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IMPACT OF LIGHT POLLUTION ON DIFFERENT TAXA OF MIGRATORY SPECIES

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1. INTRODUCTION

1.1 Background

1.1.1 What is light pollution?

The use of artificial light to illuminate our streets, homes, sports pitches, commercial and industrial properties either permanently or intermittently through the hours of darkness has become the norm in most developed countries. Lighting at night is considered essential for our security and/or convenience. Monuments, churches, bridges and other landmarks may be illuminated at night for aesthetic purposes and light is also emitted by the vehicles we use on land, at sea and in the air.

The increasing use of electric lighting has modified the natural light environment dramatically and this can have effects on both humans and wild animals. The last century has seen an unprecedented increase in the use of artificial light at night (also known as ALAN), with a global increase rate of approximately 6% per year (with a range of 0-20% depending on geographical region) according to Hölker et al. (2010b).

ALAN is also referred to as light pollution and some distinctions are made between “astronomical light pollution”, which prevents us from seeing the stars and other celestial matter, and “ecological light pollution” which has an impact on the biological functioning of species and disrupts ecosystems (Longcore and Rich, 2004). This type of light pollution can be described as occurring “when organisms are exposed to light in the wrong place, at the wrong time or at the wrong intensity” (Depledge et al., 2010).

Light pollution has been defined by the Commission of the European Communities as “the sum of all adverse impacts of artificial light on the environment, including the impact of obtrusive light” (CEC, 2009). Obtrusive light refers to “the part of the light from a lighting installation that does not serve the purpose for which the installation was designed”.

ALAN can be direct, such as the beam emitted by a streetlight and, indeed, many studies assume that the impacts of artificial light are localised and focused closely on the sources of the light (Davies and Smyth, 2017). However, when artificial light is scattered and reflected back from the atmosphere as artificial skyglow it can have an influence far beyond the individual light sources and can be observed hundreds of kilometres away, affecting otherwise pristine areas (Russart and Nelson, 2018a; Falchi et al., 2016). As well as skyglow, other types of ecological light pollution include glare (contrasts between bright and dark areas), over-illumination, light clutter (unnecessary numbers of light sources) and light trespass (unwanted light) (Rowse et al., 2016).

Light pollution is not constant and atmospheric conditions can impact sky brightness (Falchi et al., 2016). The presence of aerosols (small particles or droplets suspended in the air e.g. dust, sea salt, soot) reduces atmospheric visibility and can impact light pollution in a number of ways (Kyba et al., 2011):

“First, higher aerosol concentrations should amplify the sky glow (particularly on cloud free nights), as aerosols increase the chance that light is scattered back to Earth. Second, if the aerosols are absorbing in the visible band (which is typical in the case of smog), they could reduce the extent to which environmental changes (e.g. snow, or…cloud cover) amplify light pollution, as multiply scattered light would have increased chances of absorption. Third, in the case of very short visibility, the probability of light propagating to the city limits will be reduced, and thus the horizontal extent of the sky glow outside of the city should be reduced.”

Clouds are collections of aerosols in the form of water droplets which are very reflective and, therefore, overcast skies can cause an increase in skyglow (Kyba et al., 2011). This issue was studied in Berlin, Germany and typical skyglow in the city on an overcast night was 10.1 times brighter than on a clear moonless night and 4.1 times as bright as the skyglow at a rural location outside the city on a clear night with a high elevation moon. This cloud amplification effect may have important repercussions for species living in or near urban areas. Van Hasselt et al. (2021) found that during a moonless night with maximum cloud cover, light levels from artificial light reflecting back from the clouds were as bright as the full moon. Skyglow can also be amplified by snow (Jechow and Hölker, 2019b). A study in a suburban area south of Berlin found that snow cover and clouds resulted in a horizontal illuminance which exceeded the maximum value of a full moon by more than a factor of 2.

The spectral content of light is important when assessing how light pollution impacts different species or ecosystems because light is perceived differently by different animals. For insects, it may be the spectral composition of night-time lighting that is more significant than its intensity, for example (Longcore et al., 2015). Light behaves as waves and particles (or photons) and wavelength is measured in nanometres (nm) (Owens and Lewis, 2018). Humans perceive wavelengths between 380 and 780nm as visible light whereas fish, invertebrates, some mammals and diurnal birds can detect ultraviolet (UV) light (10-380nm), and snakes and beetles can detect infrared (IR) light (700-1000nm) (Rowse et al., 2016). Although diurnal birds can see in the UV range, most seabird species cannot (CMS, 2020b). Their photopic (daylight) vision is most sensitive in the 590-740nm (orange to red) long wavelength range and their scotopic (dark adapted) vision is more sensitive to short wavelengths (380-485nm, violet to blue). Figure 1 shows the wavelengths perceived by different species.

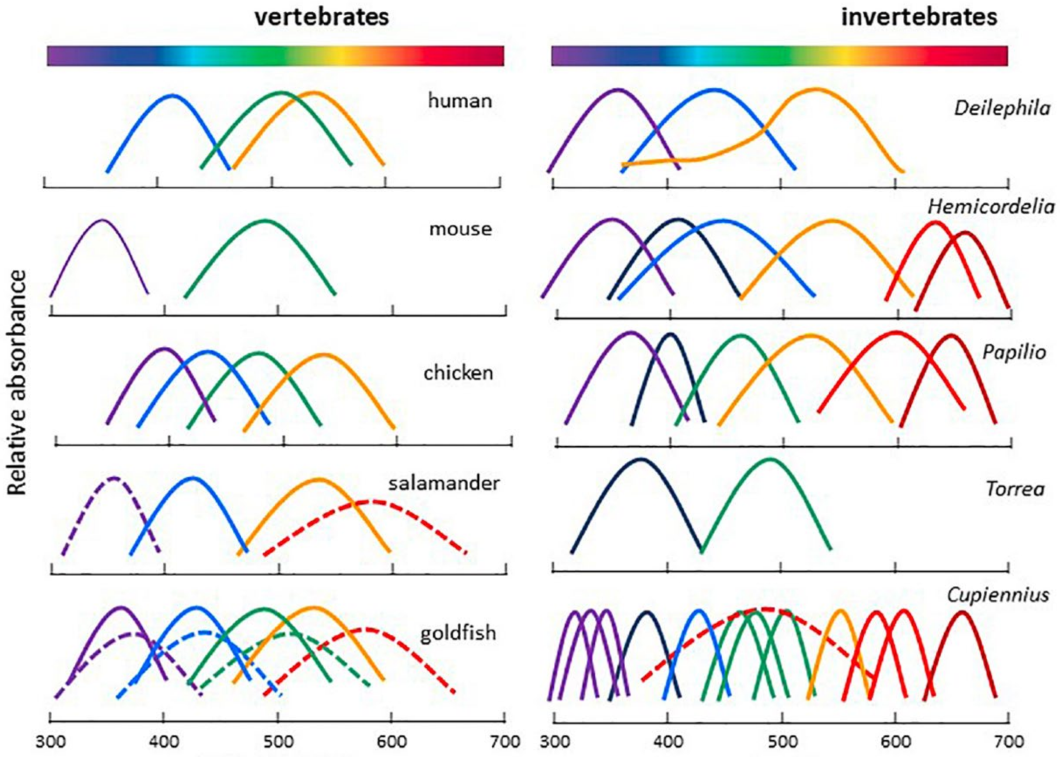

Figure 1: Spectral sensitivity curves of selected vertebrates and invertebrates. Vertebrates: human (*Homo sapiens*), mouse (*Mus musculus*), chicken (*Gallus domesticus*), salamander (*Salamandra*), goldfish (*Carassius auratus*). Invertebrates: elephant hawk moth (*Deilephila elpenor*), Tau emerald dragonfly (*Hemicordulia tau*), Asian swallowtail butterfly (*Papilio xuthus),* annelid worm *(Torrea candida*), nocturnal spider (*Cupiennius salei*). From Falcón et al. (2020) adapted and modified from Imamoto and Shichida (2014) and Warrant (2019).

Different types of lights produce different intensities and light spectra. In recent years there have been changes to the types of lights being used in some places. In the European Union, for example, high-pressure mercury vapour (HPMV) lamps were banned in 2015 and many sodium lamps are being replaced by Light-Emitting Diodes (LEDs) (Voigt et al., 2018a). LEDs are more energy efficient than other light sources, and this makes them a desirable option in many cases (CMS, 2020b). The characteristics of different lamps are summarised in Table 1.

Table 1: Types of lamps and their light characteristics (From Stone et al., 2015; Voigt et al., 2018a; Boyes et al., 2021)

Type of lamp	Colour of light produced (as seen by humans)	Spectrum	Ultraviolet?
Low-pressure sodium (LPS) / Sodium Oxide (SOX)	Yellow/orange	Narrow	No
High-pressure sodium (HPS)	Range of wavelengths mainly orange-yellow but including blue and green	Broad	Some
Light-emitting diodes (LEDs)	Any colour. Usually white/warm-white when used for street lighting. Produce more blue light than HPS.	Broad	No
High-pressure mercury vapour (HPMV)	Blue-white	Moderate	Yes
Metal halide (MH)	Blue-white	Broad	Yes (less than mercury lamps but more than HPS)
Compact fluorescent (CF)	Warm white		Some

1.1.2 The extent of light pollution

ALAN is being increasingly recognised for its impacts on human health, culture and biodiversity (Davies and Smyth, 2017). Marine, freshwater and terrestrial habitats around the world are already being affected, although the extent to which different regions and habitats are impacted is not homogenous.

Twenty-three per cent of the world's land surfaces between 75°N and 60°S have light-polluted skies (Falchi et al., 2016). Between 2012 and 2016, there was a total radiance growth of 1.8% per year with the brightness of continuously lit areas increasing by 2.2% per year (Kyba et al., 2017). There were few places where lighting growth was stable or decreasing in this period and it is expected that artificial light emission will keep increasing. In densely populated industrialised countries there has been a considerable amount of artificial light for decades (Koen et al., 2018). Half of the United States of America and 88% of Europe have light-polluted skies, for example (Falchi et al., 2016). Singapore is the most light-polluted country as sky brightness is >3000 μcd/m^2 for the entire country[1].

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[1] μcd/m2 = candelas per square metre. Falchi et al. (2016) used the following sky brightness intervals: *"(i) Up to 1% above the natural light (0 to 1.7 μcd/m^2)—pristine sky, (ii) From 1 to 8% above the natural light (1.7 to 14 μcd/m^2)—relatively unpolluted at the zenith but degraded toward the horizon, (iii) From 8 to 50% above natural nighttime brightness (14 to 87 μcd/m^2)—polluted sky degraded to the zenith, (iv) From 50% above natural to the level of light under which the Milky Way is no longer visible (87*

In the last two decades, the largest increases in light pollution have taken place in areas with active energy development e.g. central North America, Russia and Venezuela, and newly industrialised areas e.g. eastern Europe, Southeast Asia, northern India, Brazil (Koen et al., 2018). However, there are many parts of the world which are still mainly dark at night. The country with the largest non-polluted area is Greenland as only 0.12% of its area does not have pristine skies (Falchi et al., 2016). For a graphic representation see Falchi et al.'s (2016) map: https://www.lightpollutionmap.info

Koen et al. (2018) created global species richness maps for mammals, birds, reptiles and amphibians as well as for species of conservation concern of each of those groups, and six groups of nocturnal species (bats, owls, nightjars, geckos, frogs and toads, and salamanders) using data from the IUCN. These maps were then used to determine where animals were most threatened by light pollution. The most mammal and bird species potentially threatened by increasing light pollution were in South America, Southeast Asia and sub-Saharan Africa. Southeast Asia was also highlighted for its reptile species. High richness of amphibian species combined with increasing light in South America. Areas with above-average species richness were reported to have experienced larger increases in light pollution in the twenty years between 1992 and 2012 than areas with average-to-low richness. There was also a greater increase in light extent in areas with a high richness of nocturnal species and species of concern according to the IUCN Red List. South America and Southeast Asia, for example, had both an increase in the extent of light and high richness of nocturnal species (bat, owl, nightjar, frog and toad species). These areas rich in biodiversity may be the places where light pollution has a more detrimental effect.

Most studies into light pollution have focused on terrestrial areas though there is an increasing interest in coastal and marine areas. Data from 2010 showed that 22.2% of the world's coastlines (excluding Antarctica) are affected by coastal light pollution (Davies et al., 2014). This figure was much higher in some areas such as Europe (54.3%) and Asia excluding Russia (34.2%) and it is likely that these percentages have increased in the last decade. Tourism is one of the drivers of increased coastal development, bringing with it increases in light intensity in areas which may be particularly vulnerable because of their high natural diversity and environmental vulnerability (Depledge et al., 2010).

ALAN sources in the marine environment may be temporary/moving such as lights from shipping and fishing vessels or fixed e.g. offshore oil platforms and land-based developments, including towns, cities and harbours. Light from ships can have considerable impacts. It has been shown to disrupt fish and zooplankton behaviour during the polar night to depths of at least 200m and across areas of >0.125 km^2 around a research vessel (Berge et al., 2020). Skyglow from ALAN can mean that land-based light sources have an impact further out at sea (Davies et al., 2014).

1.1.3 Biological impacts of light pollution

Organisms have evolved under consistent light conditions with day and night, lunar cycles and seasonality (Seymoure, 2018). Natural light is used by wildlife as a resource and to gain information about their environment (Gaston, 2013). It is also involved in mechanisms essential for regulating metabolism, growth and behaviour, including synchronisation of internal circadian clocks (Kyba et al., 2011; Falcón et al., 2020).

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to 688 µcd/m^2)—natural appearance of the sky is lost, (v) From Milky Way loss to estimated cone stimulation (688 to 3000 µcd/m^2), (vi) Very high nighttime light intensities (>3000 µcd/m^2)—night adaptation is no longer possible for human eyes."

It is increasingly recognised that hormonal synthesis and secretion are often under circadian and circannual control, meaning that perturbation of these internal clocks will lead to hormonal imbalances and other problems (Falcón et al., 2020). Circadian rhythms are endogenous biological rhythms with 24-hour periods and though they persist without environmental cues, these cues (including light) are used by organisms to entrain their circadian rhythms (Russart and Nelson, 2018b). Light is the most effective entraining agent or *zeitgeber*.

In their recent review, Falcón et al. (2020) describe how:

"… most of the basic functions of living organisms are controlled by these internal, genetically determined, clocks. These clocks depend absolutely on the 24 h LD[2] *cycle to accurately synchronize their activity with solar time, and in turn they orchestrate a myriad of downstream biochemical, physiological and behavioural events so that the right process occurs at the right time. Thus, changing the natural LD cycle cannot be without consequences for biological organisms."*

Diurnal, nocturnal, cathemeral and crepuscular animals may react differently to ALAN (Russart and Nelson, 2018a). According to Duffy et al. (2015): "ALAN can effectively increase the length of available activity time for diurnal species, reduce it for nocturnal species and cause more complex changes to the activity cycles of crepuscular and cathemeral species." Though increased urbanisation in areas rich in biodiversity may have consequences for all species, the accompanying increase in artificial light is believed to particularly impact nocturnal species (Koen et al., 2018). As 30% of vertebrates and >60% of invertebrates are nocturnal, it is a significant proportion of species which are at risk (Hölker et al., 2010a).

One of the ways in which exposure to ALAN can disrupt circadian rhythms is via environmental endocrine disruption and particularly if the release of the hormone melatonin is affected (Dominioni et al., 2016; Russart and Nelson, 2018b). Melatonin is primarily secreted at night and is central to sleep regulation and a number of other bodily activities (Pandi-Perumal et al., 2006). It signals to the body both the time of day and the time of year, has immune enhancing properties, is an effective antioxidant and halts the spread of cancer. Several studies have shown that light pollution can alter immune function, increase vulnerability to infectious disease, effect cortisol levels and glucose metabolism (Raap et al., 2015; Helm, 2021).

Through a process known as photoperiodism, day length works as a cue for many animals living in a seasonal environment to time events such as reproduction, dormancy and migration (Bradshaw and Holzapfel, 2007). Preparation for reproduction through the acquisition of territory or other necessary resources, building up fat stores prior to dormancy or moulting prior to migration all need to take place at the appropriate time. Disruptions caused by ALAN can, therefore, impact critical behaviours which are triggered by day length (Longcore and Rich, 2004). Seasonal reproductive processes, such as the shrinking of reproductive organs in many species once the breeding season is over, can be disrupted by artificial light (Helm, 2021).

Tropical species living with constant daily cycles throughout the year may be even more vulnerable to the impacts of ALAN as they are not adapted to seasonal variations and, therefore, a shorter and/or brighter night caused by artificial light could be highly disruptive for them (Longcore and Rich, 2004).

Night length and moonlight can both impact sleep patterns for diurnal species. European starlings (*Sturnus vulgaris*) slept five hours less during the short summer nights than during longer winter nights (van Hasselt et al., 2020). Both starlings and barnacle geese (*Branta leucopsis)* have been found to sleep less during the full moon (compared to the new moon

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[2] LD = light darkness

and half-moon) which appears to be a direct result of the sleep-depriving effect of light (van Hasselt et al., 2020; van Hasselt et al., 2021). The reductions in non-rapid eye movement (NREM) sleep caused by shorter nights and the moon could also be triggered by artificial light and so sleep deprivation could be a potential impact of light pollution particularly for diurnal species. Pigeons (*Columba livia*) and Australian magpies (*Cracticus tibicen tyrannica*), for example, slept less and had more fragmented sleep patterns when they were exposed to ALAN (Aulsebrook et al., 2020a).

A recently published meta-analyses of the biological consequences of ALAN concluded that “natural light cycles are being eroded over large areas of the globe” and that this induces strong responses for physiological measures, daily activity patterns and life history traits, with “especially strong responses with regards to hormone levels, the onset of daily activity in diurnal species and life history traits, such as the number of offspring, predation, cognition and seafinding (in turtles)” (Sanders et al., 2021). The authors also note that to date there has been little work on ecosystem functions.

1.1.4 Ecological impacts of light pollution

As well as the above mentioned physiological and behavioural impacts, how organisms interact with conspecifics and other species including their prey and/or predators can be affected by light pollution, thereby having repercussions at an ecological level (Helm, 2021). For example, diel temporal partitioning which allows competitors to co-exist in the same habitat by being active at different times of day to avoid direct confrontation or to reduce competition for resources (Kronfeld-Schor and Dayan, 2003) may be disrupted by artificial light at night.

Although most research into light pollution has focused on individual species, some researchers have started to take an ecosystem approach looking at how different species in the same habitat are affected. Spoelstra et al. (2015), for example, assessed birds, bats, mice, large mammals and moths at experimental field sites in the Netherlands. They found that experimental lights facilitated foraging activity for pipistrelle bats (*Pipistrellus pipistrellus*), suppressed activity of wood mice (*Apodemus sylvaticus*) and affected birds at the community level by impacting year-to-year change in the presence of individual species. They recognised that longer-term studies were necessary especially regarding moth populations as no effects were observed on them during the study period.

Some species may begin to adapt to ALAN which could even have long-term evolutionary effects (Altermatt and Ebert, 2016). Adaptations such as reduced attraction to light sources by some moths in urban areas could have some benefits for individuals such as increased survival and reproduction but may lead to reduced mobility and negative effects on foraging. Reduced mobility could, subsequently, have an ecological impact as moths are a food source for many vertebrates as well as being important pollinators. Indeed, ALAN has been found to disrupt nocturnal pollination networks and to have an impact on plant reproductive success (Knop et al., 2017). A reduction in visits from nocturnal pollinators under ALAN conditions led to a 13% reduction in fruit set of a focal plant even though diurnal pollinators still visited the plant. As well as ALAN having a negative effect on plants through reduced pollination, diurnal pollinators can also be impacted because of the knock-on effects of plants not being able to reproduce.

Light pollution can also affect plant growth directly with negative implications for animals feeding on plants and even, potentially, at the ecosystem level (Bennie et al., 2016). Budburst in deciduous trees in the United Kingdom, for example, was found to occur up to 7.5 days earlier in areas with brighter artificial lighting with effects being more pronounced in late budding species (ffrench-Constant et al., 2016). Bennie et al. (2017) found that ALAN can alter species composition, balance of cover and biomass between species and flowering phenology in a semi-natural grassland. Larval stage moths may be impacted if the plants they rely on for

food are affected in terms of quality and quantity (Boyes et al., 2021). Nectar-reliant adult insects may also be affected if the quality of their food is altered by artificial light.
Another ecological effect of ALAN is its impact on habitat connectivity, for example in urban forests which have ALAN around their edges (Haddock et al., 2019). As not all species are similarly influenced by light, this may lead to a "species filter" whereby habitat connectivity is maintained for light-tolerant species and is prevented for those that are more sensitive to light (Bliss-Ketchum et al., 2016).

Marine organisms use light intensity and spectra as cues to regulate their depth and for vertical navigation (Davies et al., 2014). Zooplankton, for example, undertake diel vertical migrations (DVM) to feed at surface waters and normally begin their ascent near sunset and descend near sunrise though there are other patterns of DVM (see Cohen and Forward, 2009 for more details). Artificial light from vessels or coastal structures can disrupt this migration. Indeed, light from research vessels investigating marine ecosystem structures can impact the very zooplankton they are studying and may mean that new ways of taking samples need to be developed (Ludvigsen et al., 2018).

1.2 Overview of work on this project to date

In March 2021, a Preliminary Report on Light Pollution was submitted to the CMS Secretariat by Mark P. Simmonds (Councillor for Marine Pollution) and Laetitia Nunny (consultant). This research then continued and resulted in this more thorough and focused review and the recommendations that it contains.

1.3 Review of relevant literature

To assess the impacts of light pollution on different taxa of migratory species, various literature searches were undertaken. Species already covered by the CMS Light Pollution Guidelines for Wildlife (i.e. marine turtles, seabirds and migratory shorebirds) were not included in the searches.

In section 2 of this report, the impacts of ALAN as reported in the scientific literature are reviewed by taxa (birds, insects, mammals, fish and chondrichthyes, and reptiles and amphibians). Summary tables detail the recorded impacts of the ALAN studies, whether the study took place under laboratory / experimental conditions or whether field observations or surveys were undertaken. If areas for future research were identified in the paper, then these have also been recorded alongside any recommended mitigation methods.

Section 3 reviews existing guidelines and laws related to lighting standards and light pollution. A review of some available mitigation methods is given in section 4.

1.4 Review of CMS work to date and Terms of Reference for this project

At its 13th ordinary meeting (COP13, Gandhinagar, February 2020) the Conference of the Parties to CMS considered the issue of light pollution. Through *Resolution 13.5 Light Pollution Guidelines for Wildlife*, COP13 acknowledged that artificial light is increasing globally by at least 2% per year[3] and that it is "known to adversely affect many species and ecological communities by disrupting critical behaviours in wildlife and functional processes, stalling the recovery of threatened species, and interfering with a migratory species' ability to undertake long-distance migrations integral to its life cycle, or by negatively influencing insects as a main prey of some migratory species".

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[3] According to Hölker et al. (2010b) artificial lighting was increasing by around 6% per year while Kyba et al. (2017) found that between 2012 and 2016, Earth's artificially lit outdoor area grew by 2.2% per year.

Res. 13.5 endorses *National Light Pollution Guidelines* for some groups of migratory wildlife including Marine Turtles, Seabirds and Migratory Shorebirds, and recommends Parties, non-Parties and other stakeholders to use the guidelines to limit and mitigate the harmful effects of artificial light on migratory species. With a view to complementing those guidelines, COP13 through Decision 13.138 requested the Secretariat, subject to the availability of resources, to prepare guidelines for adoption by COP14 on how to effectively avoid and mitigate the indirect and direct negative effects of light pollution for those taxa not yet in the focus of the guidelines endorsed by Res. 13.5, taking also into account other existing guidance as relevant.

In consultation with the Scientific Council, the Secretariat envisages to implement the mandate received through Dec. 13.138 with a step-wise approach, which foresees:

i. The initial production of an overview of the information available on the impact of light pollution on different taxa of migratory species of relevance to CMS, and of existing guidelines or similar tools to prevent or mitigate those impacts;
ii. Based on the overview, identify possible gaps in the availability of appropriate guidelines and decide on the need to develop additional guidelines and/or consolidate existing guidelines with a view to filling those gaps; and
iii. Work towards the development of additional or consolidated guidelines with a view to submitting them to COP14 for consideration and adoption.

Decision 13.138 also stated that the Secretariat shall suggest to its partners that one of the next World Migratory Bird Days should be dedicated to highlighting the effects of light pollution on migratory birds (and also taking into account its effects on bats, marine turtles, insects and other affected animals).

2. IMPACTS OF ALAN ON DIFFERENT TAXA

The following sections review the impacts of ALAN on birds, insects, mammals, fish and chondrichthyes, reptiles and amphibians[4] according to the recent scientific literature. Note that not all the papers included refer to migratory species.

2.1 Impacts of ALAN on birds

There is a considerable and clearly growing body of literature on the effects of ALAN on avifauna and it is thought that birds may be particularly vulnerable to light pollution. This section is not intended to be comprehensive but highlights some of the key issues and some recent literature. Two of the best documented effects of light pollution on birds is the high mortality due to collision with illuminated buildings and windows, and seabirds commonly being drawn by light sources (Cabrera-Cruz et al., 2018).

An excellent overview is provided in the appendices to the Australian Government's *National Light Pollution Guidelines for Wildlife* which address shorebirds and seabirds specifically (CMS, 2020b). Here it is noted that "Seabirds have been affected by artificial light sources for centuries. Humans used fire to attract seabirds to hunt them for food and reports of collisions with lighthouses date back to 1880. More recently artificial light associated with the rapid urbanisation of coastal areas has been linked to increased seabird mortality and today, 56 petrel species worldwide are known to be affected by artificial lighting". ALAN can cause disorientation leading to collisions, entrapments, groundings and adverse effects on navigation. Behavioural responses can also lead to injury or death, with all night-active species being vulnerable. In the marine context the sources of light pollution include "coastal

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[4] There are no amphibians listed on the CMS appendices, but they are included here for reference.

residential and hotel developments, street lighting, vehicle lights, sporting facility floodlights, vessel deck and search lights, cruise ships, fishing vessels, gas flares, commercial squid vessels, security lighting, navigation aids and lighthouses". The seabird species that are active at night and directly affected include petrels, shearwaters, albatross, noddies, terns and some penguin species. Light pollution may also affect predation at seabird colonies. To give some context to the scale of light-pollution induced losses of sea birds, Rodríguez et al. (2017) estimated that, in the absence of rescue programmes, light pollution would have resulted in the death of at least 200,000 seabirds worldwide since rescue programmes were established.

With respect to shorebirds, the Australian Guidelines comment that "artificial light can disorient flying birds, affect stopover selection, and cause their death through collision with infrastructure. Birds may starve as a result of disruption to foraging, hampering their ability to prepare for breeding or migration. However, artificial light may help some species, particularly nocturnally foraging shorebirds as they may have greater access to food" (CMS, 2020b).

It is apparent from the scientific literature that many other bird species other than seabirds and migratory shorebirds are also affected by ALAN, with nocturnal migrants being at particular risk from the negative impacts (Cabrera-Cruz et al., 2018). For example, of the 298 migratory bird species considered by Cabrera-Cruz et al. (2018), all but one had light pollution in their geographic distribution range. They found that light pollution was relatively greater within the passage ranges of nocturnally-migrating birds compared to their distribution ranges at other phases of their annual cycle. Long distance migrants leave from and arrive to areas with low levels of light pollution but during migration they cross areas with high urban development and light pollution. ALAN may shape migratory routes of individual species. Horton et al. (2019) found that in the eastern USA autumn migration routes take birds over areas with more light pollution than spring routes. On the west coast, birds have higher exposure to ALAN during spring migration.

Apart from interfering with migration, ALAN can disrupt daily or photoperiodic activities as it can alter cues causing birds to wake earlier or for songbirds to sing earlier in the morning (Russart and Nelson, 2018). Such behaviour can impact predator-prey interactions and mating.

Table 2 provides further examples of the impacts of ALAN on birds which are not covered by the CMS Light Pollution Guidelines for Wildlife. One of these papers (van Hasselt et al., 2021) refers to a species listed on CMS – the Barnacle goose (*Branta leucopsis*).

Table 2: Impacts of ALAN on birds (not including migratory shorebirds or seabirds)

Species	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Little Spotted Kiwi (*Apteryx owenii*) Order: Struthioniformes Family: Apterygidae	Observational	A significant decrease in calling activity on cloudy nights, combined with no moonlight effect, suggests an impact of light pollution.	Acoustic ecology is reported as not well studied.	Further study called for.	Digby et al., 2014
Burrowing owl (*Athene cunicularia)* Order: Strigiformes Family: Strigidae	Field	Streetlights altered invertebrate availability. Owl space use was determined by streetlights and they spent more time around lights particularly at night-time. Owls selected areas close to streetlights for nesting.	Only abstract looked at.		Rodríguez et al., 2021
Barnacle goose (*Branta leucopsis*) Order: Anseriformes Family: Anatidae	Experimental - study location had average light pollution	Geese slept less when cloud coverage became stronger because of an increase in artificial light. Sleep is suppressed under full moon, and the effects of artificial light may be as strong as the effects of moon light.	Future studies could investigate how sleep is affected in places with higher intensity ALAN.		van Hasselt et al., 2021
Mottled owl (*Ciccaba virgata*) Order: Strigiformes Family: Strigidae	Observational	The presence of mottled owls increased with the size of green cover and decreased with increases in both ALAN and noise levels. At the temporal scale, green cover was positively related with the ending of the owl's vocal activity, while daily noise and ALAN levels were not related to the timing and vocal output (i.e., number of vocalisations).			Marin-Gomez et al., 2020
Domestic pigeon (*Columba livia*) Order: Columbiformes Family: Columbidae Australian magpie (*Cracticus tibicen tyrannica*) Order: Passeriformes Family: Artamidae	Experimental	Pigeons and magpies exposed to ALAN slept less, favoured non-rapid eye movement (NREM) sleep over REM sleep, slept less intensely and their sleep was more fragmented compared to when the lights were off. White and amber lights had a similar effect on pigeons. For magpies, amber light had less impact on sleep.	Long-term effects of light need to be studied to see whether birds habituate to light. A rich diversity of species needs to be studied to better understand how ALAN impacts wildlife	Amber lighting may minimise sleep disruption for some birds.	Aulsebrook et al. 2020a

Species	**Type of study**	**Impacts of ALAN**	**Information gaps / Suggestions for future research**	**Mitigation methods**	**Reference**
Black swan (*Cygnus atratus*) Order: Anseriformes Family: Anatidae	Experiment in naturalistic environment	Night-time rest was similar under amber (blue-reduced) and white (blue-rich) LED streetlights. Rest under amber lights decreased compared to dark conditions. No evidence of light treatment effecting circulating melatonin concentrations at night.	Studies of the sleep and activity patterns of swans during various life history stages (e.g., breeding and incubation, as well as offspring development) could offer interesting insights. Other species that are less flexible than swans in their daily timing of behaviour might experience greater impacts of ALAN on sleep.		Aulsebrook et al., 2020b
Great tit *(Parus major)* Order: Passeriformes Family: Paridae	Field study – nest boxes already in place	Artificial light in nest-boxes caused birds to wake up earlier, sleep less and spend less time in the nest-box. Females also spent a greater proportion of the night awake. Great tits were less likely to enter an artificially lit nest-box.	Study was carried out before the breeding season. Future studies could look at males and females during breeding season and other periods of the year, using different light intensities. The effects of sleep disruption on fitness also need assessing.		Raap et al., 2015
Great tits (*Parus major*) Order: Passeriformes Family: Paridae	Experimental	Exposure to ALAN promotes early gonadal growth.	Future work should examine the behavioural and physiological effects of light pollution as well as clarifying whether these come with health and fitness consequences.	Limiting of ALAN to minimal levels wherever possible to prevent chronically high exposure for wildlife.	Dominoni et al. 2018
House sparrow (*Passer domesticus*) Order: Passeriformes Family: Passeridae	Experimental	Exposure to low intensity broad-spectrum ALAN suppressed melatonin levels throughout the night. Exposure to broad-spectrum, blue-rich lights did not affect West Nile Virus (WNV) viremia but did increase WNV-induced mortality. Amber-hue ALAN had lower viremia and mortality. The type of ALAN birds are exposed to affects melatonin secretion and could determine how zoonotic diseases affect populations.		Amber-hue LED lightbulbs which eliminate health risks associated with blue-rich light exposure.	Kernbach et al., 2020
Purple Martin (*Progne subis*) Order: Passeriformes Family: Hiruninidae	Experimental / observational	Light-logging geolocators were used to determine the amount of ALAN experienced by long-distance migratory songbirds. Birds that experienced the highest number of nights with ALAN departed for spring migration on average 8 days earlier and arrived 8 days earlier at their breeding sites compared to those that experienced no artificial light. Early	"Due to the potentially detrimental and lethal shifts in phenology influenced by ALAN, studying its impact on avian migratory phenology and behaviour is an increasingly critical and important avenue for further research."		Smith et al., 2021

Species	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
		spring migration timing due to pre-migration ALAN experienced at overwintering sites could lead to mistiming with environmental conditions and insect abundance on the migratory route and at breeding sites, potentially impacting survival and/or reproductive success. Such effects would be particularly detrimental to species already exhibiting steep population declines.			
Blackbird (*Turdus merula*) Order: Passeriformes Family: Turdidae	Experiment	Melatonin concentrations were lower in birds exposed to ALAN than birds kept in darkness. Locomotor activity was higher in ALAN birds, increasing sharply before dawn.	Sleep patterns of birds under ALAN. An improved understanding of the physiological costs of reduced melatonin levels is needed.		Dominoni et al., 2013
Barn owl (*Tyto alba*) Order: Strigiformes Family: Tytonidae	Field	Several factors were assessed to see whether they could predict occurrence of barn owls in churches in Poland. Road density and night lights were negatively associated with barn owl occurrence.			Żmihorski et al., 2020
Tui (*Prosthemadera novaeseelandiae*) Order: Passeriformes Family: Meliphagidae Common myna (*Acridotheres tristis*) Order: Passeriformes Family: Sturnidae Silvereye (*Zosterops lateralis*) Order: Passeriformes Family: Zosteropidae Morepork (*Ninox novaeseelandiae*) Order: Strigiformes Family: Strigidae	Field study in urban sites in Auckland, New Zealand. The tui, myna (an invasive species) and silvereye were studied for their singing time. The morepork was assessed for the number of syllables vocalised.	Streetlight retrofit had significant effect on initiation of dawn song in common mynas which started singing significantly later. An effect for tui depended on the month. No significant effect was found for the silvereye. No significant change in cessation of dusk singing time was recorded for the 3 species. No evidence that the number of syllables vocalised per hour by morepork was affected. Avian species richness, relative abundances of three bird species and ground insect activity increased in the presence of LED streetlights.	"Further studies conducted in urban settings are required to determine the practical effect of the global shift to white LED lights on urban wildlife and its implications for conservation."		McNaughton et al., 2021

Species	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Other species were recorded for abundance.					
Birds migrating over North Sea	Field experiment	Migrating birds were significantly disturbed and attracted to white-light and red-light sources. In blue-light conditions, birds generally followed a seasonally appropriate migratory direction. In green light, birds were less well-oriented than in blue but less disturbed than in red or white light. Bird responses to all light conditions were strongest on overcast nights when moon and starlight were unavailable as orientation cues.	Radar should be used in future studies of nocturnally migrating birds as the methodology used in this study meant it was hard to see birds flying higher than 100m.	Changing the colour (spectral composition) of artificial lights for public roads and on human-built structures will significantly decrease the number of casualties among nocturnally migrating birds.	Poot et al., 2008
298 migratory birds (179 species in western hemisphere and 119 in eastern hemisphere)	Review	“Short distance migrants tend to spend their full annual cycle within the bright temperate regions of North America and eastern Asia and occupy ranges with higher levels of light pollution than long-distance migrants.” “Geographic ranges of species in the Western hemisphere had relatively higher levels of light pollution than those in the Eastern hemisphere.”	The levels of light at stopover sites for migrating birds needs to be measured.		Cabrera-Cruz et al., 2018
Various species	Observational	The effects on avifauna of the beams of the National September 11 Memorial & Museum’s “Tribute in Light” in New York, USA were monitored. Significant behavioural alterations were recorded, even in good visibility conditions and to altitudes up to 4 km. An estimated ≈1.1 million birds were influenced during the study period of 7 d over 7 y. When the installation was illuminated, birds aggregated in high densities, decreased flight speeds, followed circular flight paths, and vocalized frequently. Simulations revealed a high probability of disorientation and subsequent attraction for nearby birds, and bird densities near the installation exceeded magnitudes 20 times greater than surrounding	These results highlight the value of additional studies describing behavioural patterns of nocturnally migrating birds in powerful lights in urban areas as well as conservation implications for such lighting installations.	Behavioural disruptions were seen to disappear when lights were extinguished, suggesting that selective removal of light during nights with substantial bird migration is a viable strategy for minimizing potentially fatal interactions among ALAN, structures, and birds.	Van Doren et al., 2017

Species	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
		baseline densities during each year's observations.			
63 species	Experimental	Short-wavelength blue light caused the strongest phototactic response in nocturnally migrating birds. In contrast, birds were rarely attracted to long-wavelength red light. The attractive effect of blue light was greatest during nights with fog and headwinds.		1.Switching to longer wavelength lights is a convenient and economically effective way to reduce bird collisions. 2. Strengthening bird monitoring in key areas under particular weather conditions and temporarily turning off light sources when birds gather to reduce bird collisions. 3. Using light sources that are visually insensitive to birds.	Zhao et al., 2020

2.2 Impacts of ALAN on insects

The only species of insect currently listed on CMS (Appendix II) is the Monarch Butterfly (*Danaus plexippus*) (CMS, 2020c). Although climate change and anthropogenic noise have been considered in terms of how they might impact this species (Guerra and Reppert, 2015), there do not appear to be any studies considering whether artificial light at night has an impact. As monarch eclosion rhythm (when adults emerge from the chrysalis) is controlled by a light-entrained circadian clock, constant light would disrupt this (Froy et al., 2003) and, therefore, this may be deserving of investigation.

Studies on other members of the order lepidoptera with regards to ALAN have mainly focused on night-flying moths.. Kalinkat et al. (2021) have recently published a review of studies on ALAN and insects. They found only 11 studies tracking insect population trends over more than one season. Most of them took place in Europe and North America and only one study was conducted in Africa. According to van Grunsven et al. (2020), it is essential for studies to be long-term as some effects of ALAN may not be apparent immediately and may go undetected by short-term studies.

Eisenbeis (2006) reviewed the different ways in which insect behaviour is affected by artificial lights including the “fixation” or “captivity” effect, the “crash barrier” effect and the “vacuum cleaner” effect. In the first of these, the insect may fly directly into the light and die immediately, it may orbit the light until caught by a predator or until it dies from exhaustion, or it may manage to move away from the light for a while but as it remains inactive because of exhaustion or because it is dazzled by the light it is, therefore, at greater risk of predation. The “crash barrier” effect occurs when streetlights prevent insects from following their original foraging or migratory route subsequently causing them to get trapped by the “captivity” effect. The “vacuum cleaner” effect is when lights attract insects which are not foraging or migrating, leading to their deaths and, thereby, potentially causing a reduction in the local population.

Owens and Lewis (2018) offer a useful review of how ALAN impacts nocturnal insects including an overview of insect vision. They highlight temporal and spatial disorientation, attraction (phototaxis), desensitisation, impacts on individuals’ ability to recognise objects and community level impacts as potential effects of ALAN.

With nocturnal insects, males are generally more attracted to light than females (Desouhant et al., 2019). The strength of attraction depends on the type of lamp used and the wavelengths it emits. Spectral composition is more important than light intensity for insects (Longcore et al., 2015). Lights that emit UV attract more insects (Voigt et al., 2018a). Caution is needed in using how many insects are attracted to a light to assess a particular light source’s ecological impact. Some bulbs may suppress flying activity and therefore attract fewer insects (Boyes et al., 2021). The distance from which insects can be attracted to lights varies depending on background illumination and the height of the artificial light (Eisenbeis, 2006). During the full moon, fewer insects are attracted to artificial lights.

Boyes et al. (2021) provide a major review of how ALAN can impact moth populations. Figure 2 is from their review and details the effects of artificial light on moths at different stages of their lifecycle. They note that it is not fully understood why moths exhibit phototaxis (flight-to-light) or why they exhibit a diversity of behaviours at light sources including spiralling around it, crashing into it, settling at a distance or ignoring it.

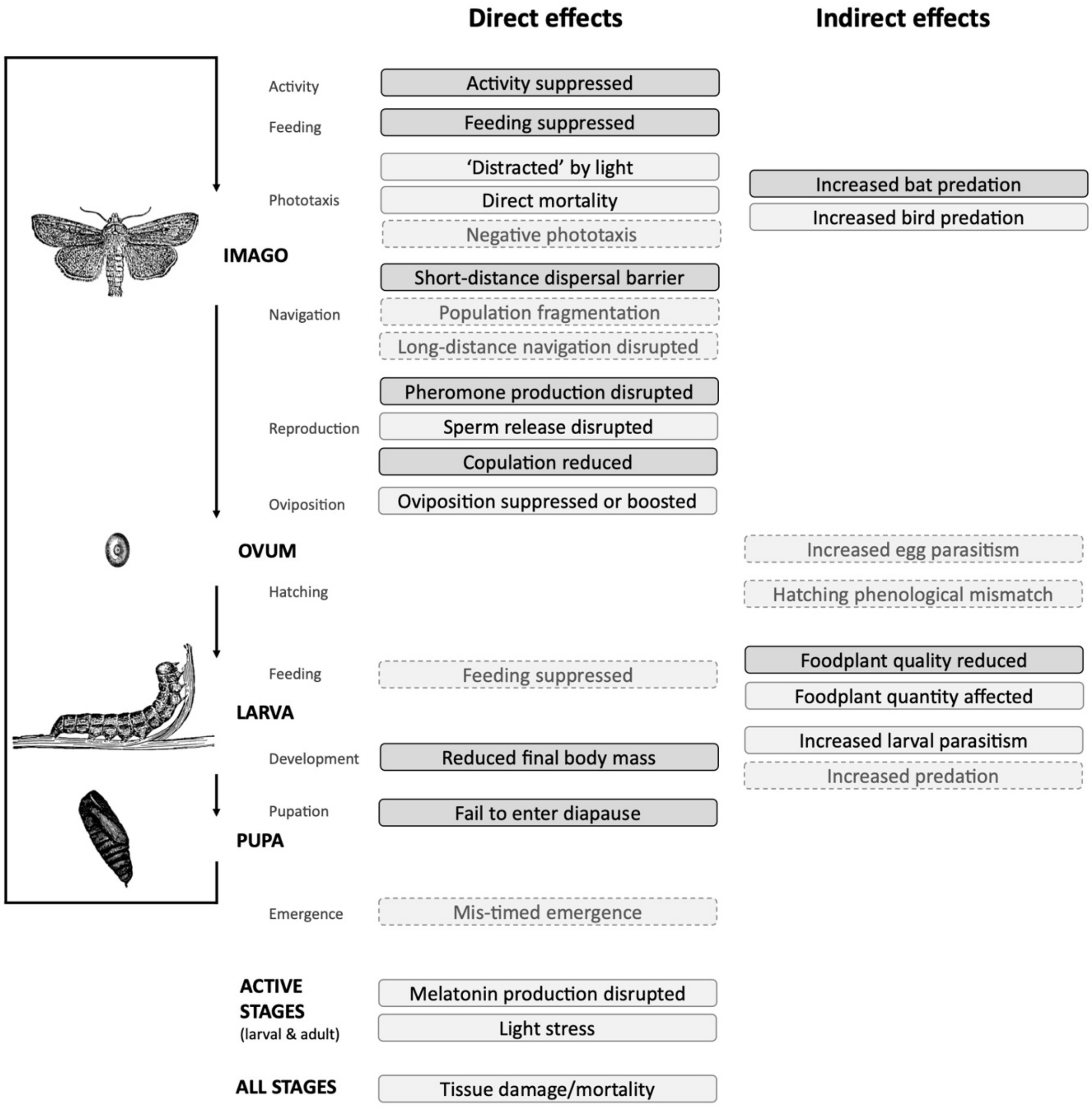

Figure 2: Effects from artificial lights on moths (From Boyes et al., 2021) Shaded boxes show effects with strong evidence. Lighter boxes are effects with anecdotal evidence in moths or effects documented at higher intensities of light, or strong evidence in another insect taxon. Dashed boxes show plausible effects with little or no evidence as yet.

There may be differences between insect orders in terms of what kind of light they are attracted to **(**Desouhant et al., 2019). Wakefield et al. (2018) found that Diptera were more common around LEDs whereas Coleoptera and Lepidoptera were more attracted to metal halide lights in their experiments. Different families of Lepidoptera respond differently to light. For example, shorter wavelength lighting attracted more Noctuidae than longer wavelength lighting (Somers-Yeates et al., 2013). Geometridae were attracted by both wavelengths. Straka et al. (2021) also stated that certain moth species or families might be more attracted by UV light than others, with those attracted to UV emitting lamps dying from either exhaustion or predation while others are less affected. Kalinkat et al. (2021) provide a useful description of how studies looking at ALAN and insects should be designed including how to measure light including spectral measurements.

Straka et al. (2021) suggested that “some moth species, so-called ‘city moths’, might have (pre)adapted to urban settings by showing a reduced flight-to-light behaviour”. A study by Altermatt and Ebert (2016) found that adult small ermine moths (*Yponomeuta cagnagella*) from populations which had been exposed to high levels of light pollution for generations had a significantly lower propensity to fly to light compared to individuals from populations from dark-sky areas.

The masking effects of ALAN can have consequences for some species. Dung beetles (*Scarabaeus satyrus*) use the Milky Way for orientation and, therefore, if it is obscured either by cloud cover or artificial light, this has implications for their ability to orientate (Dacke et al., 2013).

This preliminary assessment of the literature indicates that understanding the implications of ALAN for insects is still a rapidly developing field and not without controversy. For example, Boyes et al. (2021) believe that some studies have been premature to attribute insect declines to ALAN, although they acknowledge that not many studies have been carried out to examine population trends in relation to artificial light.

Table 3 summarises recent papers published on the impacts of ALAN on insects.

Table 3: Impacts of ALAN on insects

Species / Order	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Horse-chestnut leafminer *(Cameraria ohridella)* Order: Lepidoptera	Outdoor and greenhouse tests	After exposure to ALAN, the leafminer developed a lower proportion of diapausing pupae and a higher proportion of free pupae - leading to a further generation within the season. Chestnut trees in illuminated areas have larger leaves and extended larval activity.		Limit intensity and time that outdoor illumination is used. Limit the ratio of short wavelength light (blue light and UV radiation). Direct light to where it is needed and avoid radiation into urban trees and other green areas.	Schroer et al., 2019
Common glow-worm (*Lampyris noctiluca*) Order: Coleoptera	Experimental	Females (which glow at night to attract males) do not move away from artificial light. They delay glowing or they don't glow at all under artificial light which decreases mate attraction.	Need to investigate the fitness consequences of behavioural responses to light pollution and other human-caused disturbances.		Elgert et al., 2020
Cabbage moth (*Mamestra brassicae*), Straw dot (*Rivula sericealis*), Small fan-footed wave (*Idaea biselata*), Common marbled carpet (*Dysstroma truncata*) Order: Lepidoptera	Experimental	Moths were more likely to feed in darkness compared to under red, green and white light. Green light had lowest feeding probability. Females that do not feed lay few eggs and, in some species, pheromone production is affected meaning that fewer males are attracted. Both sexes were strongly negatively affected by artificial light.		Restoration and maintenance of darkness are essential to stop moth population declines.	van Langevelde et al., 2017

Species / Order	**Type of study**	**Impacts of ALAN**	**Information gaps / Suggestions for future research**	**Mitigation methods**	**Reference**
Cabbage moth (*Mamestra brassicae*) Order: Lepidoptera	Experimental	ALAN reduced sex pheromone production in females and altered the chemical composition of the pheromone blend. Changes were strongest under green and white light but the reduction in pheromone quantity was also significant in females under red light. These impacts may reduce effectiveness of sex pheromones, becoming less attractive to males.		Adjustment of spectral composition of artificial light.	van Geffen et al., 2015
Cabbage moth (*Mamestra brassicae*) Order: Lepidoptera	Experimental	Male caterpillars exposed to green and white light reached a lower maximum mass, pupated earlier and obtained lower pupal mass than male caterpillars under red light or darkness. ALAN also affected pupation duration for both males and females and inhibited the start of pupal diapause.		Use of red light can partly mitigate negative effects.	van Geffen et al., 2014
Photuris versicolor, Photinus pyralis Order: Coleoptera	manipulative field experiments	Light pollution reduced flashing activities in a dark-active firefly species (*P. versicolor*) by 69.69 % and courtship behaviour and mating success in a twilight-active species (*P. pyralis*). Courtship behaviour and mating success of *P. pyralis* was reduced by light pollution. No effects of light pollution on male dispersal were found.			Firebaugh and Haynes, 2016

Species / Order	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Australian black field cricket (*Teleogryllus commodus*) Order: Orthoptera	Experimental - crickets were maintained in the lab for 10 generations before study	Chronic lifetime exposure to 100 lx ALAN increased the probability of successful mating. It potentially disrupted precopulatory mating behaviour. Effects were not observed at lower light levels and were often sex specific. ALAN may reduce female mate discrimination. Courtship calling effort and structure were not affected by light treatments.	Conditions in the lab e.g. ad libitum food and water could mask effects of lower light levels in the field.		Botha et al., 2017
Small ermine moth (*Yponomeuta cagnagella*) Order: Lepidoptera	Experimental	Adult moths from populations with high light pollution were 30% less likely to fly to light than individuals from dark-sky areas. Females were less attracted to light than males.			Altermatt and Ebert, 2016
95 species of Lepidoptera (7 families)	Experimental	Moths are preferentially attracted to short-wave radiation.		Lamps with a low proportion of blue light should be prioritised in lighting planning.	Brehm et al., 2021
Diptera, Coleoptera, Lepidoptera, Hemiptera, Hymenoptera, Psocoptera, Neuroptera, Ephemeroptera, Tricoptera and Thysanoptera.	Experimental at field sites in southern England	Significantly more insects were attracted to white MH lights than white LEDs and HPS lights.		Avoid MH lights. Tailor LED lighting to prevent disturbance across multiple taxa.	Wakefield et al., 2018

Species / Order	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Macromoths Order: Lepidoptera	Experimental at field sites in Penryn, UK	Shorter wavelength (SW) lighting attracted more moths than longer wavelength (LW) lighting. More noctuids were attracted to SW than LW lighting. Geometrids showed no significant difference.		Lighting types without shorter wavelengths should be used in ecologically sensitive situations.	Somers-Yeates et al., 2013
Macromoths Order: Lepidoptera Families: Noctuidae and Geometridae	Field experiment	Streetlamps appeared to be a stronger influence on macro-moths than overall and ambient light sources – although overall light pollution is influenced by direct lighting. UV emitting streetlamps had the strongest effect on macro-moth species richness, whereas LED streetlamps lacking UV light emission had no effect on macro-moths. A negative effect of ALAN (MV lamps and overall light) was most prominent in areas with low tree coverage.		Trees may have a mitigating effect on ALAN and should be planted in lit and open areas. Mercury vapour streetlamps should be replaced with more neutral ALAN. Movement detection technology should be used so that light is only produced when necessary.	Straka et al., 2021
Arthropods in a grassland ecosystem	Manipulative field experiment	Herbivore arthropod densities tended to be slightly higher in plots exposed to ALAN than in plots only exposed to ambient light. No evidence was found that the effects of ALAN on abundance differed between arthropod herbivores and predators inhabiting the canopy of grassland vegetation.	Repeated sampling of abundance and trophic structure over time frames spanning multiple generations.		Firebaugh and Haynes, 2020

Species / Order	**Type of study**	**Impacts of ALAN**	**Information gaps / Suggestions for future research**	**Mitigation methods**	**Reference**
Order: Trichoptera *Rhyacophila nubila* and *Hydropsyche siltalai* were attracted to lights in all surveys	Experimental field study – Trichoptera were collected with light traps and passive traps	Attraction to artificial light varied between Trichoptera species. Females were more attracted than males. Species active during the day, evening and especially the night were all attracted to light.			Larsson et al., 2020
Moths from 13 different families Order: Lepidoptera	Experimental field study in rural Germany	Moth capture rate of a streetlight depended on its position. There were decreasing capture rates for corner, edge and middle lights. This pattern was independent of taxonomic family, sex and year. More male than female moths were captured. Streetlights are likely to affect short-distance dispersal of moths and landscape connectivity.		Land-use managers should try to eliminate street lighting as much as possible in prime moth habitat by turning off light at critical times in the year or by 'intelligent' dynamic lighting systems which switch on/off depending on whether or not people are passing by.	Degen et al., 2016
Macromoths Order: Lepidoptera	Experimental field study – natural habitat was experimentally illuminated with lampposts emitting white, green and red light at night, in addition to a dark control in seven locations in the Netherlands	Moth populations are negatively affected by the presence of ALAN. Possible effects can be very latent and may only be visible after multiple years. No differences were seen between the three spectra.	Long-term experiments are essential as effects over years might otherwise go undetected.	Reduction of light pollution is essential to allow insect populations to recover.	van Grunsven et al., 2020

Species / Order	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
6847 insects mainly from the order Coleoptera but also including Diptera, Heteroptera, Hymenoptera and others	Field study looking at streetlights with dimming technology in Switzerland	More insects were caught on warm, dry nights with increased illuminance at streetlights. Dimmed streetlights attracted less insects. Insect responses to light varied among taxa.	Authors note difficulties disentangling environmental effects in a peri-urban environment including air pollution and low habitat quality.	Darker nights facilitated by dimmed street-light levels may constitute an important mitigation measure to reduce light pollution and could be prioritised in areas with roads that fragment bat corridors or biodiversity-rich habitats.	Bolliger et al., 2020
Ground insects Orders: Araneae, Blattodea, Diptera, Hemiptera, Hymenoptera Orthoptera	Field study in an urban environment, Auckland, New Zealand	The likelihood of ground insect activity was significantly different between HPS and LED streetlights with ground insect activity 3.44 ± 1.69 times more likely under LED lights.			McNaughton et al., 2021
Arthropods in California, USA Orders: Diptera, Lepidoptera, Collembola, Hymenoptera and others	Experimental field study	LEDs generally attracted fewer moths and other arthropods than a compact fluorescent lamp with the same colour temperature. However, a different response of Diptera may reflect a different response spectrum for flies compared with moths and other insects; flies exhibit attraction to green and red light as well as to shorter wavelengths.	More lamps should be compared.		Longcore et al., 2015

Species / Order	**Type of study**	**Impacts of ALAN**	**Information gaps / Suggestions for future research**	**Mitigation methods**	**Reference**
Caterpillars Order: Lepidoptera	Field study at two urban sites in Hungary	No strong effects of ALAN from HPS lamps were found on local caterpillar abundances. Caterpillar biomass of individual trees was repeatable over 4 years.	Other drivers of variation in caterpillar abundance in cities need to be studied to see if they are masking the effects of ALAN.		Péter et al., 2020
1194 ground-dwelling invertebrates representing 60 taxa	Field study	Invertebrates were more abundant within close proximity to HPS street lighting independently of whether communities were sampled during the day or night. Street lighting did not simply attract certain species at night. It had a more permanent effect on the composition of invertebrate communities. Harvestmen, ants, ground beetles, woodlice and amphipods were more abundant in patches under streetlights compared with patches between streetlights.	Future research should address how light pollution affects trophic interactions in complex food webs as well as the physiology, behaviour and mortality of species.		Davies et al., 2012

2.3 Impacts of ALAN on mammals

Most studies looking at the effects of light pollution on mammals have looked at members of the orders Rodentia and Chiroptera. Many groups of mammals have yet to be studied. Aquatic mammals, for example, appear to be completely missing from the literature.

For terrestrial mammals, globally, there are few places where they do not experience some detectable ALAN and Duffy et al. (2015) found that the majority of studied mammal species (3,624 out of 4,370) had experienced a significant increase in mean night-time light between 1992 and 2012. Nocturnal species accounted for 62.4% of the affected species. Some species (n=41) had experienced decreases in ALAN in their range. For rare species, increases in ALAN were taking place in most of their range, though the authors recognised that the species range data were relatively coarse and, therefore, overlap between ALAN and species range may have been over- or under-estimated.

Gaynor et al. (2018) found that mammals increase their nocturnality when disturbed by humans, an adjustment that aids human-wildlife coexistence. Such shifts in diel activity patterns may be inhibited by ALAN.

2.3.1 Impacts of ALAN on Chiroptera

The majority of studies on how ALAN affects mammals have focused on bat species and mainly insect-feeding bats. Indeed, a large part of understanding bat behaviour around lights requires understanding how their insect prey is attracted to lights (Voigt et al., 2018a).

Little is known about how tropical fruit and nectar feeding bats are affected by ALAN (Rowse et al., 2016). ALAN may prevent frugivorous bats from commuting and dispersing seeds leading to genetic isolation of illuminated plants and other important impacts on ecosystems (Lewanzik and Voigt, 2014). In areas where deforestation and light pollution are increasing, ecosystem functioning may be seriously affected.

Sometimes bat species are referred to as either light-sensitive or light-tolerant/light-exploiting. Voigt et al. (2018a) warned against such labels as the reaction of a species to light can vary depending on several factors according to the specific situation. Table 4 shows the likely responses of bats to ALAN. Artificial lights near roost sites can negatively impact bats due to increased predation risk which disrupts their emergence activity and leads to reduced foraging opportunities (Voigt at al., 2018a). Rydell et al. (2017) found that bat colonies in churches require one side or end of the church to remain unlit, preferably the part that is nearest to surrounding tree canopies, so that they can exit and return to the roost in safety.

Table 4: Likely responses of bats to ALAN in specific situations (From Voigt et al., 2018a)

Genera	**Daytime Roosts**	**Commuting**	**Foraging**	**Drinking**	**Hibernacula**
Rousettus	Averse	Neutral	Neutral	Averse	Averse
Rhinopoma	Averse	Data Deficient	Data Deficient	Averse	Averse
Rhinolophus	Averse	Averse	Averse	Averse	Averse
Barbastella	Averse	Averse	Averse	Averse	Averse
Eptesicus	Averse	Averse	Opportunistic	Averse	Averse
Pipistrellus and *Hypsugo*	Averse	Neutral/ opportunistic	Opportunistic	Averse	Averse
Myotis	Averse	Averse	Averse	Averse	Averse
Plecotus	Averse	Averse	Averse	Averse	Averse
Vespertilio	Averse	Data Deficient	Not applicable / opportunistic	Averse	Averse
Nyctalus	Averse	Data Deficient	Not applicable / opportunistic	Averse	Averse
Miniopterus	Averse	Data Deficient	Not applicable / opportunistic	Averse	Averse
Tadarida	Averse	Data Deficient	Not applicable / opportunistic	Averse	Averse

Table key: An averse response = the bat would normally avoid ALAN. A neutral response = ALAN would not influence the spatial distribution and activity of a bat. An opportunistic response = the bat turns towards locations with ALAN under certain conditions

Studies by Voigt et al. (2018b) and Spoelstra et al. (2017) had contrasting findings regarding how red light impacted bats (see Table 5). Voigt et al. (2018b) considered this difference to be due to condition-dependent effects of ALAN on bats before and during the migration period when vision plays a more dominant role than echolocation. ALAN that is brighter than moonlight can disrupt foraging and mating in bats as well as interfering with entrainment of the circadian system (Voigt et al., 2018a).

Table 5 summarises recent papers published on the impacts of ALAN on bats.

Table 5: Impacts of ALAN on bats

Species	Field study or experimental study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Brown long-eared bats *Plecotus auritus* Family: Vespertilionidae	Field	Country churches in Sweden were surveyed in 1980s and in 2016. 13 colonies (35%) were lost between the two surveys. All churches which had been abandoned by bats had been fitted with floodlights between the 2 surveys. In unlit churches, all 13 bat colonies remained after 25+ years between surveys.	Did not consider the intensity and colour of the lights, the lighting regime (i.e. part-time lighting) and if the lights were actually functioning at the time of the survey, as these aspects may have changed during the course of the study.	Installation of floodlights on historical buildings should at least require an environmental impact assessment (EIA).	Rydell et al., 2017
Greater horseshoe bat (*Rhinolophus ferrumequinum*), Geoffroy's Bat (*Myotis emarginatus*) and Lesser mouse-eared bat (*Myotis oxygnathus*) Families: Rhinolophidae, Vespertilionidae	Field	Artificial light delays the onset or significantly prolongs the duration of emergence which is important if it means that bats miss the highest abundance of aerial insects. *M. emarginatus* was particularly sensitive and the majority would not leave the roost until it was totally dark. A whole colony of *M. emarginatus* (1000-1200 females) abandoned a roost when floodlights were installed. Juveniles were found to be significantly smaller in illuminated buildings than in non-illuminated ones.		Direct illumination needs to be eliminated during the whole reproductive season. Reducing the hours of illumination in the night has little effect: even a one-hour long lighting period after dusk causes significant disruption in behaviour and growth. Artificial reduction in foraging time is disadvantageous.	Boldogh et al., 2007
15 species of bat in the Loire estuary in western France in a Natura 2000 site	Field study	For some species, light intensity is more important, for others light type. Some species are attracted by lights and some avoid lights. Light-intolerant bats forage in darkness and prey availability could be reduced by artificial		Reduce light intensity in the early night. Restrict timing of lighting to security concerns. Lights should only illuminate target areas – for example by installing	Lacoeuilhe et al., 2014

Species	**Field study or experimental study**	**Impacts of ALAN**	**Information gaps / Suggestions for future research**	**Mitigation methods**	**Reference**
		lights. Light-tolerant species were all species that forage by aerial hawking.		them at lower heights and with controlled orientation. Replace reflective surfaces with light-absorbent ones.	
Bats in 6 urban regions in Germany	Field	The most numerous bat species in urban habitats - *Pipistrellus pipistrellus* - was 45% less active at LEDS than mercury vapour (MV) streetlamps. Activity did not depend on illuminance level. Light type did not affect activity of *P. nathusii, P. pygmaeus* or bats in *Nyctalus/Eptesicus/Vespertilio* group. Activity of *P. nathusii* increased with illuminance level. Bats in the genus *Myotis* increased activity at LEDS but illuminance level had no effect. As different species reacted differently, replacing MVs with LEDs could alter entire urban bat ensembles. Light-tolerant bats that exploited insects attracted by MV lights could be impacted in the short-term but if, long term, fewer insects are attracted to LEDs, insect populations may increase again in urban areas.			Lewanzik and Voigt, 2017
Sowell's short-tailed bat (*Carollia sowelli*) Family: Phyllostomidae	Experiment and field observations	Bats performed less explorative flights in a compartment dimly illuminated by a sodium vapour streetlight than in a dark compartment. They also harvested half as many fruits in the lit compartment. Free-ranging bats avoided ripe fruits that were experimentally illuminated.		Restrict lighting to where and when it is needed and to an illumination level that doesn't exceed what is necessary.	Lewanzik and Voigt, 2014

Species	Field study or experimental study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
		Avoidance behaviour of frugivorous bats towards ALAN reduces the probability of successful seed dispersal which has major implications for ecosystem functioning.			
Lesser horseshoe bat (*Rhinolophus hipposideros*) Family: Rhinolophidae		HPS lights were installed along bats' commuting routes. Bat activity was reduced dramatically during all lit treatments compared to control levels. The onset of commuting behaviour was delayed in the presence of lighting, with no evidence of habituation.			Stone et al., 2009
Migratory bat species in Latvia including *Pipistrellus nathusii*, *Pipistrellus pygmaeus*, *N. noctula* and *Vespertilio murinus*.	Field experiment	Flight activity increased for *P. pygmaeus* and there was a trend for higher activity for *P. nathusii* when a red LED was on. This was not associated with increased feeding. Exposure to a warm-white LED did not increase flight activity but did lead to increased foraging at the light source. Responses were dependent on light colour. Red light may attract bats and should be used with caution in certain sites e.g. at wind turbines.			Voigt et al., 2018b
Plecotus sp., *Myotis* sp. and two *Pipistrellus* sp. groups, *Nyctalus* and *Eptesicus* species.	Manipulative field experiment	*Plecotus* and *Myotis* species avoided white and green light but were equally abundant in red light and darkness. *Pipistrellus* were more abundant around white and green light probably because they were attracted by insects. They were equally abundant in red light and darkness.		White and green light should not be used near natural habitat. Red light is a better option if illumination is necessary.	Spoelstra et al., 2017
Cape serotine bats (*Neoromicia capensis)*	Manipulative field experiment	Moth consumption by bats was low under unlit conditions and increased sixfold under lit conditions despite a		Reduction of temporal, spatial and luminance redundancy in outdoor	Minnaar et al., 2015

Species	Field study or experimental study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Family: Vespertilionidae		decrease in relative moth abundance. Increase in moth consumption was due to light-induced, decreased eared-moth defensive behaviour.		lighting. Restriction of light in nature reserves and urban greenbelts.	
Pipistrellus. pipistrellus, P. pygmaeus, Nyctalus noctula, N. leisleri and *Eptesicus serotinus*	Field surveys in England and Ireland	Street-lighting was not generally linked with increased activity of common and wide-spread bat species. *N. leisleri* was more frequent in lit than dark transects. *P. pipistrellus* distribution was negatively associated with lighting.	Large-scale studies for light-sensitive bats are needed. For bats such as *N. leisleri,* which demonstrated a preference for lit areas of roadside, it is important to assess the risk of retinal damage through sustained exposure to short-wavelength light.		Mathews et al., 2015
16 species	Field surveys	Light edges and dark edges of forests had significantly lower bat activity than dark interior sites. Where light-sensitive species were present they were more likely to be active at dark edges than edges that had artificial light. *Vespadelus vulturnus* was particularly negatively affected by light, being less active and emerging later at artificially lit edges when compared with dark edges. Light-exploiting species were either unaffected by streetlights along the forest edge, such as *Chalinolobus gouldii*, or increased in activity, such as *Ozimops ridei*. Slower flying bats adapted to cluttered vegetation or with a relatively high characteristic	Investigate whether red lights are bat-friendly	In cities, we should avoid installing streetlights near ecologically sensitive areas e.g. native forests and wetlands. Dark areas need to be conserved. Part night lighting (instead of constant lighting). Lights with least disruptive spectra should be used. Red lights (620 nm – 750 nm) may be	Haddock et al., 2019

Species	Field study or experimental study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
		echolocation call frequency were negatively affected by ALAN at the forest edge.		more appropriate (though more study is needed).	
12 species or species groups including *B. barbastellus* (the commonest at drinking sites)	Field experiment in Italy	All species except *Plecotus auritus, Pipistrellus pygmaeus* and *Rhinolophus hipposideros* drank when drinking sites were illuminated by LEDs. Forest species never drank when water troughs were lit. Edge-foraging species reduced drinking activity and increased foraging under lit conditions.	Future studies should consider different light types, natural water bodies and effects over time.	Bat drinking and foraging sites should not be illuminated or, if they are, they need to be mitigated or compensated with alternative sites.	Russo et al., 2017

2.3.2 Impacts of ALAN on mammals other than Chiroptera

Other than rodents, the other mammalian orders that have been studied include Artilodactyla, Dasyuromorphia, Diprotodontia, Eulipotyphla and Primates.

Table 6 summarises recent papers published on the impacts of ALAN on mammals other than bats.

Table 6: Impacts of ALAN on mammals other than Chiroptera

Species	**Type of study**	**Impacts of ALAN**	**Information gaps / Suggestions for future research**	**Mitigation methods**	**Reference**
Common spiny mouse (*Acomys cahirinus*) and Golden spiny mouse (*Acomys russatus*) Order: Rodentia	Experimental	*A. cahirinus* (nocturnal) decreased activity and foraging with artificial light. Illumination restricted activity time and space leading to more intraspecific encounters over foraging patches. *A. russatus* (diurnal) did not expand its activity into the illuminated hours, possibly due to the presence of competing *A. cahirinus*, or to non-favourable environmental conditions. Overt interspecific competition was therefore not affected by experimental light pollution.			Rotics et al., 2011
Nile grass rats (*Arvicanthis niloticus*) Order: Rodentia	Experimental	Night-time light affected immune parameters in a diurnal rodent.			Fonken et al., 2012
Roe deer (*Capreolus capreolus)* Order: Artiodactyla	Field study in Kraków, Poland	ALAN was negatively correlated with the probability of roe deer occurring. ALAN explained the occurrence of deer better than the number of buildings or noise levels.			Ciach and Fröhlich, 2019
Stephens' kangaroo rat (*Dipodomys stephensi*) Order: Rodentia	Field study – carried out in the wild but artificial light was added to the area and animals were fed	Artificial light (including low-intensity yellow bug lighting) significantly altered foraging activity of Stephens' kangaroo rats. This may be because they are blinded when under artificial light due to physical properties of their eyes and foraging may be disrupted when they are more visible to predators.	Need to measure both irradiance and radiance to understand the effects of ALAN on a species' behavioural ecology. The relationship between light intensity and spectrum on nocturnal rodent foraging also needs further study.		Shier et al., 2020

Species	**Type of study**	**Impacts of ALAN**	**Information gaps / Suggestions for future research**	**Mitigation methods**	**Reference**
European hedgehog (*Erinaceus europaeus*) Order: Eulipotyphla	Field study at feeding stations in UK gardens	Some individual hedgehogs showed a temporal change in their activity patterns under ALAN but effects were not consistent. No overall impact of ALAN on the presence or feeding activities of hedgehogs in gardens where supplementary feeding stations were present was found.	How ALAN impacts reproductive success, territory maintenance, predation rate and natural prey availability for hedgehogs should be investigated.		Finch et al., 2020
Grey mouse lemur *(Microcebus murinus)* Order: Primates	Experimental	Light pollution modified daily rhythms of locomotor activity and core temperature. Core temperatures were higher during the night and during daily rest. The daily phase of hypothermia (torpor) was delayed and less pronounced. Nocturnal activity and feeding behaviour patterns were modified negatively.			Le Tallac et al., 2013
Grey mouse lemur *(Microcebus murinus)* Order: Primates	Experimental	The first seasonal oestrus occurred earlier in females exposed to light pollution (while they were still in a short-day photoperiod). ALAN also affected the daily rhythms of females.	Test the effect of mid-winter light pollution exposure on reproductive functions and energy saving mechanisms.		Le Tallac et al., 2015
Tammar wallaby (*Macropus eugenii*) Order: Diprotodontia	Field – free-ranging tammar wallabies on Garden Island, Western Australia	Birth dates were delayed by a month for wallabies living under ALAN compared to those animals living in the bush which were only exposed to astronomical sources of light. Births were also poorly synchronised. ALAN masked the cue of increased darkness that triggers blastocyst reactivation. Melatonin levels were also suppressed under ALAN.			Robert et al., 2015
Tammar wallaby (*Macropus eugenii*) Order: Diprotodontia		Wallabies exposed to white LED had significantly suppressed melatonin compared to those exposed to amber LED. There was no difference in lipid peroxidation. Antioxidant capacity declined from baseline to week 10 under all treatments.		Shifting the spectral output to longer wavelengths could mitigate negative physiological impacts.	Dimovski and Robert, 2018

Species	**Type of study**	**Impacts of ALAN**	**Information gaps / Suggestions for future research**	**Mitigation methods**	**Reference**
Bank vole (*Myodes glareolus*) Order: Rodentia	Experimental populations in large grassland enclosures using LED garden lamps	Bank voles under ALAN changed daily activity patterns and space use behaviour. No differences in survival and body mass or faecal glucocorticoid metabolites.	Effects of ALAN on predators and prey of small mammals needs to be investigated.		Hoffmann et al., 2018
Santa Rosa beach mice (*Peromyscus polionotus leucocephalus)* Order: Rodentia	Field experiments	Beach mice foraging in experimental resource patches (trays with seeds) were subjected to lower pressure sodium vapour lights, incandescent yellow bug lights or only new moon conditions. Patch use was significantly affected by presence of illumination, light type and distance from light source. Bug lights altered foraging activity up to 10m from the light. These lights emit a broader range of wavelengths.			Bird et al., 2004
Siberian hamster (*Phodopus sungorus*) Order: Rodentia	Experimental	Exposure to dim light at night (dLAN) of 5lx affected melatonin secretion and melatonin processing pathways, the circadian clock and the thyroid hormone system which led to disruptions in the photoperiodic response in reproduction, body mass, fur properties and immune function all of which are important for seasonal adaptation.			Ikeno et al., 2014
Siberian hamster (*Phodopus sungorus*) Order: Rodentia	Experimental	Immune responses were negatively impacted by exposure to ALAN and circadian activity patterns were disrupted.			Bedrosian et al., 2011
Common wombat (*Vombatus ursinus*) Eastern grey kangaroo (*Macropus giganteus*) Brown antechinus (*Antechinus stuartii*)	Field study with experimental lights	Floodlights illuminated the subfloor cavity of a building and were switched on continuously for 10-week periods and then off for 10 weeks. Fauna using the cavity were recorded. Nocturnal activity of wombats did not change in response to lighting. There were significantly more diurnal detections when the lights were on than off. There were more kangaroo detections during the day when the lights			Borchard and Eldridge, 2013.

Species	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Orders: Diprotodontia, Dasyuromorphia		were on, but more detections at night when the lights were off. Most recordings of antechinus were at night and significantly more when the lights were off.			
Swiss–Webster mice Order: Rodentia	Experimental	Mice housed in bright ALAN or dim ALAN had significantly increased body mass and reduced glucose tolerance compared with mice in a standard light/dark cycle. The timing of food consumption also differed.			Fonken et al., 2010
17 rainforest dwelling mammals in Brazil	Field	Night-time light radiance was used as a proxy of human disturbance. Five of the evaluated species became more nocturnal and three became more diurnal. Seven of the species which exhibited temporal shifts in their diel activity are game (hunted for meat) or persecuted (hunted to protect livestock) species.	How diel shifts affect the individual animals' survival, stress level and fitness		Mendes et al., 2020
Columbia black-tailed deer (*Odocoileus hemionus columbianus*), deer mice (*Peromyscus maniculatus*), opossum (*Didelphis virginiana*), Northern raccoon (*Procyon lotor*) Orders: Artiodactyla, Rodentia, Didelphimorphia, Carnivora	Field experiment	Sections of a bridge under-road passage structure were subjected to different light treatments. Columbia black-tailed deer traversed under unlit bridge sections much less when neighbouring sections were lit compared to when none were, suggesting avoidance due to any nearby presence of artificial light. Deer mouse and opossum track paths were less frequent in the lit sections than the ambient. The Northern raccoon did not react to light. ALAN may be reducing habitat connectivity for some species though not providing a strong barrier for others.		Structures meant for human use could have portions left unlit or include a push button system that would turn lights on only as a person passes through. Artificial light could be used to influence animal movement e.g., lights could be used as a fence to prevent animals from crossing roads. Darkness could be used to encourage them to use crossing structures.	Bliss-Ketchum et al., 2016

2.4 Impacts of ALAN on fish (actinopterygii) and chondrichthyes

No papers were found regarding whether artificial light at night has an impact on shark, ray or sawfish species (chondrichthyes). However, there is evidence that sharks are light sensitive. For example, white sharks (*Carcharodon carcharias*) that are active in the day were found to approach bait with the sun directly behind them and it has been suggested that this is to prevent an excess of sunlight in the eye chamber which reduces retinal image contrast and visual resolution (Huveneers et al., 2015). Approaching prey with the sun behind them would prevent the sharks being seen if they were attacking a surface animal e.g. a seabird, or seal or penguin with its head out of the water.

There have been several studies on how ALAN can impact freshwater and marine fish. For many freshwater fish species e.g. Eurasian perch (*Perca fluviatilis)*, the onset of darkness cues eggs to hatch (Brüning et al., 2010). By synchronising hatching at night, fish can shoal after hatching and reduce the risk of predation. Light pollution can therefore disrupt reproduction (Brüning et al., 2018).

Salmonids often migrate from their spawning areas to the ocean at night and they are therefore vulnerable to ALAN which can cause delays and changes in migratory behaviour, disorientation, temporary blindness and could increase the risk of predation (Nightingale et al., 2006). Returning adult fish also migrate at night.

A fish’s response to light alters as it matures because its vision changes over time. Juveniles require vision for vertical migration and predator avoidance, whereas adult fish may rely on their eyesight for navigation, foraging, mate selection, spatial vision and communication (Nguyen and Winger, 2019). Altered light environments along routes used by migrating fish may interrupt movement, increase predation on migrating fish and reduce the number of successful migrants (Nightingale, 2006). Streamflow and turbidity in rivers may affect the impact of artificial lighting on migrating fry (Tabor et al., 2001).

Table 7 summarises the impacts of light pollution on freshwater fish according to the published scientific literature. One of these papers (Vowles and Kemp, 2021) refers to a species listed on CMS – the European eel (*Anguilla anguilla)*.

Table 8 summarises recent papers about how ALAN impacts marine and coastal fish species.

Table 7: Impacts of ALAN on freshwater fish

Species	Migratory species?	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
White sturgeon (*Acipenser transmontanus*)	Yes (semi-anadromous)	Experimental	Age-0 (~4 months) white sturgeon were exposed to strobing or constant light with colours (green, red, blue). Sturgeon demonstrated positive phototaxis under both day and night conditions and approached the light guidance device (LGD) more often when light was continuous or strobing at 20 Hz compared to strobing at 1 Hz. Green light elicited the greatest rates of attraction overall. This has important implications for reducing negative outcomes around water in-stream infrastructure. Light can potentially be used to guide sturgeon away from danger to areas of relative safety.	More research is needed into how ambient light, light stimulus intensity, water flow, age, colour, and strobing rates might affect white sturgeon and other fish species that would encounter LED-based LGDs.		Ford et al., 2018
European eel (*Anguilla anguilla)*	Yes. Listed on Appendix II of CMS	Experimental	When given a choice, eels were more likely to choose a dark channel over an illuminated one when swimming downstream. If an illuminated channel was chosen, the eel moved more rapidly through it. Low and high intensity light conditions had similar impacts on eel behaviour. In areas where unlit routes are unavailable, eel migration may be delayed.	Investigate if eels in different life stages have changes in spectral sensitivity and impact of ALAN.		Vowles and Kemp, 2021

American eel (*Anguilla rostrata)*	Yes	Experimental	Eels chose dark (control) over LED illuminated routes in a dichotomous choice test. Blue light strobing at 30Hz elicited greatest initial avoidance response.	Note: This study aimed to find ways to guide eels during migration to keep them safe around hydropower facilities. Future studies in more natural settings are needed including with flowing water.		Elvidge et al., 2018
Bluegill *(Lepomis macrochirus)*	No	Experimental	Fish exposed to ALAN of 0.5 lux and 9 lux swam significantly less than control fish.	Only abstract was available and so it is not clear if there were further recommendations		Latchem et al., 2021
Smallmouth bass (*Micropterus dolomieu)*	Yes – when the weather cools, they travel looking for somewhere to enter semi-hibernation state (can travel 60 miles)	Field experiment	Accelerators were attached to nest-guarding males. Both continuous and intermittent light altered behaviour of nesting-guarding males by increasing their activity levels compared to control fish.	Recommend longer-term studies exploring how light pollution and behavioural changes impact population level processes.		Foster et al., 2016
Sockeye salmon (*Oncorhynchus nerka*)	Yes	Field site – light was added	The abundance of salmon fry was higher at sites with high intensity lights. Relatively high predation by cottids was observed in lighted areas. ALAN caused fry to delay migration.			Tabor et al., 2001
European perch (*Perca fluviatilis)*	No	Experimental	Melatonin production was inhibited even at the lowest light level of 1 lx. Fish exposed to higher light intensities seemed to lack any circadian melatonin rhythm. Cortisol levels did not differ between control and treatment illumination levels.	To examine whether melatonin concentration or circadian rhythm drives light dependent behaviours and physiological processes. Studying stress (cortisol) levels in a laboratory setting means that environmental influences such as predators, prey, refuges were not present. Synergistic effects of light pollution as a stressor need to be investigated.		Brüning et al., 2015

Eurasian perch (*Perca fluviatilis)*	No	Experimental	Exposure to low intensity ALAN led to a reduction of melatonin. Melatonin decreased with increasing ALAN intensity. Skyglow can partially suppress nocturnal melatonin when Eurasian perch live in transparent, shallow water.	Investigate to what extent endogenous circadian clock regulates melatonin rhythms. Different sources of melatonin need to be further studied.		Kupprat et al., 2020
Eurasian perch (*Perca fluviatilis)*	No	Experimental	After 2 weeks of exposure to ALAN, no significant changes were found in the innate immune system. Less oxidative stress than expected was recorded.	Longer term studies are needed. Effects on the hepatic metabolism might be of interest for future studies.		Kupprat et al., 2021
Eurasian perch (*Perca fluviatilis),* roach (*Rutilus rutilus)*	No	Rural experimental setting	No differences were detected in melatonin concentrations between ALAN and natural conditions. Blood concentration of sex steroids and mRNS expression of gonadotropins (luteinizing hormone, follicle stimulating hormone) was reduced in both species.			Brüning et al., 2018
Eurasian perch (*Perca fluviatilis)*, roach (*Rutilus rutilus)*, bleak (*Alburnus alburnus),* chub (*Leuciscus cephalus*)	No	Experimental	ALAN could have affected hatching and initial swim bladder filling by masking the day–night-change and thereby diminishing the trigger effect. The reactions were species specific.	Potential physiological and biorhythmical effects of light pollution on fish larvae need to be studied, and to assess threshold light levels impacting the circadian rhythms in fish by using a range of different light intensities and spectral qualities. Need for long-term field-studies and field experiments		Brüning et al., 2010
Trinidadian guppies (*Poecilia reticulata)*	No	Experimental	Individuals exposed to the light treatments (both dim and bright light) emerged quicker from a refuge and fish from the bright light treatment spent relatively more time in the open area of the arena.	Future studies quantifying the degree (and onset) of activity and sociability both during day and night-time and over longer periods, would be required to obtain a more complete picture of		Kurvers et al., 2018

				how ALAN affects such important behavioural processes.		
Atlantic salmon (*Salmo salar*)	Yes	Experimental	Fry exposed to street lighting dispersed later and were smaller at dispersal. There was also disruption to the diel pattern of dispersal. Survival to dispersal was unaffected by the lighting.	Emergence and dispersal of other freshwater fish larvae that use gravel/silt incubation should be investigated e.g. lamprey, trout, grayling, barbel. Studies should include non-invasive measurement of free cortisol. Need to determine the light intensities at which broader spectrum streetlights do not affect animal behaviour. Modelling of spatial areas impacted by ALAN to determine management.		Riley et al., 2013
Atlantic salmon (*Salmo salar*)	Yes	Experimental	Dispersal of fry was significantly delayed under streetlight intensities of 8,4,2 and 1 lux and fry had reduced available energy reserves.		Maintain and increase natural unlit areas. Flexible control systems e.g. on-demand street lighting along footpaths by rivers	Riley et al., 2015

Table 8: Impacts of ALAN on marine/coastal fish

Species	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Convict surgeonfish (*Acanthurus triostegus*)	Experimental	Changes in behaviour and physiology during larval recruitment were recorded including habitat avoidance, endocrine disruption, altered growth and increased mortality rates. Larvae exposed to ALAN showed depressed levels of T3 (an important hormone for metamorphosis). Control fish showed cautious assessment behaviour, but fish exposed to ALAN swam in rapid erratic bursts during visual cue response trials. Behavioural and physiological changes may have been driven by sleep deprivation due to exposure to ALAN.	How ALAN impacts recruitment, sensory development, behaviour and physiology of predators all need studying. Threshold values related to negative impacts need to be determined.		O'Connor et al., 2019
Bonefish (*Albula vulpes)*	Experimental	Light pollution was not found to effect swimming behaviour but did result in elevated blood glucose concentrations relative to controls, with constant light glucose levels being significantly higher (indicating stress).	Recommend studying fish over longer time periods in lab and field settings and investigating the predation risk for juvenile fish.		Szekeres et al., 2017
Common clownfish (*Amphiprion ocellaris*)	Experimental	Eggs incubated in the presence of ALAN did not hatch resulting in zero survivorship of offspring. Results may extend to other reef fish whose eggs hatch at night but ALAN may have different impacts on fish with different reproductive strategies. Species whose eggs hatch during the day will probably not be impacted in the same way.	In situ studies are needed to assess costs associated with ALAN (e.g. increased predation) and benefits (e.g. increased prey resources). Different types and different spectrums of light need to be studied for how they impact a wide range of marine organisms.		Fobert et al., 2019

Common clownfish (*Amphiprion ocellaris*)	Experimental	Fish were exposed to ALAN with warm-white and cool-white spectra. Both light colour treatments increased the number of days between spawning events. Eggs developing under ALAN were smaller than eggs under control conditions. Fewer eggs hatched under cool-white light compared to warm-white light.			Fobert et al., 2021
Blue green chromis (*Chromis viridis)*	Experimental	Changes in metabolic pathways associated with increased activity under continuous light (despite provision of shelter) were observed, specifically those associated with energy metabolism, cell signalling, responses to oxidative stress and markers of cellular damage. Predator threat moderated the influence of ALAN on metabolic change in brain and liver tissues, likely due to increased sheltering behaviour. No interaction of predator threat with ALAN was observed in metabolism of the muscle tissue.	Need to better understand how ALAN interacts with natural and anthropogenic drivers of behaviour and energy metabolism.		Hillyer et al., 2021
“Baunco” the rockfish (*Girella laevifrons)*	Experimental	Fish exposed to ALAN exhibited increased oxygen consumption and activity when compared with control animals. Fish exposed to ALAN stopped displaying the natural (circatidal and circadian) activity cycles that were observed in control fish throughout the experiment.	Activity level of *G. laevifrons* and its consumption of prey in rocky pools needs to be studied as well as assessing mortality risk due to increased exposure to predators.		Pulgar et al., 2019
Atlantic tarpon (*Megalops atlanticus*)		Abnormally-timed light exposure may disrupt normal *M. atlanticus* clock function and harm vision, which in turn may affect prey capture and predator avoidance.			Kopperud and Grace, 2017

Not identified to species level	Field	Increase in abundance of large predatory fish (>500mm) in an estuary area when a floodlight was turned on. Behaviour change of large fish – they attempted to maintain their position within the illuminated area. No clear response from 100-300mm fish. Abundance of small shoaling fish (<100mm) also increased when the light was on. Presence of larger fish may have been because they came to prey on small fish (not because they were attracted by light) .	Investigate impacts of different types of light e.g. red light, the influence of multiple light sources along a shoreline and the interaction of light and other sources of pollution. Studies should compare behaviour in daylight and under artificial light.		Becker et al., 2013

2.5 Impacts of ALAN on reptiles and amphibians

The impacts of ALAN on sea turtles are well known and reported and are included in the *Light Pollution Guidelines for Wildlife* already adopted by CMS (CMS, 2020b). Impacts on other reptiles and amphibians are not as well known or studied (Perry et al., 2008).

Some reptiles are nocturnal e.g., most geckos, and others are strongly diurnal such as the lacertid and iguanid lizards (Perry and Fisher, 2006). Many gecko species strongly associate with buildings and lights, and they may be seen feeding on insects attracted by the lights. Henderson and Powell (2001) summarised several examples of otherwise diurnal species in the West Indies actively predating at night due to extended light at night (the so-called "night-light niche").

In their review, Perry et al. (2008) failed to find any information about how ALAN impacts crocodilians and recent literature searches have also failed to reveal any papers.

Amphibians have also been little studied regarding how ALAN affects them.

See Table 9 for recent papers about the impacts of ALAN on reptiles and amphibians. Turtles have not been included here as they are already covered by the CMS Guidelines.

Table 9: Impacts of ALAN on reptiles (focusing on species other than turtles) and amphibians

Species	Type of study	Impacts of ALAN	Information gaps / Suggestions for future research	Mitigation methods	Reference
Giant Ameiva (*Ameiva ameiva*) Class: Reptilia Order: Squamata	Field observations	Though a diurnal species, an adult *A. ameiva* was observed exploiting the night-light niche by foraging on insects which had been attracted to a streetlight and had subsequently fallen on the ground.	More field sampling is needed in different biogeographical regions especially in highly-urbanised countries with diverse reptile fauna. Studies are needed to understand how activity patterns and thermal behaviours of diurnal lizard species respond to light pollution.		Hiroiuki Oda et al., 2020
Leach's Anole (*Anolis leachii*), Watt's Anole (*Anolis wattsi*), Thick-tailed Gecko *(Thecadactylus rapicauda)* Class: Reptilia Order: Squamata	Field surveys	Both anole species foraged in artificially illuminated habitats. They were more active before sunrise than in the early night. No agonistic interactions or visual displays were observed. Lizards were observed foraging on small insects and Lepidoptera. Use of the night-light niche was restricted to male anoles.	ALAN remains understudied as a topic of regional conservation concern in the Caribbean. Future research should examine whether Caribbean species show an ability to exploit the night-light niche and how this may impact species persistence and ecosystem function.		Maurer et al., 2019
Brown anole (*Anolis sagrei*) Class: Reptilia Order: Squamata	Experimental	Lizards exposed to ALAN grew more than those in normal light-dark cycle. ALAN did not affect change in body condition, nor did it affect levels of corticosterone. Females exposed to ALAN laid eggs earlier than females in the dark at night treatment. ALAN also increased reproductive output without reducing offspring quality.	Future work should include experimental manipulations of ALAN under field conditions. Behavioural observations of anoles at ALAN sources to find our whether increased energy from foraging in this niche drives enhanced growth / reproduction and if predation by nocturnal predators is a factor. Endocrine impacts of ALAN.		Thawley and Kolbe, 2020

Wall geckos (*Tarentola mauritanica*) Class: Reptilia Order: Squamata	Field survey	Moonlight increased the number of active wall geckos. Artificial light reduced the effect of moonlight on the number of active geckos but not their individual activity. Large individuals monopolised the best foraging sites around artificial light. Use of human habitats with artificial night lighting, particularly on new moon nights, can benefit the foraging activity of nocturnal lizard species			Martín et al., 2018
Wood frog (*Rana sylvaticus)* Class Amphibia. Order: Anura Blue-spotted salamander (*Ambystoma laterale*) Class: Amphibia Order: Urodela	Choice experiments in outdoor tanks	Frogs did not have a preference between deciduous or coniferous leaf litter in the dark or when the substrates were illuminated. Salamanders preferred deciduous litter in dark trials and when it was illuminated. They chose coniferous litter more often when it was illuminated.			Feuka et al. (2017)

Amphibians	Field survey and field experiment	The most common response by amphibians to the approach of a car is immobility. Responses differed across species and depended on the season of the survey. Combined stimuli of lights and noise elicited the strongest response, followed by headlights-only and the motor-only treatments.			Mazerolle et al., 2005

3. Existing Guidelines

Some countries and organisations have developed guidelines or have adopted laws to tackle the issue of light pollution. Table 10 summarises some of these. Some guidelines focus more on reducing astronomical light pollution than ecological light pollution. Some of the codes included in Table 10 are recommendations for standards of lighting and focus more on lighting needs, human safety and other technical matters rather than the issue of light pollution, though this topic may also be included or mentioned. The guidelines from four Canadian cities which aim to protect birds from numerous threats include sections on light pollution.

The International Commission on Illumination (CIE) has recently announced the establishment of a new Technical Committee on the Measurement of Obtrusive Light and Sky Glow which will provide guidelines for measuring these elements[5].

Further evaluation of all available guidelines is necessary, especially as some guidelines and laws are not available in English and there are likely to be more guidelines which have not been included here. In some countries, e.g. Italy, guidelines appear to be developed on a regional basis[6]. The guidelines for Piedmont are included here, as an example, but other Italian regions may have relevant codes as well.

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[5] http://cie.co.at/news/cie-tc-2-95-new-tc-measurement-obtrusive-light-and-sky-glow

[6] https://cielobuio.org/category/sez-leggi-norme/cat-archivioleggi/

Table 10: Guidelines and laws relating to lighting standards and/or light pollution

Guidelines / Law	Publisher / Government	Date	Includes Ecological Light Pollution / Effects on wildlife?	Reference / Link	Country / Region
National Light Pollution Guidelines for Wildlife. Including marine turtles, seabirds and migratory shorebirds	Commonwealth of Australia	2020	Yes	CMS, 2020b	Australia
Guidelines for consideration of bats in lighting projects	EUROBATS	2018	Yes	Voigt et al. 2018	Europe
Bats and artificial lighting in the UK. Guidance Note 08/18	Institute of Lighting Professionals (ILP) and Bat Conservation Trust	2018	Yes	ILP, 2018	UK
Green Standards for Light Pollution and Bird-friendly development	Ecological and Environmental Advisory Committee (EEPAC), the Advisory Committee on the Environment (ACE) and the Animal Welfare Advisory Committee (AWAC)	2018	Yes	https://pub-london.escribemeetings.com/filestream.ashx?DocumentId=46167	Canada

Bird-Friendly Development Guidelines	City of Toronto	2007	Yes	https://slidelegend.com/bird-friendly-development-guidelines-city-of-toronto_59cc17ca1723dd0cea3a1f0f.html	Canada
Best Practices for Effective Lighting (Companion to Bird-Friendly Development Guidelines)	City of Toronto	2017	Yes	https://www.toronto.ca/wp-content/uploads/2018/03/8ff6-city-planning-bird-effective-lighting.pdf	Canada
Bird-Friendly Development Guidelines. Best Practices: Glass (Companion to Bird-Friendly Development Guidelines)	City of Toronto	2016	Yes	https://www.toronto.ca/wp-content/uploads/2017/08/8d1c-Bird-Friendly-Best-Practices-Glass.pdf	Canada
Bird-Friendly Urban Design Guidelines	City of Calgary	2011	Yes	https://www.calgary.ca/pda/pd/current-studies-and-ongoing-activities/urban-design.html	Canada
Vancouver Bird Strategy	City of Vancouver	2015. Updated 2020	Yes	https://vancouver.ca/files/cov/vancouver-bird-strategy.pdf	Canada
Naravi prijaznejša razsvetljava objektov kulturne dediščine (cerkva) Priporočila (Nature-friendly lighting of cultural heritage buildings (church) Recommendations)	Projekt LIFE+ Življenje ponoči v sodelovanju s Slovensko nacionalno komisijo za UNESCO (LIFE + Life at Night project in cooperation with the Slovenian National Commission for UNESCO)	2014	Yes	http://temnonebo.com/images/pdf/naravi_prijaznejsa_razsvetljava_brosura_web.pdf In Slovenian	Slovenia

The SLL Code for Lighting	Chartered Institute of Building Service Engineers (CIBSE)	2012 (currently being updated)	Includes short section on light pollution	Available to purchase online: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I6xiAAC	UK
LG06: The Exterior Environment	CIBSE	2016	Appendix 4: Artificial lighting and its effect on animal and plant ecology	Available to purchase online: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008K5EsAAK	UK
LG15: Transport buildings	CIBSE	2017	Includes sections on lighting control, environment and energy use, sustainability	Available to purchase online: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q0O00000CzUERQA3	UK
The Reduction of Obtrusive Light	ILP	2021	Mentions ecological light pollution but not in much detail	https://theilp.org.uk/publication/guidance-note-1-for-the-reduction-of-obtrusive-light-2021/	UK
Guidance: Light Pollution	Ministry of Housing, Communities and Local Government	2014	Yes	https://www.gov.uk/guidance/light-pollution#possible-ecological-impact	UK
Guidelines for the Reduction of Light Pollution in the Maltese Islands: Consultation Document	Environment and Resources Authority and Planning Authority	2020	Includes section on ecosystems and biodiversity	Draft document available here: https://era.org.mt/wp-content/uploads/2020/06/Guidelines-for-the-Reduction-of-Light-Pollution-in-the-MI-PC-Draft.pdf	Malta
Guidelines for Countermeasures against Light Pollution (Revised Edition)	Ministry of the Environment	2006		https://www.env.go.jp/press/8023.html In Japanese	Japan

Revision of the EU Green Public Procurement Criteria for Road Lighting and traffic signals Technical report and criteria proposal	Joint Research Centre (JRC), European Commission	2019	Yes	https://ec.europa.eu/environment/gpp/pdf/tbr/190125_JRC115406_eugpp_road_lighting_technical_report.pdf	European Union
EU green public procurement criteria for road lighting and traffic signals	European Commission	2018	Yes	https://ec.europa.eu/environment/gpp/pdf/toolkit/traffic/EN.pdf	European Union
International Dark-Sky Reserve Program Guidelines	International Dark-Sky Association (IDA)	2018	Wildlife is mentioned but is not a key part of guidelines	https://www.darksky.org/wp-content/uploads/bsk-pdf-manager/2021/05/IDSR-Final-May-2021.pdf	USA
International Dark-Sky Association Board Policy on the Application of the Lighting Principles Adopted January 28, 2021	IDA	2021	Wildlife is mentioned	https://www.darksky.org/wp-content/uploads/2021/03/Values-Centered-Outdoor-Lighting-Resolution.pdf	USA
Resumen de recomendaciones para la iluminación de instalaciones exteriors o en recintos abiertos (Summary of recommendations for the lighting of outdoor installations or open spaces)	Oficina Técnica para la Protección de la calidad del cielo (Sky Protection Office)	2018	Yes	https://www.iac.es/system/files/documents/2019-09/RESUMEN_RECOMENDACIONES_AGOSTO-2018.pdf In Spanish	Spain
Guia de prescripcions en matèria de contaminació lumínica per a llicències municipals	Generalitat de Catalunya, Departament de Territori i Sostenibilitat	2019	No	http://mediambient.gencat.cat/web/.content/home/ambits_dactuacio/atmosfera/contaminacio_luminica/prevencio-vector-llum/guia_prescripcions_permisos.pdf In Catalan	Catalonia, Spain

(Guide to material prescriptions regarding light pollution for municipal licences)	(Government of Catalonia, Department of Territory and Sustainability)				
Guia per a l'execució de controls sectorials de contaminació lumínica de les activitats subjectes a la Llei 20/2009, de 4 de desembre, de prevenció i control ambiental de les activitats. (Guide for control of light pollution for activities subject to Law 20/2009 of 4th December for the environmental prevention and control of activities)	Servei de Prevenció i Control de la Contaminació Acústica i Lumínica (Service for the Prevention and Control of Noise and Light Pollution)	2019	No	http://mediambient.gencat.cat/web/.content/home/ambits_dactuacio/atmosfera/contaminacio_luminica/control_del_vector_llum/Guia_controls_sectorials/guia-execucio-controls-sectorials.pdf In Catalan	Catalonia, Spain
Llei 6/2001, de 31 de maig, d'ordenació ambiental de l'enllumenament per a la pro- tecció del medi nocturn. (Law 6/2001, of 31 May, on the environmental management of lighting for the protection of the night environment.)	El President de la Generalitat de Catalunya (President of the Catalan Government)	2001	Yes	https://www.boe.es/eli/es-ct/l/2001/05/31/6/dof/cat/pdf In Catalan	Catalonia, Spain
Practical Guide for Outdoor Lighting. Efficient Lighting and Control of Light Pollution	IAC/OTPC - CONAMA AURA CARSO ESO/OPCC	2019	Yes	https://www.fundacionstarlight.org/docs/26-comunicaciones/ https://app.box.com/s/3kk1d2dicvnejo65bzn04i86wyhsaz9q/file/551602053638	Canary Islands, Spain
Otra manera de iluminar los sitios de la UNESCO (Another way to illuminate UNESCO sites)	Fundación Starlight (Starlight Foundation)	2015	No	https://www.fundacionstarlight.org/docs/26-comunicaciones/ https://www.dropbox.com/s/sam8mnvk2rupc9r/IluminandoSitiosUNESCObr.pdf?dl=0 In Spanish	Spain

Canadian Guidelines for Outdoor Lighting (Low-Impact Lighting™) for RASC Dark-Sky Protection Programs	Royal Astronomical Society of Canada	Adopted 2008, Revised 2020	Yes	https://rasc.ca/sites/default/files/RASC-CGOL_2020_0.PDF	Canada
Decreto 43 establece norma de emission para la regulación de la contaminación lumínica, elaborada a partir de la revision del decreto no. 686, de 1998, del Ministerio de Economía, Fomento y Reconstrucción (Decree 43 establishes an emission standard for the regulation of light pollution, elaborated from the revision of decree no. 686, of 1998, of the Ministry of Economy, Development and Reconstruction)	Ministerio del Medio Ambiente (Ministry for the Environment)	2012		https://www.bcn.cl/leychile/navegar?idNorma=1050704&idParte=9349878&idVersion=2014-05-03 In Spanish	Chile
Arrêté du 27 décembre 2018 relatif à la prévention, à la réduction et à la limitation des nuisances lumineuses (Decree of 27 December 2018 relating to the prevention, reduction and limitation of light pollution)	République Française / Légifrance (French Republic)	2018		https://www.legifrance.gouv.fr/loda/id/JORFTEXT000037864346/ https://www.ecologie.gouv.fr/pollution-lumineuse In French	France
Legge regionale 9 febbraio 2018, n. 3. Modifiche alla legge regionale 24 marzo 2000, n. 31 (Disposizioni per la prevenzione e lotta all'inquinamento luminoso e	Regione Piemonte (Piedmont Region)	2018		http://www.regione.piemonte.it/governo/bollettino/abbonati/2018/07/attach/aa_aa_regione%20piemonte%20-%20legge%20regionale_2018-02-13_62152.pdf In Italian	Piedmont, Italy

per il corretto impiego delle risorse energetiche). (Regional law 9 February 2018, no. 3. Amendments to the regional law 24 March 2000, no. 31 (Provisions for the prevention and fight against light pollution and for the correct use of energy resources).)					

4. Mitigation

Some authors, for example Davies and Smyth (2017), have suggested that the problems associated with widespread artificial light could be solved immediately by switching off lights. They state that "there would be no lag effect on the physical environment following such an event, allowing the biological environment to immediately begin the recovery process". However, others (e.g. van Grunsven et al., 2020) have found that some effects of ALAN only appear after long-term exposure which may mean that populations would need more time to recover even if artificial light was removed from their environment.

Mitigation needs to be considered for any new light-emitting projects and by replacing existing lighting sources, such as streetlights, with lights that have reduced intensity and light spill and which take the spectral quality of light into consideration (McNaughton et al., 2021). It has been recommended that artificial light sources which emit UV should be limited or banned as UV is non-functional for humans and its removal would be beneficial to many nocturnal invertebrates and bats (Mathews et al., 2015; Brehm et al., 2021). LEDs need to be tuned so that they do not emit blue light as most wildlife is sensitive to it (Russart and Nelson, 2018a; McNaughton et al., 2021) and it scatters more readily in the atmosphere, therefore, contributing more to skyglow than longer wavelength light (CMS, 2020b). As human night vision and health are also both impaired by blue light, Falchi et al. (2011) recommended a ban of outdoor emission of light at wavelengths shorter than 540nm. Where wildlife is sensitive to longer wavelength light, for example in the case of some bird species, wavelength selection needs to be specific to that location / species (CMS, 2020b).

Falchi et al. (2011, 2016) have made some general recommendations for how light pollution can be reduced:

- Do not allow light sources to send any light directly at and above the horizontal;
- Do not waste downward light flux outside the area to be lit (i.e. avoid light trespass);
- Avoid over-lighting (use minimum light for the task);
- Turn off lights when an area is not in use;
- Aim for zero growth of the total installed flux;
- Strongly limit the short wavelength 'blue' light that interferes with circadian rhythms and scotopic vision;
- Implement adaptive lighting which uses sensors to take traffic and meteorological conditions into account;
- Substitute already installed light fixtures for fully-shielded ones to reduce skyglow.

The Guidelines developed by the Australian Government which have been adopted by CMS aim for artificial light to be managed so that wildlife is:

"*1. Not disrupted within, nor displaced from, important habitat; and*

2. Able to undertake critical behaviours such as foraging, reproduction and dispersal." (CMS, 2020b).

The Guidelines recommend that this be achieved by using best practice lighting design and undertaking an Environmental Impact Assessment (EIA) for species whose behaviour, survivorship or reproduction are affected by artificial light. The Guidelines offer detailed appendices with information about:

- Best practice lighting design,
- What is light and how wildlife perceive it,
- Measuring biologically relevant light,
- Artificial light auditing,
- A checklist for artificial light management, and
- Species-specific information for marine turtles, seabirds and migratory seabirds.

Voigt et al. (2018a) recommend that when new lighting schemes are necessary, a lighting plan should take into consideration wildlife so that negative impacts can be avoided or mitigated against. Post-development monitoring should also be carried out. The CMS Light Pollution Guidelines for Wildlife also recommend carrying out an EIA for the potential effects of artificial light on wildlife by following five steps (see Figure 3). Depending on the scale of the proposed activity and the susceptibility of wildlife to artificial light, the amount of detail included in each step will vary. In the Technical Appendices, specific consideration is given for marine turtles, seabirds and migratory shorebirds but the process should be adopted for other protected species as well.

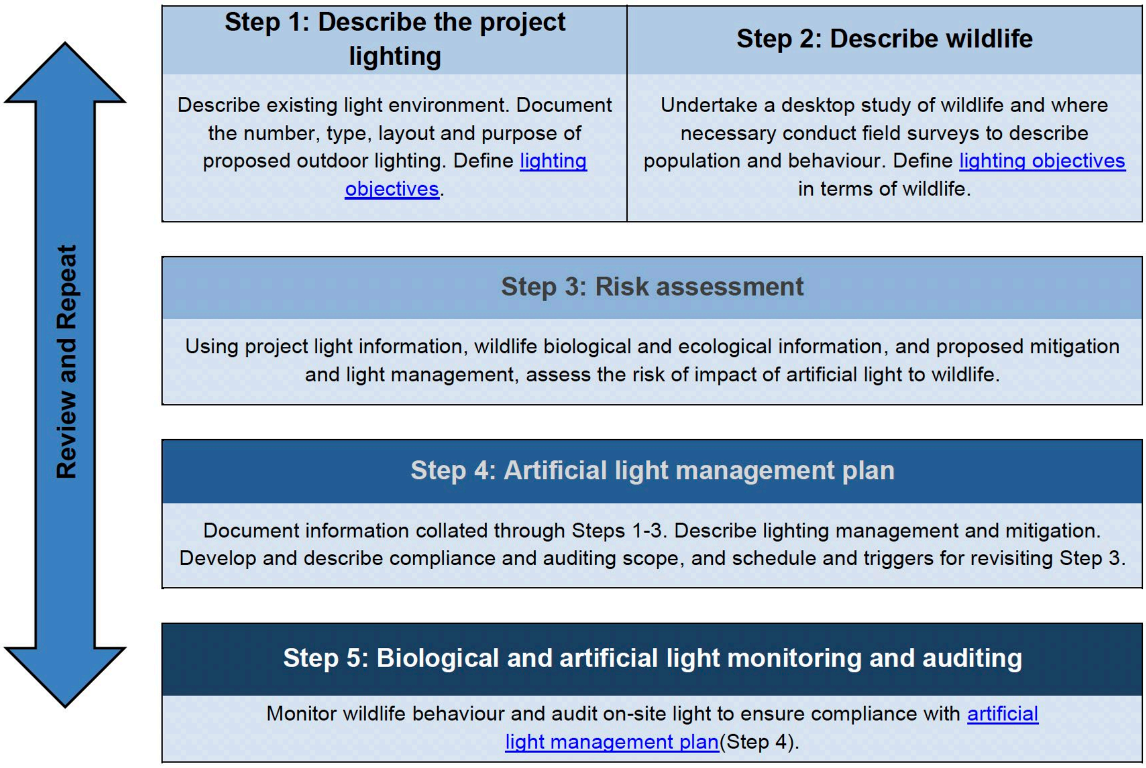

Figure 3: Environmental Impact Assessment process for artificial light (From: CMS, 2020b)

4.1 Mitigating light pollution in specific habitats / conditions

Riley et al. (2015) recommended that the best way to reduce the impacts of street lighting close to river environments is to increase natural unlit areas. However, they noted that this is not always possible due to human safety requirements. They, therefore, recommended the use of on-demand street lighting on footpaths so that human safety is protected whilst ensuring there are dark periods for river animals to exhibit normal behaviour.

Becker et al. (2012) recommended the use of red light in coastal areas as it does not penetrate water as easily. Illumination associated with infrastructure should be limited as much as possible in coastal zones.

There are several programmes to maintain dark skies in designated areas. International Dark Sky Reserves, for example, have exceptional quality starry nights and nocturnal environments and are protected for scientific, natural, education, cultural, heritage and/or public enjoyment[7]. UNESCO Starlight Reserves are natural areas with a commitment to protecting the quality of the night sky[8]. Some countries have their own designations, for example the Royal Astronomical Society of Canada has developed guidelines and requirements for three light-restricted protected areas: Dark-Sky Preserves, Nocturnal Preserves and Urban Star Parks[9].

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[7] https://www.darksky.org/our-work/conservation/idsp/reserves/
[8] https://en.fundacionstarlight.org/docs/files/89_concept-st-reserve-english.pdf
[9] https://rasc.ca/lpa/dark-sky-sites

Specific weather conditions may require ALAN to be mitigated in different ways. When snow is present, for example, illuminance levels should be reduced by using dimmable, adaptive, smart lighting to prevent the skyglow from being further amplified (Jechow and Hölker, 2019b).

4.2 Mitigating light pollution according to species

Studies which have considered the impacts of ALAN on fish, reptiles (other than marine turtles which are not considered here) and mammals (other than bats) have not made any specific light mitigation recommendations, although some papers make general remarks about the need to limit light sources or to implement technology which allows humans to activate lights when they are necessary rather than having them continuously illuminated (e.g., Riley et al., 2015; Bliss-Ketchum et al., 2016).
Actions to mitigate the impacts of ALAN on bats, birds and insects have been proposed and some of these are detailed below.

4.2.1 Mitigating light pollution for bats

Stone (2013) recommended that to mitigate the impacts of artificial light on bats, the following general questions need to be asked (note that although these are not specific to bats, the questions were asked in the context of protection for them):

1. Do we need to light?
2. Where does the light need to be?
3. What is the light required for?
4. How much light is actually needed to perform the tasks required?
5. When is the light required?

A mitigation strategy should then be developed with the following approach:

AVOID – Avoid impacts through careful assessment and planning
MITIGATE – mitigate to minimise impacts
COMPENSATE – compensate to offset effects of impacts
EVALUATE – evaluate effectiveness of mitigation and compensation.

The EUROBATS “Guidelines for consideration of bats in lighting projects” followed this strategy of avoidance, mitigation and compensation and detail how these can be done in bat habitats without putting human safety at risk (Voigt et al., 2018a). See Table 11.

Table 11: Recommendations from EUROBATS Guidelines to limit the impacts of ALAN on bat feeding areas and commuting routes (From Voigt et al., 2018a)

	Measure	Recommendations
Avoidance	Conserve dark areas	High priority areas that should remain dark: • protected areas, including roosting and underground hibernation sites • feeding areas (natural areas, vegetation patches) • commuting routes (forest edges, hedgerows, rivers, tree lines)
Only if lighting is necessary, and after an assessment of bat occupancy and patterns of activity within the landscape framework of functional habitats:		
Mitigation	Part-night lighting	Turn off public outdoor lighting within **2 hours after sunset** (civil twilight): • Especially during bat reproduction and migration periods • Particular attention within home ranges of maternity colonies
	Dimming	• Adapt dimming strategy to human activities • Keep illuminance levels as low as possible according to EU standards (not going over minimum illuminance required)
	Avoid light trespass	Avoid light trespass over 0.1 lx on surrounding surfaces: • Use fully shielded luminaires • No illumination at or above horizontal • Control streetlight height, especially along pedestrian pathways and tree lines • Use fewer light sources at points low to the ground • Consider the interaction between light from luminaires and reflecting structures, such as roads and walls
	Adapt lamp spectra	Avoid lamps emitting wavelengths below **540 nm** (blue and UV ranges) and with a correlated colour temperature > 2700 K
Compensation	Restore dark areas	No net loss of darkness: • Restore darkness to the same extent as the proportion of dark areas lost • Enhance alternative dark corridors that connect roosts and feeding areas

Stone (2013) recommended standardised surveys of light levels and bat activity prior to development and during the mitigation stage which can then be repeated post-mitigation for monitoring and evaluation of mitigation effectiveness. Species specific responses need to be taken into consideration as well as how different behaviours may be impacted.

The Guidance Note on “Bats and Artificial Lighting in the UK” published by the Bat Conservation Trust and the Institution of Lighting Professionals (ILP) recommends five steps for mitigating artificial lighting impacts on bats:

1. Determine whether bats could be present on site;
2. Determine the presence of / potential for roosts, commuting habitat and foraging habitat and evaluate their importance;
3. Avoid lighting on key habitats and features;
4. Apply mitigation methods to reduce lighting to agreed limits in other sensitive locations, and
5. Demonstrate compliance with illuminance limits and buffers (ILP, 2018).

The mitigation methods mentioned in Step 4 could include the use of:

- Dark buffers,
- Illuminance limits,
- Zonation,
- Appropriate luminaire specifications (see details below),
- Sensitive site configuration (such as footpath placement, building and wall design),
- Screening through the use of soft landscaping, walls, fences etc.,
- Glazing treatments (where windows and glass cannot be avoided),
- Creation of alternative valuable bat habitat on site, and
- Dimming and part-night lighting.

The Guidance Note includes the following specifications for appropriate luminaires:

- UV elements, metal halides and fluorescent sources should not be used,
- LEDs should be used where possible,
- A warm white spectrum should be adopted,
- Peak wavelengths should be higher than 550nm,
- Height of light columns should be considered,
- Only luminaires with an upward light ratio of 0% should be used,
- Luminaires should be mounted on the horizontal with no upward tilt,
- Security lighting should have motion-sensors and short (1 minute) timers, and
- Baffles, hoods or louvres can be used to reduce light spill.

Regarding bat species in the tropics, the maintenance of unlit habitats should be a priority so that nocturnal seed dispersers do not have their foraging activity reduced (Lewanzik and Voigt, 2014). It seems very likely that there are provisions for bats outside of Europe that were not apparent in this literature search, and this is one area where the CMS Scientific Council could provide additional advice and information.

4.2.2 Mitigating light pollution for birds

This is a major topic and requires further focused work. Nonetheless, it is clear that there is considerable evidence showing that birds are highly vulnerable to ALAN. One aspect of this is the impacts on birds on migration where lights may have energetic or even lethal effects. The identification and mapping of major light sources on flyways combined with advice about how this threat might best be addressed is a potential point of engagement. The forecasting of bird migrations could allow planning and preparation to mitigate against the negative impacts of light pollution including turning off lights and halting gas flares to prevent avian mortality (Van Doren and Horton, 2018). The BirdCast tool aims to provide real-time predictions of bird migrations[10]. Mitigation efforts may be particularly important at certain times of year. For example, the eastern USA ‘Lights Out’ campaigns need to be concentrated in the autumn, especially when juvenile birds are migrating for the first time (Horton et al., 2019). Chicago, Houston and Dallas were found to be cities which posed a particular risk for migrating birds because of the number of birds passing over them and their high levels of ALAN.

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[10] https://birdcast.info

Existing programmes which already aim to reduce the impacts of light pollution on migrating birds include the FLAP programme in Canada[11] and various Lights Out programmes in cities throughout the USA[12]. Nature Canada has a certification programme for Bird-Friendly Cities[13] and bird-friendly design guidelines to mitigate various threats, including the negative impacts of ALAN, have already been adopted by some cities in Canada[14].

The development of new international guidelines for bird species other than those already covered by the existing CMS guidelines should be considered.

4.2.3 Mitigating light pollution for insects

Restoring and maintaining darkness has been recommended to prevent further declines in moth populations (van Langevelde et al., 2017). Some negative impacts can be mitigated by adjusting the spectral composition of artificial light with red light having fewer impacts for insects (van Geffen et al., 2014, 2015). Blue light and UV radiation should be limited (Schroer et al., 2019; Brehm et al., 2021).

A further recommendation is that movement detection technology should be used so that lights are only illuminated when necessary (Degen et al., 2016; Straka et al., 2021).

Trees should be planted in lit and open areas as they can help mitigate the negative impacts of ALAN (Straka et al., 2021). However, it is important that artificial light is not directed into trees and other green areas (Schroer et al., 2019).

4.3 Challenges to mitigation

Reducing lighting in some areas may be opposed when it is considered essential for human safety. Falchi et al. (2016) recommended that studies should be carried out that look at whether lighting reduces crime and road accidents. They theorised that increased visibility could lead to drivers driving faster and subsequently increasing the risk of accidents. Such studies could help determine where lighting is necessary and where it is not.

As efficient lighting solutions are developed and the costs of artificial lighting decrease, this could lead to more lighting being installed than required (Schroer et al., 2020). Improved energy efficiency of lighting does not necessarily mean that ALAN is better for wildlife. There may be increased effects of ALAN for many species exposed to more energy efficient lighting and this needs to be taken into consideration when lighting projects are being planned.

It is important that mitigation methods are designed with an understanding of the negative impacts that the artificial lighting causes. For example, if negative impacts on moths are due to them incorrectly perceiving longer photoperiods in areas with ALAN, then turning off lights for a period during the night may still be harmful as the photoperiod would still be artificially extended (Boyes et al, 2021). The benefits to when lights are turned off may be species dependent.

Even when light quantities are reduced and its distribution is controlled so that light only goes where it is needed, some upward light emission will remain due to reflection from the lighted surface (Falchi et al., 2011).

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[11] https://flap.org

[12] https://www.audubon.org/conservation/existing-lights-out-programs

[13] https://naturecanada.ca/news/press-releases/first-canadian-bird-friendly-cities/

[14] Calgary (Alberta), London and Toronto (Ontario) and Vancouver (British Columbia) have been declared Bird-Friendly Cities (See Table 10 for each city's guidelines)

5. Review of CMS Listed Species

5.1 Species covered by CMS Light Pollution Guidelines for Wildlife – marine turtles, seabirds, migratory shorebirds

CMS *Resolution 13.5 Light Pollution Guidelines for Wildlife* adopted by COP13 in February 2020 endorses the Australian Government's "National Light Pollution Guidelines for Wildlife, including Marine Turtles, Seabirds and Migratory Shorebirds" as an Annex to the Resolution (CMS, 2020ab).

In the appendices of the Guidelines the three groups (marine turtles, seabirds and migratory shorebirds) are described including their conservation status and distribution and how they are affected by artificial light. Details of how to carry out an Environmental Impact Assessment are also given, followed by a light mitigation toolbox.

Appendix F of the Guidelines focuses on marine turtles and specifically names the six species of marine turtles that are found in Australia. All of these are listed on Appendix II of CMS and five of them are also on Appendix I (see Table A in the Annex). Two further species of turtles are listed on Appendices I and II and the Guidelines could be considered applicable for the Kemps' Ridley Turtle (*Lepidochelys kempii*) as it is another marine turtle, but they may need adapting for the South American River Turtle (*Podocnemis expansa*) as it is a river-dwelling species.

Appendix G of the Guidelines covers Seabirds specifically mentioning Procellariiformes (including petrels, shearwaters, albatrosses), some species of Charadriiformes (noddies, terns, gulls) and Sphenisciformes (penguins). CMS listed species which are covered by the Guidelines are given in Table B in the Annex.

Appendix H of the Guidelines covers Migratory Shorebirds most of which are from the families Scolopacidae (sandpipers), Charadriidae (plovers) and Glareolidae (pratincoles). The birds in those families which are listed on CMS are shown in Table C in the Annex.

5.2 Species not covered by CMS Light Pollution Guidelines for Wildlife

Chondrichthyes, insects, mammals, actonopterygii fish and reptiles (other than marine turtles) listed on CMS are not covered by the current CMS Light Pollution Guidelines for Wildlife.

Birds not considered seabirds or migratory shorebirds are not covered by the Guidelines either (see Table 12).

Table 12: Bird orders and families listed on the CMS appendices which are not covered by the current CMS Light Pollution Guidelines for Wildlife

Order	Families
Accipitriformes	Accipitridae, Pandionidae
Anseriformes	Anatidae
Cathartiformes	Carthartidae
Charadriiformes	Burhinidae
Ciconiiformes	Ardeidae, Ciconiidae
Columbiformes	Columbidae
Coraciiformes	Coraciidae, Meropidae
Falconiformes	Falconidae
Galliformes	Phasianidae
Gaviiformes	Gavidae, Gaviidae
Gruiformes	Gruidae, Rallidae
Otidiformes	Otididae
Passeriformes	Emberizidae, Fringillidae, Hirundinidae, Icteridae, Ictidae, Lanidae, Muscicapidae, Parulidae, Thraupidae, Tyrannidae
Pelecaniformes	Ardeidae, Pelecanidae, Pelecanoididae, Phalacrocoracidae, Threskiornithidae
Phoenicopteriformes	Phoenicopteridae
Podicipediformes	Podicipedidae
Psittaciformes	Psittacidae
Strigiformes	Strigidae
Suliformes	Fregatidae, Phalacrocoracidae

Some bat species listed on CMS are covered, in Europe, by the EUROBATS "Guidelines for consideration of bats in lighting projects" (Voigt et al., 2018a). There are 51 species listed on EUROBATS[15]. These guidelines may be useful to apply to other Chiroptera species on CMS. See Table D in the Annex for a full list of CMS and EUROBATS listed species.

6. Knowledge gaps

Tables 2, 3, 5, 6, 7, 8 and 9 summarise recent papers on the impacts of ALAN on species including any recommendations made regarding future studies and knowledge gaps. Some key knowledge gaps regarding the impact of ALAN on wildlife are further detailed here.

6.1 How light is measured

The study of artificial light at night is complicated by the interdisciplinary nature of the field (Kalinkat et al, 2021). Biologists, physicists and engineers need to work together to establish standardised assessment methods. There are no standard measurements to assess skyglow impact (Schroer et al., 2020) and some measurements which are commonly used to measure light may not be the most appropriate. The lux measurement, for example, expresses the brightness of light as perceived by the human eye by emphasising the wavelengths of light that the human eye detects (Longcore and Rich, 2004). Luxmeters do not measure spectral information which is necessary for ecological studies (Jechow and Hölker, 2019a). As other organisms perceive light differently to humans – including wavelengths not visible to us – these also need to be measured. Radiometric measurements detect and quantify all wavelengths from UV to IR, giving a biologically relevant measurement (CMS, 2020b).

Light monitoring instruments for wildlife are still being developed and the CMS Guidelines review different techniques currently available for monitoring light. Jechow and Hölker (2019a) found that very few spectrally resolved measurements exist for aquatic systems at night-time and that no common way of measuring has been established. Different instruments (luxmeters, spectrometers,

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[15] https://www.eurobats.org/sites/default/files/documents/pdf/Meeting_of_Parties/MoP8.Resolution%208.2%20Amendment%20of%20the%20Annex%20to%20the%20Agreement_0.pdf

SQMs and cameras) have been used and different parameters have been measured (spectral irradiance, illuminance, sky radiance at a single point, spatially resolved sky radiance) at different positions (above the surface and below the surface). This makes it difficult to compare the data. They recommend the development of more sensitive underwater and above water light measurement devices.

As there are no standard ways of measuring light, no thresholds of light intensities have been determined, below which artificial light would be considered not harmful to species or habitats (Schroer et al., 2020).

6.2 Types of studies

Much research into the effects of ALAN has taken place in the laboratory arguably without being subsequently connected to ecological studies in the field (Dominoni et al., 2016). Measures of animal health and longevity in the wild would help determine the ultimate consequences of ALAN. Measures of light levels in the real-world are necessary for data from laboratory studies to be meaningful (Jechow and Hölker, 2019a). Many studies could be said to have looked at individual species without adequately considering the ecological implications of ALAN.

During the preparation of this report, the impacts of artificial light on plants have not been considered, but it is an important issue which may have indirect impacts on pollinators and herbivores.

Many authors have highlighted the importance of long-term studies to fully understand the impacts of ALAN on species and habitats (e.g., Kurvers et al., 2018; van Grunsven et al., 2020; Kupprat et al., 2021).

6.3 Species

There is a lack of information regarding how ALAN impacts the majority of migratory species. No studies were found for any CMS-listed mammals (apart from bats), the Monarch Butterfly (the only CMS-listed insect), crocodiles or chondrichthyes. There is a limited amount of information available about some migratory fish, including the CMS-listed European eel, which raise concerns, but further research may be necessary before action can be taken. Whereas the impact of artificial light on marine turtles has been studied extensively, there is a knowledge gap when it comes to non-marine turtles (Perry et al., 2008).

Whilst many bird species have been shown to be vulnerable to light pollution, there are also calls in the literature for more research. Many of the bird species listed on CMS do not belong to the orders or families which are covered by the current Guidelines.

How the prey of migratory species is affected by ALAN also needs to be studied further, for example future research into the impacts of ALAN on moth species (which are prey for many other species) needs to consider all life stages rather than only focusing on adult moths as well as looking at more moth species (Boyes et al., 2021).

6.4 Synergies

It is not clear how ALAN works synergistically with other threats such as chemical pollutants, pesticides, noise, impoverishment of landscapes and climate change (Schroer et al., 2020). In urban environments it can be difficult to separate the effects of air pollution, low quality habitat and light pollution (Bolliger et al., 2020). However, it is highly likely that in most circumstances light pollution exacerbates other impacting factors. Animals living in a seasonal environment, perhaps in particular those that are highly migratory and needing to find food in certain places at specific times as well as appropriate breeding conditions, may have their lives disrupted by the effects of climate change. For example, arriving at a certain time at their feeding grounds but finding that the food resource they seek is not present or not of adequate quantity or quality (Laffoley and Baxter, 2016). Such problems may be exacerbated if the cues that they use to initiate key activities, such as migration, are affected by ALAN (see for example Smith et al., 2021 as detailed in Table 2).

7. Suggestions and further steps

There are undoubtedly gaps in this review of the available literature which has mainly looked at sources in the English language and it is anticipated that the CMS Scientific Council will be able to provide further information. This might include, for example, existing guidelines for bat species outside of Europe. Nonetheless, the available information shows widespread adverse impacts across taxa and ecosystems, highlighting the need for further action.

Some facilitation of a dialogue after the next meeting of the Sessional Committee with interested parties from the Scientific Council is recommended in order to gather additional information and, further to this, consultation with experts to consider the development of further guidelines, as described below.

7.1 A precautionary approach

Taking into account,

(i) the widespread effects of light pollution across all taxa, including prey and invertebrates;

(ii) the fact that many light sources emit light frequencies that we cannot see, and which are of no use to us but may still impact animals (e.g. UV);

(iii) that some light frequencies are more problematic than others; and

(iv) the existing data gaps, uncertainties and the unquantifiable impacts for many animals;

a precautionary approach would be to call for efforts to generally reduce ALAN.
CMS could help develop guidelines to show how this might be done and, in particular, how it might be applied in areas of high biodiversity.

Light pollution in riverine and marine environments has been relatively little studied, but it can be expected that aquatic species may be as vulnerable as others and, as illustrated above, there is some evidence to support this. Again, a generic call to stop shedding unnecessary light into seas and rivers and some advice on how this might be achieved from shipping or industrial structures would be appropriate.

7.2 Taxon-specific guidelines

Additionally, taxon-specific guidelines could be further developed. The available literature indicates that bats and migratory birds are particularly at risk.

Hence, light guidelines for species of migratory bats worldwide based on the EUROBATS guidelines could be developed and similarly, a suite of guidelines could be developed to address major light sources on migratory bird flight pathways. Measures could relate, for example, to the nature of lights used to illuminate landmarks and the nature of the lighting in the areas used by passage migrants.

Other taxon-specific guidelines might also be developed.

To develop such guidelines, it is proposed that this review of the available scientific evidence is completed by engaging with appropriate experts from around the world including, potentially, via virtual workshops.

This could be combined with a review of existing guidelines (a process initiated in this report) and the resulting engagement exercise would also facilitate the evaluation of:

i. what new guidelines might usefully be developed,

ii. some prioritisation of their development, and

iii. the development of draft guidelines for review at the next meeting of the Sessional Council.

7.3 Other CMS mandates

The Scientific Council might also consider linkages of the mandate on light pollution with its other mandates in relation to the mitigation of threats to taxa or groups of species, such as:

i) *Decision 13.70 Marine Turtles*, requesting the Scientific Council to review relevant scientific information on conservation and threats to marine turtles; and

ii) *Decision 13.129 Insect Decline and its Threat to Migratory Insectivorous Animal Populations*, requesting the Scientific Council to consider, in the meetings of its Sessional Committee after the 13th meeting of the Conference of the Parties (COP13), the following topics: a) identifying and prioritizing the main factors causing the established loss of insect biomass; b) collecting relevant information regarding the current insect decline, and assessing its cascading effects on migratory insectivorous animal species; c) developing guidelines for the most urgent or prioritized actions identified; d) publishing any such guidelines following circulation to all Parties for approval.

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ANNEX

Table A: Turtle species listed on CMS (From CMS, 2020bc)

Scientific name	Common name	CMS Appendix I	CMS Appendix II	Mentioned by name in current Guidelines?
Caretta caretta	Loggerhead Turtle	Yes	Yes	Yes
Chelonia mydas	Green Turtle	Yes	Yes	Yes
Dermochelys coriacea	Leatherback Turtle, Leathery Turtle	Yes	Yes	Yes
Eretmochelys imbricata	Hawksbill Turtle	Yes	Yes	Yes
Lepidochelys kempii	Kemp's Ridley Turtle, Atlantic Ridley Turtle	Yes	Yes	No
Lepidochelys olivacea	Ridley Turtle, Olive Ridley Turtle	Yes	Yes	Yes
Natator depressus	Flatback Turtle	No	Yes	Yes
Podocnemis expansa (only Upper Amazon populations)	Arrau Turtle, South American River Turtle	Yes	Yes	No

Table B: Seabird species listed on CMS which are covered by the CMS Light Pollution Guidelines for Wildlife (From: CMS 2020bc, CMS, 2021)

Scientific name	Common name	CMS Appendix I	CMS Appendix II	Family
Order: Charadriiformes				
Anous minutus worcesteri	Black Noddy		Yes	Laridae
Chlidonias leucopterus	White-Winged Black Tern		Yes	Laridae
Chlidonias niger niger	Black Tern		Yes	Laridae
Gelochelidon nilotica nilotica (West Eurasian and African populations)	Common Gull-Billed Tern		Yes	Laridae
Hydroprogne caspia (West Eurasian and African populations)	Caspian Tern		Yes	Laridae

Larus armenicus	Armenian Gull		Yes	Laridae
Larus atlanticus	Olrog's Gull	Yes		Laridae
Larus audouinii	Audouin's Gull	Yes	Yes	Laridae
Larus genei	Slender-Billed Gull		Yes	Laridae
Larus hemprichii	Sooty Gull, Hemprich's Gull, Aden Gull		Yes	Laridae
Larus ichthyaetus (West Eurasian and African population)	Great Black-Headed Gull		Yes	Laridae
Larus leucophthalmus	White-Eyed Gull	Yes	Yes	Laridae
Larus melanocephalus	Mediterranean Gull		Yes	Laridae
Larus relictus	Relict Gull	Yes		Laridae
Rynchops flavirostris	African Skimmer, Scissorbill		Yes	Laridae
Saundersilarus saundersi	Saunder's Gull, Chinese Black-Headed Gull	Yes		Laridae
Sterna dougallii (Atlantic population)	Roseate Tern		Yes	Laridae
Sterna hirundo hirundo (populations breeding in the Western Palearctic)	Common Tern		Yes	Laridae
Sterna paradisaea (Atlantic populations)	Arctic Tern		Yes	Laridae
Sterna repressa	White-Cheeked Tern		Yes	Laridae
Sternula albifrons	Little Tern		Yes	Laridae
Sternula balaenarum	Damara Tern		Yes	Laridae
Sternula lorata	Peruvian Tern	Yes		Laridae
Sternula saundersi	Saunders's Tern		Yes	Laridae
Synthliboramphus wumizusume	Japanese Murrelet, Crested Murrelet	Yes		Alcidae
Thalasseus bengalensis (African and Southwest Asian populations)	Lesser Crested Tern		Yes	Laridae

Thalasseus bergii (African and Southwest Asian populations)	Great Crested Tern		Yes	Laridae
Thalasseus bernsteini	Chinese Crested Tern	Yes		Laridae
Thalasseus maximus albididorsalis	Royal Tern		Yes	Laridae
Thalasseus sandvicensis sandvicensis	Sandwich Tern		Yes	Laridae
Order: Procellariiformes				
Ardenna creatopus	Pink-Footed Shearwater	Yes		Procellariidae
Diomedea amsterdamensis	Amsterdam Albatross	Yes		Diomedeidae
Diomedea antipodensis	Antipodean Albatross	Yes	Yes	Diomedeidae
Diomedea dabbenena	Tristan Albatross		Yes	Diomedeidae
Diomedea epomophora	Royal Albatross		Yes	Diomedeidae
Diomedea exulans	Wandering Albatross		Yes	Diomedeidae
Diomedea sanfordi	Northern Royal Albatross		Yes	Diomedeidae
Macronectes giganteus	Southern Giant Petrel		Yes	Procellaridae
Macronectes halli	Northern Giant Petrel		Yes	Procellaridae
Pelecanoides garnotii	Peruvian Diving Petrel	Yes		Pelecanoididae
Phoebastria albatrus	Short-Tailed Albatross, Steller's Albatross	Yes		Diomedeidae
Phoebastria immutabilis	Laysan Albatross		Yes	Diomedeidae
Phoebastria irrorata	Waved Albatross		Yes	Diomedeidae
Phoebastria nigripes	Black-Footed Albatross		Yes	Diomedeidae
Phoebetria fusca	Sooty Albatross		Yes	Diomedeidae
Phoebetria palpebrata	Light-Mantled Sooty Albatross		Yes	Diomedeidae

Procellaria aequinoctialis	White-Chinned Petrel		Yes	Procellaridae
Procellaria cinerea	Grey Petrel		Yes	Procellaridae
Procellaria conspicillata	Spectacled Petrel		Yes	Procellaridae
Procellaria parkinsoni	Black Petrel		Yes	Procellaridae
Procellaria westlandica	Westland Petrel		Yes	Procellaridae
Pterodroma atrata	Henderson Petrel	Yes		Procellariidae
Pterodroma cahow	Cahow, Bermuda Petrel	Yes		Procellariidae
Pterodroma phaeopygia	Dark-Rumped Petrel, Hawaiian Petrel, Galapagos Petrel	Yes		Procellariidae
Pterodroma sandwichensis	Dark-Rumped Petrel, Hawaiian Petrel, Uau	Yes		Procellariidae
Puffinus mauretanicus	Balearic Shearwater	Yes		Procellariidae
Thalassarche bulleri	Buller's Albatross		Yes	Diomedeidae
Thalassarche carteri	Indian Yellow-Nosed Albatross		Yes	Diomedeidae
Thalassarche cauta	Shy Albatross		Yes	Diomedeidae
Thalassarche chlororhynchos	Yellow-Nosed Albatross		Yes	Diomedeidae
Thalassarche chrysostoma	Grey-Headed Albatross		Yes	Diomedeidae
Thalassarche eremita	Chatham Albatross		Yes	Diomedeidae
Thalassarche impavida	Campbell Albatross		Yes	Diomedeidae
Thalassarche melanophris	Black-Browed Albatross		Yes	Diomedeidae
Thalassarche salvini	Salvin's Albatross		Yes	Diomedeidae
Thalassarche steadi	White-Capped Albatross		Yes	Diomedeidae
Order: Sphenisciformes				
Spheniscus demersus	African Penguin		Yes	Spheniscidae
Spheniscus humboldti	Humboldt Penguin	Yes		Spheniscidae

Table C: Migratory shorebirds (Order Charadriiformes) listed on CMS Appendices (From CMS, 2020bc; CMS, 2021)

Scientific name	Common name	CMS Appendix I	CMS Appendix II
Family: Charadriidae			
Charadrius alexandrinus	Kentish Plover		Yes
Charadrius asiaticus	Caspian Plover		Yes
Charadrius dubius	Little Ringed Plover		Yes
Charadrius forbesi	Forbes' Plover		Yes
Charadrius hiaticula	Common Ringed Plover		Yes
Charadrius leschenaultii	Greater Sandplover		Yes
Charadrius marginatus	White-Fronted Plover		Yes
Charadrius mongolus	Mongolian Plover, Lesser Sandplover		Yes
Charadrius pallidus	Chestnut-Banded Plover		Yes
Charadrius pecuarius	Kittlitz's Plover		Yes
Charadrius tricollaris	Three-Banded Plover		Yes
Eudromias morinellus	Eurasian Dotterel		Yes
Pluvialis apricaria	Eurasian Golden Plover		Yes
Pluvialis squatarola	Grey Plover		Yes
Vanellus albiceps	White-Headed Lapwing		Yes
Vanellus coronatus	Crowned Lapwing		Yes
Vanellus gregarius	Sociable Plover	Yes	Yes
Vanellus leucurus	White-Tailed Plover		Yes
Vanellus lugubris	Wattled Lapwing		Yes
Vanellus melanopterus	Black-Winged Lapwing		Yes
Vanellus senegallus	Senegal Lapwing		Yes
Vanellus spinosus	Spur-Winged Plover		Yes
Vanellus superciliosus	Brown-Chested Lapwing		Yes
Vanellus vanellus	Northern Lapwing		Yes

Family: Dromadidae			
Dromas ardeola	Crab Plover		Yes
Family: Glareolidae			
Glareola nordmanni	Black-Winged Pratincole		Yes
Glareola nuchalis	Rock Pratincole, White-Collared Pratincole		Yes
Glareola pratincola	Collared Pratincole		Yes
Family: Recurvirostridae			
Himantopus himantopus	Black-Winged Stilt		Yes
Recurvirostra avosetta	Pied Avocet		Yes
Family: Scolopacidae			
Arenaria interpres	Ruddy Turnstone		Yes
Calidris alba	Sanderling		Yes
Calidris alpina	Dunlin		Yes
Calidris canutus	Red Knot		Yes
Calidris canutus rufa	Red Knot	Yes	Yes
Calidris ferruginea	Curlew Sandpiper		Yes
Calidris maritima	Purple Sandpiper		Yes
Calidris minuta	Little Stint		Yes
Calidris pusilla	Semipalmated Sandpiper	Yes	Yes
Calidris pygmaea	Spoon-Billed Sandpiper	Yes	Yes
Calidris subruficollis	Buff-breasted Sandpiper	Yes	Yes
Calidris temminckii	Temminck's Stint		Yes
Calidris tenuirostris	Great Knot	Yes	Yes
Gallinago gallinago	Common Snipe		Yes
Gallinago media	Great Snipe, Double Snipe		Yes
Limicola falcinellus	Broad-Billed Sandpiper		Yes
Limosa lapponica	Bar-Tailed Godwit		Yes
Limosa limosa	Black-Tailed Godwit		Yes

Lymnocryptes minimus	Jack Snipe		Yes
Numenius arquata	Eurasian Curlew		Yes
Numenius borealis	Eskimo Curlew	Yes	Yes
Numenius madagascariensis	Far Eastern Curlew	Yes	Yes
Numenius phaeopus	Whimbrel		Yes
Numenius tahitiensis	Bristle-Thighed Curlew	Yes	Yes
Numenius tenuirostris	Slender-Billed Curlew	Yes	Yes
Phalaropus fulicaria	Grey Phalarope		Yes
Phalaropus lobatus	Red-Necked Phalarope		Yes
Philomachus pugnax	Ruff		Yes
Tringa cinerea	Terek Sandpiper		Yes
Tringa erythropus	Spotted Redshank, Dusky Redshank		Yes
Tringa glareola	Wood Sandpiper		Yes
Tringa guttifer	Spotted Greenshank, Nordmann's Greenshank	Yes	Yes
Tringa hypoleucos	Common Sandpiper		Yes
Tringa nebularia	Common Greenshank		Yes
Tringa ochropus	Green Sandpiper		Yes
Tringa stagnatilis	Marsh Sandpiper		Yes
Tringa totanus	Common Redshank		Yes

Table D: Bats listed on Appendices I and II of CMS and EUROBATS (From CMS, 2020c; CMS, 2021; [16])

Scientific Name	Common Name(s)	CMS Appendix I	CMS Appendix II	EUROBATS
Family: Emballonuridae				
Taphozous nudiventris	Naked-rumped Tomb Bat	No	No	Yes
Family: Molossidae				
Otomops madagascariensis	Madagascar free-tailed Bat	No	Yes	No
Otomops martiensseni (only African populations)	Large-Eared Free-Tailed Bat, Giant Mastiff Bat	No	Yes	No
Tadarida brasiliensis	Mexican Free-Tailed Bat	Yes	No	No
Tadarida insignis	Oriental (or East Asian) Free-tailed Bat	No	Yes	No
Tadarida latouchei	La Touche's Free-tailed Bat	No	Yes	No
Tadarida teniotis	European Free-Tailed Bat	No	Yes	Yes
Family: Pteropodidae				
Eidolon helvum (only African populations)	Straw-Coloured Fruit Bat	No	Yes	No
Rousettus aegyptiacus	Egyptian Fruit Bat	No	No	Yes
Family: Rhinolophidae (only European populations)				
Rhinolophus blasii	Blasius' Horseshoe Bat	No	Yes	Yes
Rhinolophus euryale	Mediterranean Horseshoe Bat	No	Yes	Yes
Rhinolophus ferrumequinum	Greater Horseshoe Bat	No	Yes	Yes
Rhinolophus hipposideros	Lesser Horseshoe Bat	No	Yes	Yes

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[16] https://www.eurobats.org/sites/default/files/documents/pdf/Meeting_of_Parties/MoP8.Resolution%208.2%20Amendment%20of%20the%20Annex%20to%20the%20Agreement_0.pdf

Rhinolophus mehelyi	Mehely's Horseshoe Bat	No	Yes	Yes
Vespertilionidae (V. spp. only European populations)				
Barbastella barbastellus	Barbastelle Bat	No	Yes	Yes
Barbastella capsica		No	Yes	Yes
Barbastella leucomelas	Asian barbastelle, Eastern barbastelle	No	Yes	Yes
Eptesicus anatolicus		No	Yes	Yes
Eptesicus bottae		No	Yes	(Replaced by *E. ognevi*)
Eptesicus isabellinus		No	Yes	Yes
Eptesicus nilssonii	Northern Serotine Bat	No	Yes	Yes
Eptesicus ognevi	Ognev’s Serotine	No	Yes	Yes
Eptesicus serotinus	Serotine Bat	No	Yes	Yes
Hypsugo savii	Savi's Pipistrelle Bat	No	Yes	Yes
Lasiurus blossevillii	Southern Red Bat, Western Red Bat or Desert Red Bat	No	Yes	No
Lasiurus borealis	Eastern Red Bat	No	Yes	No
Lasiurus cinereus	Hoary Bat	No	Yes	No
Lasiurus ega	Southern Yellow Bat	No	Yes	No
Miniopterus majori	Major's long-fingered bat	No	Yes	No
Miniopterus natalensis (only African populations)		No	Yes	No
Miniopterus pallidus		No	Yes	Yes
Miniopterus schreibersii (only African and European populations)	Schreibers' Bent-Winged Bat	No	Yes	Yes
Myotis alcathoe	Alcathoe Myotis	No	Yes	Yes
Myotis bechsteinii	Bechstein's Bat	No	Yes	Yes

Myotis blythii	Lesser Mouse-Eared Bat	No	Yes	Yes
Myotis brandtii	Brandt's Bat	No	Yes	Yes
Myotis capaccinii	Long-Fingered Bat	No	Yes	Yes
Myotis dasycneme	Pond Bat	No	Yes	Yes
Myotis daubentonii	Daubenton's Bat	No	Yes	Yes
Myotis davidii		No	Yes	Yes
Myotis emarginatus	Geoffroy's Bat, Notch-Eared Bat	No	Yes	Yes
Myotis escalerai		No	Yes	Yes
Myotis hajastanicus	Armenian whiskered bat, Hajastan myotis, Armenian myotis	No	Yes	No
Myotis myotis	Greater Mouse-Eared Bat	No	Yes	Yes
Myotis mystacinus	Whiskered Bat	No	Yes	Yes
Myotis nattereri	Natterer's Bat	No	Yes	Yes
Myotis nipalensis	Nepal myotis	No	Yes	No
Myotis punicus	Felton's myotis, Maghreb Mouse-eared Bat, Maghrebian Myotis	No	Yes	Yes
Myotis schaubi	Schaub's myotis	No	Yes	Yes
Nyctalus azoreum		No	Yes	Yes
Nyctalus lasiopterus	Greater Noctule Bat	No	Yes	Yes
Nyctalus leisleri	Leisler's Bat	No	Yes	Yes
Nyctalus noctula	Noctule Bat	No	Yes	Yes
Otonycteris hemprichii	Desert long-eared bat	No	Yes	Yes
Pipistrellus kuhlii	Kuhl's Pipistrelle Bat	No	Yes	Yes
Pipistrellus maderensis		No	Yes	Yes
Pipistrellus nathusii	Nathusius's Pipistrelle Bat	No	Yes	Yes
Pipistrellus pipistrellus	Common Pipistrelle	No	Yes	Yes

Pipistrellus pygmaeus	Soprano pipistrelle, Brown pipistrelle	No	Yes	Yes
Plecotus auritus	Brown Long-Eared Bat	No	Yes	Yes
Plecotus austriacus	Grey Long-Eared Bat	No	Yes	Yes
Plecotus kolombatovici	Kolombatovic's Long-eared Bat	No	Yes	Yes
Plecotus macrobullaris	Alpine Long-eared Bat	No	Yes	Yes
Plecotus sardus	Sardinian long-eared bat	No	Yes	Yes
Plecotus teneriffae		No	Yes	Yes
Vespertilio murinus	Parti-Coloured Bat	No	Yes	Yes