A synthesis of health benefits of natural sounds and their distribution in national parks

Rachel T. Buxton[a,1,2], Amber L. Pearson[b,c,1], Claudia Allou[d], Kurt Fristrup[e], and George Wittemyer[f]

[a]Department of Biology, Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, ON K1S 5B6 Canada; [b]Department of Geography, Environment and Spatial Sciences, Michigan State University, East Lansing, MI 48823; [c]Department of Public Health, University of Otago, 6242 Wellington, New Zealand; [d]James Madison College, Michigan State University, East Lansing, MI 48823; [e]Natural Sounds and Night Skies Division, National Park Service, Fort Collins, CO 80525; and [f]Department of Fish, Wildlife and Conservation Biology, Colorado State University, Fort Collins, CO 80523

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Parks are important places to listen to natural sounds and avoid human-related noise, an increasingly rare combination. We first explore whether and to what degree natural sounds influence health outcomes using a systematic literature review and meta-analysis. We identified 36 publications examining the health benefits of natural sound. Meta-analyses of 18 of these publications revealed aggregate evidence for decreased stress and annoyance (g = −0.60, 95% CI = −0.97, −0.23) and improved health and positive affective outcomes (g = 1.63, 95% CI = 0.09, 3.16). Examples of beneficial outcomes include decreased pain, lower stress, improved mood, and enhanced cognitive performance. Given this evidence, and to facilitate incorporating public health in US national park soundscape management, we then examined the distribution of natural sounds in relation to anthropogenic sound at 221 sites across 68 parks. National park soundscapes with little anthropogenic sound and abundant natural sounds occurred at 11.3% of the sites. Parks with high visitation and urban park sites had more anthropogenic sound, yet natural sounds associated with health benefits also were frequent. These included animal sounds (audible for a mean of 59.3% of the time, SD: 23.8) and sounds from wind and water (mean: 19.2%, SD: 14.8). Urban and other parks that are extensively visited offer important opportunities to experience natural sounds and are significant targets for soundscape conservation to bolster health for visitors. Our results assert that natural sounds provide important ecosystem services, and parks can bolster public health by highlighting and conserving natural soundscapes.

noise | bird song | visitor experience | water sounds | stress

The sounds of nature have long generated powerful reactions in human beings—from inspiring music and poetry (e.g., Beethoven's Pastoral Symphony) to providing the stark symbolism that ignited the environmental movement (e.g., Rachel Carlson's Silent Spring). Sounds confer a sense of place, connect people to nature, and increasing evidence suggests that natural sounds are important for human health and well-being (1).

Soundscapes are the collection of sounds perceived in an environment, including those from biological sources (e.g., bird vocalizations), geophysical sounds (e.g., wind and rain), and anthropogenic sounds [including noise from road and air traffic (2)]. Soundscapes provide crucial information for both wildlife and humans (3). Many species rely on sound to communicate (4). Sound perception enables most species, including all known vertebrates, to surveil their surroundings. Thus, hearing causes behavioral and physiological responses to soundscapes [e.g., changes in heart rate regulated by the sympathetic nervous system (1)]. Natural soundscapes are increasingly threatened due to the rapid loss of sound-producing organisms [e.g., birds (5)] and intrusion of noise. Noise causes changes in behavior, physiology, and fitness in wildlife that can alter ecosystem functioning, further altering the natural acoustic environment (6). Noise masks natural sounds, interfering with important signals and altering the character of a soundscape. For humans, noise contributes to varied health problems, including hearing loss, nonauditory physiological effects, increased occurrence of hypertension and cardiovascular disease, and high levels of annoyance (7). Noise is present even in remote protected areas in the United States, and soundscape conservation is a burgeoning priority (8).

The health benefits of exposure to nature are well documented (for a recent overview, see ref. 9). Here, we define human health broadly, encompassing physiological outcomes (e.g., stress) and potential psychological precursors along the pathway to health outcomes [e.g., preference (1)]. Two psychological theories explain the mechanistic basis of the restorative effects of exposure to nature (including sound), drawing heavily from the theory of evolution (10). Attention Restoration Theory centers on the ability of nature to replenish attention through unconscious, cognitive processes (11). In contrast to the constant fatigue-inducing stimulation in urban environments, nature does not require directed attention and simultaneously elicits pleasure and relaxation. Stress Recovery Theory posits that nature may be perceived as less threatening and thus less arousing, leading to recovery from stress through autonomic response to nature (12). As such, conserving nature has considerable health implications particularly in increasingly urbanized populations, as exposure improves birth outcomes, mortality rates, mental health and stress, cognitive performance, and the rate of a myriad of diseases (reviewed in refs. 13, 14). While

Significance

This study examines evidence of the health benefits of natural soundscapes and quantifies the prevalence of restorative acoustic environments in national parks across the United States. The results affirm that natural sounds improve health, increase positive affect, and lower stress and annoyance. Also, analyses reveal many national park sites with a high abundance of natural sound and low anthropogenic sound. Raising awareness of natural soundscapes at national parks provides opportunities to enhance visitor health outcomes. Despite more abundant anthropogenic sound, urban and frequently visited sites offered exposure to natural sounds associated with health benefits, making them a valuable target for soundscape mitigation. Our analysis can inform spatial planning that focuses on managing natural soundscapes to enhance human health and experiences.

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[1]R.T.B. and A.L.P. contributed equally to this work.

[2]To whom correspondence may be addressed. Email: Rachel.Buxton@colostate.edu.

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the benefits of viewing nature are more studied, the influence of the acoustic environment is emerging as an important mechanism through which contact with nature affects human health (15). Audiovisual interactions play a significant role in perception, and there is often synergy between the influence of visual and acoustic exposure to nature on perception of environmental quality (16).

Historically, soundscapes have been investigated in the context of the deleterious effects of noise (17). Natural soundscapes play a central role in urban environmental sustainability because they offer reduced exposure to adverse effects of noise to which urban populations are highly exposed (18). Natural sounds have also been recognized for their ability to mask noise (19), their improvement of perceived park soundscape quality and park experience (20), their ability to enhance perceptions of the built environment (21), and their capacity for psychological restoration (22). Thus, research increasingly focuses on evaluating the characteristics of soundscapes by quantifying their different components (23) to manage soundscapes as a natural resource (24).

National parks have some of the most pristine soundscapes in the United States, yet noise is still widespread across the park system (25). Congressional concerns over the impact of noise have resulted in mandated protection of acoustic environments in US national parks (17). In parks, soundscapes are managed to minimize noise exceeding levels known to be detrimental to wildlife, visitor use, and cultural values (26). Natural sounds are increasingly recognized in law and policy as a park resource and have thus become a subject for conservation and restoration management (27). Here, we explore whether conserving natural soundscapes is also an opportunity to bolster public health. To determine whether and to what degree natural sounds influence health outcomes, we conduct a systematic literature review and meta-analysis. Given the evidence showing that natural sounds do influence health and to facilitate park soundscape management for public health, we then examine the distribution of natural sounds in relation to anthropogenic sound at 221 sites in 68 national parks. We enumerate different components of soundscapes identified to be particularly important for human health. Finally, we investigate soundscapes near urban areas and in relation to park visitation, acoustic environments which may be particularly important health resources for visitors.

Results

Systematic Review and Meta-Analysis. In our systematic review of peer-reviewed literature, only 19% of studies examining the health benefits of natural sounds ($n = 7$) measured traditional health outcomes, including heart rate, blood pressure, perceived pain, skin conductance, cortisol, and t-wave amplitude. Other studies examined the potential precursors along the pathway to health, including metrics of perception, mood, and cognitive performance. For 52% of outcomes measured (13 studies in the meta-analysis), we expected to see an increase due to natural sound (i.e., health and positive affect), and in the other 48% (12 studies in the meta-analysis), we expected to see a decrease due to natural sound (i.e., stress and annoyance).

Most studies (61%, $n = 22$) occurred in a laboratory or hospital setting rather than in the field. Research occurred in 11 different countries, with the largest number in Sweden (22%, $n = 8$). Studies had a mean sample size of 150.6 (±304.3 SD) and a mean quality score, based on the Quality Assessment Tool for Quantitative Studies, of 1.8 (±0.4 SD; *SI Appendix*, Fig. S1).

The overall mean effect size for health and positive affect outcomes was 1.63 (95% CI = 0.09, 3.16), corresponding to a 184% overall improvement in groups exposed to natural sounds relative to comparison groups (Fig. 1). The large variance in effect sizes was due to one study with particularly large effect sizes (28). The overall mean effect size for stress and annoyance outcomes was −0.60 (95% CI = −0.97, −0.23), corresponding to a 28% overall decrease in groups exposed to natural sounds relative to comparisons (Fig. 1).

We found significant heterogeneity between effect sizes in all models ($Q > 248.4$, $P < 0.001$), suggesting that moderators not considered in the model influenced the health benefits of natural sound exposure. We found no obvious pattern of publication bias in the funnel plot (*SI Appendix*, Fig. S1). If we only included studies with high quality scores (≤1.5), mean effect sizes of models were still significant (*SI Appendix*, Table S1).

Of the three types of natural sounds (birds, water, and mixed), we found that water sounds had the largest mean effect size for health and positive affect outcomes (2.01, 95% CI = 0.35, 3.67), and bird sounds had the largest mean effect size for stress and annoyance (1.11, 95% CI = −1.82, −0.4, Fig. 2). Yet, relatively few studies tested bird sounds explicitly (11 effect sizes in

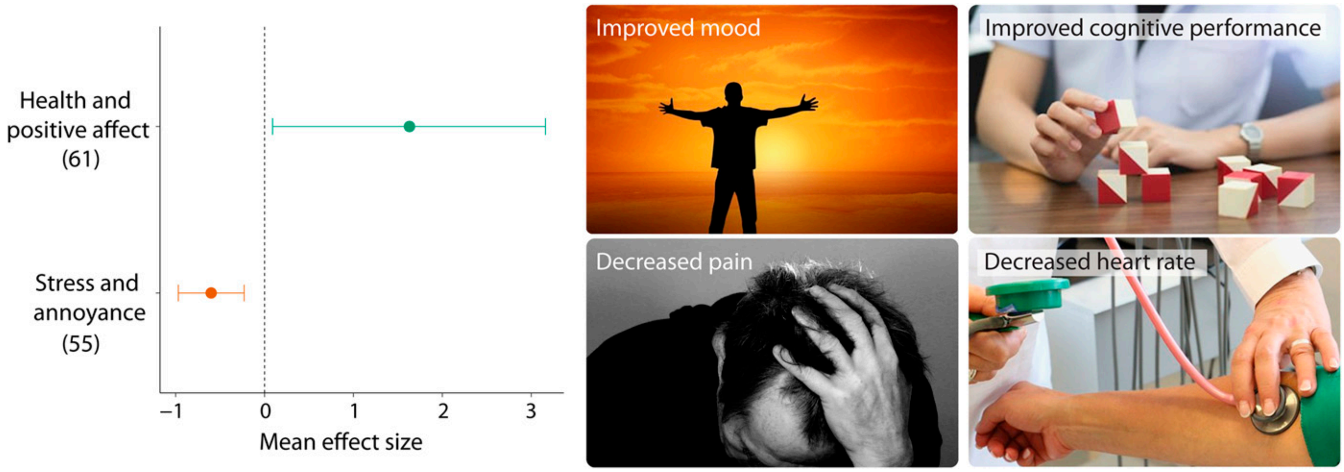

Fig. 1. Health and positive affective outcomes improved while stress and annoyance decreased in studies examining the benefits of exposure to natural sounds. Weighted mean effect sizes are from meta-analytic models of 18 studies, and the error bars indicate 95% CIs. A positive mean value (to the right of the dashed zero line) indicates health and positive affective outcomes improved in groups exposed to natural sound, and a negative value (to the left of the dashed zero line) indicates stress and annoyance indicators decreased in groups exposed to natural sound. Examples of metrics of health and positive affect included improved mood and cognitive ability, and metrics of stress and annoyance included decreased pain, heart rate, and blood pressure. All images are free for use, no attribution required.

2 studies). Comparing natural sound and noise to noise had the largest mean effect size for health and positive affective outcomes (9.9, 95% CI = 8.46, 11.29), although only one study tested this effect. Comparing natural sound to noise had the largest mean effect size for both health and positive affective outcomes (1.7, 95% CI = 0.16, 3.24) and stress and annoyance (−0.81, 95% CI = −1.21, −0.40, Fig. 2). Comparing more natural sounds versus fewer natural sounds and natural sounds versus no sound also significantly improved health and positive affect and decreased stress and annoyance. The weakest contrast in our results was between natural sounds and natural sounds mixed with noise. Only one study tested the influence of more natural sounds versus fewer (11 effect sizes).

Sounds in US National Parks. Given the evidence that natural sounds influence health outcomes and that noise can diminish positive health benefits, we examined the prevalence and distribution of soundscapes with low anthropogenic sound audibility and high natural sound audibility in US national parks. Of the 221 acoustic monitoring sites analyzed, we found 75.1% (n = 166) had high audibility of biological sounds (i.e., audible >75% of time) and 40.7% of sites (n = 90) had a high audibility of geophysical sounds. As the most important sounds for health and positive affect identified in our review, we found bird sounds were audible 42.1% (mean ± 20.1 SD) of the time among sites and water related sounds were audible 22.8% (mean ± 36.2 SD) of the time among sites. Overall, 11.3% of sites (n = 25) had low audibility of anthropogenic sound (i.e., audible <25% of time) and high audibility of biological or geophysical sounds, sites which may represent important acoustic environments for human health (*SI Appendix*, Fig. S2). Additionally, 22.6% of sites (n = 50) had moderate audibility of noise (25 to 75%) and high audibility of biological or geophysical sounds (*SI Appendix*, Fig. S2).

Parks with more annual visitors (more than the median) had a higher average audibility of anthropogenic sound (mean ± SD: 0.81 ± 0.16) than those with fewer visitors (0.59 ± 0.34) but similar audibility of biological and geological sounds. Sites with high audibility of biological or geophysical sounds and low anthropogenic sound audibility had fewer visitors on average (370,420 ± 640,939 visitors per year) than those without (1,452,147 ± 2,640,973). Most sites with high audibility of biological or geophysical sounds and low anthropogenic sound audibility were located in Alaska, Hawaii, and the Pacific Northwest (Fig. 3) and were far from urban areas (Fig. 4). Only three sites with high audibility of biological or geophysical sounds and low anthropogenic sound audibility were within 100 km of urban areas (Fig. 4). Despite anthropogenic sound being audible most of the time (mean audibility ± SD: 90.2 ± 11.7), at recording sites within urban areas (n = 5), biological sounds were audible on average 59.3% of the time (±23.8 SD), and geophysical sounds were audible 19.2% of the time (±14.8 SD).

Discussion

Results from our systematic review and meta-analysis demonstrated that exposure to natural sounds improves health outcomes and positive affect and decreases stress and annoyance. These results align with many studies documenting the health benefits of exposure to nature through other sensory stimuli. Our review showed that natural sounds alone can confer health benefits. This finding can be interpreted from an evolutionary perspective, where humans attend to patterns that signal danger and security (29). Natural acoustic environments provide indications of safety or an ordered world without danger, allowing control over mind states, reduction in stress-related behavior,

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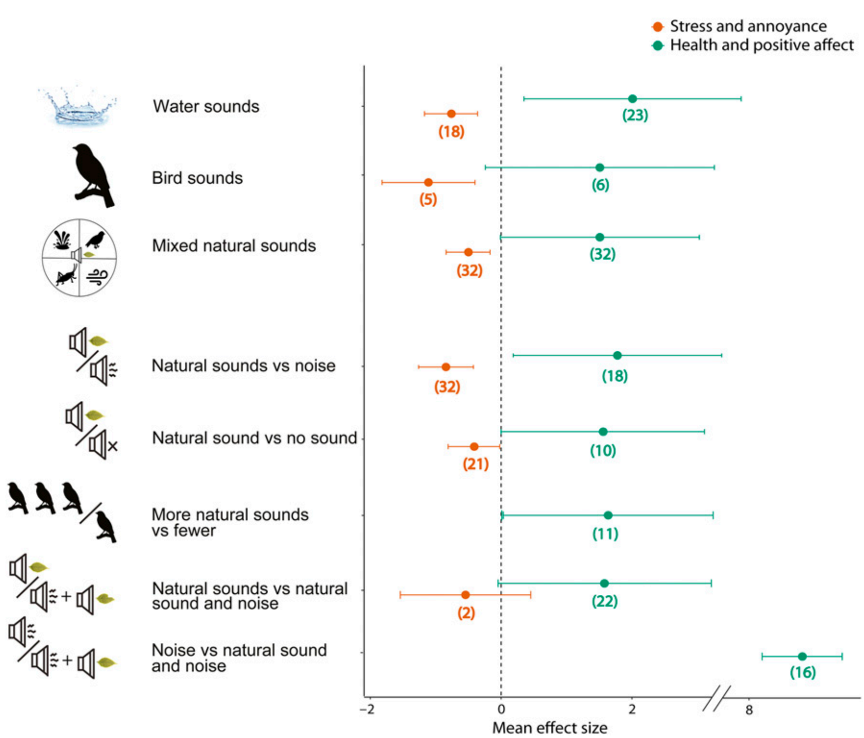

Fig. 2. Weighted mean effect sizes of natural sound on health and positive affective outcomes and stress and annoyance outcomes for different types of natural sounds and different treatment comparisons. Water sounds had the largest mean effect size for health and positive affective outcomes, bird sounds had the largest for stress and annoyance, and comparing natural sound to noise had the largest for health and positive affect and stress and annoyance. The error bars indicate 95% CIs. A positive mean value (to the right of the dashed zero line) indicates health and positive affective outcomes improved in groups exposed to natural sound, and a negative value (to the left of the dashed zero line) indicates stress and annoyance indicators decreased in groups exposed to natural sound. Part of the *x*-axis is removed for display purposes.

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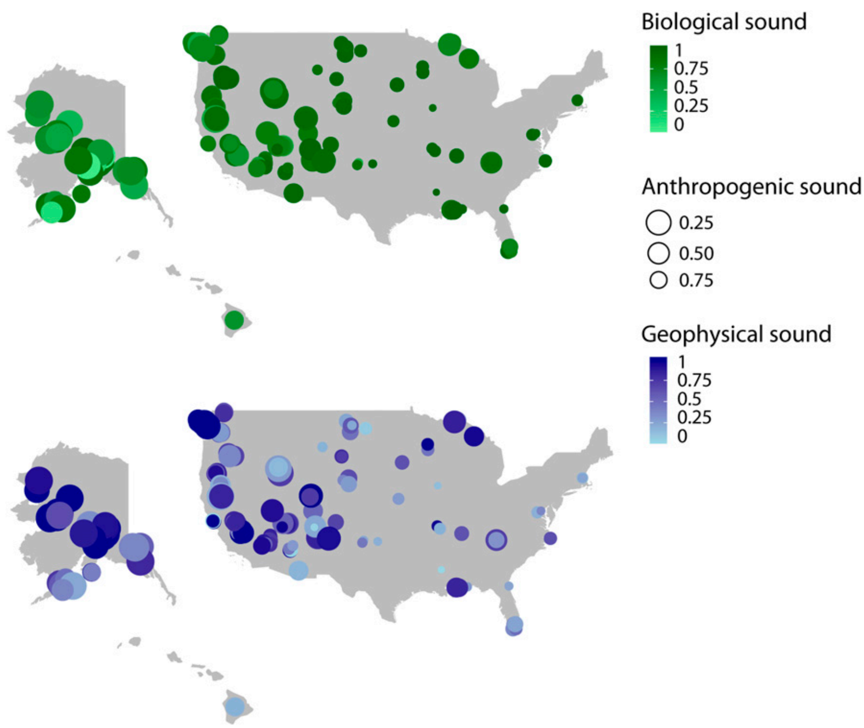

Fig. 3. The proportion of each type of sound (biological—sounds produced by animals; geophysical—sounds from water, wind, and weather; and anthropogenic—sounds produced by humans) observed in recordings collected in parks across the United States indicate acoustic environments important for human health—sites where natural sounds are more abundant (darker colors—higher audibility) and anthropogenic sounds are less abundant (larger circles—lower audibility). Audibility of sounds are predicted by generalized linear mixed models. Note that sites were not selected at random within parks or regions; they were selected to monitor specific settings of interest to park managers.

and mental recuperation (30). Conversely, an absence of natural safety indicators in the acoustic environment may provoke vigilance and autonomically induce a more alert, aroused state. The demonstrated health benefits of exposure to natural sounds affirm the importance of including acoustic environments in valuations of ecosystem services (3).

Our meta-analysis indicated that water sounds had the largest effect on health and positive affective outcomes, while bird sounds had the largest effect on alleviating stress and annoyance, and both sounds were audible >23% of the time in park recording sites. The importance of water sounds may relate to the critical role of water for survival, as well as the capacity of continuous water sounds to mask noise. Water features have often been used as urban landscape elements to enhance acoustic environments (31). Not only can sounds from water mask noise, but they also increase the pleasantness and positive perception of urban greenspace (32). Bird song is also a widespread component of nature experiences and can restore attention, enhance mood, decrease perceived stress, and increase the familiarity and pleasantness of a soundscape (33).

Our analysis showed that exposure to natural sounds offers health benefits when compared with exposure to noise. In parks, noise degrades visitor enjoyment and health directly as an environmental stressor and indirectly by altering the number of sound-producing animals and thus decreasing the diversity of natural sounds (3, 34). However, the presence of natural sounds alongside noise in some instances can improve the perception of soundscape quality, promoting calmness and reductions in annoyance (35). Prominent, persistent natural sounds may confer additional health benefits by masking noise.

The majority of studies reviewed here occurred in laboratory settings; there was limited experimental evidence from the field. Furthermore, many intriguing findings were examined by limited numbers of studies. For example, there was only one study that examined outcomes of increasing numbers of bird species' song. Although participants preferred soundscapes with a higher richness of bird song (21), the link between soundscape diversity and health benefits remains understudied. Moreover, most of the research was conducted with Western populations and ethnicity was not reported. Therefore, future research could usefully explore differences in soundscape meanings, preferences, and health benefits across a more diverse sample. Finally, further research could account for relevant moderators, such as the company of others, fatigue, exposure duration, activities while outdoors, and demographics.

We found that 11.3% of analyzed recording sites in national parks had a low audibility of anthropogenic sound and had a high audibility of natural sounds, representing soundscapes that offer important health benefits. In addition to being a major motivation for visiting parks (36), these natural soundscapes represent important resources to be protected and enhanced for both ecological and social benefits (3).

Nature-based health interventions are increasingly numerous (37), including a growing number of community collaboration projects and a national park prescription program [www.parkrx.org/ (38)]. However, explicit consideration of the acoustic environment is rare in these initiatives. Ongoing soundscape monitoring in national parks provides ample opportunities to incorporate soundscape quality and enhance health outcomes for visitors. Innovative programs like "soundwalks," or any excursion whose main purpose is listening, could be used to enhance awareness and appreciation of natural soundscapes like those identified here (39). Understanding the distribution of health-benefiting soundscapes in relation to visitation can inform spatial planning and policy making for parks and communities (40). For example, although visitation was lower in parks with soundscapes with low audibility

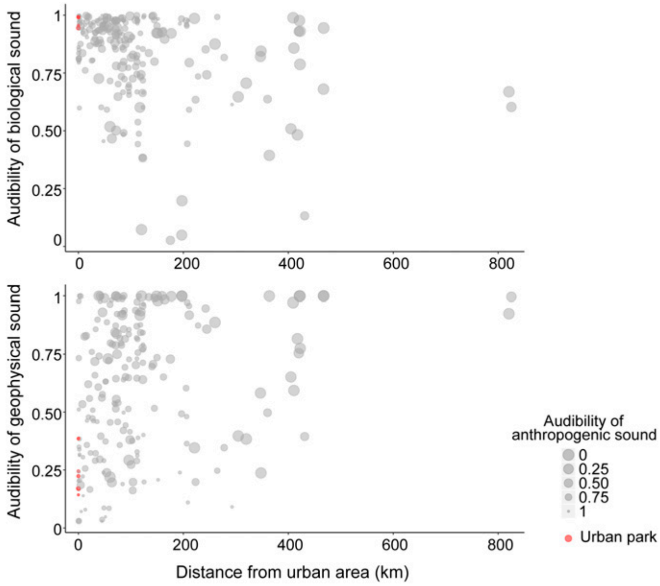

Fig. 4. Many US park sites near urban areas had a high proportion of recordings containing biological (*Top*—produced by animals) and geophysical (*Lower*—from water, wind, and weather) sounds but also high anthropogenic sounds (smaller points). Sites within urban areas (red) with high audibility of biological and geophysical sound could represent important acoustic environments important for the health of urban visitors. Audibility is the proportion of each type of sound observed in subsampled recordings collected in parks across the United States predicted by generalized linear mixed models.

of anthropogenic sound and high audibility of natural sounds, on average, over 370,000 people visit each of these parks per year. In these cases, signage identifying natural soundscapes can attract visitors to these health-benefiting sites, improve soundscapes by decreasing visitor noise (41), increase time spent in a park (42), and enhance visitor perceptions of sounds and the park (43). Additionally, noise management in parks with high visitation and high natural sound audibility can increase access to natural soundscapes (44) and their health benefits.

As human populations become increasingly urbanized, experiencing soundscapes rich in natural sound without noise will become ever more exceptional and important for enhancing the health of visitors. Our analysis shows that such sites are rarely near urban centers, with only three of these types of natural soundscapes found within 100 km of urban areas. However, biological and geophysical sounds were audible 59% and 22% of the time in urban parks on average. Although urban parks present formidable soundscape management challenges, restoring their soundscapes may produce the greatest health benefits. Nature-contact benefits can be most pronounced for low-income groups (45) whose travel options may be limited. We found 22.6% of urban park sites had high audibility of natural sounds and moderate audibility of anthropogenic sound. For these types of urban soundscapes, employing noise reduction tools (46) or soundscape augmentation (47) could produce widespread benefits for human health.

Soundscapes are important for public health, due to both the benefits of natural sounds and the adverse effects of noise. These benefits support an increasing policy focus on biodiversity conservation alongside human health (48). Moreover, awareness of the health benefits of nature will likely broaden and diversify public support because public opinion is most often driven by emotion and experience (49). Thus, the conservation of soundscapes in parks and other greenspaces has multiple benefits, including preserving important connections with nature, strengthening biodiversity conservation, and bolstering public health.

Materials and Methods

Systematic Review. To assess the empirical evidenceshowing the effect of natural sounds on human health, we systematically reviewed the literature. We searched Web of Science, PubMed, and Scopus for relevant publications using search terms that were broad enough to locate studies in a variety of disciplines which were then reviewed for inclusion (*SI Appendix*, Figs. S2 and S3 and the registered strategy with PROSPERO CRD42018095537). After selecting qualifying studies, bibliographies for each were examined for additional studies, yielding a total of 36 articles for inclusion.

To integrate information across studies, we extracted study site and design; the type of comparison groups (group exposed to natural sound versus no sound, natural sound versus noise, natural sound and noise versus noise, natural sound and noise versus natural sound, and more natural sounds versus fewer), the type of natural sound (water, bird, or mixed natural sounds), the mean and SD of health outcomes, and sample size in each group. Finally, we assessed study quality using the Quality Assessment Tool for Quantitative Studies (*SI Appendix*, Table S2).

Only 18 studies had enough information for further meta-analysis, involving calculation of effect sizes (Hedges' g) and fitting random-effects meta-analysis models in R version 3.5.2 [*SI Appendix*, Fig. S2 (51)]. We fitted models separately for health outcomes that were expected to improve (hereafter health and positive affective outcomes) or be reduced (hereafter stress and annoyance). To account for multiple comparisons and outcomes within a single study, study ID was included as a random factor in each model. To test for associations between effect size of health outcomes and attributes we extracted from studies, we used mixed-effects models with categorical moderators (i.e., type of comparison group and type of natural sound assessed). The small sample size necessitated simple models. Therefore, we tested each moderator in a separate model. Effect sizes were considered to be significantly different from zero when 95% CI did not overlap zero. We tested for heterogeneity by calculating the Q statistic for all models and examined publication bias using funnel plots of models without moderators (*SI Appendix*, Fig. S2). Finally, we carried out a sensitivity analysis to investigate the influence of study quality (*SI Appendix*, Fig. S2).

Sounds in US National Parks. To examine the distribution of natural sounds in national parks, we used the National Park Service Natural Sounds and Night Skies Division (NSNSD) nationwide acoustic dataset. Detailed methods of acoustic recording collection and analysis are outlined in Lynch, Joyce, and Fristrup (17) and Buxton et al. (25). Briefly, the NSNSD has been monitoring the acoustic environment since 2000. Trained technicians identified sounds to categories (anthropogenic, geophysical, and biological) by listening to and observing spectrograms of subsampled recordings at 221 sites in 68 parks (*SI Appendix*, Table S3).

Broad anthropogenic sound categories included aircraft, motorized vehicles, people talking, domestic animals, trains, and infrastructure maintenance (e.g., grounds care). We recognize that visitor conversation, laughter, and ranger interpretive sessions are intrinsic to park values and visitor experience. Yet, voices can also be noise in the context of experiencing natural sounds (44). It is worth noting that over 80% of anthropogenic sounds found in park recordings included transport-related noise (25), which has been shown to have deleterious effects on health. Geophysical sounds included wind, water, geothermal activity, and thunder; and biological sounds included those from insects, mammals, amphibians, and birds. These sound types were identified as present or absent in 10 s samples of audio taken continuously, or every 2 or 5 min (*SI Appendix*, Table S3). We calculated the audibility of sounds as the proportion of 10 s acoustic samples where a sound was observed during an hour of sampling.

To control for different seasons and years of acoustic recordings, we generated predictions of audibility using generalized linear mixed models. The most parsimonious model structure had a binomial error structure (*SI Appendix*, Fig. S2). All models incorporated year as a continuous variable and season and morning (7 to 9 AM) as dummy variables, with recording date nested within site nested within park as a random effect. Predicted audibility of biological, geophysical, and anthropogenic sounds were generated for summer, when biological (birds are still singing) and human (visitation peaks) sounds are high, in 2016 (highest percentage of recordings collected), in morning hours, to capture the dawn chorus. We compared the predicted audibility of geophysical, biological, and anthropogenic sounds with distance to an urban area with >50,000 people (52) and mean annual park visitation (53).

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Data Availability. All data have been deposited in Open Science Framework (https://osf.io/57vbd/) (50) and/or are included in the *SI Appendix*.

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