts on local biodiversity (Speirs Major, 2016). Similarly, many municipalities are implementing large-scale LED replacement and adaptive lighting programmes. As an example, the **Bristol LED transition programme** illustrates how lighting decisions are frequently driven by energy efficiency, climate objectives and operational considerations, while also creating opportunities to reduce unnecessary lighting and incorporate environmental criteria into lighting management (Bristol City Council, n.d.).

In recent years, dark-sky initiatives have become increasingly common through the **International Dark Sky Places programme**, which includes categories such as **Dark Sky Parks, Reserves and Communities** (DarkSky International, 2001). These initiatives have contributed to raising awareness of LP and have often delivered important reductions in skyglow and unnecessary lighting. However, ecological evidence suggests that protecting isolated areas of darkness may not necessarily guarantee ecological connectivity if surrounding habitats and movement routes remain exposed. This raises broader questions regarding how **darkness should be considered within wider ecological networks and landscape planning, rather than only within designated sites or protected areas**.

Many planning and infrastructure programmes currently focus on measures such as LED retrofits, adaptive lighting systems or dimming schemes, often motivated by energy efficiency, maintenance costs, or climate objectives. While such measures can substantially reduce energy consumption and overall light emissions, **ecological outcomes may vary considerably depending on local ecosystem characteristics and species' sensitivities**. Experimental studies have demonstrated that mitigation measures intended to reduce ecological impacts may sometimes produce unexpected responses, indicating that biodiversity benefits should not be assumed solely from reductions in lighting intensity or operating hours (Heinen et al., 2023). This suggests that **effective planning should begin with an understanding of local ecological processes and exposure pathways rather than with predefined technical solutions**.

Other planning instruments can contribute more indirectly. Planning regulations, urban design guidance, and advertising controls may influence the amount, location and character of artificial lighting within urban environments. For example, the **Landscape Resolution implemented in Gdańsk** aims primarily to improve visual quality and reduce landscape clutter, yet it has also contributed to the **removal and regulation of illuminated advertising structures**, thereby generating co-benefits for LP reduction (City Council of Gdańsk, 2021). Such examples demonstrate that biodiversity-sensitive management of LP can often be supported through planning instruments that were not originally developed for environmental protection purposes.

Several recent planning-oriented approaches illustrate this shift. Dark infrastructure projects examples from France and Switzerland demonstrate how ecological assessments, including bat surveys, habitat analyses and species movement studies, have been used to identify priority areas for conservation and connectivity before designing appropriate lighting interventions (Sordello et al., 2022). In these cases, planning did not begin with the selection of lighting technologies or lighting standards, but with the identification of ecological functions requiring protection. Such approaches highlight the potential value of ecosystem characterisation and ecological diagnosis as a foundation for biodiversity-sensitive planning.

For NP, **city-wide noise action plans** provide a planning equivalent to Urban Lighting Plans, although they are often developed primarily from a human health, wellbeing and urban-quality perspective. The **Berlin Noise Action Plan 2019-2023**, for example, combines strategic noise mapping with measures concerning quiet areas, urban rest and recreation spaces, future mobility in new neighbourhoods (Berlin Senate Department for Environment, Transport and Climate Protection, 2020). The plan demonstrates how noise reduction can be incorporated into transport and urban-development planning. However, its principal objectives remain human health, urban attractiveness and access to quiet recreational spaces; biodiversity is not the main basis for designating or monitoring these areas.

Several European countries and municipalities also use **quiet areas and soundscape planning** to preserve or improve acoustic quality. This brings possible synergies with biodiversity, climate and green infrastructure, but biodiversity is often not treated as the main basis for defining, managing or monitoring quiet areas. An example is the **Swedish Guide to Silence** initiative, implemented in several municipalities in the Stockholm region. The programme identified, mapped and communicated quiet natural and semi-natural areas and improved their accessibility to residents (Cerwén and Mossberg, 2019). It illustrates how acoustic quality can be incorporated into municipal green space and recreational planning.

A further NP-related example is the designation of **Hampstead Heath in London as Europe's first Urban Quiet Park** by Quiet Parks International in 2021. The example is primarily framed around human access to quiet, calm and nature sound within a large urban green space, but it also points towards the wider ecological relevance of acoustic quality. **Quiet Parks International** describes quiet as important not only for human health and welfare, but also for wildlife that require a clean acoustic environment to communicate and complete their life cycles (Quiet Parks International, 2021).

A more biodiversity-oriented NP example is the French concept of a *trame blanche*, or **white ecological network**. The approach aims to identify acoustically favourable connected areas for wildlife, in coordination with green, blue and dark ecological networks. It combines land-use, noise, biodiversity and ecological-network data with acoustic monitoring, and considers species' hearing sensitivities. It is important because it treats acoustic quality as part of ecological connectivity, rather than only as a human-health or engineering issue (Cerema, 2024).

Taken together, the evidence suggests that **LP and NP should represent spatial and ecological challenges that interact with broader planning objectives**. Ecological research increasingly points towards the need to **consider environmental quality, ecological connectivity and local ecosystem functioning alongside more traditional planning concerns such as land use, mobility, urban design and development management**. This creates opportunities for planning to move beyond generic exposure reduction and towards more place-based, biodiversity-sensitive approaches that better reflect local ecological conditions and priorities.

These findings also suggest that the next step for planning is not necessarily the creation of new planning instruments, but the stronger integration of ecological evidence into existing planning and governance frameworks. This includes **moving beyond purely structural concepts of connectivity, incorporating ecological diagnosis into planning processes, considering darkness and acoustic quality as components of habitat quality**, and recognising that biodiversity-sensitive management of LP and NP requires understanding how species interact with landscapes rather than focusing solely on exposure sources. Such an approach can help planning to better account for biodiversity objectives while continuing to balance broader societal goals related to safety, mobility, accessibility, aesthetics, economic activity and public acceptance.

3.3.3 Implementation, monitoring and validation

Implementation of planning measures depends on more than the formal adoption of a plan, designation or planning condition. For biodiversity-sensitive LP and NP mitigation, planning measures need to be linked to ecological diagnosis. In practical terms, implementation can be supported by spatially explicit ecological information, enforceable planning instruments and follow-up mechanisms such as compliance checks or periodic review. Examples include **GIS-ready sensitivity maps for lighting overlays, habitat maps and defined distances for ecological setbacks, corridor maps for dark or dark-quiet networks, and clear boundaries and management rules for quiet zone**s (Shannon et al., 2016; Sordello et al., 2022; Stanley et al., 2023).

For LP, implementation also depends on monitoring information that can support planning decisions at the relevant scale. This includes measurable indicators such as total a**rtificial light emissions, nocturnal ecological connectivity and nightscape quality**, rather than relying only on small-scale measurements or general lighting-compliance checks (Sánchez de Miguel & Pascual, 2025). This is relevant for planning because measures such as lighting overlays, dark corridors and setback areas require evidence on where artificial light is emitted, where it propagates, and where it intersects with ecological functions.

Experimental evidence on ALAN indicates that ecological responses may depend on timing and biological context rather than light reduction alone (Heinen et al., 2023). This supports a cautious approach to implementation: planning measures should not assume that reduced exposure automatically produces biodiversity benefits. Instead, they should specify which species and ecological functions are being protected, how exposure will be changed, and how ecological response will be checked.

Recent **dark-infrastructure and dark-network approaches** illustrate this need for ecological diagnosis. In the Douai example, dark ecological continuities were informed by an acoustic bat survey across the commune territory before lighting interventions were selected (Sordello et al., 2022). This demonstrates that **planning can begin with the identification of ecological functions requiring protection rather than with lighting technologies or standards**. Such approaches highlight the potential value of ecosystem characterisation and species-specific information as a foundation for biodiversity-sensitive planning.

For NP, a similar principle applies. Measures such as **quiet zones, ecological setbacks from noise sources and traffic rerouting** away from sensitive habitats require implementation support in the form of source mapping, habitat-sensitivity mapping, enforceable separation rules, coordination with transport or land-use authorities, and monitoring of possible displacement effects (Forman & Deblinger, 2000; Shannon et al., 2016). For biodiversity-sensitive implementation, these measures need to be linked to behavioural functional cycles (Tembrock 1982, 1983) and ecological functions such as communication, reproduction, movement, migration, foraging, habitat use, hibernation etc. rather than only to general noise reduction.

Monitoring should be designed around the measure's intended pathway. For spatial separation and setbacks, monitoring should test whether exposure gradients are reduced at the relevant scale and whether sensitive species still use the protected habitat or buffer. For dark corridors and dark-quiet corridors, monitoring should assess corridor continuity, light and/or noise gradients, and movement or activity across corridor segments. For lighting overlays, monitoring should check whether planning conditions translate into reduced lighting levels, direction, timing or spectrum in mapped sensitive areas. For quiet zones or traffic rerouting, monitoring should assess noise exposure, event frequency, displacement effects and habitat use before and after implementation (Jiang et al., 2023; Narins, 2013; Pauwels et al., 2021).

Effectiveness should only be claimed where three elements are demonstrated together: exposure change, implementation fidelity and, response. In the UK, for example, the statutory nuisance framework for artificial light has increased attention to lighting impacts, and **Institution of Lighting Professionals (ILP) guidance** supports **Environmental Lighting Impact Assessments** for new development (Department for Environment, Food & Rural Affairs, 2015; Institution of Lighting Professionals, 2013). However, these instruments are primarily assessment and nuisance-management tools; they do not by themselves demonstrate biodiversity benefit.

The **minimum validation standard** should show that exposure changed at the relevant scale, that the planning rule or intervention was implemented as intended, and that the ecological function of concern was monitored through suitable indicators. This is especially important for planning measures because their effects are often indirect and can be altered by later development, maintenance practices, traffic displacement or cumulative LP and NP exposure. **For this reason, biodiversity-sensitive planning should be treated as an iterative process, supported by monitoring, periodic review and adaptive management.**

3.3.4 Links with other measure families

Planning measures are closely linked with regulatory, technological, environmental and social measures. Their main contribution is to identify where exposure should be avoided or reduced, which organisms or ecological functions are affected, and which other measures are most appropriate in that location.

Planning can guide **technological measures** such as fully shielded warm lighting, adaptive dimming, part-night lighting reduction, low-noise road surfaces, quieter equipment retrofits and source-control maintenance programmes. These measures may reduce LP or NP exposure, but their biodiversity relevance depends on whether they are applied near sensitive habitats, movement routes, roosting areas, breeding sites or ecological corridors, and whether their effects are checked at a relevant scale.

Planning also supports **environmental measures** such as dark-quiet habitat buffers, vegetated dark buffers, habitat buffers from transport noise, dark-quiet refuge restoration, earth berm noise buffers, habitat-edge screening vegetation and topographic screening. These measures depend on knowing where sensitive species or habitats occur and how exposure reaches them. Planning can define the buffers, refuges, corridors or management areas within which relevant protection is needed.

Regulatory measures provide the formal backing that planning often requires. Permit conditions, zoning requirements, monitoring obligations, activity restrictions, procurement criteria, sanctions, incentives and requirements for responsible use of ALAN can turn planning priorities into enforceable or repeatable requirements.

Social measures can support acceptance, compliance and long-term maintenance of planning objectives. Lights-out campaigns, citizen audits of ecological lighting, community quiet-hours agreements, noise-awareness programmes, citizen-science stewardship and dark-quiet stewardship programmes are especially relevant where exposure depends on everyday behaviours.

3.4 Technological measures: reducing emissions at source or pathway

Technological measures are one of the main tools available to reduce ALAN and anthropogenic noise pressures, working primarily by **changing what is emitted at source**, **limiting when** and **how strongly a pollutant is produced**, or **intercepting exposure** along the pathway between source and impacted organism, habitat or ecosystem service. Their role is practical: they provide the means to translate **spatial priorities** and **ecological objectives** into **measurable reductions in exposure.** However, installing a technological solution is not the same as demonstrating ecological mitigation. A new lighting system, a dimming schedule, a low-noise surface, a sensor-based control system or a maintenance programme only becomes ecologically relevant when it reduces the exposure that matters for sensitive species, organism groups, habitats or ecological processes. This means that technological measures should be assessed by where they are applied, when they operate, what exposure pathway they address, and whether their effect can be checked at the receptor scale.

The core role of this family is to **change how light and noise are produced and delivered**. For street lighting, this means adjusting the light-emitting diode (LED) spectrum, reducing intensity through dimming, applying part-night operation, improving shielding, using full cut-off optics and directing light downwards so that less light reaches surrounding habitats. These measures can reduce ecologically relevant exposure when they are specified and operated correctly. However, switching from one light source type to another is not automatically mitigation. The spectrum, intensity, direction, visibility of the source, operating hours, and maintenance regime all determine whether light pollution is reduced. For noise pollution, technological measures focus on reducing sound emissions at source or controlling how and when noise is generated. Examples include low-noise road surfaces, quieter equipment, source-control maintenance programmes, operational scheduling, and acoustic monitoring. Their ecological value cannot be judged only by average decibel reduction, because frequency composition, masking, intermittency, timing, and receptor location may determine whether the noise remains biologically relevant.

Figure 3.4.1 summarises the main technological pathways used in this review. These pathways include controlling lighting timing and intensity, modifying light spectrum and direction, reducing noise at source, maintaining source performance, and coordinating light and noise control where both pressures occur together. The figure also highlights that each technological pathway needs ecological caution and validation, because technical change only supports mitigation when it reduces relevant exposure in the right place, during the relevant period and at an appropriate spatial scale.

1. Control timing and intensity of light

Typical measures	Adaptive dimming with motion sensors; part-night lighting reduction.
Ecological caution	Generic schedules may miss sensitive activity periods.
Validation focus	Check receptor-scale light levels before/after implementation and during biologically relevant periods.

2. Modify light spectrum and direction

Typical measures	Fully shielded warm lighting; full cut-off optics; spectral control.
Ecological caution	Warmer light is not automatically safe for all taxa, and poor installation may still increase exposure.
Validation focus	Check spectrum, directionality, spill light, skyglow and receptor response where feasible.

3. Reduce noise at source

Typical measures	Low-noise road surfaces; quieter equipment retrofit.
Ecological caution	Average dB reduction may miss frequency, masking, timing or breeding-season disturbance.
Validation focus	Check sound level, frequency bands, temporal pattern and masking risk at receptor locations.

4. Maintain source performance

Typical measures	Source-control maintenance programme.
Ecological caution	Settings may be overridden; equipment can degrade or be replaced incorrectly.
Validation focus	Check implementation fidelity, maintenance records, repeated exposure measurements and compliance.

5. Coordinate light and noise control

Typical measures	Integrated smart site control; joint sensor-based control; coordinated operational control.
Ecological caution	Combined mitigation may be combined in name only if light and noise are not monitored together.
Validation focus	Check light and noise jointly, in the same spatial units and biologically relevant periods.

Figure 3.4.1. Technological mitigation pathways for reducing ecologically relevant light and noise exposure. The figure summarises the main technological pathways: control of lighting timing and intensity, source-side noise reduction, and maintenance of source performance.

Technological measures are also important because they can be specified, procured, installed, monitored, and maintained. This makes them suitable for practical implementation by authorities, infrastructure operators, lighting designers, acoustic engineers, site managers, and consultants. At the same time, they can fail when specifications are too generic, when ecological criteria are missing from procurement, when sensors are not linked to actual exposure reduction, or when equipment is not maintained over time. For this reason, the technological family should be interpreted as a set of source-side and pathway-side interventions that require validation, rather than as a list of devices that automatically solve the problem.

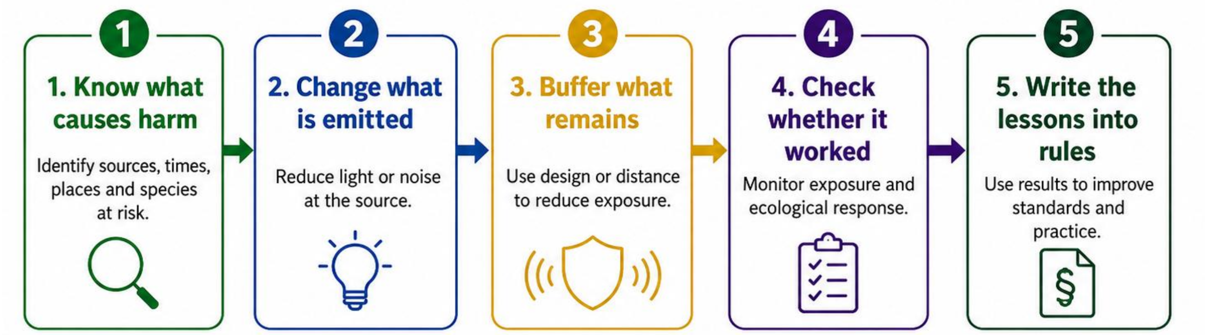
The practical strength of technological measures is that they **can be applied at different scales**. **At the luminaire or site level**, a luminaire can be shielded, dimmed, retimed, or replaced to reduce exposure at a sensitive location. **At the road or infrastructure-corridor scale**, lighting schedules, spectral standards, low-noise surfaces and quieter equipment can reduce cumulative exposure across larger areas. **At wider governance scales**, technical specifications and procurement rules can make better practice more consistent across many installations or maintenance cycles. **Scale matters because light and noise pressures are cumulative**; isolated technical changes may have limited ecological value if the surrounding landscape remains unmanaged.

Monitoring is essential at each of these scales. Technical performance should be checked at the receptor scale, not only at the source. For light, this may include spill light, source of visibility, spectrum, skyglow, timing and exposure of gradients near habitats or corridors. For noise, it may include sound level, frequency composition, masking risk, timing, and propagation at sensitive locations. Biosensors, biomarkers and other biological detection tools may support validation, but they should be treated as monitoring tools rather than mitigation measures unless they are part of an active control system that changes light, noise or operational conditions.

The main users of this chapter are actors who specify, procure, install, manage or assess lighting and noise-generating infrastructure. These include authorities, infrastructure operators, lighting professionals, acoustic engineers, environmental consultants, procurement officers, site managers, land managers, and conservation bodies. For these users, the key message is that technological mitigation should not be judged only by installation or technical efficiency. It should be judged by whether the measure reduces ecologically relevant exposure, whether it is implemented and maintained as intended, and whether its effects can be checked over time.

3.4.1 Main technological pathways

Technological measures work through **four practical pathways**. Together they follow a clear logic: (1) know what causes harm, (2) change what is emitted, (3) buffer what remains, (4) check whether it worked, and (5) write the lessons into rules. This interpretation, together with examples, is listed in *Figure 3.4.1.1*. The Figure links diagnosis of ecologically relevant exposure with source reduction, control of residual transmission, validation of physical and biological responses, and translation of verified results into standards and operational practice. Representative examples are shown separately for light and noise, together with their main applications and validation indicators.



Pressure	Example measures	How it works	Typical applications	Key validation
Light	• Shielded warm lighting • Adaptive dimming • Part-night reduction • Directional optics	Reduces intensity, duration, spill and damaging wavelengths.	Street lighting, paths, car parks, buildings and visitor sites.	• Light level at receptor • Spectrum / colour • Timing of operation • Biological response
Noise	• Low-noise road surfaces • Quieter equipment • Operational scheduling • Noise barriers / enclosures	Reduces sound generation, transmission or exposure in time and space.	Roads, railways, industry, construction sites and urban areas.	• Sound level at receptor • Frequency content • Timing and duration • Biological response

Figure 3.4.1.1 Technological mitigation measures within the wider light- and noise-management cycle.

Effective **technological mitigation begins by identifying which characteristics of light and noise create ecologically relevant exposure**, where that exposure occurs, and which species or ecological functions are affected. These pressures require different physical indicators, but they can be assessed within the same **source–pathway–receptor framework** (Francis & Barber, 2013; Gaston & Sánchez De Miguel, 2022). Zielinska-Dabkowska identifies eight existing lighting type categories that can serve as significant sources of disturbance for terrestrial biodiversity, contributing to nuisance from artificial light at night (Zielińska-Dabkowska et al., 2020).

Hale et al. (2015) demonstrated how street lighting can disrupt bat movement across an urban landscape, while Brumm and Slabbekoorn (2005) showed how anthropogenic noise can reduce the effective communication space available to birds and trigger costly changes in vocal behaviour. Jerem and Mathews (2020) further highlight that receptor-scale exposure and response relationships remain insufficiently documented for many species and settings. The most direct technological response is to modify what is emitted. For lighting, this may involve reducing intensity and operating duration, limiting short-wavelength emissions where appropriate, shielding luminaires and directing light only towards the intended area (Evans, 2023; Schroer & Hölker, 2017). For noise, corresponding source-side measures include low-noise road surfaces, quieter machinery and equipment, vibration isolation, enclosures, maintenance and operational controls. In both cases, replacing existing equipment is not automatically beneficial (Francis & Barber, 2013; Sordello et al., 2020). Hung et al. (2021) showed that a transition from sodium lighting to brighter and more blue-rich LEDs increased skyglow, illustrating that installation, output and operation matter as much as the nominal technology. The same principle applies to noise: a new surface, barrier or machine should be evaluated by the exposure it produces at receptor locations rather than by its technical label alone (Jerem & Mathews, 2020).

Where source reduction is insufficient, residual exposure can be limited through additional design and transmission controls. Light spill can be reduced through improved optics, baffles, physical screening, source orientation and greater separation from sensitive habitats (Jägerbrand & Bouroussis, 2021). Noise transmission can be addressed through acoustic enclosures, barriers, earth bunds, vibration breaks and suitable source–receptor distance (Sordello et al., 2020). These measures may complement spatial planning and habitat-based interventions, but their technological performance must be assessed in relation to the actual light or sound reaching sensitive receptors.

Checking whether an intervention worked **requires separate evidence that physical exposure changed and that the relevant organisms responded**. Reduced illuminance does not automatically demonstrate renewed bat movement or moth activity, just as lower sound levels do not automatically demonstrate restored bird communication or breeding success (Hale et al., 2015; Stanley et al., 2023). Monitoring should therefore combine receptor-scale light or sound measurements with appropriate biological indicators, such as activity, movement, vocal behaviour, timing, habitat use or reproductive responses.

Finally, **verified results need to be translated into procurement specifications, operating procedures, maintenance requirements and regulatory instruments**, in particular **standards**. Technological measures remain effective only when they are installed correctly, operated as intended and maintained over time. Evans emphasises the importance of including lighting intensity and spectral requirements in procurement, while species-level evidence on acoustic masking and communication can support more ecologically meaningful noise limits near sensitive habitats (Evans, 2023). The same evidence chain should therefore guide both pressures: identify harmful exposure, modify the source, control residual transmission, verify physical and biological outcomes, and incorporate the resulting lessons into durable practice.

3.4.2. Representative technological examples.

The following three **case studies illustrate how technological measures can be used to reduce ALAN, anthropogenic noise, and their combined effects in TBES**. The examples consider interventions that act directly at the source, alter the pathway by which pollution reaches sensitive species and habitats, or adapt the timing and intensity of emissions to biologically important periods. They also **demonstrate that no single technological solution is universally beneficial, as effectiveness depends on the affected organisms, local environmental conditions, and possible ecological side effects**. Consequently, technological mitigation should be accompanied by site-specific assessment and monitoring to verify whether exposure and ecological responses improve after implementation.

Case Study 1 — Light Pollution

Source: Macgregor (2016), DOI: 10.1111/gcb.13371 / Evans (2023), DOI: 10.1098/rstb.2022.0355

Pollutant: Artificial light at night (ALAN) from street lighting

Organisms affected: Nocturnal moths and flowering plants

Ecosystem service at risk: Nocturnal pollination

A significant share of plant pollination by moths happens at night. These insects visit flowers after dark, carrying pollen from plant to plant, including some crop species, e.g. oilseed rape and peas. Street lighting is disrupting this service in a measurable and serious way. Researchers compared moth activity and pollen transport at lit and unlit sites along UK roads. At lit sites, moth abundance at ground level was halved compared to unlit sites. Species richness dropped by >25%. The moths had not disappeared; they had been pulled upward toward the light itself, where flight activity was 70% greater. The lights acted as a trap, drawing moths away from the flowers they would otherwise have visited. The study also examined the pollen moths were carrying. At lit sites, overall pollen transport was reduced, meaning that flowers were receiving fewer visits from pollen-carrying moths. This suggests that even moderate street lighting along road verges and hedgerows can quietly undermine nocturnal pollination across an entire landscape.

Technological measures: Four technological interventions directly address this problem. First, **part-night lighting reduction**, switching street lights off at or after midnight based on proposed curfews, has been shown to restore nocturnal pollination rates to levels indistinguishable from complete darkness, the most effective single measure identified so far, with the added benefit of saving energy. Second, LED spectrum modification, shifting from broad-spectrum white LEDs rich in blue wavelengths to fully **shielded warm-white LED lighting or narrower amber LEDs**, reduces moth attraction to the light source and keeps more moths active at ground level near flowers. Third, **adaptive dimming with motion sensors** and **Integrated smart site control for lighting and noise** that automatically reduce light intensity based on traffic volume or time of night, lower overall light emissions during peak moth activity hours. Together, these measures can be retrofitted into existing street lighting infrastructure at modest cost, making them practical tools for local authorities seeking to protect pollination services along road verges and in semi-rural landscapes.

A note of caution – amber and red-shifted lighting is not a universal solution: Recently proposed as a solution, amber and red-shifted lighting are often not ecologically neutral and can form new problems for other species. According to research by Owens & Lewis (2021), organisms such as fireflies interact thanks to bioluminescent signals, and amber lighting, being close to the yellow-green wavelengths they use for mate attraction, has been shown to suppress female responsivity more severely than white LED lighting, effectively silencing the mating dialogue the insects depend on. For plants, red and amber wavelengths are detected by phytochrome, the photoreceptor that controls flowering timing, bud dormancy, and seasonal growth. Even low levels of red ALAN can delay flowering in short-day species, disturb bud burst in trees, and cause abnormal stem elongation, potentially undermining the phenology of the very plants that moths depend on for nectar. No single spectral choice is safe for all species simultaneously. Reducing light duration through part-night switching remains more reliably beneficial than spectral substitution alone.

Case Study 2 — Noise Pollution

Source: Brumm & Slabbekoorn (2005), DOI: 10.1016/S0065-3454(05)35004-2

Pollutant: Anthropogenic noise (traffic, industry, urban background noise)

Organisms affected: Songbirds and other acoustically communicating terrestrial vertebrates

Ecosystem service at risk: Reproductive success, territory defence, and bird population health

Birdsong is not just decoration — it is how birds find mates, defend territories, warn of predators, and coordinate with their offspring. For all of this to work, the song must actually reach its intended receiver clearly enough to be understood. Background noise directly threatens that: it shrinks the area over which a song can be heard, reduces its clarity, and can mask it entirely.

Brumm and Slabbekoorn (2005) brought together a large body of evidence to show that anthropogenic noise, particularly traffic, operates like a curtain drawn around a singing bird. As noise levels rise, the effective range of a bird's song collapses. A territory that might once have been defended acoustically over several hundred metres can shrink dramatically in a noisy roadside environment. The same applies to courtship: a female that cannot hear a male clearly enough to assess the quality of his song may simply not respond. Birds are not passive victims.

The research documents several ways in which they adjust: some sing louder (the Lombard effect — the same automatic response humans show when raising their voice in a crowd (Bottalico et al., 2017)); others shift their songs to higher frequencies to avoid the low-frequency roar of traffic; others change the timing of their songs to exploit quieter moments of the day. Great tits in cities, for example, have been found to consistently sing at higher minimum frequencies than their rural counterparts, matching the spectral gap in traffic noise where their songs can still be heard.

These adjustments, however, come at a cost and have limits. Singing louder is physically demanding. Shifting frequency may make songs less attractive to potential mates or less effective at deterring rivals. Species that cannot adjust, those with inflexible, innate song patterns, may simply be excluded from noisy habitats altogether, reducing bird diversity near roads and in cities. The practical implication is clear: reducing noise levels near important wildlife habitats, even modestly, restores the acoustic space birds need to communicate, reproduce, and sustain their populations.

Technological measures: Several measures can restore this acoustic space. Noise barriers, such as walls or earthen mounds placed alongside roads, can reduce traffic noise reaching adjacent habitats by 5 to 15 decibels, a reduction large enough to meaningfully expand the broadcast area of birdsong. **Low-noise road surfaces**, which reduce tyre-road noise at source, have been shown to cut road noise by several decibels without any change to traffic volume or speed. Dense vegetation buffers, e.g. rows of trees and shrubs planted between roads and wildlife habitats, attenuate sound through absorption and diffraction while simultaneously providing habitat. At a finer scale, **source-control maintenance programme** with acoustic monitoring technology now allows land managers to measure actual noise levels at specific sites and track whether bird communities recover following interventions, turning management into an evidence-based cycle rather than a one-time action. Together, these measures address the core problem of restoring a sufficient signal-to-noise ratio for birds to communicate effectively within their territories.

Case Study 3 — Combined Light and Noise Pollution

Source: Marin Gomez (2022), DOI: 10.3390/ani12081015

Pollutants: Artificial light at night (ALAN) and traffic noise

Organisms affected: Urban songbirds (Saffron Finch *Sicalis flaveola*)

Ecosystem service at risk: Reproductive success and bird population health

Hearing birds singing at first light (natural or artificial) is how male birds promote area, draw mates and synchronise breeding. Timing is critical: birds that sing too early may not be heard by rivals, while those that sing too late risk having their signals masked by rush-hour noise. Urban birds are affected by both pressures. A recent study performed in Colombia on the *Saffron Finch* bird species found that in urbanised areas, birds started singing much earlier in the morning compared to birds located in darker, quieter areas. When the researchers separated the effects of LNP, they found that **LP was the dominant** driver of the shift in timing. The urban skyglow created by the city appeared to signal an earlier dawn to the birds, advancing their biological clocks and altering the timing of their daily activities. But **noise has an impact** as well. In other urban bird studies, traffic noise has been shown to push birds to sing earlier as a strategy to get their calls out before the morning traffic peak masks them. In urbanised areas, birds often sing at times that are out of sync with natural conditions, altering mate attraction, breeding phenology, and ultimately reproductive output. This case study highlights that LNP do not act in isolation. In cities, their combined effects can exceed those of either stressor alone, making integrated mitigation measures, such as reducing blue-rich lighting and implementing traffic calming/noise barriers near key habitats, more effective than addressing each pressure separately.

Technological measures: Because both pollutants are acting simultaneously, the most effective technological response combines measures from both domains. For light, fully **shielded warm lighting** or amber LEDs and **part-night lighting reduction** reduces the false dawn signal that advances bird singing into biologically inappropriate hours, allowing circadian rhythms to reset toward natural timing. Another technical aspect worth considering is the **G-index,** an indicator used in EU road lighting procurement rules to capture how much blue light a lamp gives off (EC Joint Research Centre & Vito, 2019). It matters for **TS9 ("Ecological light pollution and star visibility")** because blue light is thought to have a disproportionate effect on skyglow and on the disturbance of nocturnal wildlife. The G-index therefore provides a more robust basis than colour temperature alone for assessing when lighting in parks, gardens, and other ecologically sensitive areas — or near astronomical observatories — can be considered acceptable. Under TS9, lighting in these areas must meet a minimum G-index value (e.g., ≥1.5 or ≥2.0, depending on sensitivity), along with dimming or switch-off programmes during night-time closing hours.

For noise, **low-noise road surfaces,** traffic-calming infrastructure, and vegetated acoustic buffers near parks and green corridors lower the background noise level against which birds must compete to be heard. Crucially, wooded street corridors serve both functions at once: trees and dense hedgerows scatter and absorb both LNP before they reach sensitive habitat, providing passive, low-maintenance mitigation for both stressors simultaneously. Biosensor and acoustic monitoring technology can then be deployed to verify whether bird singing times and reproductive success return toward baseline levels, closing the loop between intervention and evidence of recovery.

3.4.3 Implementation, monitoring and validation

Installing or **proposing a technological measure** — a new LED fitting, a noise barrier, a dimming schedule — **is not the same as demonstrating that it works.** A large **gap exists between implementation** and **validates and** closing that gap requires three distinct checks: (1) verifying that exposure to the pollutant has actually changed, (2) confirming that organisms have responded in a measurable way, and (3) establishing that the implementation itself was carried out as intended. The first requirement is **physical measurement before and after the intervention**. Although light and noise require different physical indicators, the same monitoring principle applies exposure should be measured at ecologically relevant locations and during biologically relevant periods.

Hung et al. provide a cautionary lighting example. A countywide replacement of 3,693 high-pressure sodium streetlights with LEDs was expected to reduce light pollution, yet ground-based measurements showed that skyglow increased. Satellite observations did not adequately detect the change because the sensors used were less sensitive to the blue-shifted output of the new luminaires. Hale et al. similarly assessed lighting at different distances from streetlights to represent the exposure gradients experienced by bats, rather than relying only on lamp specifications.

Equivalent care is required for noise-control measures. A low-noise road surface, acoustic barrier or quieter machine may reduce the sound level measured close to the source without producing the same reduction at nearby breeding, foraging or movement habitats. Average sound level alone may also conceal frequency-specific masking, intermittent events or exposure during biologically sensitive periods. Monitoring should therefore include calibrated measurements of sound level, frequency composition, intermittency, timing and duration at locations actually used by wildlife. This addresses a recurring limitation identified by Jerem and Mathews, who found that many field studies relied on distance from a road or another source as a proxy rather than measuring the noise experienced by the organisms.

The second requirement is an independently measured biological or ecological response. A reduction in physical exposure is necessary but does not, by itself, demonstrate biodiversity benefit. Reduced illuminance does not automatically mean that bats have resumed using a corridor or that moths have returned to flowers. Stanley et al. demonstrate this distinction: streetlight dimming changed lighting conditions, but bat activity did not increase, whereas wooded streets were associated with greater bat use. The same distinction applies to noise. A reduction in average decibels does not automatically demonstrate that acoustic communication, habitat use or breeding conditions have recovered. Brumm and Slabbekoorn showed that anthropogenic noise can reduce communication range and trigger changes in vocal amplitude, frequency and timing. Monitoring a noise intervention should therefore assess whether the relevant ecological mechanism has changed- for example, whether masking has declined, communication distance has increased, vocal behaviour has moved towards reference conditions, or occupancy and breeding-related responses have improved.

The third check, often overlooked, is implementation fidelity: **was the measure installed correctly, operated as intended and maintained over time?** Lighting schedules may be overridden, luminaires may be incorrectly aimed, shielding may be incomplete, and specified spectral characteristics may change during routine replacement. Noise barriers may be installed with gaps, low-noise road surfaces may deteriorate, acoustic enclosures may remain open, quieter machinery may be operated in inappropriate modes, and vibration-control components may lose performance. Sensors and adaptive systems may also lose calibration or use thresholds that are not ecologically relevant.

Validation therefore requires technical inspections, operating and maintenance records, calibration checks and repeated receptor-scale exposure measurements. These checks should be repeated across relevant seasons and over a period appropriate to the expected ecological response, rather than being limited to a single survey immediately after installation.

Claiming that a technological measure is effective therefore requires a connected chain of evidence for light, noise or both pressures: (1) verified implementation and continued operation according to specification; (2) a confirmed change in relevant physical exposure at ecologically meaningful locations and times; and (3) a measured response in the target organisms or ecological functions. Where only installation has been confirmed, the measure should be reported as installed. Where physical exposure has changed but no biological response has been demonstrated, it should be described as exposure effective.

3.4.4 Links with other measure families

Technological measures work best as part of a wider system. On their own, they can reduce exposure to light or noise, but they depend on other measure families to identify where action is needed, protect what remains, and ensure delivery is sustained.

Planning measures identify where to act. More broadly, planning gives technological measures their spatial logic: without a prior diagnosis of which corridors, habitats or zones are sensitive, technology has no basis for deciding where dimming, shielding or low-noise retrofits should be prioritised. This dependency also runs in reverse, since planning designations such as dark corridors or quiet zones only become ecologically meaningful once technological measures are deployed within them to actually reduce exposure. **Environmental measures** protect species when technology alone is not enough. The two families work together: technology reduces what is emitted, green infrastructure buffers what remains. **Regulatory measures** make technological action obligatory rather than recommended. Hung et al. (2021) showed that an unregulated LED retrofit programme increased LP rather than reduced it. Without spectral standards written into procurement rules, well-intentioned upgrades can cause harm. Brumm & Slabbekoorn (2005) provide the species-specific acoustic thresholds that regulatory bodies need to set meaningful noise limits near sensitive habitats. **Social measures** secure the acceptance and maintenance that allow technological measures to persist over time. Collaboration with industry and local government is essential to embedding mitigation measures widely within road lighting projects. When communities and decision-makers grasp the reasoning behind dimming a luminaire or altering a road surface, such measures are more likely to be sustained and expanded over time.

Family of technological measures **does not organise space**. It cannot designate dark sky zones, create quiet areas, restrict development near sensitive habitats, or zone land use. That requires planning measures. It also does not, on its own, enforce compliance or provide legal obligations. Its role is to **reduce exposure**, **generate evidence**, and **provide the tools** that planning, environmental, and regulatory families need to act effectively. For noise in particular, **this family is stronger on diagnosis than on solutions** — it explains what is happening and why, yet the technical remedies attempted are less numerous and less established than on the lighting side.

3.5 Environmental measures: protecting receptors, habitats and ecological functions

Environmental measures aim to protect biodiversity mainly at the habitat and landscape level. Environmental measures do not necessarily reduce light or noise emissions at the source. Instead, they reduce the exposure experienced by organisms in habitats, corridors, refugees, breeding areas, roosting sites, or habitat edges (Sanders et al., 2021; Shannon et al., 2016; Sordello et al., 2020). Their role is therefore complementary to other mitigation families. Planning measures help identify where protection is needed. Technological measures reduce emissions or modify source pathways. Regulatory measures can make protection obligatory or enforceable. Social measures can support stewardship, reporting and long-term maintenance. Environmental measures add the receptor-side layer: they protect the places where species, habitats and ecological functions experience light and noise pressure (Convention on Biological Diversity, 2022; Jägerbrand & Bouroussis, 2021).

Environmental measures are especially relevant where complete source reduction is not feasible, where **infrastructure cannot be relocated**, or where **residual exposure** remains after source controls have been applied. They can increase separation between sources and sensitive habitats, weaken light or sound propagation, create or maintain lower-disturbance refuges, protect habitat edges and support ecological continuity across fragmented landscapes (Azam et al., 2018; Haddock et al., 2019; Ware et al., 2015; Zeale et al., 2018). Their value depends on whether they are aligned with receptor ecology, sensitive life stages, seasonal activity periods and the actual pathway through which light or noise reaches the organism or habitat.

3.5.1 Main environmental pathways

Environmental measures can be grouped into four main pathways. The **first pathway** is **buffering sensitive habitats from exposure**. Buffers reduce exposure by increasing separation between sources and receptors (Sanders et al., 2021; Shannon et al., 2016). This pathway includes habitat buffers from transport noise, vegetated acoustic buffers, vegetated dark buffers, dark-quiet habitat buffers and integrated habitat buffers for light and noise reduction. These measures may be relevant near roads, railways, infrastructure corridors, protected-area edges, breeding sites, roosts, foraging areas and movement routes. The **second pathway** is **screening light, visibility and acoustic propagation**. Screening measures interrupt or weaken the pathway between the source and the receptor (Grubisic et al., 2018; Lewanzik et al., 2021; Pérez Vega et al., 2022). They may reduce lateral light spill, direct line-of-sight illumination, glare, edge contrast or sound propagation. Examples include habitat-edge screening vegetation, topographic screening for light intrusion reduction and earth berm noise buffers. These measures can be useful where species or habitats are affected by direct visibility of lighting, infrastructure-related light intrusion or acoustic propagation from roads or technical sources. The **third pathway** is **creating or maintaining low-disturbance refuges**. Some measures aim to protect places that remain darker, quieter or less disturbed than the surrounding landscape (Seewagen et al., 2023; Zhao et al., 2022). Dark-quiet habitat buffers and dark-quiet refuge restoration are examples of this pathway. Their ecological value depends on whether the refuge is lower in exposure, remains connected to suitable habitat and is usable by target species. The refuge must remain accessible, protected from new disturbance sources and relevant to the behaviour and life cycle of the intended receptors. The **fourth pathway** is **supporting ecological functions and ecosystem services**. Environmental measures may contribute to terrestrial biodiversity and ecosystem services when reduced exposure supports movement, habitat use, activity, breeding, foraging, communication or interactions between organisms.

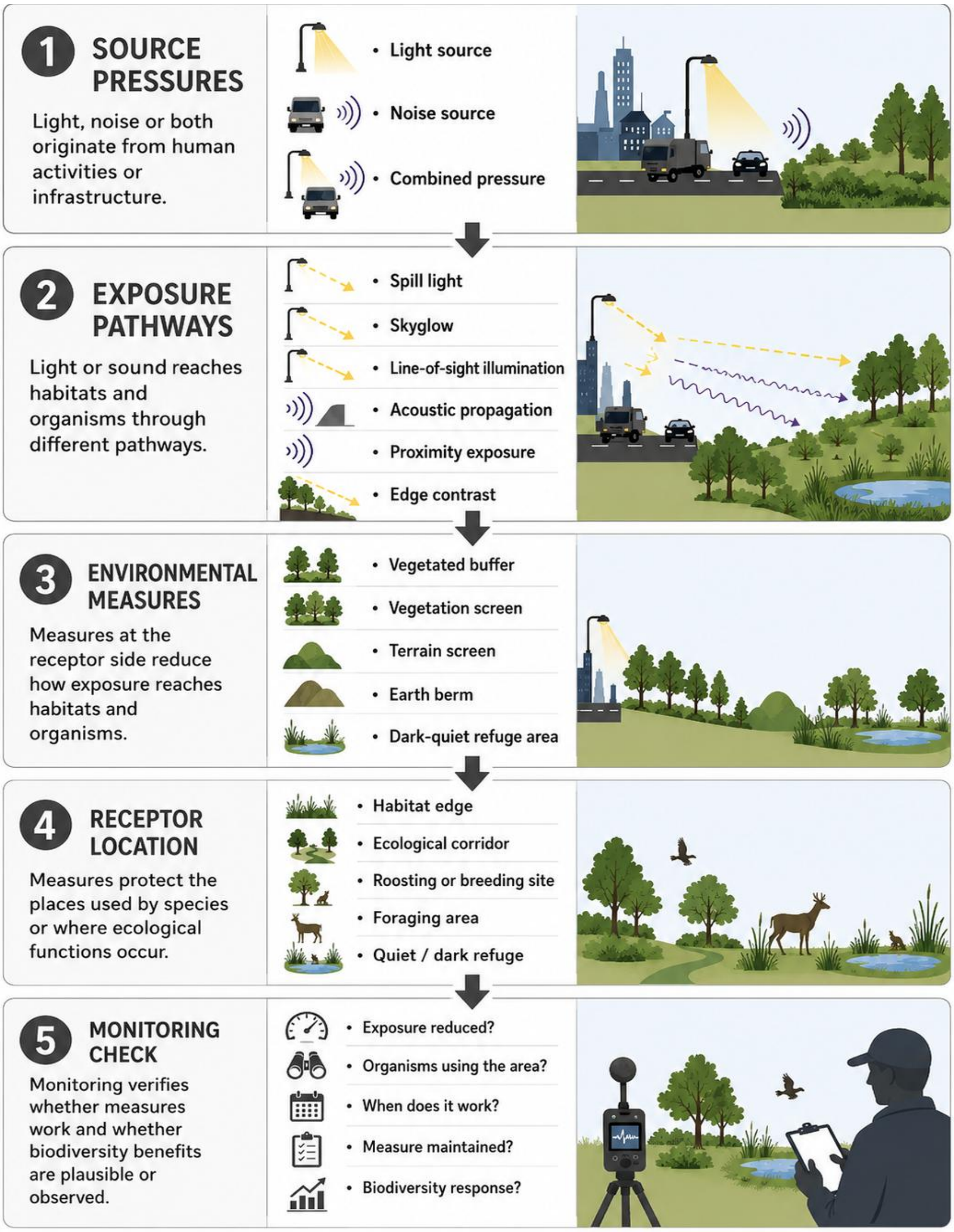


Figure 3.5.1.1 Environmental measures as receptor-side mitigation pathways. The figure was generated with the assistance of OpenAI's image-generation capability within ChatGPT, based on the conceptual structure, content specifications and iterative prompts developed by the authors from the findings of this study. The authors reviewed and refined the generated output and retained full responsibility for the scientific content, interpretation, accuracy and final selection of the figure.

Figure 3.5.1.1 illustrates how environmental measures can reduce the light and/or noise exposure that reaches habitats, ecological corridors, refuges and organism groups. The pathway starts with source pressure, follows the exposure route through which light or sound reaches the sensitive locations, and shows how buffers, vegetation screens, terrain screens, berms or dark-quiet refuges may reduce receptor-side exposure.

3.5.2 Representative environmental measures

A further concept relevant to this family is **dark-sky infrastructure**. In this report, dark-sky infrastructure is understood as a planned network of dark or low-light ecological spaces, including dark corridors, dark refuges, low-light habitat edges, dark buffers, protected nightscape areas and areas where skyglow, spill light and source visibility are actively limited. It should not be interpreted only as a dark-sky park or as a visual landscape designation. Its ecological value depends on whether it maintains darkness or lower light exposure in places that are actually used by nocturnal or light-sensitive organisms.

Dark-sky infrastructure is closely **linked to planning and regulatory measures**, but it is also relevant to environmental mitigation because it protects receptor-side conditions in habitats, corridors and refuges. It can support movement, foraging, roosting, breeding, pollination or other ecological functions where organisms depend on low-light conditions. However, the designation of a dark area is not sufficient by itself. The key question is whether ecologically relevant light exposure is reduced at the receptor scale and whether the protected dark area remains connected, maintained and usable by target species.

Environmental Lighting Zones can support this logic by defining where different levels of lighting control are expected. In this sense, they are not environmental measures by themselves, but they can help translate ecological sensitivity into practical lighting expectations for different landscape contexts. For example, stricter low-light conditions may be needed near protected areas, ecological corridors, roosts, wetlands, breeding sites or dark refuges, while other areas may require less restrictive controls. Their value for biodiversity depends on how they are applied: the zone should be linked to receptor sensitivity, exposure pathways, lighting design, monitoring and enforcement. If Environmental Lighting Zones are used only as generic lighting categories, without receptor-scale validation, they should be treated as planning support rather than demonstrated ecological mitigation.

The role of *Table 3.5.2.1* is to show how environmental measures should be interpreted before they are treated as effective receptor-side mitigation. The table includes dark-sky infrastructure and Environmental Lighting Zone-linked protection, while keeping the same logic of pathway, typical measures, ecological risk and validation focus.

Table 3.5.2.1. Environmental mitigation pathways, dark-sky infrastructure, ecological risks and validation focus.

Environmental pathway	Typical measures	Main ecological risk	Validation focus
Buffering sensitive habitats from exposure	Habitat buffers, dark-quiet habitat buffers, integrated light-noise buffers, vegetated acoustic buffers	A buffer may be too narrow, poorly located or disconnected from the area used by organisms.	Check whether light and/or noise exposure is reduced inside the habitat used by target species or organism groups.

Screening light, visibility or sound propagation	Vegetated dark buffers, habitat-edge screening vegetation, topographic screening, earth berms	Screening may fail where gaps, skyglow, reflected light, flanking sound paths or poor maintenance remain.	Check line-of-sight, sound propagation, vegetation or berm continuity and receptor-scale exposure after implementation.
Protecting dark-sky infrastructure and low-light ecological networks	Dark corridors, dark-sky habitat networks, low-light habitat edges, dark buffers, protected nightscape areas, Environmental Lighting Zone-linked low-light areas	A dark-sky or low-light area may be designated on a map but still be affected by skyglow, spill light, visible luminaires, poor connectivity or weak enforcement.	Check night-time light conditions, source visibility, skyglow, spill light, ecological connectivity and whether target organisms use the dark or low-light network.
Creating or maintaining low-disturbance refuges	Dark-quiet refuges, refuge restoration, protected lower-exposure habitat patches	A refuge may exist on a map but not be darker, quieter, connected or usable for the intended organisms.	Check whether the refuge is genuinely lower in exposure and whether target species use it during relevant periods.
Supporting ecological functions and ecosystem services	Buffers, refuges, dark-sky infrastructure and screening measures linked to connectivity, pollination, breeding, foraging or habitat use	Ecosystem-service benefits may be inferred too quickly from exposure reduction alone.	Check whether exposure reduction is linked to movement, activity, breeding, visitation, occupancy, regeneration or other receptor-specific ecological indicators.

Dark-sky infrastructure and Environmental Lighting Zones should therefore be used carefully in the report. They are useful because they make darkness visible as an ecological asset and help connect habitat protection with lighting control. However, they **should not be presented as proof of ecological effectiveness on their own**. Their strongest role is to support spatially coherent mitigation: planning identifies where low-light conditions are needed, technological measures reduce light emissions, regulatory measures secure lighting limits or permit conditions, environmental measures protect the receptor-side dark network, and monitoring checks whether the area is actually dark enough and ecologically functional.

This addition also helps clarify the **relationship between environmental and planning measures**. Planning measures may define the zone, corridor or protected nightscape. Environmental measures explain why the zone matters for receptors, habitats and ecological functions. Technological measures then specify how lighting should be changed or controlled within or near the zone. In practice, these elements should be treated as a package rather than as separate actions.

3.5.3 Implementation, monitoring and validation

Environmental measures often **depend on space availability, land control, habitat condition, vegetation establishment, terrain, maintenance capacity** and **long-term management.** Their performance may vary between habitats, seasons, receptor groups and exposure pathways. A measure that is appropriate in one landscape or for one organism group may be insufficient or problematic in another.

Implementation should begin with a clear **definition of the ecological receptor**, the **exposure pathway** and the **function** that the measure is intended to protect. It is important to distinguish between proposing a measure, installing it and demonstrating that it is effective. A planted buffer, mapped refuge, proposed corridor, earth berm or screening structure should not be treated as proven mitigation simply because it exists in a plan or has been physically implemented.

Monitoring should focus on the exposure that reaches habitats, corridors, refuges or other receptor locations. For light, relevant variables may include illuminance, radiance, spectral characteristics, glare, visibility of luminaires, direct line-of-sight intrusion and, where relevant, reflected light or skyglow. For noise, relevant variables may include sound pressure level, frequency bands, timing of exposure, traffic or operational patterns and propagation gradients. Where a measure addresses both light and noise, both pressures should be assessed in the same biologically relevant periods.

Exposure monitoring should be **linked**, where feasible, with **ecological indicators** that match the stated objective. Depending on the receptor group and claimed pathway, this may include habitat use, movement, activity, occupancy, breeding, roosting, foraging, communication, refuge use, pollinator visitation, plant reproductive responses, predator-prey interactions, seed dispersal or regeneration. The indicator should follow the ecological claim. A corridor-protection claim should be supported by movement or habitat-use evidence. A pollination claim should be supported by pollinator activity, visitation rates or plant reproductive response. A refuge claim should be supported by evidence that the target species uses the refuge under lower-exposure conditions.

Maintenance is also essential. Vegetation may require time to develop sufficient density, may lose screening capacity seasonally or may develop gaps. Berms may perform poorly if they are too low, discontinuous or incorrectly positioned. Refuges may lose value if they become isolated from suitable habitats or if new sources of light or noise are introduced nearby. Buffers may be weakened by later development, infill, unmanaged access or changes in surrounding land use. Environmental measures should therefore include implementation-fidelity checks, maintenance responsibilities and periodic review.

3.5.4 Trade-offs and safeguards

Environmental measures can **create trade-offs**. Dense vegetation or berms may reduce exposure but affect visibility, safety, drainage, maintenance or movement permeability. Screening may reduce direct light intrusion but remains insufficient where diffuse skyglow or reflected light is important. Buffers may reduce exposure close to a source but be too narrow for species with larger movement ranges. Refuges may provide lower-disturbance patches but fail if they are disconnected from suitable habitat or not used by the intended organisms. For this reason, environmental measures should be assessed within the wider landscape and infrastructure context. Their purpose is not simply to add green structure, but to reduce ecologically relevant exposure while maintaining habitat quality, connectivity and long-term functionality. Before effectiveness is claimed, the minimum evidence should include a clearly defined exposure pathway, receptor-scale exposure monitoring, implementation-fidelity checks and, where biodiversity benefits are claimed, receptor-specific ecological monitoring. Where these elements are not available, the measure should be described as proposed, plausible or supportive rather than as demonstrated ecological mitigation.

3.5.5 Links with other measure families

Environmental measures operate at the receptor, habitat or landscape level and therefore often depend on measures from other families to be implemented effectively. **Planning measures** can identify where buffers, refuges, habitat edges, ecological corridors or setback zones are needed. Technological measures can reduce light or noise at source, thereby lowering the residual pressure that environmental measures are expected to attenuate.

For co-occurring light and noise pressures, environmental measures should be designed around the same receptor locations and ecological functions rather than as two unrelated sets of actions. A dark–quiet corridor, refuge or buffer may therefore combine spatial separation, vegetation, terrain or other receptor-side features intended to reduce both visual and acoustic exposure. Light and noise should still be measured using pressure-specific indicators, but the location, ecological purpose and management responsibility of the environmental measure can be considered jointly.

The **role of this measure family** is to **reduce the exposure that reaches sensitive habitats and organisms after source-side and spatial controls have been considered**. Environmental measures may complement technological source reduction and planning controls, but they should not be presented as substitutes for reducing avoidable emissions. Their implementation should specify the target receptor, the pressure pathway being addressed, the expected protective function and the monitoring needed to determine whether the habitat, corridor or refuge remains ecologically functional.

Environmental measures therefore provide an essential receptor-side component of mitigation. They can protect habitats, corridors, refuges and ecological functions, but they should not be used as a substitute for reducing excessive emissions at source. Their strongest role is within coordinated mitigation packages, where planning identifies where protection is needed, technology reduces exposure, regulation secures implementation, social measures support stewardship, and monitoring checks whether biodiversity-relevant outcomes are plausible or observed.

3.6 Social measures: supporting acceptance, compliance and adaptive implementation

3.6.1. The role of social and behavioural measures

Socially informed measures are particularly **important where exposure is linked to human behaviour**, local routines, recreation, tourism, events, deliveries, private lighting, site use or weak compliance. They may **lead to changes in practice**, such as switching lights off, dimming, shielding, changing delivery times, respecting quiet hours, reporting non-compliance, or maintaining agreed management rules. In these contexts, ecological mitigation depends not only on technical design but also on whether people understand the purpose of the measure, understand what they need to do, and appreciate the reasoning behind it.

It is important to understand perceptions and experiences of LNP and attitudes towards these issues. Whilst there are particular measures that are 'social' in approach, which we explore in the following, it is also important to understand the societal implications of environmental, technical, regulatory and other interventions.

3.6.2. Understanding experiences, perceptions and practices

Effective engagement with citizens on LNP is predicated on a good understanding of their complex relationship with these environmental factors. This can help to **increase levels of acceptance and compliance**, as well as also prompt behavioural changes that reduce ALAN and unwanted noise. Although this can be challenging, it is not necessary to assume that this is always about 'people versus nature'.

Human health and wellbeing are affected by LNP, and the extent and nature of that pollution can determine the level of impact. Whilst inventions may therefore benefit people and wildlife synergistically, there will also be trade-offs and tensions around human needs, societal expectations and ecosystem impacts. Many interventions will be contentious, making it all the more important to understand the ways in which people perceive and potentially benefit from these forms of pollution. Policymakers need to have a good grasp of these impacts in order to intervene in ways that are effective, acceptable, and fair.

Some interventions require active support from, and involvement of, the public. This may be on a periodic or infrequent basis, such as when purchasing a new, quieter vehicle, or on an ongoing basis, such as practising eco-driving on daily journeys. It is therefore important to understand the motivations and barriers to practices that generate noise (in these examples, driving and types of driving).

It is also important to identify and understand differences across and between population groups, such as nationality, ethnicity, age, gender, disability, and income. For example, electric car purchasing may only be an option for wealthier residents, and women and older people are more concerned about safety on public transport. With exposure to noise pollution (Hayward et al 2025) and ALAN (Nadybal et al 2020, Helbich et al 2024) already reflecting environmental inequalities (Ramachandran 2026), it is important that mitigation measures do not disproportionately affect particular social groups, particularly on the basis on income, ethnicity or gender.

Other interventions may require the placement of restrictions on what people do. Examples include speed limits when driving and curfews for drinking outside. Understanding motivations and barriers to practices that generate noise can help to increase compliance levels and ensure that regulations are fair. This can generate tensions, with a need for engagement and dialogue: examples would be local residents being affected by noise from tourism or loud bars and music venues, when there is a need to balance conflicting priorities, namely sleep, enjoyment and economic activity.

Some interventions may affect behaviour even if this is not the primary intention. Examples might include an increase in driving as a result of reduced lighting at public transport interchanges. These changes may have unintended consequences for biodiversity and may ultimately affect support for, and the long-term viability of, measures.

3.6.3. Social pathways and approaches

A. Identifying opportunities for change

The process of developing social mitigation measures begins by **first identifying the key actors** involved in the generation of environmental pollutants. This includes: recognising those whose behaviours contribute to emissions, as well as those who are affected by exposure and are therefore central to the design and effectiveness of targeted interventions (Sharpe et al., 2021). The potential population of interest is diverse and includes residents, visitors, businesses, transport operators, event organisers, site managers, NGOs, local authorities, and citizen-science groups.

There are likely specific points in time at which people are receptive to information about changing behaviour. These include buying a new car, learning to drive, moving house, having children, or planning a holiday. Many relevant practices will be habitual and therefore difficult to change, but intervening at these 'trigger points' can help to bring about change. Many of the behavioural changes aimed at reducing LNP are associated with other agendas and impacts, and it may, therefore, be useful to make connections with other issues that concern people, such as climate change, health and wellbeing, and fairness. There will also be tensions and trade-offs: the local nightlife brings jobs but disturbs sleep; lighting on pathways may disrupt ecosystems but help people to feel safe. Interventions may have unexpected behavioural consequences: reducing lighting on pathways may mean people are less confident walking and begin to drive more often, causing traffic noise.

This understanding of the current situation provides a foundation that supports more targeted and effective awareness and behaviour-change measures, which are outlined below.

B. Awareness, campaigns and community-led action

Awareness and behaviour-change measures represent an **initial step in addressing LNP** by influencing how individuals, organisations, and communities use artificial lighting and generate noise. Independent of technological and environmental solutions, such interventions seek to increase public knowledge and target everyday practices, to minimise excessive noise and light at source.

An example in the context of **LP is that of 'lights out'** campaigns, which seek to reduce unnecessary ALAN at specific points, such as during migration, mating, and peak activity periods. Given that building light output is a factor in fatal collisions of migrating birds (Van Doren et al., 2021), encouraging people to turn out lights can help. An example of such a campaign is *Lights Out Chicago*, a voluntary conservation programme established in 2000 that encourages building owners and occupants to switch off non-essential interior and decorative lighting during peak bird migration periods, thereby reducing the risk of bird disorientation and fatal building collisions (Chicago Bird Alliance, n.d.).

Noise Action Week is a long-running public awareness campaign in the UK that seeks to highlight the health and wellbeing impacts of excessive noise while promoting practical behavioural changes to reduce unwanted noise exposure in homes, communities, and workplaces (Institution of Environmental Sciences, 2026).

Stewardship and community-led implementation measures focus on translating evidence into local action, with communities taking an active role in managing and reducing light and noise pollution.

Zielińska-Dabkowska et al. (2020) describe initiatives that engaged members of the public in collecting LP data and participating in awareness campaigns, demonstrating how citizen involvement can contribute to both knowledge generation and environmental stewardship. An example is the **Fatal Light Awareness Program** (FLAP) in Canada, which includes education and policy development around safeguarding migratory birds. Another is **National Dark Sky Week**, USA, from 2003, people worldwide are encouraged to switch off their lights to preserve the night sky. Related initiatives have also contributed to the **growth of dark sky tourism**, whereby communities promote locations with low levels of artificial light as destinations for stargazing and night-time recreation. Evidence suggests that dark sky tourism can **generate economic benefits** for local communities whilst **simultaneously creating incentives to protect dark skies and reduce light pollution** (Mitchell & Gallaway, 2019; Yakushina & Cameron, 2022).

Other examples include community lighting stewardship programmes that involve residents, local organisations, and other stakeholders in monitoring, managing, and advocating for environmentally responsible outdoor lighting to reduce light pollution and protect night-time ecosystems. In the context of NP, Radicchi (2018) discusses the **concept of "everyday quiet areas"** as a form of urban soundscape stewardship. She illustrates how low-noise environments can be identified and protected through a combination of acoustic data and community organisation.

While stewardship approaches can potentially enable locally driven action to reduce light and noise pollution, their long-term effectiveness relies on the maintenance of such activity, enabled by sustained community engagement and support. Initiatives, be they focused on light or noise pollution, are dependent on public awareness, stakeholder participation, and the acceptance of measures (Baros, 2024; Zielińska-Dabkowska, 2020). The available evidence collectively reinforces the crucial point that any intervention for LNP, whether regulatory, technological, environmental, or social, rely on community buy-in, shared value, and trust between residents, stakeholders, and decision-makers.

Awareness and behaviour-change measures seek to reduce light and noise pollution by encouraging individuals and organisations to adopt less polluting practices. While these approaches can increase knowledge and promote voluntary action, their effectiveness can be strengthened when supported by evidence on local pollution conditions and impacts. The next section therefore examines citizen audit and participatory monitoring measures, which engage the public in collecting data to inform awareness, management, and policy responses to LNP.

C. Citizen science and participatory monitoring

Citizen audit and participatory monitoring measures focus on **generating data and evidence through the involvement of citizens** in observing, recording and assessing light and noise pollution within their local communities. They **contribute to scientific work** whilst also **engaging people** with particular issues and giving them opportunities to learn about the impacts of LNP. Van Noordwijk et al (2021) consider the pathways through which citizen science can have impact, observing that it can lead to evidence for policy, community action, social network championing, political advocacy, and behavioural change.

An example in the context of LP is citizen audits of ecological lighting, such as the *Tatort Streetlight project* (Schroer et al. 2021). This involved citizen scientists assessing insect-friendly road lighting through monitoring insect behaviour, measuring night-sky brightness, and evaluating stakeholder awareness before and after lighting interventions. Schroer et al. comment on the potential educational value of the citizen science activities to increase awareness of ecosystem services. D'Hondt et al. (2013) used a citizen science approach in which 13 volunteers collected smartphone-based noise measurements across Antwerp, Belgium, producing noise maps with accuracy comparable to official models and demonstrating that citizen-generated data can effectively support environmental noise monitoring. Zielińska-Dabkowska et al. (2020) describe initiatives that engaged members of the public in collecting LP data and participating in awareness campaigns, demonstrating how citizen involvement can contribute to both knowledge generation and environmental stewardship. In the context of noise pollution, Gale and Ednie (2020) proposed involving visitors to protected areas in reporting soundscape conditions and perceived noise sources, finding that crowdsourced observations can help managers identify noise-related issues and support more proactive environmental management. PLAN-B similarly engage citizens in campaigns, such as the Lost at Night application and activities performed with COPs at pilot study areas (surveys, monitoring, practices, etc).

Through such citizen science approaches, public awareness of LNP increases, alongside the capacity to monitor and collect valuable data. This, in turn, strengthens the evidence base for intervention. However, the value of each individual initiative ultimately depends upon how the harnessed data is utilised for sustained local action, as explored in the section below.

3.6.4. Implementation, monitoring and validation

Social measures often appear **feasible and low-cost, but their ecological effectiveness is conditional.** They require clear responsibilities, sustained participation, trust, and feedback loops. In terms of monitoring, organisations should seek clear evidence that social action changed exposure rather than assuming this is the case.

Four questions should be used when interpreting social measures:

1. **Participation:** who took part, and was participation sustained?
2. **Action:** did awareness, reporting, or agreement lead to a real management action?
3. **Exposure:** did light or noise pollution exposure actually decrease?
4. **Ecology:** was receptor activity, habitat use or an ecosystem-service pathway monitored?

A social measure should not be judged only by the number of participants, workshops, reports, or campaign materials. These are implementation indicators. They become ecologically meaningful only when they are linked to reduced exposure and, where possible, receptor response.

3.6.5. Links with other measure families

Social approaches to LNP are many and varied. They generally involve working directly with people to understand and influence their behaviour. They are often an essential component of other categories of measure.

Technological measures, for example, tend to be more effective when accompanied by appropriate education and engagement so that people understand and value them.

It is important not to simply think about 'social measures' in isolation, however. All **LNP** in some way **connects with human behaviour and economic activity**. It is therefore important to understand that all mitigation measures – whether technological, regulatory or environmental – take place in a social world. The **acceptability and effectiveness** of those approaches will be **determined by many social factors**, including how well they are understood by people, what engagement people have had in their design and implementation, and the extent to which they act fairly and alleviate rather than deepen social inequalities. Social measures such as citizen science and community agreement can inform and shape environmental and regulatory approaches at a larger scale.

3.7 Summary of practical use

The practical value of a mitigation measure depends on whether it reduces the exposure pathway that is ecologically relevant for the receptor, place and period in which the pressure occurs. **Measures** should therefore not be selected only because they are available, technically feasible or already used elsewhere. They **should be selected** because they **address** a defined light, noise or combined light-noise **problem affecting sensitive species, organism groups, habitats, ecological corridors or ecosystem service functions**.

In practice, mitigation should usually be designed as a **package of complementary measures** rather than as one isolated action. Regulatory and planning measures create the enabling and spatial framework. Technological measures reduce emissions at source or along the pathway. Environmental measures protect receptors, habitats, refuges and ecological functions, including through restoration where degraded habitats or corridors need to regain lower-exposure conditions. Social measures support acceptance, compliance, reporting, stewardship and adaptive management.

The **minimum practical requirement** is to demonstrate that **relevant exposure** has been **reduced**. Where feasible, this should be complemented by monitoring of receptor response, implementation fidelity and long-term maintenance. The table below (*Table 3.7.1*) gives simplified examples of how measures may be combined in different contexts. These examples serve as indicative selections, not as universal prescriptions.

Table 3.7.1 Practical examples of mitigation packages and checks across implementation contexts.

Context	Possible measure package	What should be checked
Protected-area edge	Zoning + lighting curfew + shielding + access guidance + dark/quiet refuge	Exposure at the boundary, compliance, sensitive receptors, habitat use
Road near habitat	Speed/noise reduction + low-noise surface + habitat buffer + receptor-scale monitoring	Noise level, frequency/masking risk, light spill, habitat use, movement routes
Urban Park	Adaptive lighting + spectral control + quiet/dark refuge + citizen reporting	Light level, spectrum, public acceptance, biodiversity indicators, maintenance

Peri-urban fringe	Lighting restrictions + ecological setback + buffer vegetation + visitor guidance	Edge exposure, corridor continuity, land-use pressure, compliance
Rural landscape	Part-night lighting + machinery/noise timing rules + habitat buffers + stewardship	Timing of exposure, breeding/foraging periods, farm or infrastructure compliance
Tourist landscape	Seasonal restrictions + visitor guidance + protected routes + monitoring	Timing of disturbance, visitor compliance, receptor response, refuge use
Ecological corridor	Dark corridor + lighting restrictions + habitat buffer + movement monitoring	Continuity, movement routes, exposure hotspots, barrier effects
Restoration area	Exposure reduction + habitat restoration + dark/quiet refuge protection + adaptive monitoring	Whether restoration improves habitat quality, lowers exposure and supports target species or functions

Mitigation should connect ecological objectives with implementation capacity. A useful measure is not simply one that is listed in a database or installed in the field. It is one that reduces the relevant exposure pathway, protects the intended receptor or ecological function, can be maintained over time and can be adjusted when monitoring shows that the expected effect has not been achieved.

4. Conflicts, trade-offs and co-benefits

4.1 Why conflicts are normal and how to work through them

Measures to reduce harmful LNP interact with road safety, transport systems, land use planning, legal frameworks, local economies, tourism and the everyday expectations of residents and businesses (Gaston & others, 2023). Conflicts should therefore be treated as a normal part of mitigation planning, not as exceptional problems or reasons to delay action (European Environment Agency, 2020). The right question is not whether conflicts exist, but how they can be detected early and managed in a way that keeps ecological goals intact.

The **guiding principle** throughout is that **nature conservation and restoration** should remain the **primary reference point** when designing measures for TBES (Díaz et al., 2019). Human safety, accessibility, economic activity and public acceptance all matter, but they should not automatically override ecological needs. The challenge is to find ways to maintain human functions while reducing the light and noise exposure that harms sensitive species, habitats and ecological processes.

This requires moving away from a purely human-centred approach and towards a receptor-oriented approach (Sanders et al., 2021). Instead of measuring light and sound only against human comfort thresholds, a receptor-oriented approach looks at exposure in relation to the organisms that matter: their sensory sensitivity, their activity timing, their location and the ecological processes — pollination, movement, reproduction, communication — that can be disrupted (Gese & Terletzky, 2015).

Another key principle is that **single measures rarely work alone** (Gaston & others, 2023). A lighting reduction presented only as 'less light' may face safety objections. A speed limit presented only as a transport constraint may be challenged on economic grounds. A quiet zone presented only as a restriction may be opposed socially. When the same **measures are presented as a package** — combining targeted lighting, adaptive dimming, low-noise surfaces, buffer zones, seasonal access rules, monitoring and community engagement — they **become more defensible, more effective and more durable**.

Figure 4.1.1 Main conflicts, trade-offs and practical responses in biodiversity-sensitive light and noise mitigation. The figure was generated with the assistance of OpenAI's image-generation capability within ChatGPT, based on the conceptual structure, content specifications and iterative prompts developed by the authors from the findings of this study. The authors reviewed and refined the generated output and retained full responsibility for the scientific content, interpretation, accuracy and final selection of the figure.

4.2 Seven conflict areas: trade-offs, responses and co-benefits

Figure 4.1.1 sets out the **seven main conflict** areas identified in current evidence and practice (Gaston & others, 2023). For each area, it shows the typical trade-off that arises, the type of practical response most likely to manage conflict without losing ecological purpose, and the co-benefits and monitoring checks that can confirm whether measures are working (IPBES, 2019).

Across all seven areas, three cross-cutting points apply. First, conflicts are rarely isolated: a noise restriction near a sensitive habitat may also create transport concerns, enforcement difficulties and social resistance. Responses must therefore be designed as coordinated packages, not standalone rules (European Environment Agency, 2020). Second, policy instruments should be assessed across at least three dimensions: ecological effectiveness, cost-effectiveness for those who must implement them, and perceived legitimacy among affected stakeholders. Neglecting any of these increases the risk of non-compliance or reversal (Wiedemann et al., 2022). Third, legal and institutional context — the clarity of legal powers, the distribution of responsibilities and the strength of planning requirements — determines whether sound technical measures can actually be delivered and sustained (Wiedemann et al., 2022).

4.2.1. Public and road safety

Safety concerns are among the most common objections to lighting reduction. Residents, visitors and road safety authorities often equate less light with greater risk. However, ecological mitigation does not mean removing all lighting. In most cases, the practical goal is to avoid unnecessary lighting, eliminate spill light, direct light only where it is needed, use adaptive dimming linked to actual use patterns, and avoid ecologically sensitive wavelengths — particularly short-wavelength blue light — where alternatives exist.

Evidence shows that **well-directed, glare-free lighting can improve both road safety and ecological conditions simultaneously**. The trade-off should therefore be framed as better lighting, not simply less lighting. For noise and road safety, the same logic applies: speed management, quieter road surfaces, traffic calming and targeted routing can reduce wildlife disturbance without assuming that ecological protection and road safety are inherently opposed.

4.2.2. Transport efficiency

Speed limits, rerouting, quiet zones, delivery restrictions and construction curfews can be perceived as reducing mobility or increasing operational costs. These concerns are legitimate and must be weighed honestly. However, they must also be weighed against the cumulative ecological disturbance caused by unrestricted transport infrastructure: chronic noise exposure, habitat fragmentation and the loss of landscape permeability for wildlife.

The practical response is to identify where **transport-related restrictions are most ecologically justified**, apply them proportionately, phase them in where needed, and use monitoring near sensitive receptors to demonstrate whether exposure is actually reduced. This approach makes restrictions targeted rather than broad, and evidence-based rather than precautionary in the pejorative sense.

4.2.3. Maintenance costs and operational capacity

Technical measures often look effective at the moment of installation, but lose value over time. Shielding can be incorrectly fitted or damaged. Dimming schedules can be overridden. Sensors can fail. Low-noise road surfaces degrade, sometimes within a few years. Vegetation buffers lose structure if not managed. Access signs are ignored. A measure that is not maintained is unlikely to deliver long-term ecological benefit.

The practical response is to **include maintenance, responsibility, inspection and review from the start of planning** — not as an afterthought. Procurement standards can embed maintenance obligations. Monitoring protocols can flag performance degradation. Clear ownership avoids the situation where no single actor takes responsibility for a measure's continued function.

4.2.4. Legal feasibility and enforcement

Some measures are ecologically desirable but legally fragile. Responsibilities may be shared across planning, transport and environmental authorities with no clear lead. Legal instruments may rely on human-centred thresholds that do not capture ecologically relevant exposure. Or a rule may exist on paper but be unenforceable in practice because inspection capacity is insufficient.

The practical response is to **connect mitigation with concrete legal and procedural anchors**: permit conditions, protected-area rules, environmental impact requirements, procurement conditions, management plans and monitoring obligations. Enforcement should be realistic from the outset. A rule that cannot be checked, maintained or broadly accepted is unlikely to deliver long-term ecological improvement — and may undermine confidence in the regulatory system as a whole. Additionally, the competence of the responsible authorities to reduce LNP should be clearly defined.

4.2.5. Social acceptance and behaviour

Local actors — residents, businesses, land managers, event organisers — may resist restrictions if they appear to be imposed from outside, if the rationale is unclear, or if they are perceived as economically damaging or culturally unwanted. This is especially relevant for lighting changes, access restrictions, quiet hours and measures affecting private land or small businesses.

Participation can improve both the legitimacy and the practical effectiveness of measures, but it should not be used to dilute ecological objectives. Co-design works best when it begins early, when it involves genuine decision-sharing rather than consultation after plans are fixed, and when it is linked to transparent monitoring so that communities can see whether measures are having the intended effect. Citizen science programmes have shown promise in building both evidence ownership and public understanding.

4.2.6. Tourism, recreation, entertainment and the night economy

Tourism, outdoor recreation, festivals, illuminated public spaces and night-time hospitality support local economies and public engagement with the natural environment. But the same activities can increase light and noise disturbance in dark or quiet refuges, at breeding sites, in roosting areas and along sensitive habitat edges.

The response is not to frame biodiversity protection as anti-tourism. Instead, **mitigation should guide activity to less sensitive places and times**. Seasonal access rules designated quiet routes, visitor information, lighting curfews tied to ecological calendars, event conditions and participatory monitoring can maintain tourism and recreation while reducing pressure on sensitive receptors. Evidence from dark-sky tourism and wildlife-watching shows that ecological quality can itself become an economic asset.

4.2.7. Human-centred standards and the receptor gap

Many existing monitoring standards were designed to protect human health and comfort — not to describe ecological exposure. illuminance (Lux), CCT (K), dB, Lden (Day-Evening-Night Level) and Lnight (average night-time noise exposure) values are useful for human-oriented regulation, but they often miss what matters for biodiversity: spectral composition at wavelengths relevant to specific taxa, light and sound levels at habitat edges rather than at road surfaces, timing and duration of exposure during sensitive periods such as dawn chorus or insect emergence, and the directional and spatial spread of both light and sound.

The practical response is not to abandon **existing standards**, but to **complement** them **with receptor-oriented indicators**. This means monitoring light at habitat edges, assessing spectral spill, measuring sound at frequencies relevant to communication or masking for the species present, and linking exposure monitoring with observations of receptor activity, movement, occupancy or breeding success where feasible.

4.3 Co-benefits: what good mitigation delivers beyond ecology

Well-designed light and noise reduction measures not only reduce ecological harm. They **generate** real **co-benefits** for human health, infrastructure performance, economic activity and governance quality (Gaston & others, 2023). Recognising these co-benefits is important both for building the case for action and for evaluating instruments honestly across their full range of effects (IPBES, 2019).

- Better-directed, glare-free lighting improves road safety and reduces sky glow, energy use and light trespass simultaneously (Cheng et al., 2014; Hölker et al., 2010).

- Noise reduction supports public health outcomes including lower rates of cardiovascular disease, sleep disturbance and stress (Cheng et al., 2014; Hölker et al., 2010).

Dark and quiet corridors support biodiversity, landscape identity, cultural ecosystem services and nature-based tourism (Braun et al., 2015; Müller & Wittmer, 2023).

- Maintenance programmes that track performance over time reduce long-term infrastructure costs and energy emissions (Cinzano & Falchi, 2012).
- Citizen science and community stewardship improve monitoring capacity, public understanding and voluntary compliance (Pocock et al., 2017).
- Lower vehicle speeds and quieter road surfaces correlate with reduced fuel consumption and vehicle emissions (Forman & Deblinger, 1998).

Co-benefits should, however, be described with care. A measure that benefits people does not automatically benefit biodiversity (Sanders et al., 2021). A lighting change that improves human comfort may still cause ecological harm if it shifts to a different wavelength that is highly disruptive to insects. A noise barrier that reduces road noise at residential facades may not reduce exposure at a nearby wetland if it is not positioned to cover the relevant sound pathways (Elgert et al., 2020). The ecological claim depends on whether the measure reduces the relevant exposure pathway for the relevant receptor, in the relevant place and at the relevant time.

4.4 Monitoring and adaptive management

Monitoring is the mechanism that **allows mitigation to remain ecologically meaningful** over time. Even well-designed measures can fail through poor installation, lack of maintenance, regulatory drift, or changes in the surrounding landscape that alter cumulative exposure patterns. Monitoring can show whether the intended exposure reduction occurred, whether it was implemented correctly, and whether there is any observable ecological response (Van Der Veen et al., 2021). Where evidence is incomplete, which is common, adaptive management provides a structured way to act under uncertainty. Measures are introduced based on the best available evidence, monitored rigorously, and adjusted as results come in (Díaz et al., 2019). This is especially important given the significant gaps that remain in ecological dose-response data: for most terrestrial species, the relationships between light intensity, spectral composition, noise level, frequency content and ecological outcomes are not fully characterised (Slabbekoorn & Ripmeester, 2008).

Monitoring frameworks should therefore **track receptor-scale ecological exposure** and, where feasible, b**iological indicators** — activity patterns, breeding success, movement, occupancy — at sensitive locations (Gese & Terletzky, 2015). This combination **makes adaptive management ecologically meaningful** rather than simply procedurally compliant (Van Der Veen et al., 2021).

Conflicts and trade-offs are a design and governance challenge (European Environment Agency, 2020). The evidence reviewed in this chapter shows that most conflicts can be managed through measure packages that combine legal feasibility, spatial planning, technical reduction, receptor-scale protection, social engagement, monitoring and maintenance (Gaston & others, 2023). No single measure is sufficient, and no conflict area is insurmountable with careful, evidence-informed planning. The purpose of conflict management is not to remove all human activity from landscapes. It is to ensure that **human use does not continue to erode the sensory conditions** — darkness, quiet, spectral integrity, that TBES depend on (Díaz et al., 2019). In this sense, managing conflicts well is the same task as reducing ecologically relevant light and noise exposure (IPBES, 2019).

5. Conclusions and innovation needs

This review shows that many existing measures can already contribute to the prevention and mitigation of LNP on TBES. However, their value depends on how they are selected, combined, implemented and monitored. A measure should not be treated as effective only because it exists in guidance, legislation, planning practice, technical design or local management. Its ecological relevance depends on whether it reduces the exposure pathway that matters for sensitive species, organism groups, habitats, ecological processes or ecosystem-service functions.

The main conclusions of the review are as follows:

1. Existing measures are available across several fields of action, including regulation, planning, technology, environmental management and social engagement.
2. These measures should not be applied in isolation. They have different roles and should be combined into coherent mitigation packages where needed.
3. Evidence is generally stronger for exposure reduction than for direct biodiversity recovery or ecosystem-service improvement.

4. LNP should be recognised as significant ecological pressures. They are different stressors, with different physical properties, standards and mitigation options, and they often need to be assessed and regulated separately.
5. Where light and noise co-occur in the same habitats, corridors, protected-area edges, transport systems or recreational landscapes, both pressures should be considered in ecological assessment and mitigation planning.
6. Ground-based measurement, receptor-scale monitoring and implementation checks are essential before strong ecological claims are made.
7. The main innovation needed is to improve the evidence-to-action chain linking source control, exposure reduction, ecological response, governance feasibility and long-term maintenance.

A central finding is that mitigation must move from a measure-based approach to a pathway-based approach. The key question is not simply "which measure is available?", but "which exposure pathway needs to be reduced, at which place and during which sensitive period?" This distinction is important because the same measure may have different ecological meanings in different settings. A lighting curfew, buffer, quiet zone, low-noise surface, shielding requirement or visitor restriction may be useful in one context and insufficient in another.

The review also shows that the strongest current evidence often concerns the first part of the mitigation chain: reducing light or noise exposure. There is less consistent evidence showing that such reductions lead to measurable recovery of species, habitats, ecological functions or ecosystem services. This does not make existing measures irrelevant or inadequate. It means that they should be presented with an appropriate level of certainty. Exposure reduction can be a valid and necessary mitigation objective, but it should not automatically be described as biodiversity recovery unless biological or ecological responses are observed or strongly supported.

A key limitation is the lack of widely applicable measuring tools and metrics that describe light and noise exposure from the point of view of species, habitats and ecological processes. Human-centred indicators, such as illuminance, CCT, sound level or average noise indicators, are useful for regulation, engineering and public management, but they do not always describe biologically relevant exposure. Light and noise should therefore be treated in a balanced way. They should not be merged into one generic pressure, because they act through different mechanisms and require different indicators, standards, and technical responses. At the same time, they should not be ignored as co-occurring ecological pressures where both affect the same receptors or places. The practical need is to keep their measurement and regulation sufficiently specific, while improving methods for identifying overlap, and situations where coordinated mitigation packages are needed.

The innovation needs are therefore scientific, technical, institutional, and communicative. Scientifically, there is a need to connect exposure reduction with measurable ecological response. This requires better before-and-after monitoring, control-impact designs where feasible, taxa-sensitive indicators, and clearer separation between plausible ecological pathways and demonstrated outcomes. Technically, there is a need for practical measuring tools and monitoring protocols that can be applied by authorities, site managers, consultants, infrastructure operators, and conservation bodies. Institutionally, biodiversity-sensitive light and noise mitigation should be embedded into policy, legislation, planning, procurement, permitting, environmental assessment, protected-area management and maintenance routines. Communicatively, research findings need to be translated into practical guidance that lighting practitioners, acoustic professionals, planners, infrastructure operators and industry can understand and apply.

Future work should focus on the following priorities:

- developing practical protocols for selecting measures according to receptor sensitivity, exposure pathway, timing and spatial scale;
- creating assessment procedures that treat light and noise as distinct pressures, while also identifying places where both need to be considered together;
- defining minimum monitoring requirements before ecological effectiveness is claimed;
- developing adaptive mitigation packages that combine regulatory, planning, technological, environmental and social measures where appropriate;
- improving definitions and guidance for different settings, including urban, peri-urban, rural, natural and protected-area contexts;
- strengthening the role of nature conservation and restoration in policy and legal instruments addressing light and noise pollution;
- improving communication between researchers, lighting practitioners, acoustic professionals, planners, engineers, conservation practitioners, infrastructure operators and public authorities;
- connecting citizen science and stakeholder input with clear ecological questions, monitoring needs and management responses.

This requires action at several governance and implementation levels. At international, European and national levels, relevant policies and legal instruments should recognise light and noise pollution more clearly as ecological pressures, not only as issues of energy use, nuisance, public health or human comfort. At regional and local levels, planning, protected-area management, procurement, permits and operational rules should translate this recognition into practical exposure reduction. At the professional and community level, awareness, training, citizen science and stakeholder engagement should help ensure that measures are understood, accepted, maintained and checked over time.

In conclusion, the available evidence already supports action. Existing measures can reduce ecologically relevant light and noise exposure, especially when they are selected according to receptor sensitivity, exposure pathway, timing and spatial scale. The main limitation is the uneven connection between measures, ecological mechanisms, implementation conditions and monitored outcomes. The main innovation needed is therefore to build a stronger evidence-to-action framework that links exposure reduction, biodiversity response, governance feasibility, social acceptance and long-term adaptive management. This is the basis for moving from general mitigation recommendations towards biodiversity-sensitive practice that supports nature conservation, restoration and terrestrial ecosystem-service functions.

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Annex I. Checklist and Q&A

Move practical questions, checklists and user guidance here.

This annex provides a simple checklist and short practical guidance for readers who need to use the report in planning, assessment, procurement, site management, conservation practice, monitoring or implementation. It is intended for authorities, protected-area managers, planners, infrastructure operators, consultants, conservation bodies, land managers, community organisations and other responsible actors.

The annex should be read as practical guidance, not as a substitute for local ecological assessment. The same measure may work differently depending on the species or organism group, habitat, season, exposure pathway, governance context and monitoring capacity.

Table I.1. Practical checklist for selecting and checking mitigation measures

Step	Question	What to check
1. Define the ecological target	What species, organism group, habitat, ecological process or ecosystem-service function is being protected?	The measure should be linked to a clear receptor and ecological objective, such as movement, breeding, foraging, communication, pollination, refuge protection or restoration.
2. Define the pressure	Is the pressure light, noise or both?	Light and noise have different metrics and mitigation options. Where both occur in the same place, both should be considered in the assessment.
3. Locate the exposure pathway	Where does exposure occur?	Check whether exposure occurs at the source, along the pathway, at a habitat edge, in a corridor, in a refuge, in a protected area or across a wider landscape.
4. Avoid or reduce exposure first	Can unnecessary light or noise be avoided or reduced before other measures are added?	Avoidance and source reduction are usually stronger than later compensation. This may include switching off unnecessary lighting, reducing operating times, reducing traffic or machinery noise, or changing the location or timing of activities.
5. Select a measure package	Which combination of measures is needed?	Most situations require a package of measures, for example planning control, technical source reduction, habitat protection, communication, enforcement and monitoring.
6. Check technical and ecological fit	Does the measure address the relevant exposure pathway?	For light, check intensity, spectrum, direction, source visibility, spill light and timing. For noise, check level, frequency, masking, intermittency, propagation and biologically relevant timing.
7. Identify responsibility and legal basis	Who can require, implement and maintain the measure?	Responsibility may sit with an authority, regulator, operator, land manager, protected-area manager, consultant, infrastructure owner or community organisation. Check whether there is a legal, planning, permit, procurement or management hook.

8. Assess trade-offs	Could the measure create other problems?	Consider safety, access, tourism, recreation, maintenance, drainage, landscape permeability, social acceptance and possible ecological side effects.
9. Monitor implementation and exposure	How will the measure be checked?	Monitor exposure before and after implementation, check whether the measure was installed and maintained correctly, and use ground-based or receptor-scale measurements where possible.
10. Review and adapt	What happens if the measure does not work?	Monitoring should lead to revision where the measure is ineffective, poorly maintained, socially unacceptable or ecologically insufficient.

Table I.2. Short answers to common practical questions

Practical question	Short answer
Are warmer LEDs always better for wildlife?	No. Warmer spectra can reduce some risks, but ecological effects depend on the full spectrum, light level, direction, timing, duration, spatial context and receptor group.
Is switching to LED automatically a mitigation measure?	No. A retrofit may reduce energy use but still increase ecological exposure if the new light is brighter, poorly shielded, too blue-rich, visible from sensitive habitats or operated for longer periods.
Are noise barriers or vegetation buffers always effective?	No. They can reduce exposure in some contexts, but their value depends on design, height, width, continuity, receptor location, maintenance and landscape permeability. Vegetation should not be treated as a substitute for source reduction unless monitoring confirms receptor-scale exposure reduction.
What is the difference between a dark corridor, a dark refuge and a quiet refuge?	A dark corridor supports movement through the landscape. A dark refuge protects a lower-light habitat patch. A quiet refuge protects an area where organisms experience lower noise exposure. All should be checked at receptor scale.
Should light and noise be managed together?	They should remain technically distinct because they have different metrics and mitigation options. However, where both affect the same habitat, corridor, protected-area edge or receptor group, both should be considered in the mitigation package.
What if biodiversity protection conflicts with safety, tourism or recreation?	Use context-sensitive design rather than treating the conflict as absolute. Options may include targeted lighting, adaptive dimming, seasonal restrictions, designated routes, quiet periods, event conditions, communication and monitoring.

Plain-language definitions for readers

The following definitions explain key terms used in the report. They are written for non-specialist readers so that the annex can be used without consulting external sources. More detailed lighting terminology can be aligned with specialised lighting references, including Appendix A, “Terminologies and Definitions Connected to Natural and Artificial Light”, in Pérez Vega et al. (2022).

Receptor

A receptor is the organism, group of organisms, habitat or ecological function that may be affected by light or noise. In this report, a receptor is not a person receiving a complaint. It means the ecological target of concern. Examples include bats using a commuting route, insects visiting flowers at night, birds communicating near a road, amphibians calling at a breeding pond, plants affected through pollination or phenology, or a habitat edge exposed to lighting.

Exposure

Exposure means the amount, type, timing and location of light or noise that reaches a receptor. It is not only the amount emitted by a lamp, road, machine or event. What matters is what reaching the organism, habitat or ecological process. For example, a lamp may be technically efficient but still expose a hedgerow, pond, roost or corridor to ecologically relevant light.

Pressure

A pressure is the source of disturbance or environmental change. In this report, the main pressures are artificial light at night, anthropogenic noise and combined light-noise pressure. A pressure becomes ecologically important when it changes the conditions under which organisms move, feed, communicate, reproduce, rest or interact.

Exposure pathway

An exposure pathway is the route through which light or noise travels from the source to the receptor. For light, this may include direct illumination, spill light, glare, source visibility, reflected light or skyglow. For noise, this may include propagation from roads, railways, machinery, events or infrastructure, including the way sound travels through terrain, vegetation, buildings or open space.

Receptor-scale monitoring

Receptor-scale monitoring means checking exposure where the organism or habitat experiences it, not only at the source. For light, this may mean measuring light at a habitat edge, roost, pond, corridor or refuge. For noise, this may mean measuring sound at the breeding site, foraging area, communication site or movement route.

Ecologically relevant exposure

Ecologically relevant exposure is exposure that is likely to affect organisms, habitats, ecological processes or ecosystem-service functions. It may depend on level, wavelength, spectrum, direction, timing, duration, frequency, masking, intermittency or spatial scale. Average values alone may not describe ecological relevance.

Species or organism group

A species is a particular biological species. An organism group is a broader group used for practical interpretation, such as birds, bats, amphibians, insects, pollinators, mammals, plants or other invertebrates. Organism groups are useful in a broad review, but local assessment should be as specific as possible.

Habitat

A habitat is the place where organisms live, move, feed, breed, rest or interact. In this report, habitats may include forests, wetlands, grasslands, hedgerows, ponds, parks, road verges, protected-area edges, ecological corridors, roosting sites, breeding sites and foraging areas.

Ecological process

An ecological process is an interaction or function that helps ecosystems work. Examples include movement, communication, breeding, foraging, pollination, seed dispersal, biological control, decomposition, nutrient cycling and ecological connectivity.

Terrestrial biodiversity and ecosystem services

Terrestrial biodiversity and ecosystem services, or TBES, refers to living organisms, habitats, ecological functions and the benefits that people and nature receive from terrestrial ecosystems. These benefits may include pollination, seed dispersal, pest regulation, soil processes, cultural value, recreation, landscape identity and the value of dark and quiet environments.

Mitigation measure

A mitigation measure is an action that can prevent, reduce, redirect, manage or monitor ecologically relevant light or noise exposure. Measures may be regulatory, planning-related, technological, environmental or social.

Measure package

A measure package is a combination of complementary measures. For example, a protected-area edge may need zoning, lighting curfews, shielding, visitor guidance, habitat buffers and monitoring. A package is often more realistic than relying on one measure alone.

Implementation fidelity

Implementation fidelity means whether the measure was implemented as intended. For example, a shield may be installed incorrectly, a dimming schedule may be overridden, a low-noise surface may degrade, a buffer may be too narrow, or visitor restrictions may not be followed.

Adaptive management

Adaptive management means adjusting a measure after monitoring shows what is working and what is not. It recognises that mitigation is not always correct at the first attempt and may need revision over time.

Local validation

Local validation means checking whether a measure works in the specific place where it is applied. Evidence from another country, habitat or species group may be useful, but it does not automatically prove that the same measure will work locally.

Plain-language lighting terms

Term	**Plain-language meaning**
Artificial light at night	Human-made light used at night, for example from street lighting, buildings, vehicles, advertising, sports facilities or industrial sites.
Light pollution	Artificial light that is unnecessary, excessive, poorly directed, poorly timed or ecologically harmful.
Illuminance	The amount of light falling on a surface. It is often measured in lux, but lux is based on human vision and may not fully describe how wildlife experiences light.

Luminance	The brightness of a surface or light source as seen from a direction. It can be relevant where visible bright sources affect organisms or create glare.
Spectrum	The mix of wavelengths in light. Different organisms can respond differently to blue, green, amber, red or broad-spectrum light.
Wavelength	The physical property that relates to the colour or spectral part of light. It is usually measured in nanometres.
Colour temperature / CCT	A lighting descriptor often used to describe whether a lamp appears warmer or cooler to humans. It does not fully describe ecological risk because two lights with the same CCT can have different spectra.
Spill light	Light that reaches places where it was not intended, such as habitats, water bodies, vegetation, roosts, gardens or protected-area edges.
Glare	Bright or uncomfortable light from a visible source. For biodiversity, source visibility and contrast may also matter, not only human discomfort.
Skyglow	Brightening of the night sky caused by artificial light scattered in the atmosphere. It can affect areas far from the original source.
Timing and duration	When light is present and how long it lasts. Exposure during nocturnal activity, migration, breeding, foraging or roosting may be especially important.
Shielding	A technical design that blocks or redirects light so that less light spills into the sky or nearby habitats.

Plain-language noise terms

The following terms provide a general explanation for non-specialist readers. They should be aligned with the noise terminology used in the final technical and legal review where appropriate.

Term	**Plain-language meaning**
Anthropogenic noise	Noise caused by human activity, such as road traffic, railways, aircraft, machinery, construction, industry, recreation or events.
Noise pollution	Noise that changes the acoustic environment in a way that can disturb organisms, habitats, ecological processes or people.
Sound level	A measure of how strong a sound is. It is often expressed in decibels, but average decibel values do not always explain ecological effects.
Decibel / dB	A logarithmic unit used to describe sound level. A small numerical change in dB can represent a meaningful change in sound energy or perception.
Frequency	The pitch of a sound, usually measured in hertz. Low and high frequencies may affect different organisms in different ways.
Masking	A situation where noise makes it harder for organisms to hear biologically important sounds, such as mating calls, alarm signals, predator cues or prey sounds.
Intermittency	The pattern of noise appearing and disappearing. Occasional loud events may affect organisms differently from continuous background noise.
Propagation	The way sound travels through space. Terrain, vegetation, buildings, weather and distance can all influence how noise reaches a receptor.
Timing of noise	The period when noise occurs. Noise during breeding, calling, foraging, roosting, migration or other sensitive periods can be more important than noise at less sensitive times.

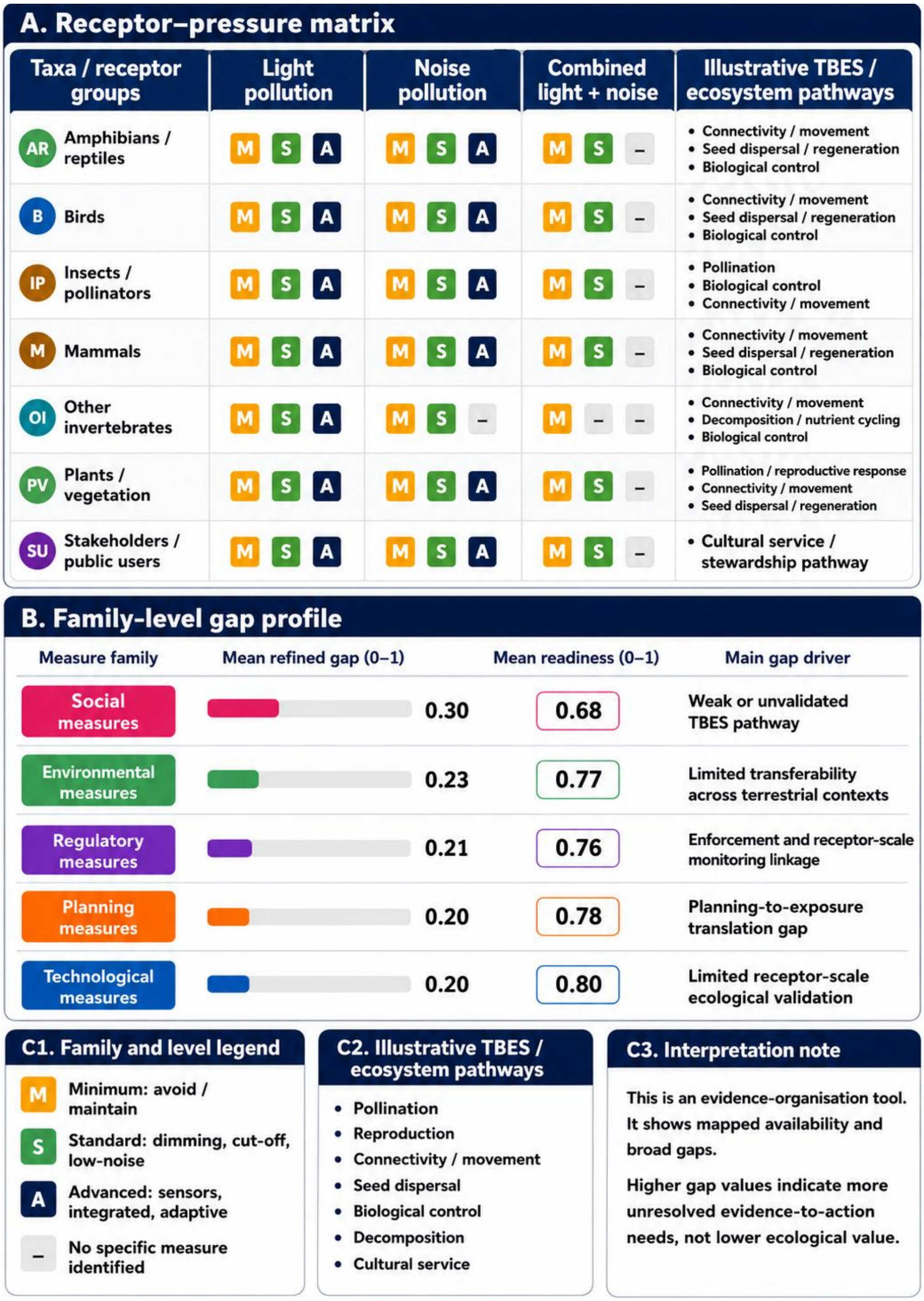
Annex II. Receptor groups, pressure domains and evidence-gap profile for existing mitigation measures

This annex provides an illustrative synthesis of how existing mitigation measure classes relate to terrestrial receptor groups, pressure domains and broad evidence gaps. It brings together information from the working Excel outputs prepared for the regulatory, planning, technological, environmental and social measure families. The matrix shows which receptor groups are linked to light pollution, noise pollution and combined light-noise pressure, while the family-level profile summarises indicative gaps and readiness patterns across measure families. The annex should be read as an evidence-organisation and interpretation tool, not as a ranking of ecological effectiveness.

The figure is organised in three parts. Panel A presents an illustrative receptor–pressure matrix. It shows how broad terrestrial receptor groups are linked to light pollution, noise pollution and combined light-noise pressure. The codes M, S and A indicate whether the working classification identified minimum, standard or advanced measure levels for a given receptor–pressure combination. A dash indicates that no specific measure class was identified for that combination in the working material. The right-hand column links each receptor group with illustrative TBES and ecosystem-service pathways, such as pollination, connectivity, movement, seed dispersal, biological control, decomposition or cultural-service pathways.

Panel B summarises the family-level evidence-gap profile. The mean refined gap value indicates the relative level of unresolved evidence-to-action needs for each measure family. Higher values should be interpreted as a stronger need for clarification, validation or implementation support, not as evidence that the family is less useful. The readiness value gives an indicative view of how implementation-ready the measure family appears in the working classification. The main gap driver explains what limits interpretation most strongly, for example weak TBES linkage, limited transferability, enforcement gaps, planning-to-exposure translation gaps or limited receptor-scale ecological validation.

Panel C explains how to read the codes and pathways. The M, S and A levels describe indicative maturity or complexity of measures, from basic avoidance or maintenance, through standard mitigation actions, to more advanced sensor-based, integrated or adaptive solutions. The TBES pathways are illustrative links between mitigation and ecological functions. They should not be read as proof that a measure has already delivered biodiversity recovery. Overall, the figure shows where the evidence base is richer, where practical measure classes are already visible, and where further validation, monitoring or transferability work is still needed.



A. Receptor–pressure matrix

Taxa / receptor groups	Light pollution	Noise pollution	Combined light + noise	Illustrative TBES / ecosystem pathways
AR Amphibians / reptiles	M S A	M S A	M S –	• Connectivity / movement • Seed dispersal / regeneration • Biological control
B Birds	M S A	M S A	M S –	• Connectivity / movement • Seed dispersal / regeneration • Biological control
IP Insects / pollinators	M S A	M S A	M S –	• Pollination • Biological control • Connectivity / movement
M Mammals	M S A	M S A	M S –	• Connectivity / movement • Seed dispersal / regeneration • Biological control
OI Other invertebrates	M S A	M S –	M – –	• Connectivity / movement • Decomposition / nutrient cycling • Biological control
PV Plants / vegetation	M S A	M S A	M S –	• Pollination / reproductive response • Connectivity / movement • Seed dispersal / regeneration
SU Stakeholders / public users	M S A	M S A	M S –	• Cultural service / stewardship pathway

B. Family-level gap profile

Measure family	Mean refined gap (0–1)	Mean readiness (0–1)	Main gap driver
Social measures	0.30	0.68	Weak or unvalidated TBES pathway
Environmental measures	0.23	0.77	Limited transferability across terrestrial contexts
Regulatory measures	0.21	0.76	Enforcement and receptor-scale monitoring linkage
Planning measures	0.20	0.78	Planning-to-exposure translation gap
Technological measures	0.20	0.80	Limited receptor-scale ecological validation

C1. Family and level legend

- M — Minimum: avoid / maintain
- S — Standard: dimming, cut-off, low-noise
- A — Advanced: sensors, integrated, adaptive
- – — No specific measure identified

C2. Illustrative TBES / ecosystem pathways

- Pollination
- Reproduction
- Connectivity / movement
- Seed dispersal
- Biological control
- Decomposition
- Cultural service

C3. Interpretation note

This is an evidence-organisation tool. It shows mapped availability and broad gaps.

Higher gap values indicate more unresolved evidence-to-action needs, not lower ecological value.

Figure AII.1. Taxa/receptor-group pressure matrix and family-level evidence-gap profile for existing mitigation measures. The figure was generated with the assistance of OpenAI and reviewed by the authors.