



## Review

## Acoustic environments matter: Synergistic benefits to humans and ecological communities



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## ABSTRACT

Protected areas are critical locations worldwide for biodiversity preservation and offer important opportunities for increasingly urbanized humans to experience nature. However, biodiversity preservation and visitor access are often at odds and creative solutions are needed to safeguard protected area natural resources in the face of high visitor use. Managing human impacts to natural soundscapes could serve as a powerful tool for resolving these conflicting objectives. Here, we review emerging research that demonstrates that the acoustic environment is critical to wildlife and that sounds shape the quality of nature-based experiences for humans. Human-made noise is known to affect animal behavior, distributions and reproductive success, and the organization of ecological communities. Additionally, new research suggests that interactions with nature, including natural sounds, confer benefits to human welfare termed psychological ecosystem services. In areas influenced by noise, elevated human-made noise not only limits the variety and abundance of organisms accessible to outdoor recreationists, but also impairs their capacity to perceive the wildlife that remains. Thus soundscape changes can degrade, and potentially limit the benefits derived from experiences with nature via indirect and direct mechanisms. We discuss the effects of noise on wildlife and visitors through the concept of listening area and demonstrate how the perceptual worlds of both birds and humans are reduced by noise. Finally, we discuss how management of soundscapes in protected areas may be an innovative solution to safeguarding both and recommend several key questions and research directions to stimulate new research.

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## 1. Introduction

The total area of protected lands worldwide has more than doubled in the last three decades and designated terrestrial protected areas now cover 18.4 million km<sup>2</sup> or 12.5% of the earth's land surface (Watson et al., 2014). The world's protected areas receive approximately 8 billion visits by people per year, 3.3 billion of which are in North America alone (Balmford et al., 2015). In the United States, the National Park Service (NPS) manages a little more than 10% of all protected areas and NPS's keystone parks present the most salient examples of tensions between protecting wildlife and providing for visitor enjoyment (Borrie et al., 2002). The Organic Act of 1916 (PL 39 Stat. 535) gives the NPS its mission, '... which purpose is to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations'. Protected areas are caught in a "park paradox" that reflects the negative covariance between visitor use and biodiversity (Runte, 1977).

Higher levels of visitor use and associated access are likely to lead to greater habitat degradation (Fahrig and Rytwinski, 2009) and it is clear that visitor transportation corridors in protected areas impose significant ecological costs (Benítez-López et al., 2010). Roadways are a dominant human footprint on earth and are rapidly expanding. Over 25 million kilometers of new roads are anticipated by 2050, a value 60% greater than the estimated 'roadprint' in 2010 (Laurance et al., 2014). Protected areas are not immune from new roads (Theobald et al., 2010; Theobald, 2010). Furthermore, use of protected areas is likely to continue, thus increasing associated impacts to the social and ecological conditions (Manning et al., 2014).

Noise from roadways and other sources is an important mediator of ecological costs (Fahrig and Rytwinski, 2009; Francis and Barber, 2013). In fact, recent evidence shows that broadcasting traffic noise in otherwise quiet habitats can experimentally induce many of the ecological effects of roads on wildlife and degrade habitat quality (McClure et al., 2013, 2016; Ware et al., 2015). Anthropogenic noise from other sources (e.g., energy sector noise – Bayne et al., 2008; Francis et al., 2009; talking visitors – Pilcher et al., 2009; Karp and Guevara, 2011; sonar and other sounds from military activities, Hatch and Fristrup, 2009) is an increasingly recognized cost of human activities; a cost imposed on both visitors (Newman et al., 2010b) and biodiversity in protected areas (Hatch and Fristrup, 2009). The potential for its influence is so great that the NPS created a new program – the Division of Natural Sounds and Night Skies – devoted to conserving the sounds of nature (Newman et al., 2013). These acoustic resources are monitored, managed and protected by mandate (Newman et al., 2013). Despite protection, NPS monitoring and modeling has shown that noise is a pervasive issue across the system (Buxton et al., 2017), yet it

remains unclear how noise management integrates with or contributes to efforts to conserve critical habitats. Perhaps most importantly for conservation, it is unknown to what degree biological and ecological responses to altered acoustic conditions feedback on human experiences, and thus conservation ethic and action among citizens who visit and ultimately support the parks.

In this paper, we review literature across several disciplines that, collectively, point to the conclusion that management of acoustic resources both within and outside of protected areas is essential and that natural acoustic conditions should be thought of as a vital "ecosystem service." Additionally, thorough understanding of acoustic resources through coupled human-nature relationships will enlighten management of protected area acoustic environments. We begin by reviewing the concept of a soundscape and explain how and why natural sounds are both ecologically critical and key to human experiences in natural settings. We then provide an overview of the relevance of rising anthropogenic noise levels by describing its global reach and introduce the concept of listening area and its relevance to the effects of noise on human wellbeing and ecological systems. Finally, we conclude with a conceptual framework explaining how soundscape modification via human activities should be considered alongside other well-recognized threats to biodiversity and human wellbeing, such as climate change and chemical pollution and emphasize how soundscapes are a key element that couples human experience and ecological systems through psychological ecosystem services and individual and collective human behavior relevant to conservation.

## 2. Soundscapes and the role of natural sounds

Soundscapes have been defined two ways. We prefer soundscape as a perceptual construct, following the Soundscape Working Group of the International Standards Organization and recent NPS policy: the acoustic environment as perceived by a receiver (i.e., a listener), and usually a person (ISO 12913-1:2014). Previous NPS policy and Farina (2014) define soundscape as encompassing all physical acoustic phenomena. Terminological ambiguity aside, the term soundscape underscores the substantial role that sounds play in linking human and natural systems. Terrestrial soundscapes have always included sounds from wind, moving water and other abiotic sources. Familiar biological sources, such as singing birds and chorusing frogs and insects have characterized terrestrial environments since the Early Eocene, i.e., >50 million years before present (Gill, 2007; Senter, 2008). Since industrialization, however, many landscapes are increasingly characterized by anthropogenic sounds (Barber et al., 2010; Buxton et al., 2017) and copious evidence suggests that these changing soundscapes can profoundly affect human wellbeing and ecological systems.

## 2.1. Natural systems

Sounds with biological origins serve myriad functions in the lives of distantly related animals. These sounds include signals, which are intentionally emitted and serve to influence the behavior of other individuals, and cues, which include sounds emitted by individuals that are both intentional and unintentional and are used by receivers in a variety of contexts. Intentional signals include those produced for mate attraction, to maintain group cohesion or to inform others of threats. Cues, on the other hand, can be used by unintended receivers for functions spanning spatial navigation to predator and prey detection (Francis and Barber, 2013). For example, Cope's gray tree frog (*Hyla chrysoscelis*) uses conspecific choruses as cues to find new breeding areas over hundreds of meters (Buxton et al., 2015) and gleaning bats use the inadvertent rustling sounds made by moving insects as cues to localize and catch prey (Goerlitz et al., 2008). In marine environments, fish larvae use sounds made by reef crustaceans and fish as cues to locate and settle on favorable reef environments (Simpson et al., 2005).

Although the vast majority of animals use biotic sounds, abiotic sounds from moving water, wind and other sources have the potential to influence ecological systems. Most well known is the influence of abiotic sounds on animal activity patterns. For example, increased sound levels from wind cause king penguins (*Aptenodytes patagonicus*) to increase call rate (Lengagne et al., 1999) and chaffinches (*Fringilla coelebs*) sing songs of longer duration near cascades (Brumm and Slater, 2006), both representing behavioral adjustments that could improve communication in noisy environments. These behavioral responses to abiotic sounds are not limited to communication among conspecifics; laboratory work suggests that gleaning bats experience reduced foraging success when hunting during playback of sounds from wind-blown vegetation (Schaub et al., 2008). Still unclear is to what degree these abiotic sounds function as acoustic beacons for animal navigation and whether they influence the distribution of individual species and the assemblage of ecological communities.

## 2.2. Humans

A long history of research regarding protected area use demonstrates that humans interact with the environment to satisfy certain needs (Driver and Tocher, 1970). When met, these needs can be described as benefits and can be organized into different categories, among them, psychological and physiological benefits (Manning, 2010; Sandifer et al., 2015). Humans rank experiencing natural sounds as a key motivation for visiting natural areas (Haas and Wakefield, 1998; Marin et al., 2011), and experiencing biotic and abiotic natural sounds improves the perceived quality of nature-based experiences (Newman et al., 2013) by adding to overall satisfaction (Marin et al., 2011; Newman et al., 2012; Pilcher et al., 2009), enhancing perceptions of natural landscapes (Weinzimmer et al., 2014), mood (Benfield et al., 2014) and cognitive function (Abbott et al., 2016). Finally, emerging research demonstrates the physiological changes linked to the well-documented psychological benefits of natural landscapes and soundscapes. For example, although the role of hearing in relation to other sensory modalities was not separated, Bratman et al. (2015) demonstrated that, relative to participants who experienced a 90-min walk in an urban environment, participants who walked for 90-min in a natural environment not only reported lower levels of rumination (repetitive negative thoughts about self), but also had reduced brain activity in areas where elevated activity is linked to mental illness.

In contrast to the demonstrated benefits of experiences with

nature and natural sounds, there are costs associated with degraded opportunities to experience natural sounds and quiet (Newman et al., 2010b), such as aesthetic degradation (Weinzimmer et al., 2014), decreases in cognitive restoration (Abbott et al., 2016; Wilson et al., 2016), memory (Benfield et al., 2010), and mood states (Benfield et al., 2014). Given the costs associated with noise, it is not surprising that people will pay for the benefits of quiet or to hear natural sounds. This has been shown in consumer behavior related to housing and distance to parks (Crompton, 2005), for property costs related to noise levels, even when controlling for other factors (Łowicki and Piotrowska, 2015), and in the deliberate construction of nature and water sounds to enhance urban settings (Jeon et al., 2010).

Two theories articulate the psychological and physiological basis of improved human wellbeing with experiences in nature: attention restoration (Kaplan and Kaplan, 1989) and stress recovery (Ulrich, 1993; Ulrich et al., 1991). Importantly, many studies demonstrate support for both theories, which collectively can be considered the restorative effects of nature (Hartig et al., 1991). A large body of research within the framework of attention restoration theory supports the notion that the natural world and biodiversity can facilitate the recovery of cognitive function following mental fatigue (reviewed in Bratman et al., 2012). For example, Ratcliffe et al. (2013) found that birdsong led to self-reports of both stress recovery and attention restoration. Another recent laboratory-based study found that study subjects who were recuperating from mental fatigue and received a natural sound condition containing birdsong cognitively outperformed those that received no sound or control condition, suggesting that natural sounds can potentially facilitate attention restoration (Abbott et al., 2016).

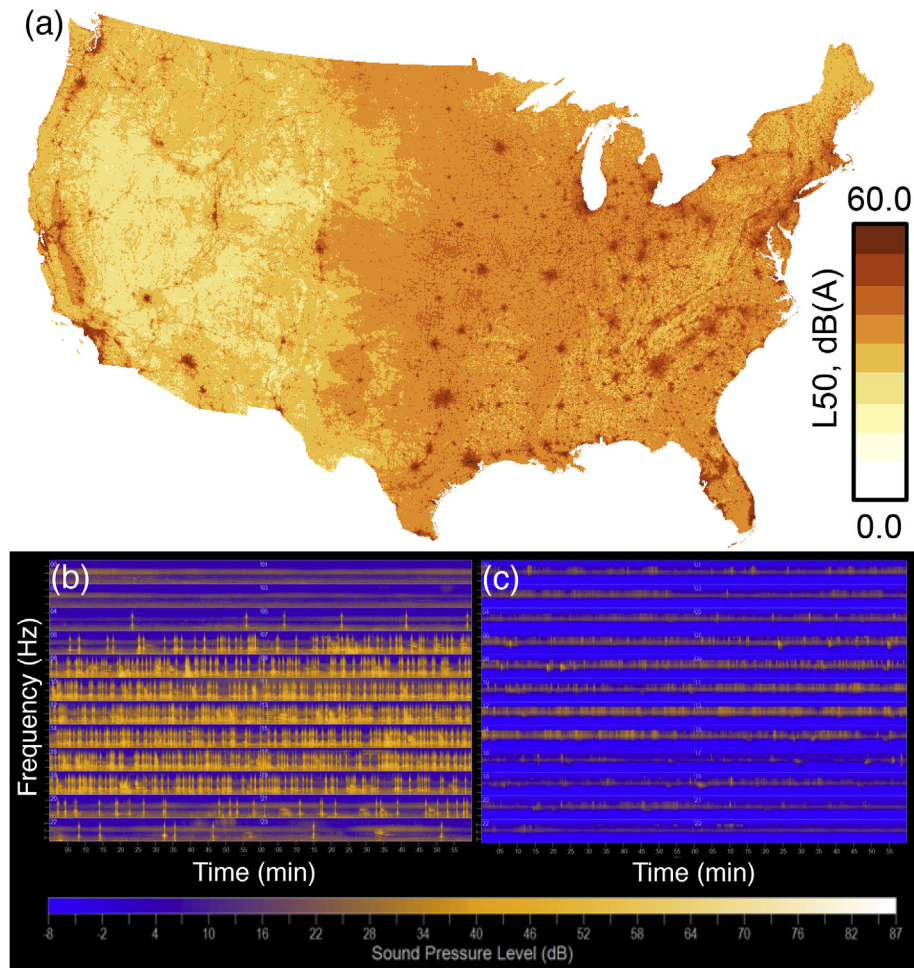
Interactions with natural environments can also improve recovery from stressful events (Bratman et al., 2012; Ratcliffe et al., 2013; Ulrich et al., 1991). Additional studies have found that natural sounds, such as morning bird choruses, are linked to feelings of safety and security. Katcher and Wilkins (1993) found support for the concept that humans attend to the “form and motion patterns that signal danger and security”. In other words, the presence of birdsong may represent an ordered world without danger (i.e., the birds are not disturbed) and trigger emotions related to safety, thus perhaps allowing subconscious reductions in stress-related behaviors and recovery from more stressful settings.

Collectively, how and why soundscapes influence human wellbeing falls squarely within the framework of ecosystem services (Millennium Ecosystem Assessment, 2005; Sandifer et al., 2015) and, more specifically, a recently proposed category of benefits afforded to humans by nature called psychological ecosystem services (Bratman et al., 2012). Despite recent improvements in the economic valuation of inputs and outputs of ecosystems, such as through carbon markets (Hamilton et al., 2007), the same valuation has not been widely applied to psychological ecosystem services (Milcu et al., 2013). However, psychological ecosystem services are likely among the most important benefits afforded to people by nature in terms of broad scale support for conservation. Humans often base decisions on their emotional state (Larson et al., 2016; Loewenstein and Lerner, 2003; Wieczorek Hudenko, 2012), thus psychological ecosystem services provided by individual and aggregate experiences in nature are highly relevant to public support for conservation actions.

## 3. Human-influenced soundscapes

The influence of anthropogenic noise is global – soundscapes throughout the world are influenced by anthropogenic sounds that create, evolutionarily speaking, novel acoustic conditions (Swaddle et al., 2015). Over 80% of the contiguous United States experiences





**Fig. 1.** Anthropogenic noise is widespread. (a) Estimated sound levels (L50 SPL, dB(A) re 20  $\mu$ Pa) caused by anthropogenic noise across the contiguous United States (Mennitt et al., 2013). (b and c) Twenty-four hour spectrograms display sound levels in Grand Teton National Park on 30 September 2013 (b) and 05 October 2013 (c). Lighter colors reflect higher sound levels. Differences between (b) and (c) can be attributed to visitor access in (b), whereas the park was closed when (c) was recorded due to a government shutdown. The limited acoustic energy observed in (c) is due to wind. Frequency, spanning 12–20,000 Hz, is represented on the y-axis and time (min) on the x-axis. Each of the 12 horizontal panels represents a 2-h block of time.

elevated sound levels (Mennitt et al., 2013, Fig. 1) and 65% of European citizens experience background sound levels exceeding 55 dB A-weighting [dB(A)] (Chepesiuk, 2005), which is a level known to degrade habitat quality for many species (Francis et al., 2009; McClure et al., 2013; reviewed in Shannon et al., 2015; Ware et al., 2015). Moreover, noise from human activities is pervasive across US protected areas (Buxton et al., 2017). Noise degrades the quality of interactions between humans and wildlife in many ways. Many animals tend to decline in abundance in response to noise or avoid noisy areas altogether (Bayne et al., 2008; Francis, 2015; McClure et al., 2013) and numerous behavioral changes in response to noise have also been documented, such as altered vocal, foraging and movement behavior (reviewed in Francis and Barber, 2013; Shannon et al., 2015), which are also relevant to visitors' abilities to experience wildlife. Importantly, the majority of visitor activity in many US parks is concentrated within several hundred meters of roads, and therefore occurring in some of the noisiest areas (Monz et al., 2016; Newman et al., 2010a; Park et al., 2010). Thus, opportunities to see and hear wildlife are likely reduced for most visitors simply due to common responses of animals to the sounds we produce. Still, visitors' abilities to experience wildlife that remain in noisy areas may be further compromised due to the masking effects of noise and its ability to distract. That is, visitors may not hear the sounds of remaining

animals through the background noise or be too distracted by human sounds to recognize acoustic or visual cues of an animal's presence. We elaborate on these issues below, but first introduce a concept key to wildlife responses and human's impaired ability to experience wildlife – listening area.

### 3.1. Listening area

Assuming that a sound is within an organism's hearing range (i.e., frequencies audible to an organism), the ability to detect, discriminate and recognize a signal from a noisy background becomes the limiting factor. When other sounds interfere with the perception of a sound, masking occurs. Masking is important for humans and other animals as it limits the ability to receive information acoustically (Barber et al., 2010; Francis and Barber, 2013).

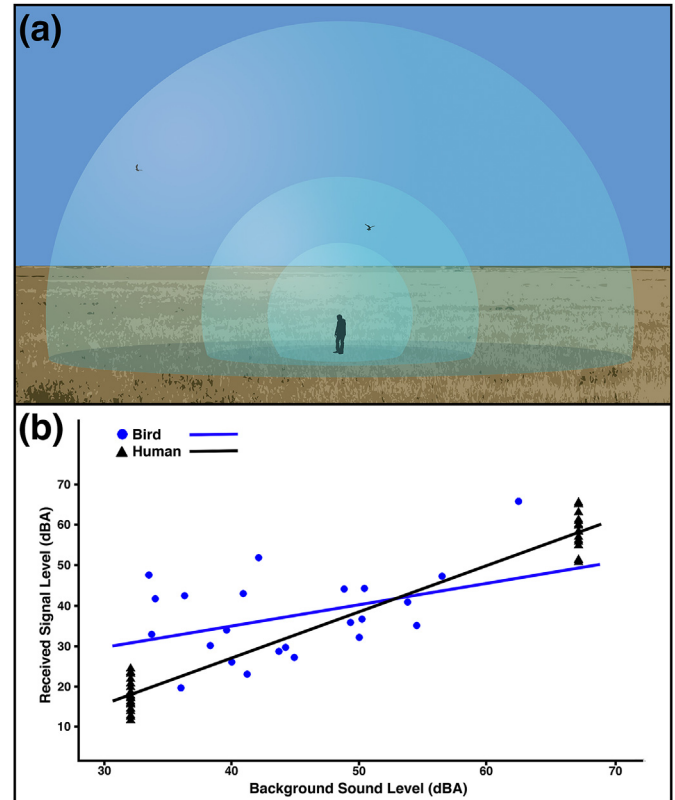
Decades of research in animal communication have focused on the active space of vocalizations, or the distance that a vocalization travels (Lohret et al., 2003). Listening area is a parallel construct to the active space of a vocalization, with a listener replacing the signaler as the focus (Box 1; Barber et al., 2010). Sounds within an animal's listening area can be heard, whereas sounds outside of an animal's listening area will be too diminished by spreading and other propagation losses to be detected. Listening area therefore defines the region within which an organism perceives the

**Box 1****Percent Listening Area: Theory and Practice.**

Maintaining a high signal-to-noise ratio is crucial for passive and active listening. Increasing background sound levels can dramatically reduce the size of an individual's listening area when noise elevates an already masked hearing threshold for a sound that is in the same frequency band. Listening area is the area of a circle whose radius is the alerting distance, the distance at which an individual is first able to detect a sound (Barber et al., 2010; Lynch et al., 2011). This model of hearing predicts that for each 3-dB increase in background sound level there is a 50% loss of listening area (Theory curve;  $k = 10^{-N/10}$ , where  $k$  is the fraction of original listening area and  $N$  is the increase in background dB; see Barber et al., 2010; Buxton et al., 2017 for details; Fig. 2a). With the exception of nocturnal avian predators, humans can hear approximately twice as far as birds (reviewed in Dooling and Popper, 2007). This halving of listening area is thought to be largely due to anatomical differences in the avian ear when compared to the mammalian ear, such as reduced and/or fused auditory structures (Dooling and Popper, 2007). The difference in critical ratio (how much higher the signal level must be above the noise to be detected) of approximately 6 dB between humans and birds has been documented across a range of frequencies in the lab (1–5 kHz; Dooling and Popper, 2007). Critical ratios are measured by determining an animal's threshold for detecting tones in noise that is limited to the critical band, a paradigm derived from the spectral width of auditory filters in the cochlea (Dooling and Popper, 2007; Moore, 2012). Biological sounds, unlike pure tones, concentrate energy across auditory filters in a bird's peripheral and central auditory system (Klump, 1996) and the consequences for hearing in nature, where background noise spans multiple critical bands, is essentially unstudied (but see laboratory-based studies Lohret et al., 2003; Vélez et al., 2015).

In an original field-based playback experiment, we tested the abilities of wild Brewer's sparrows (*Spizella breweri*) and human participants to detect Brewer's sparrow song in background noise. As listening area declines with increased noise levels, received levels of birdsong must be louder for both Brewer's sparrow and human detection (See supplement; Fig. 2b). However, these preliminary data reveal interesting differences between hearing in noise between birds and humans, plus differences in the observed relationship between background sound level and detected received levels and the relationship expected from theory. These insights underscore two key points: 1) it is essential that we develop methods to quantify hearing of relevant signals and cues in natural acoustic environments, an even more difficult task for wildlife compared to querying a human listener, as 2) revealing the mechanisms driving behavioral responses to noise are key for understanding ecological patterns and predicting responses of unstudied communities to noise exposure. There is much to learn about hearing in complex acoustic environments and potentially important differences between signal detection, signal discrimination and the extraction of higher-level information (e.g., Templeton et al., 2005; Henry and Lucas, 2010) from sounds in the environment (*sensu* Lohret et al., 2003). The roles of masking release mechanisms are also poorly understood, again, particularly in the field.

Several strategies have the potential to increase signal detection or discrimination in noisy conditions, such as changing head position/head scans (Yorzinski and Hermann, 2016), changing receiver height (Polak, 2014), listening in quiet gaps (Höbel, 2014), and multimodal facilitation (Gomes et al., 2016). If and how they are employed by wild organisms is ripe for future research (for a review on human strategies to optimize hearing in noise see Moore, 2012; also see Box 2: Outstanding Questions and Suggested Research Directions).



**Fig. 2.** Hearing in Noise. (a) Theory predicts that for every 3 dB increase in background sound level the listening area is reduced by 50% for sounds within the bandwidth of the noise. Each successive sphere inward represents this halving of listening area due to each 3 dB noise increase. (b) The received level of a signal must be much louder in noisy conditions. Blue dots and trendline ( $y = 0.52x + 13.48$ ) indicate the signal level required for a territorial Brewer's sparrow (*Spizella breweri*) to discriminate playback of an intruding male's song with increasing background sound levels. A similar relationship exists for human listeners discriminating Brewer's sparrow song played back along the same acoustic gradient (black triangles and trendline;  $y = 1.17x - 19.95$ ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

soundscape to gain information about its environment—it is the area in which a songbird can detect potential mates and rivals, or the area that a human can hear a calling frog or a rare bird's song.

Importantly, listening area is a dynamic property and introduced anthropogenic noise can drastically reduce auditory range. For example, an increase in 3 dB of anthropogenic noise at the same frequency as a relevant signal or cue can reduce the listening area for that signal by 50% (Barber et al., 2010). Yet the global rise in anthropogenic noise levels far exceeds 3 dB and many studies report at least a full order of magnitude increase in acoustic power

(i.e., >10 dB higher; see references in Francis and Barber, 2013; Shannon et al., 2015). In effect, the ensuing reduced listening area translates into a diminished ability to detect and respond to signals and cues in the environment. This is analogous to navigating through thick fog visually—incrementally perceiving, interpreting and navigating the world a few meters at a time.

### 3.2. Natural systems

Reduced listening areas may explain a variety of recently documented impacts from anthropogenic noise that span animal foraging and anti-predator behavior, reproductive success, plus population density and community structure (reviewed in Barber et al., 2010; Ellison et al., 2012; Francis and Barber, 2013; Kight and Swaddle, 2011). Studies involving birds have provided the most insights thus far. Anthropogenic noise affects both bird distributions and their ability to reproduce in noisy environments, even when potentially confounding factors that often accompany human activity and noise (e.g., edge effects, pollution, visual disturbance and collisions associated with roads and traffic) are controlled for statistically or experimentally. For example, Bayne et al. (2008) found a one-third reduction in songbird density at noisy gas compressor stations in Canada compared to nearby well pads that were almost identical in habitat, but were much quieter. McClure et al. (2013) reported similar effects when they experimentally added traffic noise to the landscape. Using the same experimental landscape, Ware et al. (2015) found that migratory birds exposed to traffic noise gained weight more slowly than birds that were not, which could have grave consequences for individuals departing on energetically demanding migrations. Additionally, several single species studies show that noise decreases male birds' abilities to successfully attract mates (Gross et al., 2010; Habib et al., 2007), or if mated, pairs breeding in noisy areas produce fewer young (Halfwerk et al., 2011; Kight et al., 2012). Collectively, these studies suggest that noise strongly affects both the composition and density of a bird community and that birds that settle in or temporarily use noisy habitats may incur fitness costs.

The weight of current evidence indicates that although other forces—such as animals perceiving noises as a threat or being distracted by sound sources—may be at play, acoustic masking is the most supported and most understood mechanism behind the reported effects of noise on birds and other animals (Francis and Barber, 2013). Birds depend heavily on vocal communication to attract mates and defend territories (Catchpole and Slater, 2003). Therefore species with vocalization frequencies overlapping those of background noise generally avoid noisy areas, thereby avoiding masking—a prediction supported by several field studies and a recent synthesis of 14 studies spanning several countries (Francis, 2015).

### 3.3. Human systems

Considerable evidence indicates that anthropogenic noise also has negative cognitive and physiological effects on humans. Exposure to traffic noise is associated with hypertension and cardiovascular disease risk (van Kempen and Babisch, 2012) and negatively affects cognitive processing among school children (Lercher et al., 2003). Besides these impacts, or perhaps as an element within them, anthropogenic noise greatly impacts the human ability to hear natural sounds via a diminished listening area. For example, background noise greatly impairs trained field biologists' ability to hear and, ultimately, correctly identify birds (Ortega and Francis, 2012; Pacifici et al., 2008; Simons et al., 2007). Effects of noise on bird detectability are not just limited to professional, trained observers, but may be even more pronounced for

people seeking experiences with animals in natural areas. Because several metrics of human wellbeing are positively associated with their experience with biodiversity (reviewed in Sandifer et al., 2015), and that emerging evidence indicates that humans experience greater attention restoration when exposed to birdsong compared to quiet conditions (Abbott et al., 2016), the problem of anthropogenic noise dominating soundscapes becomes particularly relevant (Berman et al., 2008; Hansmann et al., 2007; Hartig et al., 1991).

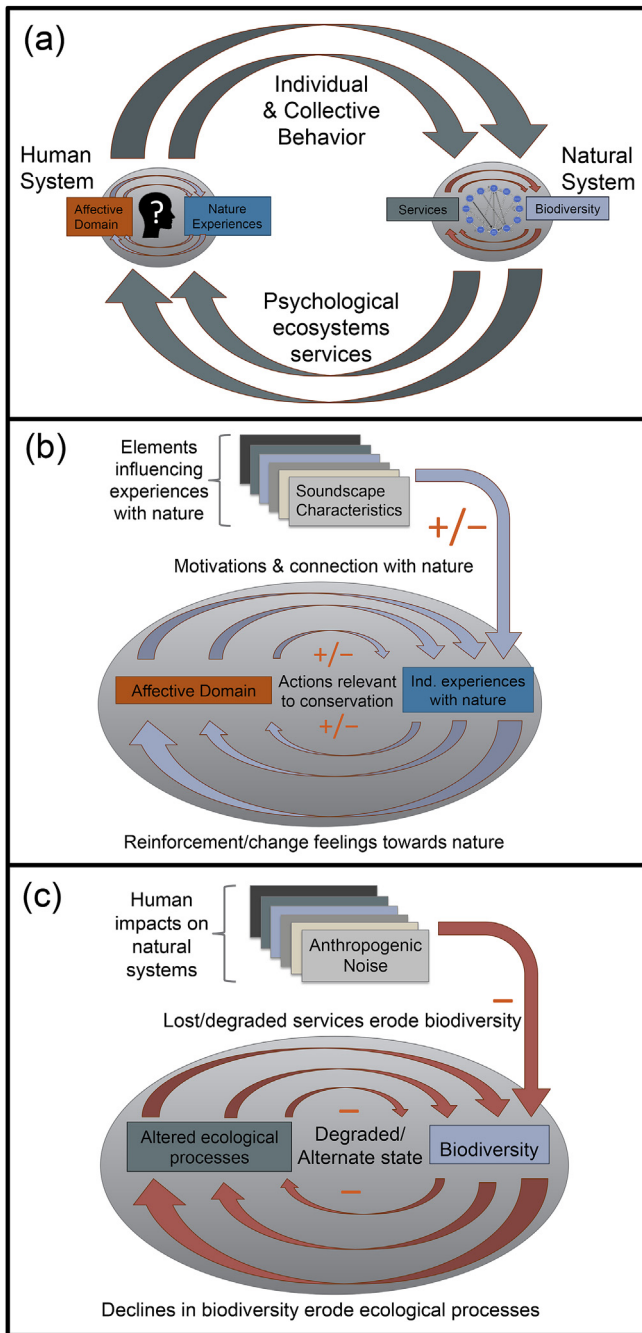
## 4. Human and natural system coupling through soundscapes

We hypothesize that biodiversity and human wellbeing are inextricably linked in a coupled dynamic that responds to and generates soundscape changes; psychological ecosystem services provided by natural soundscapes link wildlife to people and individual and collective human behaviors that alter soundscapes link humans to ecological systems. Importantly, the coupling that bridges ecological to human systems occurs through at least two mechanisms: first, soundscape characteristics influence the distribution of organisms across the environment and, secondly, by influencing human perceptual abilities that allow them to experience nature and wildlife. These mechanisms may operate additively or even synergistically on individual valuation of an experience in nature, an individual's overall perception of nature and a group's collective ethos associated with conservation of protected areas and the ecological systems therein (Fig. 3a). We discuss the feedbacks between natural and human systems by first describing how soundscapes influence feedback loops within human (Fig. 3b) and natural (Fig. 3c) systems, then describe how changes in soundscapes can alter their dynamics.

First, soundscapes dominated by natural sounds provide benefits to humans through psychological ecosystem services. We can illustrate this benefit using a ubiquitous source of natural sounds, which also has been proposed as an index of community biodiversity: birdsong (Gasc et al., 2013; Sueur et al., 2008). As mentioned previously, recent physiological lab studies suggest that natural sounds, including birdsong, create more rapid stress recovery rates (Alvarsson et al., 2010). While this and other studies suggest that natural sounds can reduce stress, natural sounds can also improve cognitive function through attention restoration (Abbott et al., 2016). Thus, evidence supporting both the stress recovery hypothesis and the attention restoration hypothesis suggests that natural sounds provide measurable benefits to people and it is likely that other psychological and physiological benefits have yet to be discovered (Fig. 3b). Less straightforward is how experiencing natural sounds reinforce or change individuals' feelings towards nature, their connections with nature, and their motivations for visiting and supporting conservation within natural areas.

Personal experiences can serve as the foundations upon which individuals develop their general valuation of nature that is linked to how they behave and make decisions that can impact ecological systems (Hausmann et al., 2016). Several studies suggest humans rank natural sounds as key motivations for visiting natural places (Haas and Wakefield, 1998; Marin et al., 2011) and that the presence of natural sounds enhances visitor experiences (Newman et al., 2013). However, how do experiences with sounds in protected areas influence visitors' decisions to visit areas again or to support protection of, or programs within, protected areas? Evidence suggests that the quality of experiences in nature can influence future behavior (Lee and Jan 2015; Taplin et al., 2016; Tonge et al., 2015). Yet it is not always clear what aspects of experiences in nature influence this feedback from experience to valuation to behavior (Ardoin et al., 2015). Aural experiences of the acoustic environment





**Fig. 3.** (a) Soundscapes link human experiences and valuation of nature and ecological systems. Soundscapes contribute to the psychological ecosystem services that humans obtain from interactions with nature and individual experiences in nature influence an individual's behavior in and towards nature. (b) Human system: Soundscapes characteristics, among other elements, influence experiences in nature that feedback to reinforce the way in which people feel about nature and their motivation to pursue future interactions in nature. (c) Natural system: Anthropogenic sounds negatively impact biodiversity and can cause feedbacks between biodiversity loss (or gain) and ecological function loss (or gain).

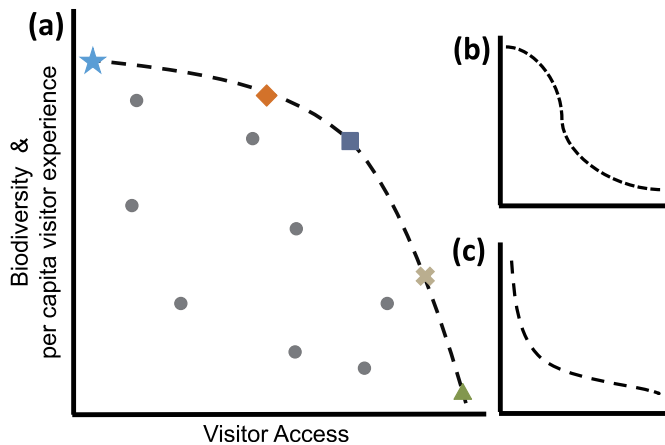
could influence this chain both consciously and subconsciously and it is possible that multi-sensory experiences with nature have synergistic effects that are larger than the sum of effects from each sensory modality in isolation. Thus, understanding how soundscapes influence human perception of nature during and after experiences in protected areas is especially important and provides context for the services that soundscapes in ecosystems provide.

Therefore, because changes in soundscapes can drastically influence an individual's ability to hear natural sounds (Box 1; Fig. 2a), there is a clear need for understanding how elevated anthropogenic noise is associated with declines in associated benefits with visits to protected areas and how these experiences influence individual valuation of protected areas and nature more broadly.

Many animals rely on their auditory systems as a primary modality to obtain and respond to cues and signals in their environment. Thus, just as changes in the acoustic environment influence a human's ability to hear sounds, anthropogenic noise can profoundly impair organisms' abilities to carry out essential functions. Indeed, anthropogenic noise is known to substantially alter behavior, physiology, reproductive success and distributions of wildlife (Barber et al., 2010; Francis and Barber, 2013; Shannon et al., 2015; Swaddle et al., 2015). These direct responses by animals to noise can have cascading impacts on the greater ecosystem, but research on these community-level effects are scarce. In one known example, noise causes declines in foraging activity in the Woodhouse's scrub-jay (*Aphelocoma woodhouseii*), which is a key seed disperser of piñon pine (*Pinus edulis*), and loss of dispersal services by this species are linked to lower recruitment of piñon pine in areas exposed to anthropogenic noise compared to less noisy areas (Francis et al., 2012). Due to piñon pine's role as a foundational species that supports approximately 1000 species (Mueller et al., 2005), indirect reductions in pine densities could have profound ecosystem consequences. More broadly, the ecological literature is replete with examples of how species loss impairs ecological function or how biodiversity in general is linked to ecological function (e.g., Anderson et al., 2011; Duffy, 2002; Estes et al., 2011; Hooper et al., 2005; Loreau et al., 2001). Thus it should be no surprise that species loss in ecosystems exposed to noise should also exhibit a decline in ecological function. Additionally, given recent studies documenting declines in foraging rates for animals exposed to noise (Mason et al., 2016; Senzaki et al., 2016; Siemers and Schaub, 2011; Ware et al., 2015), including a keystone species (Shannon et al., 2014), declines in ecological function can be the result of a functional response in the absence of, and in addition to, effects from species loss or declines in abundance (Fig. 3c). Cycles of reductions in species abundance and loss due to noise and the subsequent decline in ecological function could cause further biodiversity loss through positive feedbacks.

When anthropogenic noise dominates the soundscape, negative outputs overshadow positive, concomitantly impacting both natural and human systems. When anthropogenic noise dominates, biodiversity declines via acoustic filtering of the animal community (noise drives some animals away) and human listeners perceive a much smaller acoustic world (i.e., hear fewer animals). These combined effects result in a degraded experience, which can change individuals' valuation of, and connection to, nature. Importantly, the decline in valuation of nature could set-up a feedback cycle wherein human behaviors and policies that sustain natural soundscapes could be reduced, leading to acoustic conditions, and human activities associated with louder conditions, that trigger further declines in biodiversity. As biodiversity decays and anthropogenic noise fills the soundscape, individual and group valuation of both wildlife and the acoustic environment decline, reducing support for nature conservation, ratcheting declines in biodiversity further downward.

Alternatively, we hypothesize, when natural sounds are the dominant input to the soundscape, the positive effects of the soundscape on human and natural systems become paramount. Biodiversity is maintained in non-degraded acoustic environments, humans perceive a much larger acoustic world (i.e., hear more wildlife) and see more wildlife that might be otherwise displaced by noise. Thus, the overall human experience in nature improves



**Fig. 4.** Management solutions to the park paradox can be evaluated in a trade-off framework. (a) Individual management strategies can be plotted as a function of how they influence visitor access (X axis) as well as biodiversity and visitor experiences at the level of the individual (Y axis). The curved dotted line passes through the most efficient combinations of the management solutions under consideration and circles inside the dotted curve represent inefficient management strategies. As extreme examples, the star would represent a management option that prohibits nearly all visitor access to maximize biodiversity, whereas the triangle might represent the opposite strategy with unlimited and unregulated visitor access with considerable costs to biodiversity. The diamond, X, and square represent hypothetical strategies of compromise, such as the introduction of a shuttle system to transport visitors, reduced speed limits on park roads, or a reservation system to limit daily visitor numbers, which may strike a balance between access and biodiversity preservation and per capita visitor experiences. (b & c) Curves linking efficient management strategies may vary in shape and are dictated by the functional responses of biodiversity and per capita visitor experience to changes in access.

via provisioning of these psychological ecosystem services. As a consequence, we propose that individual and group valuation of the soundscape and biodiversity should increase and may lead to increased support for nature conservation via behaviors and policies that sustain natural soundscapes. Once in place, this positive feedback cycle may amplify the benefits to biodiversity. Understanding the degree to which this coupling exists, plus the role sounds contribute to the dynamics will be challenging (see Box 2 for key questions and research directions), but worth pursuing given the possible benefits of identifying the causal links between biodiversity and human wellbeing and potential management solutions to maintaining biodiversity in protected areas. Finally, although we focus on soundscapes here, this framework can be extended to other dimensions of the environment that are relevant to human experiences in and with nature (Fig. 3b) and the distribution of species and structure of ecological communities (Fig. 3c).

## 5. Conclusions

The role of natural soundscape conditions for human experience and for processes within ecological communities is not yet fully known, but the weight of evidence suggests that soundscapes play a larger role in regulating ecological communities and human experiences than we would have ever imagined just ten years ago. Importantly, these conditions are changing so rapidly that we may lose the opportunities to understand how human and nonhuman systems operate in the absence of the din of human activities. Take Yellowstone National Park as an example: in 2016 48% more people visited the park in 2016 compared to a decade earlier (National Park Service Visitor Use Statistics, 2016) and a by-product of this increase in access is substantial anthropogenic noise. More broadly, across many National Parks, noise from traffic and aircraft is audible at individual sites over 50% of the time (Lynch et al., 2011). Remote

## Box 2

### Outstanding Questions and Suggested Research Directions.

- Important ecological habitats in protected areas should be selected for experimental noise abatement experiments (e.g., reduced speed limit, closures during crepuscular hours, quiet road surfaces) to determine the effects on wildlife, people and their coupling. Critical ecological questions remain: how much noise is too much? Do inflection points exist at particular noise levels above ambient beyond which biodiversity or visitor experiences decline?
- Understanding how humans and wildlife hear in natural environments is essential for revealing the mechanisms underlying community structuring by noise. Is masking of information entirely an energetic problem (Moore, 2012), which assumes information is lost entirely due to poor signal-to-noise ratio within the frequency band of the noise? In contrast, does non-energetic masking (i.e., informational masking; Durlach et al., 2003), an attentionally-mediated set of mechanisms that do not necessarily require frequency or precise temporal overlap between the sound of interest and noise, also govern hearing in loud acoustic environments?
- Given the diversity of motivations for visiting protected areas, which visitors perceive the level of biodiversity and through which sensory modalities? Dallimer et al. (2012) found that estimates of biodiversity (i.e., number of species) made by protected area visitors loosely correlated with the number of plants and birds, but what sensory information did visitors use to make their estimates? We know natural sounds are associated with benefits individuals gain from experiences with nature, including attention restoration (Abbott et al., 2016), but does the strength of the relationship depend on the level of diversity experienced acoustically?
- The role of the soundscape in the valuation of psychological ecosystem services needs urgent attention by the research and protected area management communities. Can we estimate the value or utility of a specific location for psychological ecosystem services based on its background sound level and amount of biodiversity?
- What management scenarios are most likely to provide the appropriate trade-off between visitor access and protection of habitat quality for biodiversity? Individual management strategies can be plotted as a function of how they influence visitor access as well as biodiversity and visitor experiences at the level of the individual (Fig. 4). For example, management actions that decrease visitor access generally lead to soundscapes that are predominately natural rather than anthropogenic, thus promoting biodiversity and positive per capita visitor experiences.
- Does education involving the importance of natural acoustic conditions increase the perceived value of natural soundscapes and positively influence visitors' willingness to alter their behavior and embrace management efforts to minimize noise?

wilderness areas are not immune, because high traffic corridors generate substantial noise that propagates over many kilometers. For example, anthropogenic sound is audible at the Snow Flats site



in Yosemite National Park nearly 70% of the time during peak traffic hours (Barber et al., 2010). State, county and private protected areas closer to urban areas are typically smaller than the average national park and are likely to experience even greater noise exposure. Given the predominance of anthropogenic sounds in these areas, understanding the full impact of changing soundscapes on ecological systems and human visitors should be a priority. Doing so may provide unforeseen opportunities for lessening the tension between protecting biodiversity and providing public access that is at the heart of protected areas' missions.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jenvman.2017.07.041>.

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