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REVIEW

SPECIAL ISSUE
SENSORY PERCEPTION IN A CHANGING WORLD

Challenges for wildlife seeking sleep in a disturbed world

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ABSTRACT

Sleep serves many functions that enable effective performance of the awake animal. Failure to obtain adequate sleep leads to lapses in motivation, attention and reaction times, coordination, and learning and memory. How do animals living in modified landscapes obtain their daily amount of sleep in the presence of pollution and anthropogenic disturbance? We review a subset of the studies examining if, and how, animals sleep in this disturbed world with a focus on artificial light at night, urban noise, psychoactive pollutants in waterways, agricultural practices, introduced species and a warming world. We highlight gaps in understanding and prescribe areas for future work. Notably, there is limited knowledge on truly wild animals, as well as the functional consequences of disrupted sleep for the efficacy of waking performance, fitness and survival. We close with ideas for mitigation, including tips that are achievable locally, by individuals. Such efforts will make it easier for wildlife to sleep soundly.

KEY WORDS: Anthropocene, Anthropogenic disturbance, Cognition, Modified landscapes, Neurobehavioural performance, Pollution, REM sleep, SWS

Good Morning, Good Morning (Introduction)

Founded in 1925, The Company of Biologists recently celebrated its 100-year anniversary with a scientific conference in Liverpool (UK). Four scientific tracks ran simultaneously, including 'Sensory Perception in a Changing World: Impacts on Physiology and Behaviour'. Presentations focused on the biological impacts of anthropogenic disturbances, such as noise, light, and climate change, among others. The backdrop for this programme – North West England – was appropriate, as this region was the crucible of the Industrial Revolution (c. 1760). The cities of Liverpool and neighbouring Manchester at least doubled their population sizes from 1773 to 1801. Yet, industrial progress wrought unintended (and present-day familiar) problems, from overcrowding to environmental pollution.

The historical arc of this progress bends from the Industrial Revolution to a time fewer than three centuries later. There is broad acceptance that the world today, not unlike North West England in the late 18th century, is one characterised by rapid and accelerating environmental change perpetuated by human activity. Yet, in the 21st century, such change is found globally, manifested by the large-scale modification of natural spaces for use in, for example, agriculture, roads, quarries, industry and cities. Human activities degrade air and water quality, disrupt weather patterns, and contaminate land, freshwater and seawater with pollution. Population growth motivates renewed land clearing, material consumption and the production of waste. Many (and perhaps most) animals must contend with modified landscapes, changing weather and the proliferation of pollution. Doing so has the potential to challenge physiological systems that evolved during periods of greater environmental and ecological stability. Here, we will review a subset of the studies examining how animals deal with this disturbed world, but with a focus on an often-overlooked state that is central to the optimal behavioural and physiological performance of animals – sleep.

Sleep is an interesting and enigmatic behaviour. First, the sleeping animal is vulnerable, owing to attenuated awareness and reduced responsiveness (Lima et al., 2005). Second, sleep is widespread across the animal kingdom, found even in the earliest branching lineages (Lesku et al., 2019; Rattenborg and Ungurean, 2023). Third, sleep constitutes a large part of the life of an animal, and many animals sleep more than they are awake, including armadillo, opossum and members of the Rodentia (Lesku et al., 2008). While some animals can sleep little, no animal is known to forgo sleep entirely (Lesku and Rattenborg, 2022). Fourth, rather than abstaining from sleep altogether, some animals have evolved adaptations that blur the boundary between wake and sleep, such as the abilities to sleep while watching, chewing, swimming and flying (Lyamin et al., 2008; Lesku et al., 2011a; Aulsebrook et al., 2016; Rattenborg et al., 2016; Furrer et al., 2024). Fifth, severe sleep loss appears to be lethal: fruit flies survive no longer than 11 days without sleep, and rats die, or show signs of impending death, after 2–3 weeks of extended wakefulness (Rechtschaffen and Bergmann, 2002; Vaccaro et al., 2020; Chen et al., 2025). Taken together, these points indicate that sleep must perform important, and seemingly inescapable, functions.

Before we consider those functions, we must first characterise sleep. Across animals, sleep can be identified as a restful state of reduced responsiveness, and one that is rapidly reversible to wakefulness with sufficient stimulation. Another feature of sleep is that it is homeostatically regulated, such that the need to sleep builds with the time spent awake; circadian processes influence the timing of sleep (Tobler, 2005; Borbély, 2022). Many aspects of sleep are evolutionarily conserved. For example, melatonin is a hormone present in all animal lineages (Schippers and Nichols, 2014). Melatonin is produced primarily during darkness, acting as a physiological link between (external) light-dark cycles and (internal) circadian processes. As well as playing a crucial role in the circadian regulation of sleep, melatonin might also impact sleep homeostatic processes (Gandhi et al., 2015; Comai and Gobbi, 2024).

In at least some species, sleep is not a homogenous state. In birds and mammals, sleep is composed of two sub-states (Lesku and Rattenborg, 2014; Canavan and Margoliash, 2020). Non-REM sleep is characterised by large, slow brain waves in the electroencephalogram. Conversely, REM sleep is characterised by small, fast (wake-like) brain activity, as well as rapid eye movements under closed eyelids and reduced muscle tone (Blumberg et al., 2020). These types of sleep are thought to serve different, and perhaps complementary, functions

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(Vyazovskiy and Delogu, 2014). Furthermore, non-REM sleep can vary in depth or intensity, with the amount and size of slow brain waves (typically <4.5 Hz power density) in the electroencephalogram reflecting more intense, deeper non-REM sleep. Non-REM sleep intensity is also highest after consolidated periods of wakefulness and declines with time spent asleep (Tobler, 2005; Martinez-Gonzalez et al., 2008; Johnsson et al., 2022a; Zaid et al., 2022), reflecting homeostatically regulated processes linked to sleep function (Huber et al., 2004; Lesku et al., 2011b; Tononi and Cirelli, 2014). There is emerging evidence of multiple sleep states in other animals, including lizards, spiders and cephalopods (Shein-Idelson et al., 2016; Rößler et al., 2022; Pophale et al., 2023), although any homology to mammalian and avian sleep states is unclear (Rattenborg and Ungurean, 2023). Nevertheless, quantifying the composition and intensity of sleep remains relevant for understanding how disturbance affects the functions of sleep.

Sleep serves many, often non-exclusive, processes. Such processes occur at various spatial scales within the animal, from molecular (DNA repair: Zada et al., 2021) and cellular (synaptic scaling: Tononi and Cirelli, 2014) through to neurological systems (sensorimotor mapping: Blumberg et al., 2022) and maintenance of the brain itself (temperature and energy homeostasis: Parmeggiani, 2003; Lesku and Schmidt, 2022; waste clearance: Kroesbergen et al., 2024 preprint). The aim of most sleep functions is to contribute towards the optimal performance of the nervous system, which in turn improves performance of the animal while it is awake. Indeed, acute sleep loss and chronic sleep restriction typically lead to lapses in motivation, attention and reaction times, coordination, and learning and memory (Van Dongen et al., 2003; Klein et al., 2010; Rasch and Born, 2013; Pinheiro-da-Silva et al., 2017; Samson et al., 2019; Johnsson et al., 2022b). Direct costs to survival and fitness arising from sleep loss remain unstudied in wild animals (but see Lesku et al., 2012). Nevertheless, there is potential for even momentary inattention to be decisive in certain ecological interactions, such as anti-predator vigilance and male–male competition (Lima et al., 2005).

Our focus here is to highlight the varied anthropogenic challenges faced by animals seeking sleep in a world dominated by human influence. The best studied of these challenges are artificial light at night and urban noise. We also highlight an emerging appreciation of lesser-studied factors, including psychoactive pollutants in waterways, agricultural practices, introduced species and a warming world. Owing to the Liverpudlian venue of the scientific conference that spurred this Review, please indulge our use of section headers coined by the most famous sons of Liverpool.

A Hard Day's Night (artificial light at night)

Some forms of pollution blur the boundary between day and night, perhaps none more so than artificial light at night. Throughout most of human evolution, the only sources of light after sundown came from stars and sunlight reflected off the moon, and some bioluminescent organisms. Electric lighting has existed for only 150 years. Compared with earlier forms of lighting adopted by humans, such as torches, candles and oil lamps, electric lighting permeates farther into the surrounding environment, appears brighter and is more convenient to maintain. Owing to these advantages, the adoption of electric lighting moved fast: half the homes in the USA had some ability to support electric lighting by 1925. In 2025, six-and-a-half billion people live under light-polluted skies (Linares Arroyo et al., 2024). The past 20 years have seen increasing concern for the impact of light pollution on the behaviour and physiology of wildlife (Longcore and Rich, 2004). The impacts wrought by artificial light at night are diverse, and include changes to hormone levels and diel profiles, shifts in singing, roosting, activity and the timing of reproduction (Robert et al., 2015; Sanders et al., 2021).

There are multiple ways in which artificial light at night is expected to impact sleep (Aulsebrook et al., 2018, 2021). First, in diurnal species that depend on vision for foraging, movement or other (wakeful) behaviours, light pollution may facilitate increased nocturnal activity (Russ et al., 2015; Sanders et al., 2021; Evens et al., 2023). Second, for many organisms, light is an important environmental cue, or zeitgeber, through which (internal) physiology is entrained to (external) conditions based on the Earth's approximately 24 h rotation (Blume et al., 2019; Helm et al., 2024). A key way for light to entrain the circadian clock is through the hormone melatonin, which is a time-keeping molecule that is produced during darkness. Its production is hampered by artificial light at night in both diurnal and nocturnal species (Grubisic et al., 2019; Helm et al., 2024; Yang et al., 2024). The disruption of these circadian processes can therefore disrupt the regulation of sleep. Third, melatonin can influence sleep independently of the circadian system by influencing homeostatic processes and promoting sleep in diurnal species, presenting additional physiological pathways by which artificial light can alter sleep (Czeisler, 2013; Gandhi et al., 2015; Aulsebrook et al., 2018).

Humans routinely welcome artificial light at night into their bedroom well after sunset. Devoid of the natural darkness that signals it is night-time, the circadian clock shifts forward, melatonin is suppressed and sleep onset is delayed (Czeisler, 2013). Some animals are protected by artificial light at night by virtue of where they sleep. Great tits (*Parus major*) roost in tree cavities, but will also reside in nest boxes. In a behavioural study, Raap et al. (2018) set up lights outside some nest boxes to mimic street lighting. They found that the birds inside enjoyed as much night-time sleep as birds in 'dark' boxes that were not subjected to artificial light at night. Conversely, when the lights were moved inside the nest box, the tits slept less and awoke earlier in the morning (Raap et al., 2015).

Animals that sleep in more exposed locations are not afforded the same protection. Here, exposure to artificial light at night can have profoundly disruptive impacts on avian sleep (Aulsebrook et al., 2021). Domestic pigeons (*Columba livia*), the archetypal urban bird, were brought into the laboratory for the first electroencephalographic study of simulated street lighting on sleep. When perched under artificial light at night, the amount of REM and non-REM sleep, and non-REM sleep intensity, were all reduced, and sleep state episodes were shorter (Aulsebrook et al., 2020a). Similar results were found for wild-caught Australian magpies (*Gymnorhina tibicen*) (Aulsebrook et al., 2020a). In another study, black swans (*Cygnus atratus*) housed in large outdoor pens had less night-time sleep under street lights (Aulsebrook et al., 2020b). In barnacle geese (*Branta leucopsis*), the suppressive effect of artificial light on non-REM sleep was amplified by cloud cover at night, as clouds reflected terrestrial lights to augment skyglow (van Hasselt et al., 2021). When great tits roosted on tree branches, they were more active at night and had the strongest reduction of oxalic acid (Ouyang et al., 2017), a biomarker of sleep loss (Weljie et al., 2015; Zaid et al., 2024). Taken together, field studies of sleep behaviour, and captive studies measuring brain activity, indicate that artificial light at night disrupts sleep in birds.

Different wavelengths of light are expected to impact sleep to different degrees. Warmer coloured (amber) light emits less light in the blue region of the colour spectrum and has a less suppressive effect on the production of melatonin (Yang et al., 2024). This is precisely why smart devices shift towards amber light after sunset and emit white (blue-rich) light during the daytime. When

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Australian magpies perched under white light, the amounts of REM and non-REM sleep were reduced, as was non-REM sleep intensity. Although sleep was also negatively impacted by amber light, the impact was less severe (Aulsebrook et al., 2020a). However, switching to amber-coloured lighting is unlikely to be a solution of universal appeal. Sleep in pigeons and black swans was equally disrupted by white and amber light (Aulsebrook et al., 2020a,b). It is therefore important to consider responses from species individually, rather than from, for example, 'birds', when designing management strategies for the benefit of wildlife.

More study is also needed on the capacity of animals to either avoid, adapt to or endure light at night. Although avoiding light would seem an easy and obvious choice, some birds even prefer to roost near artificial light at night (Daoud-Opit and Jones, 2016; Ulgezen et al., 2019). There is some evidence for adaptation from a laboratory study of wild-caught house finches (*Haemorhous mexicanus*) from urban and rural sites (Hutton et al., 2024). Although light at night reduced sleep in all birds, the reduction was more modest in urban finches. But does disturbed sleep result in a meaningful impairment to waking performance, or can animals simply endure sleep loss without repercussions? Kumar et al. (2023) housed zebra finches (*Taeniopygia guttata*) on a photoperiod of 12 h daytime light, followed by either 12 h of darkness or 12 h of dim light at night for 6 weeks. Unsurprisingly, sleep was disrupted by the dim night-time light. Importantly, though, the birds exposed to light at night also explored a novel object less, took longer to complete a colour discrimination task and made more errors on that task relative to the better-rested controls. More studies of this type are needed, as are studies looking at how sleep-dependent attention, motivation and memory might compromise fitness and survival (see Georgiou et al., 2024 for promising work on fish). A recent analysis showed that the majority of North American birds are in decline (Johnston et al., 2025). While the causes may vary across species, modified landscapes and pollution likely play a role.

Here, we have highlighted the impacts of artificial light at night on sleep in birds, as this is the taxonomic group for which the available data are strongest. Nevertheless, artificial light at night likely has broad impacts across diverse animal taxa. There is evidence that exposure to artificial light can impact inactivity and/or sleep in species ranging from honey bees (*Apis mellifera*; Kim et al., 2024) to laboratory rats (Tobler et al., 1994). However, for most taxonomic groups, data are lacking in regard to: (1) ecologically realistic levels of nocturnal lighting (as opposed to continuous exposure to daytime levels of light) and/or (2) more direct measurements of sleep (rather than relying solely on inactivity levels as a proxy). In addition, although it is generally presumed that artificial light is primarily an issue for sleep in diurnal species, the pathways by which light disrupts sleep also have the potential to affect nocturnal species. Further study of a broader range of taxonomic groups will be important for understanding the extent of such impacts.

Helter Skelter (urban noise)

The celebrated auditory assault that is 'Helter Skelter' pales against the cacophony of the urban soundscape, with the sounds of traffic, public transportation, concerts and fireworks, and construction and industry. Animals sleeping outdoors have little insulation against such noise. As with the examples detailed above for artificial light at night, here too there is a strong bias towards the study of birds. Noise pollution can cause stress (Kleist et al., 2018), delay offspring growth (Zollinger et al., 2019), impair vocal development and suppress immune function (Brumm et al., 2021), increase call amplitude (Brumm, 2004; Kight and Swaddle, 2015), and mask important auditory cues (Templeton et al., 2016; Arcangeli et al., 2023). And yet, the effects of anthropogenic noise on sleep per se have received far less attention. Jackdaws (*Corvus monedula*) called more at night, and likely slept less, when roosting in noisier environments (Broad et al., 2024). Australian magpies were played a recording of an urban soundscape in the laboratory while the electroencephalogram monitored their sleep/wake patterns (Connelly et al., 2020). Magpies had fewer and shorter REM sleep episodes, compared to a quiet night, resulting in half as much REM sleep. The reduction in the amount of non-REM sleep was less severe, yet the reduction in the intensity of non-REM sleep lasted the entire night.

Are there any behavioural or physiological consequences from urban noise that arise from sleep loss? There has been very little research to address this question. Australian magpies are well suited to provide insight because they are quick to learn and are eager participants for cognitive testing (Ashton et al., 2018; Johnsson et al., 2023, 2024). When kept awake for an entire night, wild-caught magpies showed evidence of impaired learning: birds took longer to interact with a reversal learning task and were less likely to succeed at the task; the one bird (out of eight) that did succeed required more attempts and made more errors (Johnsson et al., 2022b). In contrast, birds performed equally well on associative and reversal learning tasks, inhibitory control, and spatial memory tests following a quiet night or one with the playback of the urban soundscape (Connelly et al., 2024). However, the magnitude of sleep loss induced by urban noise (Connelly et al., 2020) was not nearly so severe as in the former study (Johnsson et al., 2022a,b). One possible interpretation is that magpies, and potentially other birds, can endure sleeping less in noisy environments without cost to some aspects of their performance.

In the wild, animals faced with urban noise may fare even better than in the laboratory. When choosing where to sleep, wild boar (*Sus scrofa*) prefer familiarity over proximity to sources of anthropogenic noise, such as roads and villages (Fradin and Chamaillé-Jammes, 2023). Great tits around the city of Munich sleep for similar amounts of time irrespective of the level of local urban noise (Caorsi et al., 2019). This may also explain why Australian magpies in city parks do not vary in their cognitive performance along a noise gradient (Connelly et al., 2022). Urban wildlife may become accustomed to sleeping with noise pollution.

Golden Slumbers (psychoactive pollutants)

Pharmaceutical pollution is an issue worldwide, with pharmaceutical compounds found in the environment on all continents (Wilkinson et al., 2022). A study of aquatic invertebrates living in streams in one city detected 60 such compounds, including antiarrhythmics, antibiotics and antidepressants, among many others (Richmond et al., 2018). Pharmaceuticals dissolved in urine are released as effluence from wastewater treatment plants, but can also enter the environment from leaking sewage pipes and septic tanks. Once in the environment, the concentration of the drugs is very low, measured in millionths of a gram of drug per gram of water. Nevertheless, the drugs can bioaccumulate and can have biological impacts, even at low doses (Arnold et al., 2014). Below, we provide two contrasting examples of how pharmaceutical pollution might impact sleep in fish. However, many other animals are also exposed to psychoactive pollutants, including other aquatic animals and the predators who eat them.

Some forms of pharmaceutical pollution can increase sleep. Antidepressants are interesting owing to their ability to influence sleep in humans. Fluoxetine, sold under the brand name Prozac, can cause daytime sleepiness in some people. When given chronically for 1 month at very low doses to turquoise killifish

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(*Nothobranchius furzeri*), the fish swam less in the morning, suggesting that they were sleeping more (Thoré et al., 2021, 2024). Similarly, after acute exposure to low levels of fluoxetine in naïve eastern mosquitofish (*Gambusia holbrooki*), the normally diurnal fish no longer showed a preference for activity during the day over the night, owing to an increase in daytime restfulness (Tan et al., 2023). These effects may be explained by impacts of fluoxetine on melatonin and circadian rhythms. In zebrafish larvae (*Danio rerio*), increased daytime rest during exposure to fluoxetine was also associated with decreased melatonin production at night and with decreased expression of circadian genes (Wei et al., 2022). In all of these studies, fish were exposed to similar fluoxetine levels to those detected in waterways in the wild.

Marine animals are not isolated from chemical pollutants. Brazilian sharpnose sharks (*Rhizoprionodon lalandii*) have been found with high levels of cocaine and a cocaine metabolite in their muscle and liver (de Farias Araujo et al., 2024). The cocaine is thought to enter the ocean from sewage, but also more clandestine sources, such as illegal refining operations and drifting cocaine packs. Sharpnose sharks are top predators and may obtain cocaine directly from the environment, but also from ingesting drugged prey. In humans, chronic cocaine use, but also cocaine withdrawal, can severely disrupt sleep (Angarita et al., 2016). While sharks do sleep (Kelly et al., 2021, 2022; Lesku et al., 2024; see also Norman et al., 2024), it is unknown whether ‘cocaine sharks’ similarly experience insomnia from long-term exposure, or sleep disturbance from withdrawal. Still, these studies reveal two important points: (1) even low levels of environmental pharmaceuticals can affect sleep; and (2) psychoactive pollutants are not confined to streams, but are likely a much larger problem than generally appreciated.

Strawberry Fields Forever (agricultural practices)

Some agricultural practices have relevance for the discussion on how animals sleep in response to disturbance. The most prolific pollinators of strawberry fields and many other crops are bees. Yet, bees face a number of pressures in the modern world, including a decline in flowers, spread of parasites and widespread use of agrochemicals (Goulson et al., 2015). One class of agrochemicals, the neonicotinoids, are sprayed onto plants, absorbed and contaminate nectar. Honey bees drink the nectar and in doing so dose themselves with an insecticide. Bees given neonicotinoids (clothianidin or thiamethoxam) over at least 4 days lost their normal diurnal activity pattern and became arrhythmic (Tackenberg et al., 2020). Both types of neonicotinoid reduced the amount of sleep; thiamethoxam halved the time spent asleep. This finding has ecological relevance because honey bees perform their waggle dance to communicate directional information to food, yet do so with less precision when kept awake at night (Klein et al., 2010). Thus, there is potential for insecticides to keep wild bees awake, decreasing the health of the colony and impairing the efficacy of an ecosystem service that is central to crop production and biodiversity.

A very different agricultural practice threatens birds inhabiting olive tree plantations around the Mediterranean Sea. Spain is the largest producer of olive oil in the world. Olives are harvested at night, as cooler temperatures preserve certain favourable aromatic compounds. Separating olive from olive tree is carried out using industrial suction harvesters. These tall vehicles drive down each plantation row and the olive trees pass through a large central tunnel under the harvester in seconds. The timing of olive harvest coincides with the migration of millions of birds from northern Europe to Spain and other Mediterranean countries (Pérez et al., 2023). Historically, 2.6 million birds were suctioned off trees at night in Spain each year (da Silva and Mata, 2019). Birds were killed as they slept, or once awoken by the approaching machinery, were reluctant to take flight at night. Fortunately, since the 2019–2020 season, Spain and Portugal have suspended the night-time harvesting of olives. Other olive oil-producing countries have, to our knowledge, yet to do likewise.

Don’t Bother Me (introduced species)

Poor sleep can arise from unwelcome interactions, often with humans. People might be protective about their own sleep, yet insensitive about sleep in other animals. For example, some might thoughtlessly disturb a lap cat, or tap the glass at a zoo exhibit to awaken a sleeping animal. Others might approach sleeping animals too closely in search of a selfish selfie (Lenzi et al., 2020). A GPS-based study on the activity patterns of brown bears (*Ursus arctos*) found that bears have a crepuscular activity rhythm (Donatelli et al., 2025). Yet, bears increase night-time activity in response to human encroachment. Whether this temporal shift influences the timing or amount of sleep is unclear. Hawaiian spinner dolphins (*Stenella longirostris longirostris*) are charismatic cetaceans and a popular sight among snorkelling ecotourists. Spinner dolphins hunt in the open ocean at night, and move to shallower waters to sleep in the morning (Norris et al., 1994). They sleep while swimming slowly, as do other dolphins (Lyamin et al., 2008), and can be intercepted by swimming humans aided by fins. Approaching dolphins within 50 yards is now prohibited, giving them the space and silence to sleep. Similarly, passionate birders can too-closely approach owls roosting by day. When aroused, owls may flush and are often then mobbed by other birds. Such occurrences led the American Birding Association to revise their code of birding ethics to: ‘Avoid stressing birds or exposing them to danger. Be particularly cautious around active nests and nesting colonies, roosts, display sites, and feeding sites…Always exercise caution and restraint when photographing, recording, or otherwise approaching birds’ (www.aba.org/aba-code-of-birding-ethics).

Keeping a leash on pets can be harder. Cats roam at night and kill diurnal wildlife, notably birds, at a time when they are sleeping and vulnerable (van Heezik et al., 2010). Dogs running down the coastline disturb the sleep of shorebirds napping on the beach (McBlain et al., 2020). The pet trade can also have far-reaching and unexpected consequences for sleep in wild animals. Aquarium enthusiasts will be familiar with armoured catfish (*Pterygoplichthys* spp.) that, when small, are innocuous yet helpful at cleaning algae from glass and substrate. But armoured catfish can grow to more than half a metre long and have been released into freshwater springs far from their native home of South America. In Florida, catfish encounter the endangered Florida manatee (*Trichechus manatus latirostris*), whose backs serve a meal of epibiota to catfish. Feeding by catfish can cause wounds on manatees (Pérez-Flores and Pigenutt-Galindo, 2020). Most manatees have been observed with one attached catfish, but others have been burdened by two dozen. Manatees respond by rolling or flipping their tail to temporarily dislodge feeding catfish, limiting their own time available for sleep and increasing energy expenditure while awake (Nico et al., 2009; Gibbs et al., 2010).

Another introduced species causes greater harm than mere injury. Candy-striped spiders (*Enoplognatha latimana* and *E. ovata*) were unintentionally introduced from Europe to North America. The spiders hunt at dawn, before their diurnal prey have woken up (Scott and McCann, 2023). They eat many different pollinating insects, including flesh flies (Sarcophagidae), hoverflies (Syrphidae), bee flies (*Villa* sp.) and, especially, beewolves (*Philanthus crabroniformis*), sand wasps (*Bembix americana*) and thread-waisted wasps (*Ammophila* spp. and *Prionyx* spp.). It remains unclear whether, by

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eating pollinators as they sleep, the spiders have a broader influence on plant diversity at the landscape level.

Here Comes the Sun (warming world)

Climate change increases the occurrence of extreme weather events, such as storms and heat waves, both of which could disrupt sleep. In 2024, the world was 1.47°C warmer relative to the pre-industrial average (1850–1900). Each of the years from 2014 to 2024 were the warmest recorded. When it is too hot during the daytime, diurnal animals might become more active at night. Alpine ibex (*Capra ibex*) live in the Alps. On cool days, they are active during the daytime; on warmer days, they increase their activity at night (Brivio et al., 2024). Similar patterns can be observed in hotter places on Earth. The activity patterns of eight African herbivores were studied (Veldhuis et al., 2020). All were diurnal when lions (*Panthera leo*) were in the area. When the lions moved farther afield, the herbivores shifted some daytime activity to the night, perhaps to avoid the heat of the midday sun. In both cases, whether the amount or composition of sleep was affected is unknown.

The increase in average global temperature is felt most in the polar regions. Since 1979, the Arctic has warmed almost four times faster than elsewhere on Earth (Rantanen et al., 2022). The loss of sunlight-reflecting sea ice contributes further to polar warming, which further reduces the area and mass of ice sheets (Screen and Simmonds, 2010; Ding et al., 2019). Polar bears (*Ursus maritimus*) are dependent on sea ice for both food and rest. Although polar bears can scavenge food, their natural prey is seals, which they hunt by waiting at breathing holes that perforate the ice. Unlike seals, which can sleep on land and in water alike (Lyamin et al., 2018), polar bears have not been observed sleeping at sea. Consequently, retreating sea ice means that polar bears must swim farther in search of ice on which to feed and sleep. One polar bear mother, accompanied by her cub, was equipped with a collar bearing an accelerometer, temperature sensor and GPS unit (Durner et al., 2011). Swimming through 2–6°C water, she swam for 232 h, covering 687 km. Over the journey, she lost 22% of her starting body weight and her young cub. It is likely that this mother went without sleep for nearly 10 days. Unfortunately, polar bears are likely to face more sleepless days in the decades ahead.

Overall, the implication of climate change for sleep is generally not considered. We need to understand the factors that might drive sleep resiliency and what animals might be most vulnerable. It is also unclear how a species response to warming (e.g. shifting activity to the night) might interact with other forms of pollution (e.g. artificial light at night). Understanding how animals sleep in a warming world requires urgent attention.

We Can Work It Out (concluding remarks)

We have tried to highlight the diversity of challenges faced by wildlife seeking to achieve the sleep that they need at their appropriate time of day (Fig. 1). There is direct and indirect evidence to indicate that human impacts on the environment are disrupting sleep in wildlife. Many of these issues disturb sleep in humans too, such as light and noise pollution and extreme weather

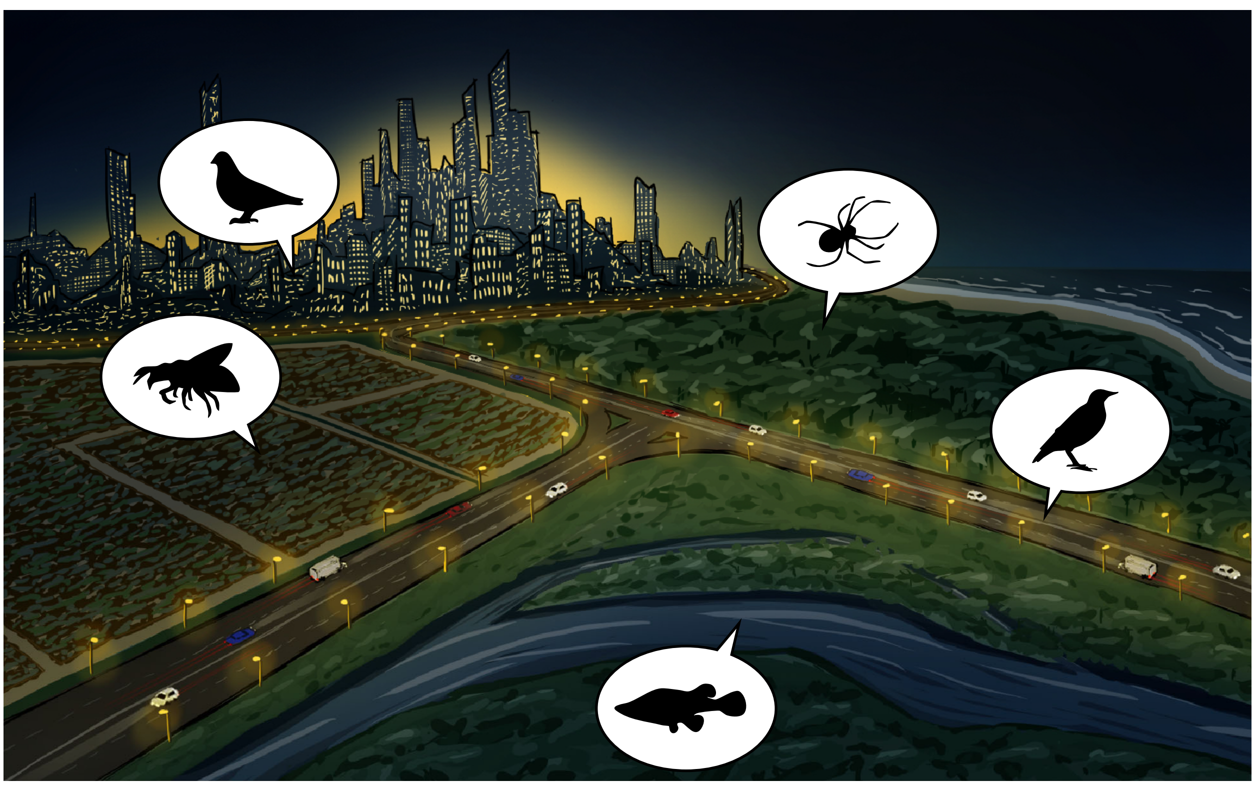

Fig. 1. Modern landscapes and waterscapes present multiple challenges for sleep across a diverse range of animals. Clockwise from the pigeon: (1) Artificial light at night emanates from buildings and street lights, and can be reflected as skyglow from clouds overhead. Light at night disrupts sleep in all avian species examined so far. There is a lack of data on how light at night impacts sleep in non-avian wildlife. (2) Introduced predators, such as the candy-striped spider, hunt sleeping prey and can therefore increase the risks associated with sleeping. (3) Anthropogenic noise, such as traffic noise, can also disrupt sleep. As with artificial light, impacts have been predominantly studied in birds. (4) Psychoactive pollutants, such as fluoxetine, have been shown to augment daytime sleep in fishes, and likely impact other aquatic species. (5) Some insecticides impair sleep in bees. Other challenges undoubtedly remain to be identified. Illustrations by Laura X. Tan.

events. Mitigating these effects for humans and wildlife involves the concerted efforts of individuals, neighbourhoods, businesses and governments. Voting in favour of environmental policies can help, but only when members of government are aware of the problem. Here, scientists turned advocates can draw attention to emerging problems that influence ecosystem health. Those 2.6 million birds killed each year by suction harvesters operating in olive plantations at night are a good example (da Silva and Mata, 2019). Other scientists push the pharmaceutical industry to design drugs that degrade into benign compounds once excreted, to limit the exposure of wildlife to bioactive pollutants (Brodin et al., 2024; Thoré et al., 2024). Others advocate for the conservation of night-time darkness for the benefit of nocturnal animals (Kalinkat et al., 2025). The integrity of night-time sleep in diurnal animals would also benefit from such efforts. To this end, solutions can also begin around the home and neighbourhood. To reduce the impacts of artificial light at night, outdoor lighting should be used only where and when it is needed. Lights should also be dim, red and directed downwards, away from likely locations of sleeping wildlife. Indoor lighting can be kept indoors with curtains drawn in the evening, and lights turned off when not needed. Urban noise can be lessened by supporting quieter forms of transportation: walking, cycling, driving electric cars or using public transportation. Doing so around the clock helps nocturnal animals that sleep by day. Pets can be kept indoors and on leads. By being mindful of our individual effects on sleep in wildlife, we might scale towards larger positive effects as a community to allow wildlife to sleep more soundly.

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