

SYMPOSIUM

Assessing the Vulnerabilities of Vertebrate Species to Light and Noise Pollution: Expert Surveys Illuminate the Impacts on Specialist Species

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From the symposium “SICB-Wide Symposium: Blinded by the light: Effects of light pollution across diverse natural systems” presented at the virtual annual meeting of the Society for Integrative and Comparative Biology, January 3–7, 2021.

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Synopsis Global expansion of lighting and noise pollution alters how animals receive and interpret environmental cues. However, we lack a cross-taxon understanding of how animal traits influence species vulnerability to this growing phenomenon. This knowledge is needed to improve the design and implementation of policies that mitigate or reduce sensory pollutants. We present results from an expert knowledge survey that quantified the relative influence of 21 ecological, anatomical, and physiological traits on the vulnerability of terrestrial vertebrates to elevated levels of anthropogenic lighting and noise. We aimed not only to quantify the importance of threats and the relative influence of traits as viewed by sensory and wildlife experts, but to examine knowledge gaps based on the variation in responses. Identifying traits that had less consensus can guide future research for strengthening ecologists’ and conservation biologists’ understanding of sensory abilities. Our findings, based on 280 responses of expert opinion, highlight the increasing recognition among experts that sensory pollutants are important to consider in management and conservation decisions. Participant responses show mounting threats to species with narrow niches; especially habitat specialists, nocturnal species, and those with the greatest ability to differentiate environmental visual and auditory cues. Our results call attention to the threat specialist species face and provide a generalizable understanding of which species require additional considerations when developing conservation policies and mitigation strategies in a world altered by expanding sensory pollutant footprints. We provide a step-by-step example for translating these results to on-the-ground conservation planning using two species as case studies.

Introduction

All organismal interactions with their environments are mediated by sensory inputs. Two sensory pollutants, anthropogenic light at night and anthropogenic noise, are pervasive, growing, and intensifying (Buxton et al. 2017; Kyba et al. 2017). These fundamentally alter auditory and visual performance on a

global scale for many species (Dominoni et al. 2020). Importantly, these sensory pollutants disrupt environmental cues and ecological processes near their source and extend far beyond the altered landcover (Barber et al. 2010; Kyba et al. 2015b). Approximately 80% of the IUCN’s Global Key Biodiversity Areas experience excess nighttime

luminance (Garrett et al. 2019) and 12% of the IUCN's designated wilderness areas in North America experience anthropogenic noise above natural levels (Buxton et al. 2017).

Numerous studies assessing the impacts of lighting or noise provide examples of altered behaviors, and fitness costs have been documented (Longcore and Rich 2004; Francis and Barber 2013; Gaston et al. 2013). Evaluating these examples from an evolutionary perspective can reveal selective forces arising from novel stimuli (Swaddle et al. 2015; Hopkins et al. 2018) and identify the plausible taxonomic and ecological extents of similar effects. Noise reduces the ability to perceive acoustic signals while lighting affects visual perception. Both can fundamentally alter spatial orientation and create mismatched biological timings (Gaston et al. 2017). These sensory disturbances in turn create a myriad of behavioral alterations, affecting orientation and movement (Slabbekoorn and Bouton 2008; Cabrera-Cruz et al. 2018), communication (Francis and Barber 2013), foraging and hunting efficiency (Bennie et al. 2015; Bunkley and Barber 2015; Mason et al. 2016), altered energy budgets (Read et al. 2014; Touzot et al. 2019), and predation risk (Francis and Barber 2013; Ditmer et al. 2020), along with stress hormone dysregulation (Kleist et al. 2018). Recent research has also shown that variation in these sensory pollutants can better explain patterns of habitat selection than common ecological variables alone, such as landcover (Kleist et al. 2017; Ditmer et al. 2020) and can better reflect the dynamic human footprint relative to other measurements (e.g., housing density; Ditmer et al. 2021a).

Most impacts of these sensory pollutants have been demonstrated with a relatively small number of species at local scales, primarily within North America and Europe. Studies involving terrestrial mammals are especially scarce (Shannon et al. 2016). Biological and ecological traits have frequently been linked with species' vulnerability to environmental change and threat of extinction (Chown 2012; Foden et al. 2013), but with limited treatment in the context of vulnerabilities to anthropogenic lighting and noise (primarily avian species; see Francis 2015; Senzaki et al. 2020). Therefore, for species where scientific studies on the impacts of sensory pollutants are scarce or nonexistent, understanding how relevant traits may be predictive of a species' response to sensory pollution is most practical for developing policies and conservation actions.

Here, synthesizing knowledge from experts around the world, we ranked the degree to which a range of

ecological, anatomical, and physiological traits contribute to a species' vulnerability to lighting and noise. Vulnerability is considered a function of exposure to a threat, sensitivity to the threat, and the corresponding adaptive capacity (McCarthy et al. 2001). Given the lack of published data on the subject across different taxa, we used an expert knowledge elicitation. This method has successfully been used to develop conservation policy (Martin et al. 2012), especially for subjects with incomplete scientific understanding (Foden et al. 2013), emerging threats (Klein et al. 2017), or when resource limitations preclude in-depth studies (Carwardine et al. 2012; Gerber et al. 2018). Our survey did not ask questions regarding exposure to sensory pollutants, because levels may vary greatly within and among species and regions. Instead, we followed the approach by Foden et al. (2013), who incorporated data from expert surveys to quantify the degree to which biological traits—reflecting sensitivity (i.e., the degree to which the survival, persistence, fitness, performance, or regeneration of a species is reliant on the current night light and noise levels or characteristics) and adaptive capacity (i.e., the capacity of the species to persist in situ, shift to suitable microhabitats, or migrate to suitable regions [Dawson et al. 2011])—influenced the threats of climate change. We collected independent responses from numerous experts, identified as sensory or wildlife ecologists with ~3 or more years of study/experience with a vertebrate taxon across multiple geographic and ecological regions. By leveraging the experience and ecological knowledge of these experts, our aim was to identify traits that influence vulnerability to lighting and noise.

In addition to identifying links between traits and sensory vulnerabilities, we highlight traits with high variation in vulnerability ratings and expert ratings that counter emerging scientific literature. Both outcomes reveal knowledge gaps. Recent discoveries often require time and additional supportive studies to achieve broad recognition. Also, experts likely differ in how they estimate vulnerability when they perceive a lack of data. These findings reveal opportunities for future studies that would clarify relationships among traits in and vulnerability to sensory pollutants.

Materials and methods

Survey development and design

Based on the methods of Foden et al. (2013), we designed an online survey (hosted at Qualtrics.com) to assess how and to what degree

select biological traits contribute to anthropogenic light and noise vulnerability. We informed participants that the survey was only considering direct, negative impacts of anthropogenic lighting and noise on adult, terrestrial vertebrates. Traits incorporated into our survey were selected from recommendations developed at a 3-day workshop of experts in sensory ecology and animal physiology, where the effects of sensory pollutants and the mechanisms of disturbance were extensively discussed across a diverse range of taxa (Dominoni et al. 2020).

We selected traits that were associated with increased extinction risk and allowed participants to complete the survey regardless of their primary species or taxa studied. As such, respondents were instructed not to consider idiosyncratic responses, but to focus on traits that are generally linked to increased vulnerability across vertebrate taxa. The survey specifically instructed experts to “please respond as to how the trait would affect vulnerability for most species under most circumstances” and gave an example quote: “I believe activity pattern is a relatively important trait when determining if a species is vulnerable to anthropogenic night light. I believe nocturnal species are the most vulnerable regardless of species.” We provided definitions (and some examples) of each trait considered in the survey (Table 1), and we based our definition of vulnerability (provided to respondents) on the 2001 Assessment Report, in which vulnerability is a function of exposure, sensitivity, and adaptive capacity (McCarthy et al. 2001). We classified traits as either related to ecological, anatomical/physiological sensitivity, or adaptive capacity (Table 1). However, “use of migration” was the only trait classified as adaptive capacity, so we grouped it with the ecological sensitivity traits in the “Results” section.

The survey began with two questions on the importance of anthropogenic light and noise within the systems that the experts study and/or manage. The five response options to these questions ranged from “very important,” “important,” “moderately important,” “slightly important,” and “not important.” The next section elicited responses on specific traits and how each is related to vulnerability from lighting and noise. We asked experts about the impacts of lighting and noise (separately) on the same eight ecological sensitivity traits and “use of migration.” Because physiological and anatomical sensitivity traits were specific to either vision or hearing, we asked experts about the influence of lighting on six traits that were different from the seven traits considering the impacts of noise (Table 1).

We asked experts to provide a numeric value in response to three questions for each combination of sensory pollutant and trait. The first question asked about the importance of the trait and its effect on vulnerability if levels of lighting or noise are elevated. The six possible responses were: “0: no effect,” “1: small,” “2 and 3: medium,” “4 and 5: large.” The second question asked which direction of the trait’s magnitude (“0: no effect,” “1: lowest/smallest/least,” up to “5: highest/greatest/most”), or for some traits, specific categories (e.g., “nocturnal,” “diurnal,” or “no effect”) would increase vulnerability to lighting and noise the most (Table 1 and Figs. 1–4). We then asked experts to assess the level of certainty in their responses (“0: none” up to “5: high”; see Figs. 1–4 for details).

Survey elicitation

We sought participants for our online survey by first seeking experts in the field of sensory ecology using a combination of input from our team of sensory ecologists and a Google Scholar search for authors in the field. When contacting the initial 34 sensory ecology experts, we asked for additional referrals of experts who may be willing to participate and contacted them. We also sought participation from wildlife ecology experts in general by reaching out to 135 authors of International Union for Conservation of Nature reports on North American mammals. Next, we requested participation from a variety of groups and organizations that regularly had contact with species’ experts and popular science-focused email listservs, such as ECOLOG-L, and through snowball sampling in which survey participants recommend the survey to colleagues.

When reaching out we made sure to highlight that participants needed to be considered an expert in sensory ecology or wildlife biology. Within the survey itself, we specifically stated that we were interested in participants that include, “sensory ecologists or those with ~3 or more years of study/experience with a particular vertebrate species/genus/taxon. A Ph.D. candidate studying sea turtle nesting success, a biologist working in Everglades National Park for 10 years, or an assistant professor would all potentially be suitable for this survey.” Respondents reported diverse areas of expertise, including “astrophysicist with experience in animal behavior,” and experience working with a variety of species (primary area of expertise: mammal(s) = 43%; bird(s) = 25%; amphibian(s) = 13%; invertebrate(s) = 8%; reptile(s) = 5%; fish = 5%).

Table 1 Summary of expert survey

Biological trait category	Trait	Definition	Pollutant	Responses (n)
				L = light; N = noise
Ecological sensitivity ^a	Activity pattern	Whether the vertebrate is primarily nocturnal or diurnal.	Both	L = 123; N = 96
	Latitude	Where the vertebrate is primarily located latitudinally. If the animal is migratory, this should be reflected in the trait "use of migration" (see below).	Both	L = 115; N = 96
	Trophic level	Whether the vertebrate is mainly a producer, primary consumer, secondary consumer, or tertiary consumer.	Both	L = 116; N = 96
	Stratum in biosphere	Whether the vertebrate is primarily fossorial, terrestrial, arboreal, or aerial.	Both	L = 109; N = 96
	Vagility	The degree the vertebrate can move throughout its environment due to intrinsic factors.	Both	L = 108; N = 96
	Habitat specialization	The degree the vertebrate specializes both spatially and temporally. For example, requiring certain habitat characteristics during the breeding season.	Both	L = 111; N = 96
	Dietary specialization	The degree the vertebrate's diet is specialized.	Both	L = 109; N = 96
Anatomical/physiological sensitivity	Spectral color resolution	Ability to distinguish between many narrow wavelengths or shades of color. For example, a species able to distinguish teal and blue has greater color resolution compared with a species that perceives teal and blue as the same color.	Light	99
	Ability to see wide range of colors	Ability to perceive different wavelengths. For example, a species able to detect blue, green, and red wavelengths has a greater ability than a species only able to detect blue and green wavelengths.	Light	97
	Ability to see in low light levels	Ability to see when there is very little light.	Light	101
	Dark adaptation speed	The speed at which the vertebrate's eyes adjust to new illumination levels.	Light	100
	Visual-temporal acuity	Ability to distinguish visual events in time, for example the ability to distinguish a steady light from a flickering light.	Light	98
	Visual-spatial acuity	Ability to resolve two points in space. For example, the spatial acuity of humans is measured by optometrists using eye charts with alphabet letters.	Light	96
	Auditory spectral resolution	Ability to distinguish between fine-scale differences in sound. Analogous to "spectral color resolution."	Noise	93
	Auditory bandwidth	Ability to hear a wide range of auditory wavelengths. Analogous to "ability to see wide range of colors."	Noise	94
	Ability to discriminate in noisy environments	Ability to detect and distinguish informative signals from other noises.	Noise	98
	Background noise suppression	Ability to ignore background noises (not habituation to noises over time).	Noise	93
	Absolute hearing thresholds	The lowest sound level an organism can hear and that elicits a response 50% of the time.	Noise	92

(continued)

Table 1 Continued

Biological trait category	Trait	Definition	Pollutant	Responses (n)
				L = light; N = noise
	Temporal resolving power	Ability to distinguish rapid changes in sounds over time. Analogous to “visual–temporal acuity.”	Noise	90
	Spatial resolving power	Ability to resolve the spatial location of a sound. Analogous to “visual–spatial acuity.”	Noise	93
Adaptive capacity ^b	Use of migration	If the animal moves a long-distance from one area to another.	Both	L = 109; N = 96

Attributes include all biological traits that were assessed for their ability to increase vulnerability to anthropogenic night light and noise, the specific sensory pollutant we asked the expert to consider (light, noise, or both) and the trait definition provided to expert within the survey. Experts were asked to assess the traits as they applied to all vertebrate species.

^aSensitivity was defined to experts as the degree to which the survival, persistence, fitness, performance, or regeneration of a species is reliant on current night light and noise levels or characteristics.

^bAdaptive capacity was defined to experts based on the IPCC's 2001 Assessment Report (McCarthy et al. 2001): a combination of strengths, attributes, and resources available to prepare for and undertake actions to reduce and/or moderate adverse impacts and/or to exploit beneficial opportunities. This is the capacity of the species to persist *in situ*, shift to suitable microhabitats, or migrate to suitable regions.

Our survey provided an informed consent document to all participants that reminded the reader that participation was voluntary; it included detailed information on the purpose of the study, names, and contacts of the principal investigators; and project sponsors. Participants were informed that we would make every effort to protect participants' confidentiality and we asked participants to sign and date the informed consent form. The research protocols were approved by Boise State's University Office of Research Compliance (approved IRB#: 193-SB18-068).

Survey data analysis

We calculated the weighted mean and weighted standard deviation of the responses indicating the level of influence on vulnerability to elevated levels of lighting or noise for each trait using the expert's reported level of certainty to weight each metric. We used the package “diagis” (Helske 2018) in program R (R Core Team 2019) to compute the estimates. The functions “weighted_mean” and “weighted_se” use probability weights instead of frequency weights. We constructed 95% confidence intervals by multiplying the weighted standard error by 1.96. The percentage of choices among options describing the direction of the trait's magnitude was also calculated for each trait and sensory pollutant type. Participants were not required to answer all questions and we report the number of responses in the Results section and Table 1.

Results

Nearly half of the experts (48.4%; $n = 280$ responses) considered noise to be “very important” or

“important” in the system each expert studies or manages, while 14.6% of experts considered noise as “not important.” Slightly fewer experts (43.5%) considered (Fig. 5) lighting to be “very important” or “important,” and slightly more (20.0%) considered lighting to be “not important.”

Vulnerability to lighting and noise based on ecological traits

Experts believed that elevated levels of lighting would increase the vulnerability of species that are highly migratory, are more nocturnally active, and are considered specialists when it comes to habitat use (Fig. 1). Beyond these, several traits had similar, and lower, weighted mean survey responses. Although of moderate importance relative to other traits, there was consensus among the experts that dietary specialists have more vulnerability than dietary generalists to lighting and noise (Fig. 1).

Habitat use specialists were considered most vulnerable to increased levels of noise (Fig. 2). Activity pattern, vagility, stratum in the biosphere, and dietary breadth had similar weighted mean responses, but beyond dietary specialization, there was little consensus on the specific directionality or category of these traits (Fig. 2).

Vulnerability to lighting and noise based on anatomical and physiological traits

Respondents largely agreed (74.3%) that species with greater abilities to see in low light, and those with the fastest dark adaption speed (50% of responses) would be relatively more susceptible to light

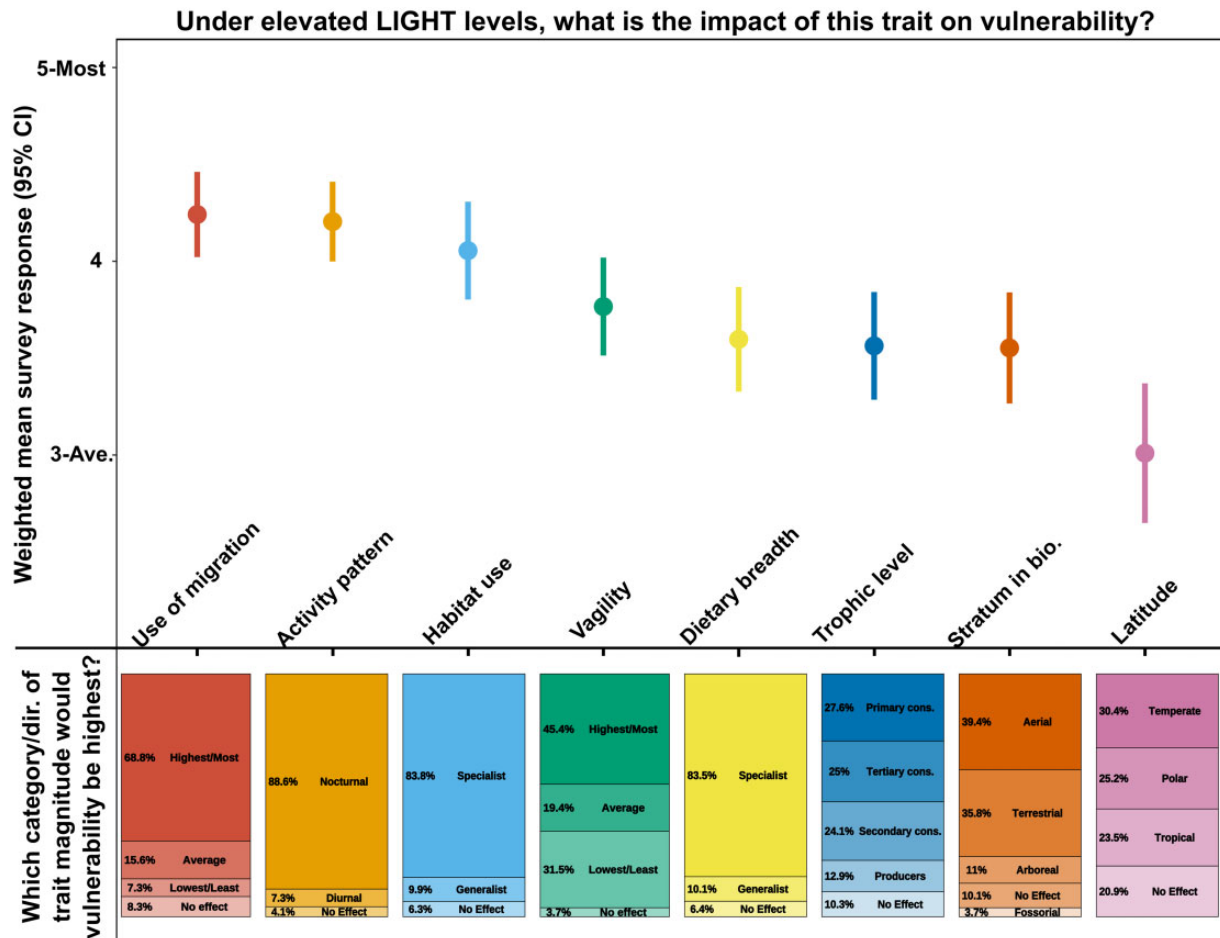


Fig. 1. Results indicating the responses of experts assessing how ecological sensitivity and adaptive capacity traits influenced species' vulnerability to anthropogenic night light, and whether having more/less of the trait, or specific attributes increased the magnitude of vulnerability. The 95% confidence intervals associated with the weighted mean vulnerability for each trait were derived using weighted errors from each respondent's confidence in their answer. Confidence was scored [0–5 scale] as the following: 5 = "I have extensive knowledge of this trait and am very confident in my response," 3 = "I have some knowledge of this trait and am moderately confident in my response," 1 = "I have limited knowledge of this trait and am not confident in my response," and 0 = "none." Darker tones within each traits's magnitude response (bottom stacked bar charts) correspond to higher percentages of selection for a given option.

pollution (Fig. 3). There was little difference among traits with lower weighted mean values but having the ability to see a wide range of colors (40.3% of responses) was considered to increase vulnerability the least (Fig. 3).

When considering elevated levels of noise pollution, auditory spectral resolution and the ability to discriminate wavelengths of sound in noisy environments were considered most likely to increase the vulnerability of species (Fig. 4). For both, experts generally agreed that having the most/highest ability of either trait increased vulnerability the most (68.8% and 73.4%, respectively; Fig. 4). Temporal resolving power had the lowest mean survey response of all traits considered to influence the vulnerability to noise pollution (Fig. 4).

Discussion

We demonstrated that experts recognized the importance of sensory pollutants as ecological stressors in the system they research or manage. Furthermore, the experts considered several traits, especially those related to having a narrow niche breadth (e.g., habitat and diet specialists), or more specialized visual or hearing abilities (e.g., greatest abilities to see in low lights or discriminate signals in noisy environments), to make species more vulnerable to sensory pollution. These traits serve as heuristics when considering disturbances from lighting and noise in developing policies for species that share the same traits. This trait analysis combines with direct studies of sensitivity to noise or light pollution to broaden foundations for assessing species' vulnerabilities, yet

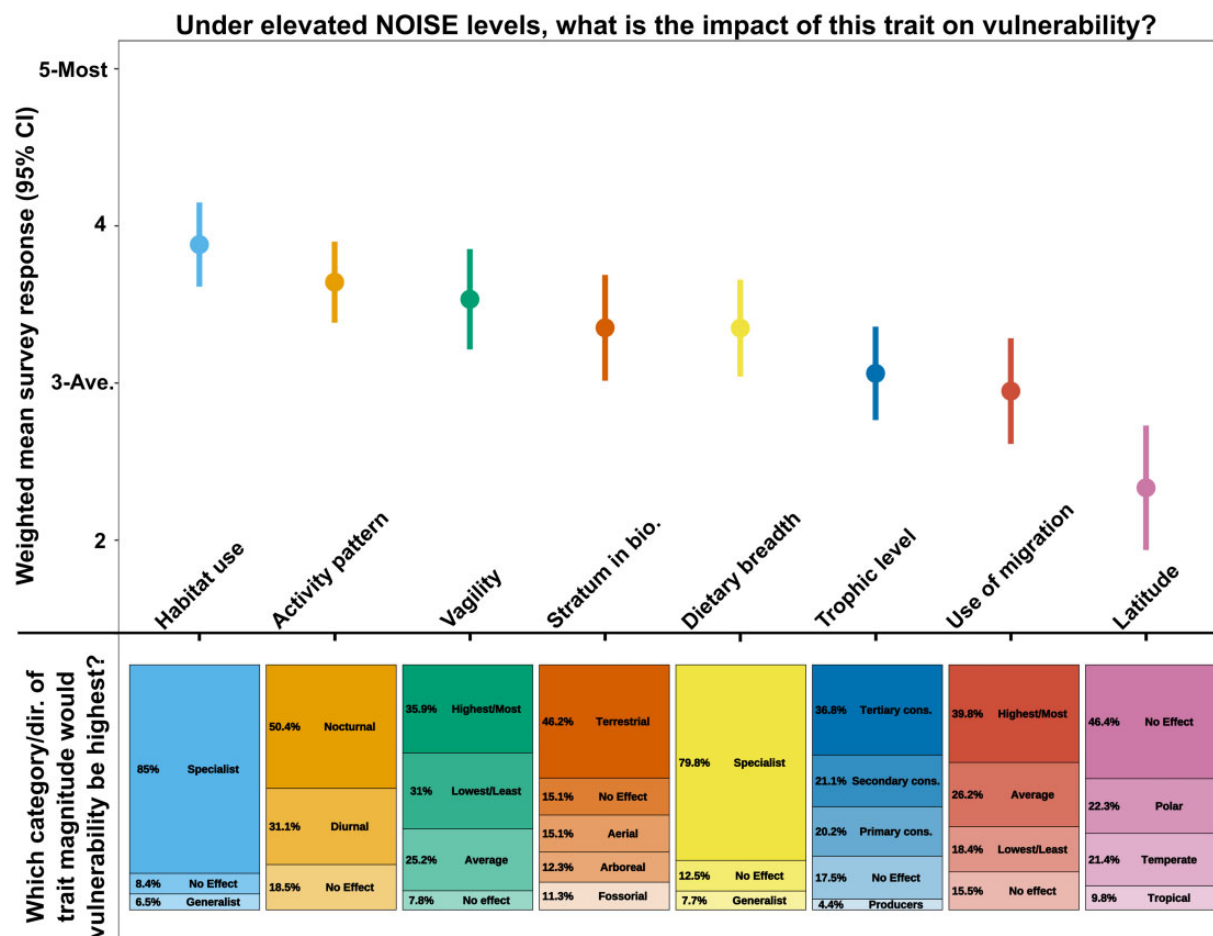


Fig. 2. Results indicating the responses of experts assessing how ecological sensitivity and adaptive capacity traits influenced species' vulnerability to anthropogenic noise, and whether having more/less of the trait, or specific attributes increased the magnitude of vulnerability. The 95% confidence intervals associated with the weighted mean vulnerability for each trait were derived using weighted errors from each respondent's confidence in their answer. Confidence was scored [0–5 scale] as the following: 5 = "I have extensive knowledge of this trait and am very confident in my response," 3 = "I have some knowledge of this trait and am moderately confident in my response," 1 = "I have limited knowledge of this trait and am not confident in my response," and 0 = "none." Darker tones within each traits's magnitude response (bottom stacked bar charts) correspond to higher percentages of selection for a given option.

additional research is needed to produce more accurate predictions of the phylogenetic distribution of hearing and visual abilities for many taxa. These data will be the key to better understanding and predicting sensitivities to these stimuli.

In many ways, expert responses considering the threats from sensory pollutants aligned with assessments of climate change vulnerability (Julliard et al. 2004; Clavel et al. 2011) by emphasizing the sensitivity of species with highly specialized habitat requirements. This analysis, however, expands upon this finding by focusing on the intersection of niche specialization with highly developed sensory function. The logic is simple: sensory degradation may critically depress productivity among habitat specialists. Although noise and lighting have not been

featured in recovery plans for several habitat specialists, such as the spotted owl (*Strix occidentalis*; USFWS 2011) and the black-footed ferret (*Mustela nigripes*; see below and USFWS 2013), our analysis considering the input of hundreds of experts suggests they should be.

Here, we apply the framework of assessing sensory pollutant vulnerability to two endangered species to illustrate why noise and lighting management seems apt for their conservation plans. Gray bats (*Myotis grisescens*) have a nocturnal activity pattern, are habitat specialists (95% of the population roosts in 11 caves), and have eyes adapted to very low light levels. These traits, combined with the responsiveness of their prey to lighting, suggest they will be especially vulnerable to light pollution (Fig. 5). Indeed, this

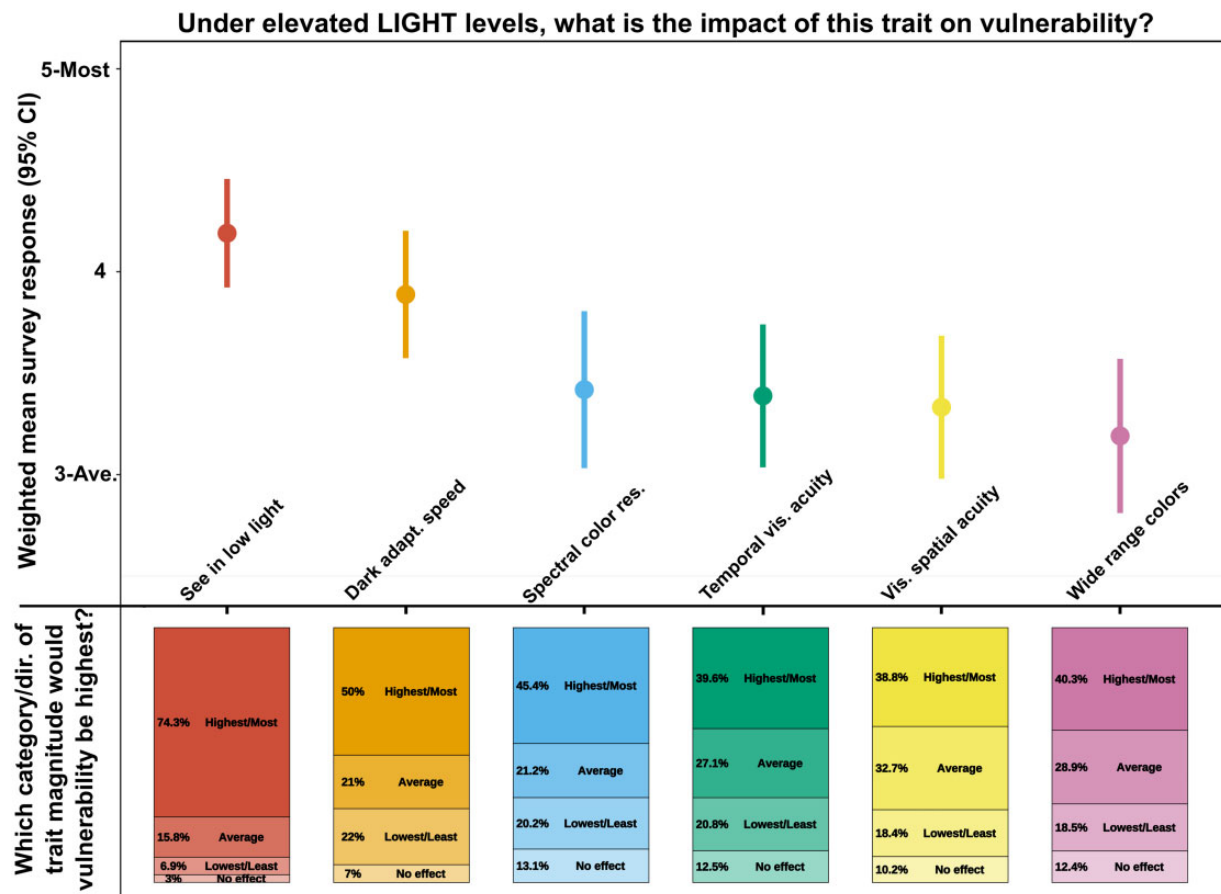


Fig. 3. Results indicating the responses of experts assessing how anatomical and physiological sensitivity traits influenced species' vulnerability to anthropogenic night light, and whether having more/less of the trait, or specific attributes increased the magnitude of vulnerability. The 95% confidence intervals associated with the weighted mean vulnerability for each trait were derived using weighted errors from each respondent's confidence in their answer. Confidence was scored [0–5 scale] as the following: 5 = "I have extensive knowledge of this trait and am very confident in my response," 3 = "I have some knowledge of this trait and am moderately confident in my response," 1 = "I have limited knowledge of this trait and am not confident in my response," and 0 = "none." Darker tones within each traits's magnitude response (bottom stacked bar charts) correspond to higher percentages of selection for a given option.

species avoids areas affected by lighting (Cravens et al. 2018). Reduced light pollution can be realized by decreasing lumen output (or eliminating lights), better control over the spatial extent of lighting, limiting lighting to portions of the spectrum to which the bats and their prey are less sensitive, and limiting the seasonal and diel scheduling of lighting.

The black-footed ferret has extremely specific habitat needs (USFWS 2013), and ferrets have an exceptionally capable hearing on par with humans below 20 kHz, and extending to an upper frequency limit of 40 kHz (Nodal and King 2014). Acute hearing is crucial for hunting in subterranean burrows and for avoiding predation by mesocarnivores above ground. Ferret ultrasonic hearing sensitivity enables them to eavesdrop on many rodent vocalizations that humans cannot hear. The prairie dog towns they require occur in open habitats lacking terrain

shielding or sound attenuation due to vegetation, so noise propagates without obstruction. Noise can be reduced at the source through barriers, muffling, and scheduling of activities (Francis et al. 2011). For both of these endangered species, adaptive management could reduce these pollutants in a controlled experimental framework to quantify the benefits to these species and allow for mitigation methods to iteratively improve over time, while facilitating their adoption across many sites experiencing sensory pollution. See below our description of data sources that provide spatially explicit estimates of sensory pollutants for considering the exposure portion of this framework (Fig. 5). In addition, Ditmer et al. (2021b) quantified exposure and fragmentation of dark sensory environments from light pollution within the geographic ranges of 351 mammal species in the USA.

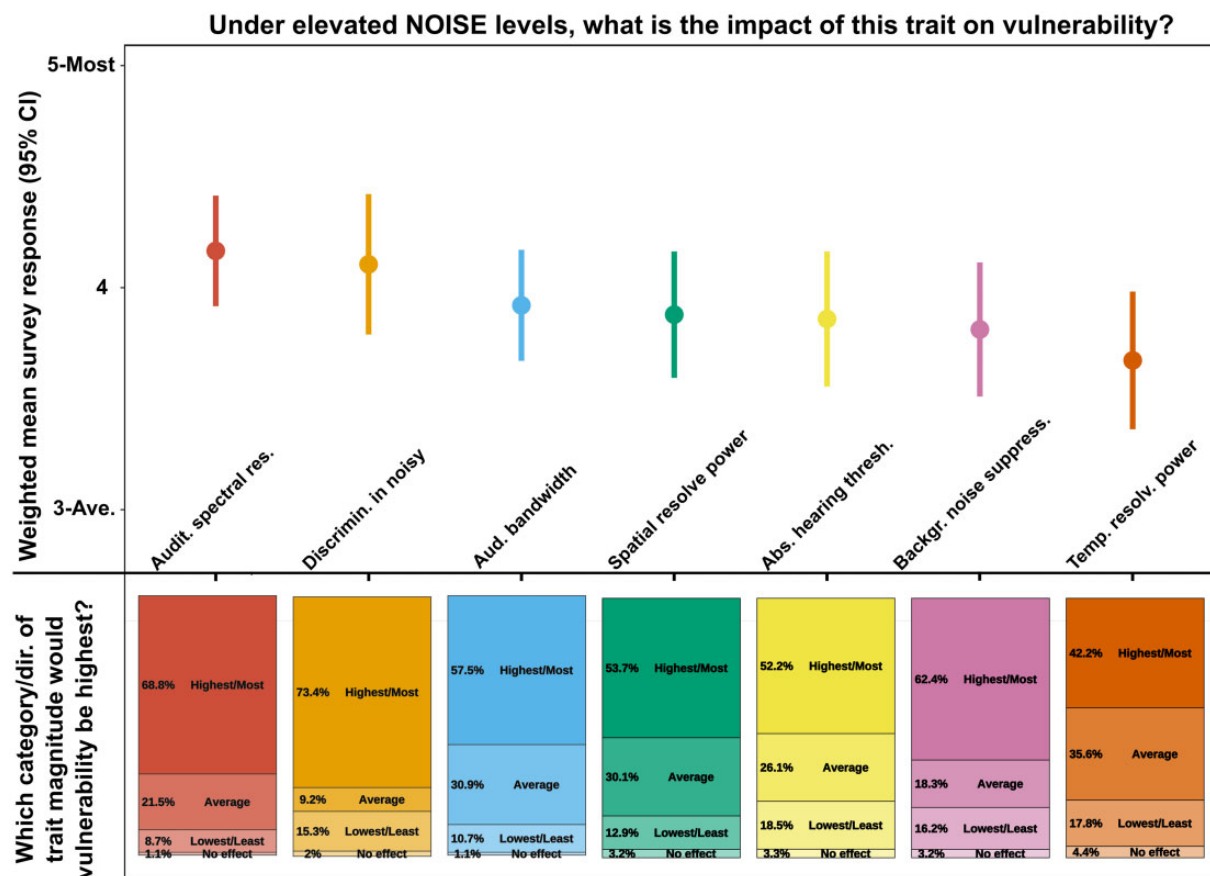


Fig. 4. Results indicating the responses of experts assessing how anatomical and physiological sensitivity traits influenced species' vulnerability to anthropogenic noise, and whether having more/less of the trait, or specific attributes increased the magnitude of vulnerability. The 95% confidence intervals associated with the weighted mean vulnerability for each trait were derived using weighted errors from each respondent's confidence in their answer. Confidence was scored [0–5 scale] as the following: 5 = "I have extensive knowledge of this trait and am very confident in my response," 3 = "I have some knowledge of this trait and am moderately confident in my response," 1 = "I have limited knowledge of this trait and am not confident in my response," and 0 = "none." Darker tones within each traits's magnitude response (bottom stacked bar charts) correspond to higher percentages of selection for a given option.

The aggregate responses of experts suggest that traits indicating highly developed sensory function—sensitivity to lower stimulus levels, better spectral resolution, better capacity to hear in noise or rapidly dark adapt after exposure to light—were generally regarded as indications that degraded sensory conditions would be more problematic. For the latter two traits, varied responses likely arose because some experts interpreted these traits as evolutionary evidence for heightened dependence on these senses, while others regarded these traits as evidence of better capacity to tolerate noise and lighting. Another grouping of responses exhibits a similar divergence of responses. Stratum in the biosphere, vagility, and migration can be assessed from two perspectives. More vagile species may have more options to get away from adverse sensory conditions, mitigating the effects of these pollutants. Alternatively, more vagile

species may be more heavily dependent upon sensory function for orientation, navigation, and surveillance in habitats where they have no recent experience. In the latter view, more philopatric species can use cognitive maps and recent familiarity with habitat conditions to offset some loss of sensory function. A dramatic demonstration of this latter perspective is the fatal, disorienting effects of light for highly migratory species (Van Doren et al. 2017; McLaren et al. 2018).

Diel activity patterns emerged as the second most emphasized ecological factor affecting sensitivity to noise and light (Figs. 1 and 2). The general consensus among experts points to sensitivity among nocturnal species that alter behavior in response to variation in artificial and natural light levels (Prugh and Golden 2014; Willems et al. 2021), plus nocturnal acoustic specialists that respond negatively to

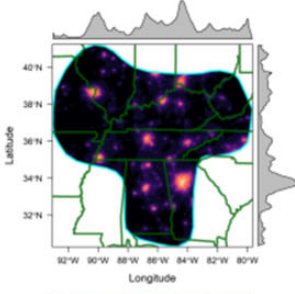
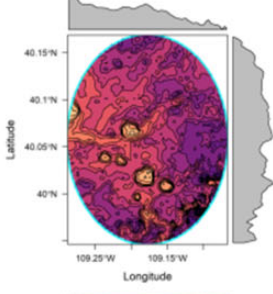
	Species	<i>Myotis grisescens</i> (gray bat)	<i>Mustela nigripes</i> (black-footed ferret)
			
Vulnerability to night light and noise	Sensory pollutant of concern	Light	Noise
	Sensitivity (based on expert survey)	↑ Nocturnal activity pattern ↑ Habitat specialist ↑ High ability to see in low light	↑ Auditory specialist ↑ Habitat specialist ↑ Dietary specialist
	Adaptive capacity (down is more adaptive/ less vulnerable)	↓ Aerial ↑ Specific structures required for roosting	↑ Very limited: human barriers & specific habitat needs
	Exposure (based on publicly avail. data)	 Skyglow in the southeastern U.S.	 Anthropogenic noise in Utah range
		Federally (U.S.) listed as Endangered & considered "Vulnerable" by the IUCN (*recent conservation efforts have increased the population) Reduce sources of art. light near hibernaculum and roosts Reduce luminance near roadways (billboards) or other sources of mortality (wind farms)	Federally (U.S.) listed as Endangered & considered "Endangered" by the IUCN Sensitive to noise for communication & predator avoidance Determine if and where expanding energy development and associated traffic noise overlap remaining range

Fig. 5 Applying expert survey to developing vulnerability risk assessments and potential future research and/or management actions. Here, we selected two species of conservation concern to demonstrate how the results of our survey can be used to assess the overall vulnerability of a species to sensory pollutants. We used the entire species' range of the gray bat in the southeastern USA and mapped the exposure based on estimates of nighttime skyglow (all-sky light pollution ratio) developed by [Duriscoe et al. \(2018\)](#). For the black-footed ferret, we highlighted the species range in Utah only and mapped the estimated nighttime (ferrets are nocturnal) anthropogenic noise (L_{50} ; anthropogenic nighttime A-weighted decibels [dB] of sound levels that exceed the value 50% of the measurement period) as developed by [Mennitt and Frstrup \(2016\)](#). Histograms show the mean values of each sensory pollutant across longitude and latitude.

noise exposure (Senzaki *et al.* 2016). Although the expert concordance was relatively high, it is possible that this general consensus may reflect sparse evidence among diurnal species, rather than an absence of effects. The impacts of light pollution on species are not always easily observable (Gaston and Bennie 2014), and more studies are finding deleterious influences of artificial light on diurnal (Sanders *et al.* 2021) and urban species that otherwise thrive in heavily built environments (Berger *et al.* 2020). Although studies of sensory function during sleep in wildlife are sparse, new studies suggest exposure to sensory pollutants play an important role in sleep because hearing is a crucial alerting function during sleep and light exposure appears to influence multiple physiological systems. Light disrupts the intensity, continuity, and length of sleep in birds (Aulsebrook *et al.* 2020a, 2020b) and noise appears to fragment and degrade sleep in birds much as it does in humans (Connelly *et al.* 2020; Grunst *et al.* 2021). Thus, additional work is necessary to understand whether the costs of noise and light exposure are greater for nocturnal or diurnal species.

Notably, some of the expert responses differed from our expectations based on empirical studies. For example, we expected latitude to be considered an important trait for vulnerability to lighting (Fig. 3). In contrast to populations at higher and lower latitudes, tropical populations have very consistent light cycles throughout the year, but changes in light radiance levels at twilight or loss of night could lead to misalignments in diel activity patterns within communities. In contrast, resident populations at high latitudes confront very long periods of night. When exposed to artificial light, the duration may be substantial. Tropical and temperate populations may also differ strongly in their responses to lighting depending on the degree to which variation in light regimes is a phenological cue. Many, but not all, temperate bird species appear to strongly advance their breeding season in response to lighting (Kempnaers *et al.* 2010; Senzaki *et al.* 2020). For hearing, low absolute hearing thresholds would seem to be a prerequisite for elevated noise sensitivity. Some hearing experts might reasonably counter that the critical ratios are the more important feature, but we were surprised by the lesser emphasis placed on this measure of auditory performance in our survey.

Although most biological traits may change relatively slowly, lighting and noise are far less static, and may change dramatically within a population's or a species' range over the course of a single generation (Kyba *et al.* 2017). Exposure is one of the

three key components of vulnerability (Dawson *et al.* 2011). Geospatial models of skyglow have been developed (Falchi *et al.* 2016; Duriscoe *et al.* 2018), and Longcore *et al.* (2018) created an approach to predict species' responses to spectral outputs based on behavioral and visual characteristics. Spatially explicit estimates of anthropogenic noise for the USA were developed by Mennitt and Fristrup (2016) and have been successfully applied to explaining how noise influences variation in avian reproductive success across North America (Senzaki *et al.* 2020). However, these geospatial models confront emerging challenges. The day–night band product from NASA's VIIRS system cannot detect photons with wavelengths shorter than 500 nm. LED lamps that are rapidly proliferating through lighting upgrades have a prominent spectral peak at 470 nm, so global predictions of sky glow will require recalibration, and minimum estimates (Kyba *et al.* 2015a). The geospatial sound map was a composite created from 10 years of measurements. More extensive monitoring and more sophisticated analyses will be required to produce the capacity to measure or predict trends.

Our study draws upon methods previously used to assess the vulnerability of species to other anthropogenic changes, including climate change (Foden *et al.* 2013). A limitation of this approach is that expert responses may be subjective, particularly if there is a paucity of research. However, this limitation, along with the following potential drawbacks of our approach, also provides crucial insights for future research directions. First, we only considered negative impacts from lighting and noise. However, future work should consider all effects, such as increased foraging opportunities for crepuscular species exposed to lighting (Santos *et al.* 2010) and enhanced ability to track resource peaks which are increasingly shifted temporally due to climate change (Senzaki *et al.* 2020). We also did not assess the impacts on invertebrates, an important group of animals that contributes a large percentage to many vertebrate diets, that are highly sensitive to changes in environmental cues (van Klink *et al.* 2020; Owens *et al.* 2020), although 8% of respondents identified as experts of invertebrate species. In addition, our rankings only provide relative estimates of vulnerability. Combining these rankings with empirical measures of species response to sensory pollutants, such as reductions in survival, would mark an important advancement.

Despite the heightened understanding of the impacts that lighting and noise can pose to species, few conservation plans account for the expanding

sensory footprint of the Anthropocene. Our survey demonstrated an increasing awareness that integrating sensory ecology is critical to conservation science (Dominoni et al. 2020). Our findings highlight some disagreement among ecological experts regarding the vulnerability of certain traits and responses that differ from the quickly growing body of scientific literature on sensory pollution (Jerem and Mathews 2021; Sanders et al. 2021). As such, disseminating information on the impacts of sensory pollutants to wildlife managers should be a point of emphasis to direct future research on questions surrounding these traits and to improve species' conservation and management. Our study offers a generalized foundation for evaluating the ecological consequences of noise and lighting. It provides justification for management actions today. Although we understand enough to act now, and some governmental agencies are beginning to recognize the threats to wildlife from sensory pollutants and provide practical management solutions (see Mayer-Pinto et al. [2020] for Australia), further studies are needed to determine the most economical and effective options to reduce sensory pollution at large enough scales to reduce harm to wildlife populations and ecosystem functions.

Data availability

The data underlying this article can be made available via request to the corresponding author.

Acknowledgments

We thank K. Markham for assisting in developing and soliciting the survey.

Funding

This work was supported by the NASA Ecological Forecasting grant NNX17AG36G.

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