Review

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A framework to assess evolutionary responses to anthropogenic light and sound

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Human activities have caused a near-ubiquitous and evolutionarily-unprecedented increase in environmental sound levels and artificial night lighting. These stimuli reorganize communities by interfering with species-specific perception of time-cues, habitat features, and auditory and visual signals. Rapid evolutionary changes could occur in response to light and noise, given their magnitude, geographical extent, and degree to which they represent unprecedented environmental conditions. We present a framework for investigating anthropogenic light and noise as agents of selection, and as drivers of other evolutionary processes, to influence a range of behavioral and physiological traits such as phenological characters and sensory and signaling systems. In this context, opportunities abound for understanding contemporary and rapid evolution in response to human-caused environmental change.

Global changes in distribution of anthropogenic light and sound

Worldwide human population growth dramatically influences organisms through urbanization, industrialization, and transportation infrastructure [1]. The environmental disruption associated with the exponential increase in human populations has led to extinction, altered community structure, and degraded ecosystem function [1]. Pollution is among the key aspects of human-induced rapid environmental change. Anthropogenic noise and artificial light are sensory pollutants that have increased over recent decades, and they pose a global environmental challenge to terrestrial [2] and aquatic environments [3]. In 2001 approximately 40% of the world population lived in areas that never experienced sub-moonlight illuminance [4]. Baseline night light levels are increased by skyglow, artificial light scattered by the atmosphere back towards the ground. The overcast night sky radiance in urban areas

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Glossary

Background extinction rates: pre-human rates of extinction outside of recognized mass extinction events.
Background speciation rates: pre-human rates of speciation outside of the recovery period following mass extinction events.
Behavioral flexibility: immediate adjustments of behavior and physiology in response to environmental conditions.
Developmental plasticity: a change in developmental trajectory and phenotypic outcome of a single genotype in response to a different environmental condition.
Heritability: the proportion of phenotypic variance attributable to genetic variance.
Macroevolution: the study of patterns and processes of evolution that occur at or above the level of species.
Microevolution: change in allele frequencies in a population over time.
Reaction norm: depiction of the range of phenotypes expressed by a single genotype across different environments.
Zeitgeber: any external cue that entrains the biological rhythms of an organism to environmental cycles.

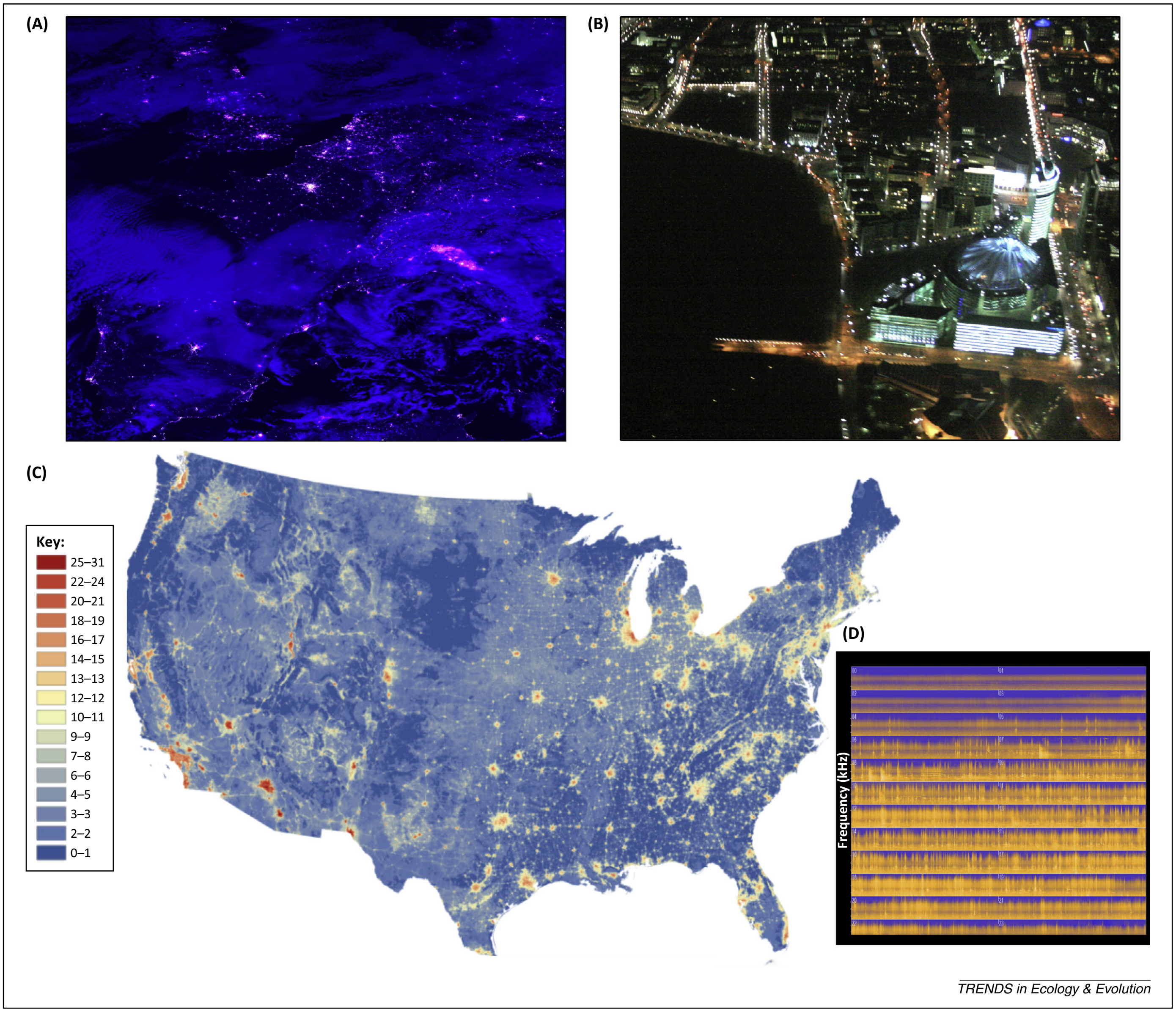

Figure 1. Increasing anthropogenic night lighting and sound levels represent a global phenomenon that constitutes environmental changes unprecedented in the history of life on Earth. **(A)** Europe at night. Areas colored blue are emitting an intensity of light upwards that is comparable to moonlight, pink areas are brighter than moonlight, and white areas are many times brighter than moonlight. **(B)** Light is extremely heterogeneous at both landscape and local (few meters) spatial scales. **(C)** Estimated sound levels (L50 SPL dB(A) re 20 μPa) created by human activities that exceed background levels created by natural sources [7]. **(D)** Temporal heterogeneity in anthropogenic sounds as a 24 h spectrogram, which illustrates acoustic energy across the frequency spectrum for 24 h, with each row representing 2 h. Lighter colors reflect higher sound levels. Brighter colors prominent in the fourth row (i.e., beginning at 06.00 h) through the final row display anthropogenic sounds from road traffic and aircraft in Grand Teton National Park in late September of 2013. (A) Image and Data processing by the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center, (B) courtesy Freie Universität Berlin, and (C) modified from Mennitt *et al.* [7]. Both (C) and (D) are courtesy of the US National Parks Natural Sounds and Night Skies Division. Abbreviations: dB(A), A-weighted decibels; L50, median SPL; re, reference pressure; SPL, sound pressure level.

has been found to be as much as four orders of magnitude larger than in natural settings (Figure 1) [5]. Similarly, increased noise levels affect a sizable proportion of the human population. In Europe, for instance, 65% of the population is exposed to ambient sound levels exceeding 55 dB(A) [6], roughly equivalent to constant rainfall. Of the land in the contiguous USA, 88% is estimated to experience elevated sound levels from anthropogenic noise (Figure 1) [7]. These effects are not limited to terrestrial environments; ocean noise levels are estimated to have increased by 12 decibels (an ~16-fold increase in sound intensity) in the past few decades from commercial shipping alone [8], while an estimated 22% of the global coastline is exposed to artificial light [3], and many offshore coral reefs are chronically exposed to artificial lighting from cities, fishing boats, and hydrocarbon extraction [9].

The changes in light at night and noise levels are occurring on a global scale similar to well-recognized ecological and evolutionary forces such as land-cover and climate changes. In parallel with research involving climate change [10], much of our understanding of organismal response to noise and light is restricted to short-term behavioral reactions. Organismal responses might be associated with tolerance to these stimuli in terms of habitat use [11,12], or include shifts to quieter and darker areas [13,14]. Although organisms have responded to land-cover