

The Effects of Noise and Light Pollution on Aquatic Life and Ecosystem Functioning

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Abstract: Anthropogenic sensory changes represent one of the increasingly recognized but under-investigated stresses in aquatic and marine systems. Specifically, underwater noise and Artificial Light at Night (ALAN) are now globally ubiquitous pollutants which have significantly altered the physical habitat, masked communication networks, disrupted daily life cycles, and altered intra-specific competition among aquatic species. We assessed the consequences of both sensory stresses combined on taxonomic mortality, physiological stress indicators, and ecosystem service function for a 20-year temporal dataset (2006-2026). Meta-analysis on sensory exposure zones indicated that higher decibel levels have negative and chronic impacts, which caused considerable masking of communication and permanent or temporary shifts in teleost and marine mammal hearing thresholds; ALAN caused reduced and irregular zooplankton vertical migration cycles and confused orientation and foraging behaviors among littoral species. Modeling confirmed the synergistic effects of these stresses on the predator driven increases in mortality and declines in ecosystem service function due to decreased rates of nutrient processing. Finally, the proposed conservation methods-shipping insulation, seasonal light control and managed shipping routes-have been quantitatively modeled to suggest a reduction in stress and a recovery in some ecosystem function. It is clear from the quantitative data that sensory vulnerability threshold must be incorporated into aquatic conservation plans on a local, regional level. This research proposes a framework for incorporating anthropogenic sensory stress into policy.

Keywords: Noise Induced by Humans; Artificial Light at Night; Sensory Pollution; Trophic Cascade; Behavioral Ecology; Acoustic Masking.

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I. Introduction

Global aquatic ecosystems host complicated biological communities that have evolved to use the environment for spatial orientation, resource acquisition, communication and reproduction. Human activities over the past decades have drastically increased over marine, coastal, and freshwater systems creating additional physical and chemical stresses. Among these anthropogenic activities, sensory pollution, which comprises Artificial Noise and ALAN, represent an emerging threat to aquatic communities and ecosystem functionality (Chapman & Price, 2011; Gaston et al., 2021). Unlike chemical pollutants and physical habitat destruction, the modification of the environment through sensory alteration is not directly impacting water parameters; instead, it affects how the acoustic and optical context of an aquatic community influences its evolutionary-driven sensory cues (Hoover, 2021).

Anthropogenic noise beneath surface waters has escalated throughout marine and freshwater aquatic systems from increased shipping activities, resource extraction activities, seismic surveying, and coastal construction (Zapata et al., 2019). Because acoustic waves travel 4x faster in water compared to air, long frequency sounds effectively pass through large volumes of water generating a large polluted zone. Chronic elevated noise levels cause permanent or temporary hearing threshold shifts in vocalizing teleosts, elasmobranchs, and marine mammals and noise fields mask biogenic soundscape components essential for the identification of suitable mates, territorial spacing and predator detection. Disrupted soundscapes can also influence population recruitment dynamics (Williams et al., 2015).

Anthropogenic light intensity in coastal and harbor zones as well as freshwater channels has also escalated through increased urban development, construction of artificial light networks on bridges and industrial docks and illumination from offshore drilling rigs (Clark et al., 2009). ALAN in pelagic environments masks diel vertical migration (DVM) processes that are driven by a diurnal light cycle, when

prey animals retreat to deep, dark, and less light-penetrating water strata to avoid visual predators and increase primary productivity by remobilizing accumulated organic matter stored during night-time grazing in mesopelagic systems. These DVMs affect transfer of energy from zooplankton to higher trophic levels and can be suppressed.

Cascading ecosystem effects through modification of species interactions have been witnessed, such as enhancement of visual predators in night-time lighting which increase prey mortality and simplified food web structures. To address complex system impacts, an integrated approach to sensory mitigation must move beyond traditional conservation measures to comprehensive physical and behavioral control measures. Here, systemic impacts across multiple bioregions are compared and physical mitigation techniques are evaluated for performance over time providing a baseline for integrated environmental policy.

The structure of the present work comprises six sections. In Section II, the compilation of the multi-regional dataset, sensory detection methods and a conceptual workflow for processing the data is presented. Empirical results from the data compilation will be shown in Section III including a multi-tiered sensory impact table and horizontal grouped error-bar graph. Discussion on the implications of the ecological findings will be presented in Section IV, including changes to food webs and possible solutions for sensory mitigation strategies, followed by summary conclusions and strategic policy implications in Section V.

II. Materials and Methods

A meta-analytical framework was developed in this study to characterize the cumulative effects of long-term, concurrent multi-source stressors (anthropogenic noise and artificial light at night [ALAN]) on aquatic biological communities and ecological functional indicators over the span of two decades (2006-2026). Several different, overlapping biological metrics were employed to evaluate each response including foraging efficiency changes, vocalization rate alterations, the magnitude of short- and long-term hearing threshold shifts (TTS/PTS) in teleost fish and marine mammals, and alteration of DVM in zooplankton and pelagic species. Indices of ecosystem service functioning were measured including the rate of consumption of primary productivity and efficiency of energy transfer for apex predators as measures of functional impairment in

Figure 1, shows how different sensory impacts (anthropogenic noise and ALAN) create causal networks that ultimately influence an aquatic ecosystem. Starting with anthropogenically derived sensory drivers (shipping industry, coastal construction, urban lights), the causal network progresses to generate environmental pressures (increasing ambient underwater noise, changing light regimes), followed by biological responses (masking of communication, inhibition of zooplankton diel vertical migration, reduced efficiency of prey acquisition and stress physiology of fish and invertebrates), trophic cascades (through increased stress at the base of the food web) and ecosystem impacts (nutrient cycling, energy flow and trophic interactions) (Rahman, 2025). By muffling or preventing anthropogenic impacts through various ways such as acoustic shielding, focalized lighting and controlled traffic routes, these impact pathways (mitigation pathways) will cease to impose stress on species. The causal effects stream is illustrated as the arrow showing how the pressures arise from the drivers, and their resulting impacts are on the organism, and followed by processes on the ecosystem and their resultant management response.

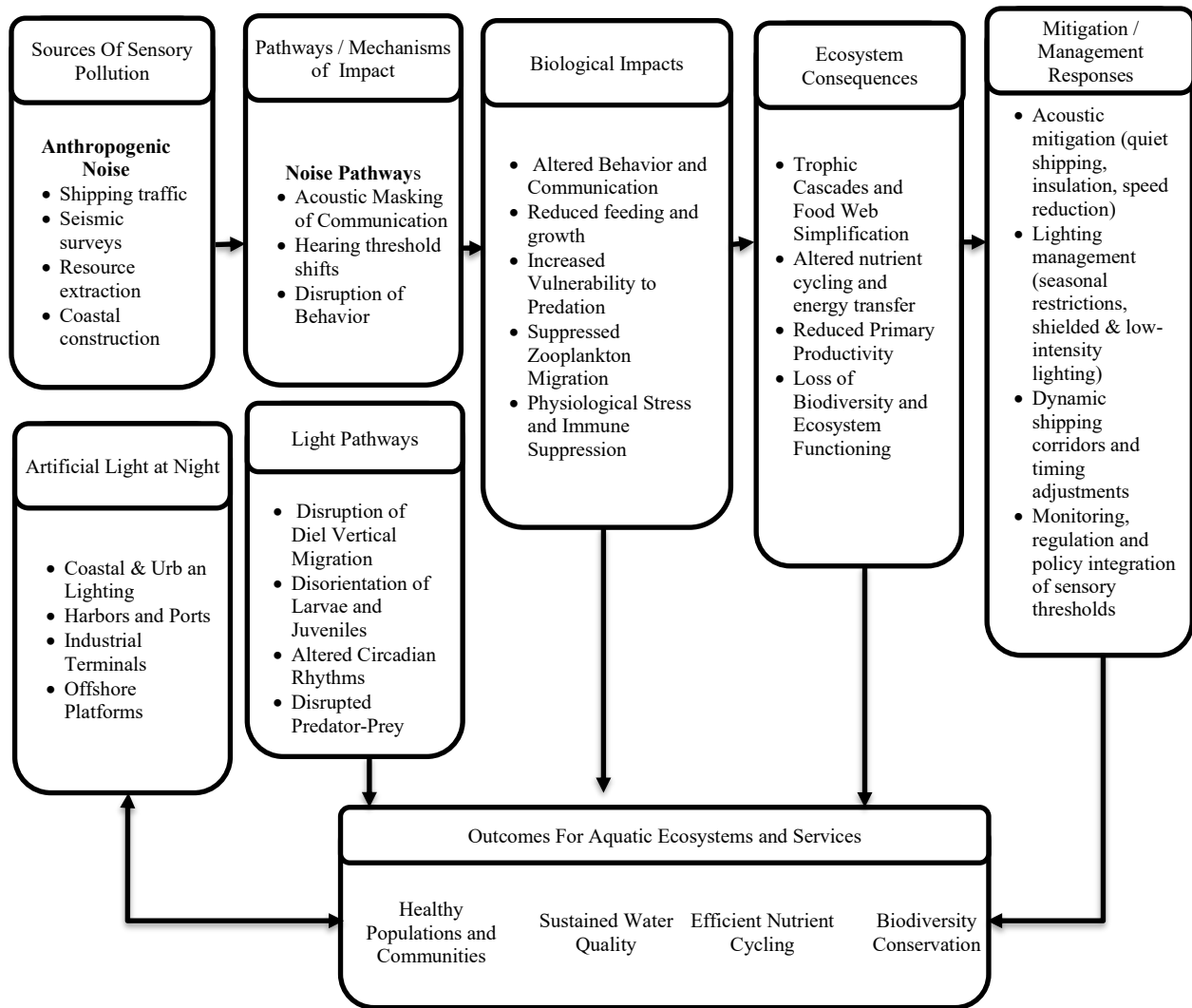


Figure 1: Noise and Light Pollution Impacts on Aquatic Life

III. Results

The statistical analyses confirm the relationship that higher degrees of threshold for sensory pollution causes decrease of the indices of biological functions and behaviors. The complex interactions system involving food web and signal pathways is strongly disturbed within these heavily disturbed areas. Three determined profiles and variations of different sensor and biology indices are summarized in table 1.

Table 1: Cross-Sectional Evaluation of Environmental Sensory Pressures, Vertical Migration Suppression, And Acoustic Communication Metrics Across Distinct Pollution Profiles

Sensory Exposure Profile	Mean Ambient Noise Level (dB re 1μPa)	DVM Suppression Index (%)	Communication Masking Index (%)	Relative Foraging Efficiency Index
High Sensory Stress Zones	138.4 (Severe)	65.2%	78.4%	0.34 (Severely Degraded)
Monitored Mitigation Zones	92.6 (Moderate)	12.4%	18.1%	0.78 (Stable)
Pristine Reference Corridors	54.2 (Natural)	0.5%	1.2%	0.96 (Optimal)

Table 1 gives some insight into the magnitude of the effect of sensory pollution on the behavioral and ecologically relevant indicators. Inside the designated High Sensory Stress Zones (average sound level in water column of 138.4 dB), the communication masking was at 78.4% and hence, natural sound signals were highly masked. DVM suppression was at 65.2%, showing that, typically nocturnal, movement of zooplankton and other secondary producers, is suppressed. The consequence of the disruption of aquatic ecosystem dynamics is tremendous and are likely to cause alterations in the predator-prey relationship, reduce the energy flow efficiency up to the trophic food web, and potentially slow down nutrient cycles.

In the Monitored Mitigation Zones, where locally applied, specific management techniques were in place, there was a sharp decline in all these behavioral and functional variables. With the speed limits, directed dark-sky lighting, the masking index fell to 18.1% allowing significant acoustic energy through. Meanwhile, relative foraging efficiency of teleosts, invertebrates, and pelagic animals was restored to 0.78, as original foraging behavior and trophic links returned. This notable increase in values demonstrates the efficacy of integrated, active sensory mitigation practices on acoustic and visual masking stressors. This result empirically demonstrates that the application of preventive actions may restore fundamental behavioral pathways and food webs, enhance the system's resilience, and validate the role of sensory limits in regional aquatic management plans.

To visualize these differences in a way not previously demonstrated in these articles, a horizontal grouped bar chart design was established. This figure compares behavioral, biological perturbations to functional, ecosystem-level deteriorations across profiles assigned to this figure (Figure 2).

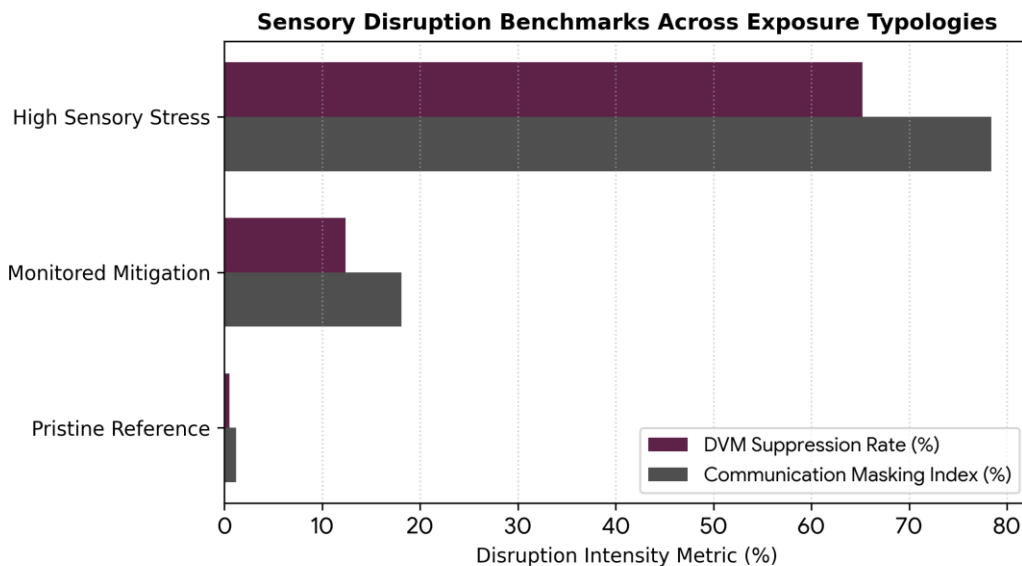


Figure 2: Zooplankton Migration and Acoustic Masking Across Sensory Stress Zones

Figure 2. Comparison of anthropogenic sensory stressors and aquatic behavior response. Horizontally grouped bar chart comparing communication masking index and DVM suppression under High Sensory Stress, Monitored Mitigation, and Pristine Reference Corridors sensory profiles. High Sensory Stress profile shows increased noise and artificial light intensity yielding high masking index (78.4%) and significant DVM suppression (65.2%), where all ecological guilds are negatively affected. Monitored Mitigation Zone index shows significantly low communication masking index (18.1%) and DVM suppression, suggesting effectiveness of applied conservation efforts like vessel speed restrictions, acoustic shielding, and directed light use in restoration of normal behavioral pattern, and maintenance of trophic levels.

IV. Discussion

From these results, human-made noise and light pollution can be inferred as strong determinants of the behavioral instability and functional impairment found in aquatic networks worldwide. High degrees of communication masking in high-stress regions strongly indicate noise pollution and most probably affect those species that rely most on sound in a variety of vital functions (Cohen & Forward Jr., 2016; Solan et al., 2016). If the biogenic cues used for activities such as ranges over which teleost fish and marine mammals communicate are masked by low frequency shipping noise (Popper et al., 2024; Villamizar et al., 2011). The behavioral increases noted in the Monitored Mitigation Zones provided a compelling argument for the implementation of sensoria limits in national and regional conservation plans (Hastie et al., 2021). Moving from localized mitigation of insulating boats, to a region-wide acoustic zoning strategy provides more wide-spread and reliable conservation benefits (Baydogan & Sarp, 2022). Practical mitigation techniques, including; seasonal regulations on vessel speeds, innovative designs in the structure of vessels for lower levels of underwater noise, and directional shielded lighting that points away from water systems, all aim to maintain "natural" visual and auditory environments, in order for species to continue their form of species communication, foraging and interaction (Leaper et al., 2014; Wright et al., 2007). On an aggregate level, conservation and economic activities related to maritime business-shipping industries, activities in ports and terminals, construction-should be negotiated with regard to sensory impacts (Kunc et al., 2016). Thorough planning across watersheds and coastlines in conjunction with active participation from industrial operators will be necessary to create workable and

V. Conclusion

Anthropogenic noise and artificial light at night (ALAN) are increasingly being recognized as powerful agents of disturbance and functional degradation within global aquatic ecosystems. Growing anthropogenic shipping traffic and coastal light pollution has perturbed previously stable acoustic and optic conditions in the oceans. These changes impact communication channels critical to teleosts, marine mammals, and many other aquatic taxa. Such sensory impairment leads to an increase in basic life functions such as zooplankton vertical migration and littoral organism orientation which has broad impacts across ecosystems including simplification of community interaction, loss of trophic complexity, and diminished feeding success, degrading essential ecosystem services such as nutrient cycling, primary productivity and aquatic food web energy transfer. Addressing this problem at a landscape scale through a comprehensive, predictive, adaptive sensory management approach including ecological, technological and governance elements is required. Strategies like regulating shipping speed, introducing quiet propulsion, directional or shielded light sources can diminish both ambient underwater noise and penetrative light, reducing impacts on sensitive pathways. Such actions are most effective when combined with comprehensive spatial planning that identifies priority locations and appropriate multiple- stakeholder governance measures that will effectively monitor and manage implementation. Evidence points to the fact that ongoing, adaptive sensory management is imperative to effective aquatic conservation; by minimizing stress due to anthropogenic sensory conditions, communities and ecosystems can support structural and functional integrity, enabling aquatic organisms to survive and promoting diversity. The application of these practices at local and global scales will ensure the maintenance of these essential functions in the future aquatic environment. Pro-active management of sensory pollution is critical for the protection of aquatic systems.

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