

REVIEW SUMMARY

NOISE POLLUTION

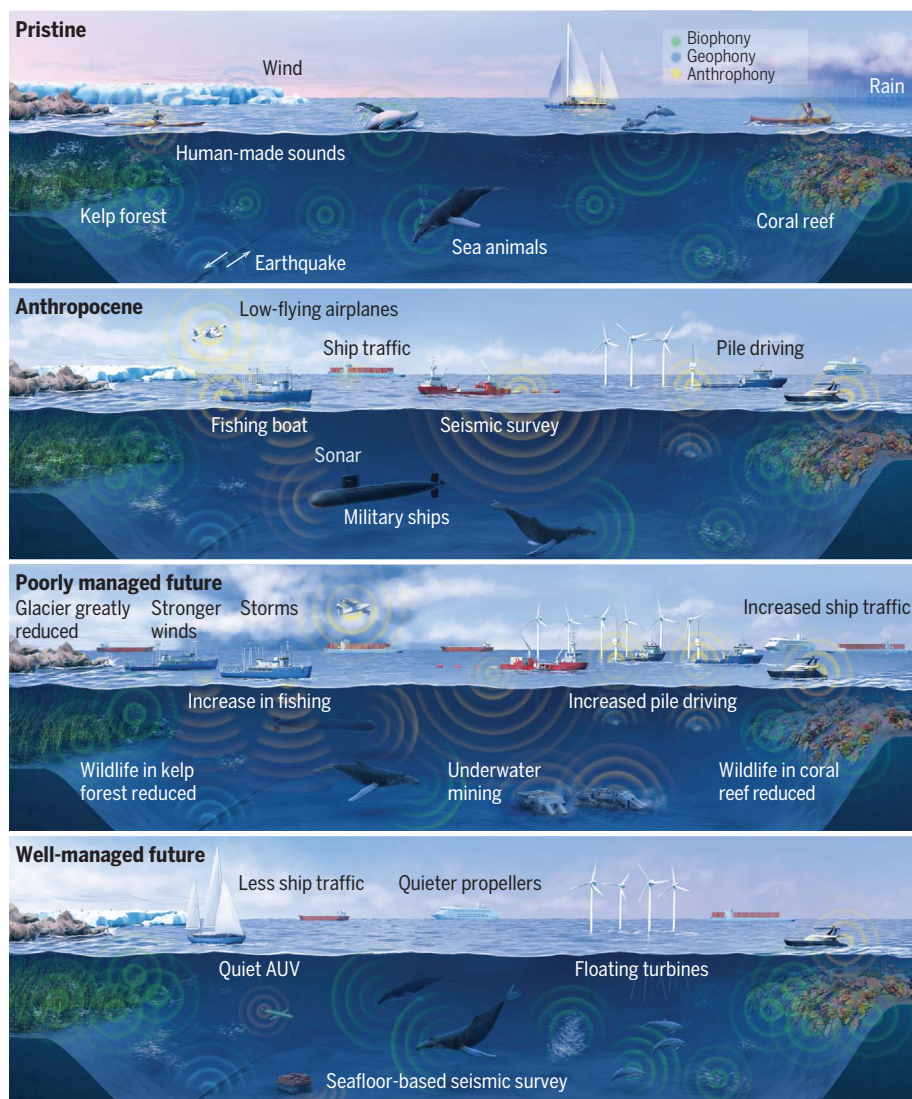
The soundscape of the Anthropocene ocean

Carlos M. Duarte*, Lucile Chapuis, Shaun P. Collin, Daniel P. Costa, Reny P. Devassy, Victor M. Eguiluz, Christine Erbe, Timothy A. C. Gordon, Benjamin S. Halpern, Harry R. Harding, Michelle N. Havlik, Mark Meekan, Nathan D. Merchant, Jennifer L. Miksis-Olds, Miles Parsons, Milica Predragovic, Andrew N. Radford, Craig A. Radford, Stephen D. Simpson, Hans Slabbekoorn, Erica Staatterman, Ilse C. Van Opzeeland, Jana Winderen, Xiangliang Zhang, Francis Juanes

BACKGROUND: Sound is the sensory cue that travels farthest through the ocean and is used by marine animals, ranging from invertebrates to great whales, to interpret and explore the marine environment and to interact within and among species. Ocean soundscapes are rapidly changing because of massive declines in the abundance of sound-producing animals, increases in anthropogenic noise, and altered

contributions of geophysical sources, such as sea ice and storms, owing to climate change. As a result, the soundscape of the Anthropocene ocean is fundamentally different from that of preindustrial times, with anthropogenic noise negatively impacting marine life.

ADVANCES: We find evidence that anthropogenic noise negatively affects marine animals.



Strong evidence for such impacts is available for marine mammals, and some studies also find impacts for fishes and invertebrates, marine birds, and reptiles. Noise from vessels, active sonar, synthetic sounds (artificial tones and white noise), and acoustic deterrent devices are all found to affect marine animals, as are noise from energy and construction infrastructure and seismic surveys. Although there is clear evidence that noise compromises hearing ability and induces physiological and behavioral changes in marine animals, there is lower confidence that anthropogenic noise increases the mortality of marine animals and the settlement of their larvae.

OUTLOOK: Anthropogenic noise is a stressor for marine animals. Thus, we call for it to be included in assessments of cumulative pressures on marine ecosystems. Compared with other stressors that are persistent in the environment, such as carbon dioxide emitted to the atmosphere or persistent organic pollutants delivered to marine ecosystems, anthropogenic noise is typically a point-source pollutant, the effects of which decline swiftly once sources are removed. The evidence summarized here encourages national and international policies to become more ambitious in regulating and deploying existing technological solutions to mitigate marine noise and improve the human stewardship of ocean soundscapes to maintain a healthy ocean. We provide a range of solutions that may help, supported by appropriate managerial and policy frameworks that may help to mitigate impacts on marine animals derived from anthropogenic noise and perturbations of soundscapes. ■

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Changing ocean soundscapes. The illustrations from top to bottom show ocean soundscapes from before the industrial revolution that were largely composed of sounds from geological (geophony) and biological sources (biophony), with minor contributions from human sources (anthropophony), to the present Anthropocene oceans, where anthropogenic noise and reduced biophony owing to the depleted abundance of marine animals and healthy habitats have led to impacts on marine animals. These impacts range from behavioral and physiological to, in extreme cases, death. As human activities in the ocean continue to increase, management options need to be deployed to prevent these impacts from growing under a “business-as-usual” scenario and instead lead to well-managed soundscapes in a future, healthy ocean. AUV, autonomous underwater vehicle.

REVIEW

NOISE POLLUTION

The soundscape of the Anthropocene ocean

Carlos M. Duarte^{1,2*}, Lucille Chapuis³, Shaun P. Collin⁴, Daniel P. Costa⁵, Reny P. Devassy¹, Victor M. Eguiluz⁶, Christine Erbe⁷, Timothy A. C. Gordon^{3,8}, Benjamin S. Halpern^{9,10}, Harry R. Harding¹¹, Michelle N. Havlik¹, Mark Meekan⁸, Nathan D. Merchant¹², Jennifer L. Miksis-Olds¹³, Miles Parsons^{8,7}, Milica Predragovic¹, Andrew N. Radford¹¹, Craig A. Radford¹⁴, Stephen D. Simpson³, Hans Slabbekoorn¹⁵, Erica Staaterman¹⁶, Ilse C. Van Opzeeland¹⁷, Jana Winderen¹⁸, Xiangliang Zhang¹⁹, Francis Juanes²⁰

Oceans have become substantially noisier since the Industrial Revolution. Shipping, resource exploration, and infrastructure development have increased the anthrophony (sounds generated by human activities), whereas the biophony (sounds of biological origin) has been reduced by hunting, fishing, and habitat degradation. Climate change is affecting geophony (abiotic, natural sounds). Existing evidence shows that anthrophony affects marine animals at multiple levels, including their behavior, physiology, and, in extreme cases, survival. This should prompt management actions to deploy existing solutions to reduce noise levels in the ocean, thereby allowing marine animals to reestablish their use of ocean sound as a central ecological trait in a healthy ocean.

Soundscapes, defined as “ambient sound in terms of its spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field” (1), are changing rapidly in the Anthropocene. In contrast to the long-standing recognition of the effects of anthropogenic sound in terrestrial systems (2), the impacts of changing ocean soundscapes on marine animals have received relatively limited attention. This neglect percolates reviews of cumulative stressors

(3, 4) and drivers of global change in the ocean (5, 6), as well as scientific assessments (7) and policy frameworks [United Nations Convention on Biological Diversity (UNCBD), UN Convention for the Law of the Sea (UNCLOS), UN Sustainable Development Goals (UN SDGs)] aimed at improving ocean conservation and sustainability. Given the rapid pace of change in ocean soundscapes, we argue that there is an urgent need to assess the evidence for impacts of anthropogenic noise on marine life, which will enable policy frameworks to mitigate human impacts on ocean soundscapes as a necessary foundation for a healthy ocean.

Here, we review how the changing ocean soundscape of the Anthropocene is affecting marine life. We do so by first summarizing our current understanding of the importance of sound to marine animals and the components and ecological relevance of undisturbed ocean soundscapes. We show how ocean soundscapes are changing in the Anthropocene and assess, on the basis of a systematic review of four decades of published research, the evidence for the resulting impacts on marine animals. We then discuss how available solutions, if supported by appropriate managerial and policy frameworks, may help mitigate impacts on marine animals that arise from anthropogenic noise and perturbations of soundscapes.

Hearing the ocean soundscape

Sound propagates relatively fast and far under water, carrying information over greater spatial scales than most other sensory cues such as light or chemicals (8). As a result, marine animals have evolved a wide range of receptors to detect sound, which have been well studied for marine mammals but have been

only recently described for invertebrates, such as jellyfish (9, 10) (Fig. 1). Hearing in marine animals (Fig. 1) ranges from marine invertebrates, fishes, and reptiles, which perceive sounds of relatively low frequency (generally <5 kHz), to cetaceans, which can detect high-frequency (up to 200 kHz) sound (Figs. 1 and 2B). The hearing range of marine animals is a key determinant of their potential responses to different components of ocean soundscapes and their vulnerability to impacts from different sources of underwater noise (Fig. 2B).

Before the Industrial Revolution, ocean soundscapes were largely composed of sounds from geological (geophony) and biological sources, produced both intentionally and unintentionally (biophony), with minor contributions from human sources (anthrophony). Understanding the contexts and relative contributions of these sound sources provides key insights into how anthropogenic changes to ocean soundscapes may affect marine life and the overall health of the ocean.

Weather conditions and geological processes make important contributions to marine soundscapes. Wind blowing over the ocean, waves breaking, rain or hail falling onto the sea surface, and gas bubbles vibrating, rising, and bursting at the surface all generate characteristic sound spectra [(11, 12); Fig. 2A]. In polar regions, seasonal processes like ice melting, pressure cracking, and iceberg calving dominate soundscapes (13), and noise from earthquakes, undersea volcanoes, and hydrothermal vent activity (14) potentially propagate thousands of kilometers [(15); Fig. 2A]. Each of these geophonic components produces sound over different frequencies and spatial and temporal scales (Fig. 2A), which is, therefore, perceived differently by various types of animals (Fig. 2B).

Marine animals intentionally produce sounds ranging from infrasonic (<20 Hz) to ultrasonic (>20 kHz), although most are emitted between 10 Hz and 20 kHz and are audible to a wide range of taxa (Fig. 2B). These sounds may be frequency and/or amplitude modulated and can be emitted as single pulses or occur in regular sequences or temporal patterns, such as pulse trains of fish calls and melodic phrases of whale songs. The continuous singing of single individuals, the gregarious chorusing of a group, or the collective sounds of some animals foraging or moving (e.g., urchins or crabs across a reef) can increase sound levels in particular frequency bands. Biophony may also be modulated by changes in weather, currents, and other factors, exemplified by the cessation of fish chorusing due to the passage of a hurricane (16).

Animals produce sounds for a range of reasons, including navigation, foraging, agonistic displays, territorial defense, mate attraction, and reproductive courtship (17–19). For example,

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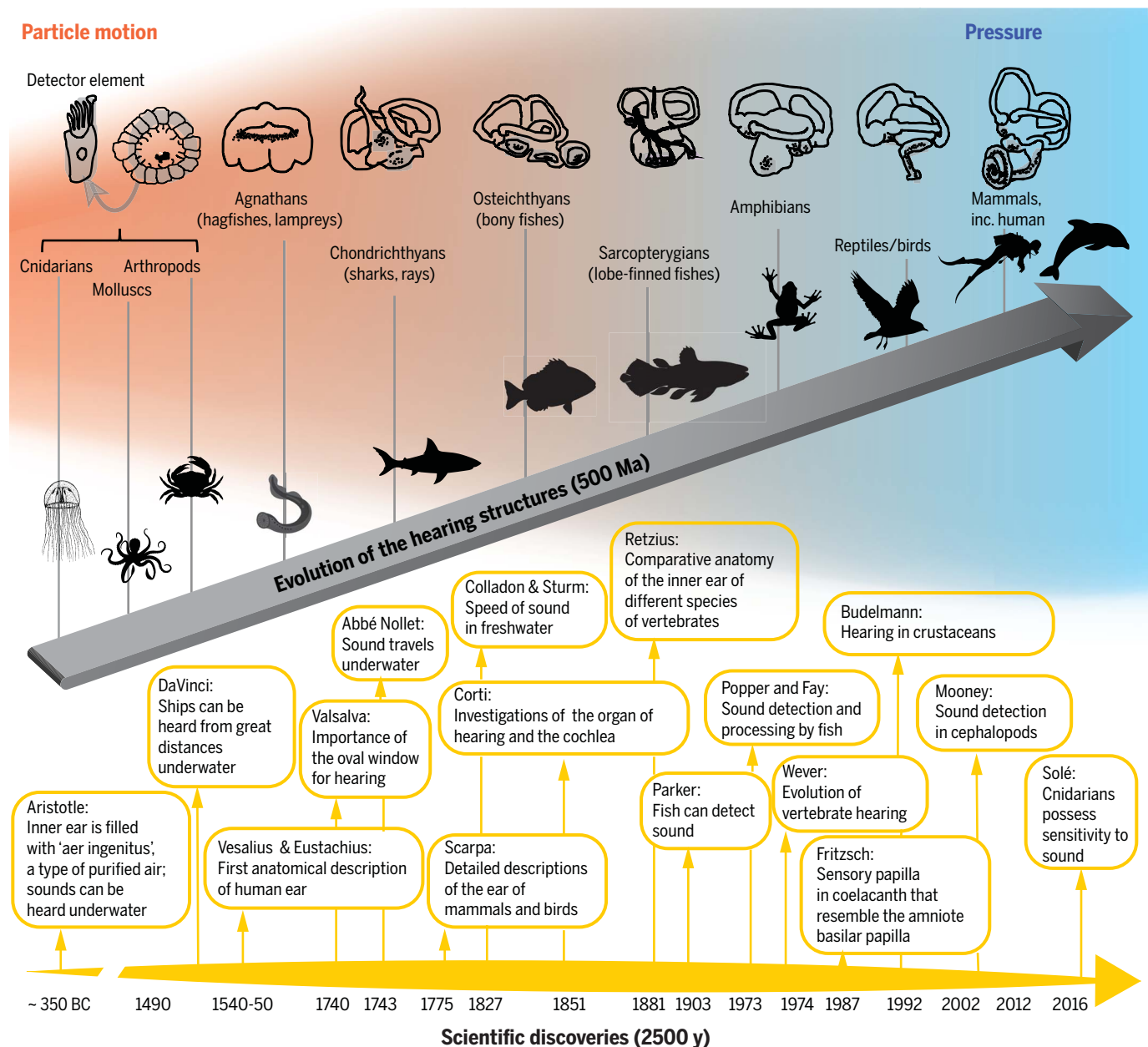


Fig. 1. Evolution of hearing under water and timeline of scientific advances.

Evolution and timeline events are from (129). Hair cells as a mechanosensory receptor for hearing appeared early in the evolution of animals (10), evolving from invertebrate statocysts, which detect gravity and vibrations underwater, to fish ears, which perceive sounds of relatively low frequency (<5 kHz). Some bony fishes (Osteichthyes) have evolved ancillary hearing structures that connect the ear with the swim bladder, increasing hearing bandwidth and sensitivity (25). When marine tetrapods moved onto land, acoustic organs, adapted to hearing sound as pressure waves (89), evolved to compensate for communication in air,

a lower-density medium, which slowed the movement of sound waves relative to water. Impedance-matching structures, or tympanic middle ears, appeared independently in reptiles, birds, and mammals (90), increasing the overall sensitivity of hearing to exceed, in some mammals, 50 kHz. Further changes in the pressure-sensing ear occurred as reptiles and mammals returned to the ocean (130). In toothed whales, the middle ear evolved to receive sound passing through the fatty tissues in the jaws, an effective means of conduction that increases the upper hearing limit of these mammals to 200 kHz (131). Ma, million years ago; y, years.

male toadfish guard benthic nests and produce "hums" to attract females, rendering these sounds key components of some night-time soundscapes [e.g., (20, 21)]. Fishes—such as Atlantic cod (*Gadus morhua*), croakers (Sciaenidae), and groupers (Serranidae)—use sounds to gather in large aggregations and

coordinate spawning activities (22–24). Marine mammals use vocal communication to aid in mating, rearing of young, and group cohesion, among other social (25) and feeding functions (26). Pinnipeds produce sounds both in air and under water that are associated with territorial and mating behavior, particularly during the

breeding season (27). Bearded seals (*Erignathus barbatus*), for example, produce frequency-modulated trills, which are a major component of Arctic soundscapes in spring (28). Baleen whales produce low-frequency reproductive and social calls that can travel across ocean basins (29), with humpback whales

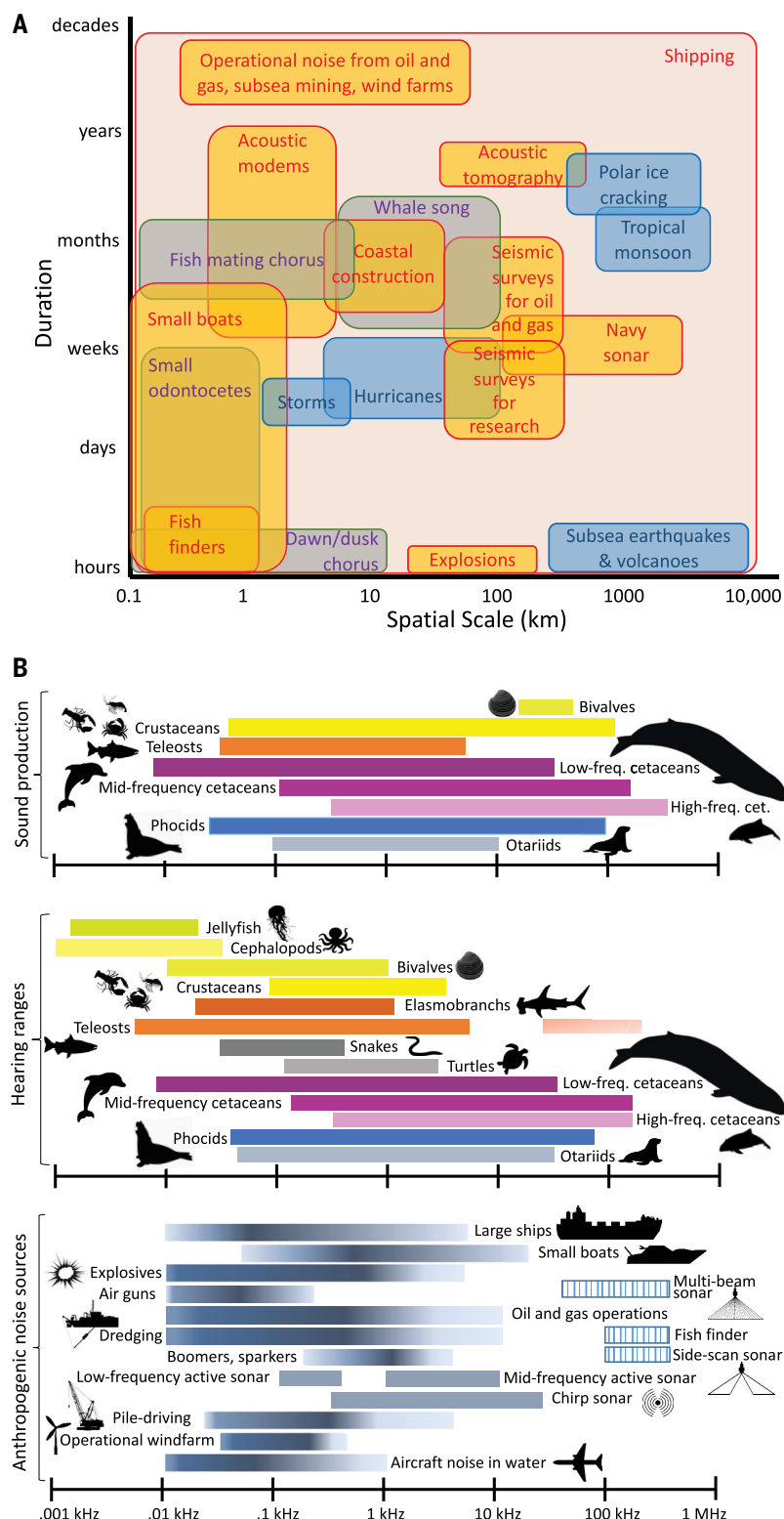


Fig. 2. Sources and animal receivers of sound in the ocean soundscape.

(A) Stommel diagram showing the spatial extent and duration of selected biophony (rounded gray squares), geophony (rounded blue squares), and anthropophony (rounded yellow squares) events. Events (rounded squares) reflect the spatial and temporal period over which signals or bouts of signals typically occur. Although some sound sources, such as those used in hydrographic surveys, do not propagate particularly far, survey efforts can cover a large spatial extent (an entire Exclusive Economic Zone). “Dawn/dusk chorus” refers to the daily sounds produced by a

collection of species (e.g., fish, snapping shrimp). Shipping noise encompasses the full range of spatial and temporal scales. (B) Approximate sound production and hearing ranges of marine taxa and frequency ranges of selected anthropogenic sound sources. These ranges represent the acoustic energy over the dominant frequency range of the sound source, and color shading roughly corresponds to the dominant energy band of each source. Dashed lines represent sonars to depict the multifrequency nature of these sounds. Sources for the data displayed in the figures are (9, 18, 25, 53, 75, 83, 131–139).

(*Megaptera novaeangliae*) singing complex songs as part of male reproductive displays that have regional dialects and change over time (30).

Marine animals also produce mechanical sounds, such as those produced by the impact of different body parts on environmental substrates (e.g., breaching, tail slaps), which often convey information about body mass and size (31) and movement and foraging behaviors (32, 33). Sea urchins and parrotfishes, for example, make scraping or crunching sounds as a by-product of foraging that occur in predictable peaks associated with tidal or diurnal cycles (34, 35). Other animals use sound to forage. Snapping shrimps produce a “snap” sound to stun prey, which creates a loud “crackling” sound that is present in many coastal habitats that support dense colonies of these shrimps (36). Odontocetes, such as sperm whales (*Physeter macrocephalus*) and various species of dolphins and porpoises, also possess sophisticated biosonar systems that produce sounds to echolocate, select, and pursue prey under water (26).

The diversity, composition, and density of the biophonic community are key components of the soundscape ecology paradigm, which seeks to identify habitats and assess their health status using sound. An ecological role

for ocean soundscapes is supported by the fact that many species use ocean soundscapes as a cue to find their habitats at key life stages. For example, larvae and juveniles of some invertebrate and vertebrate reef species use soundscapes as a navigational cue to locate suitable settlement habitats (37). Indeed, the distinctive sound-producing structures or organs of marine animals provide, in many cases, an acoustic fingerprint that aids their identification within soundscapes, allowing for inferences on their identity, behavior, and sometimes relevant life history and physical traits (38–40).

Advances in acoustic-recording technology allow ocean soundscapes to be characterized for longer periods of time and at greater depths than previously possible (36). In parallel, new tools for soundscape analysis facilitate both species-specific call recognition and summative approaches to resolve the entire acoustic spectrum. Despite this progress, the paradigm that soundscapes can be used as proxies for ecosystem health, developed for terrestrial ecosystems (41), has been applied to the marine environment with only limited success [e.g., (42, 43)]. In some cases, sound-pressure levels in low frequencies correlate positively with visual measures of fish diversity, coral

cover, and invertebrate abundance (44, 45). Efforts to reduce the dimensionality of a complex soundscape to a single number that reflects the diversity or complexity of a soundscape [e.g., (46)] may provide useful biological information (27, 42) but cannot be readily generalized, because the results obtained are highly sensitive to parameterization (47). Instead, multiple indices relating to characteristics of individual sounds can be combined to provide an indication of the contribution of particular sound types (48). Overall, assessments of ocean soundscapes demonstrate a growing contribution of human activities across the ocean (Fig. 3).

The soundscape of the Anthropocene ocean

Human activity has altered biophony and geophony and has, either deliberately or as a by-product, added an increasingly prevalent third component—anthrophony—across a broad range of frequencies to ocean soundscapes (2) (Fig. 2B). Examples of deliberate human use of marine sound include seismic surveys that produce high-energy, low-frequency, short-duration sounds aimed at detecting the presence of petroleum and gas deposits below the seafloor, as well as multibeam echosounders and side-scan sonars that generally produce high-frequency sounds to map the seabed and

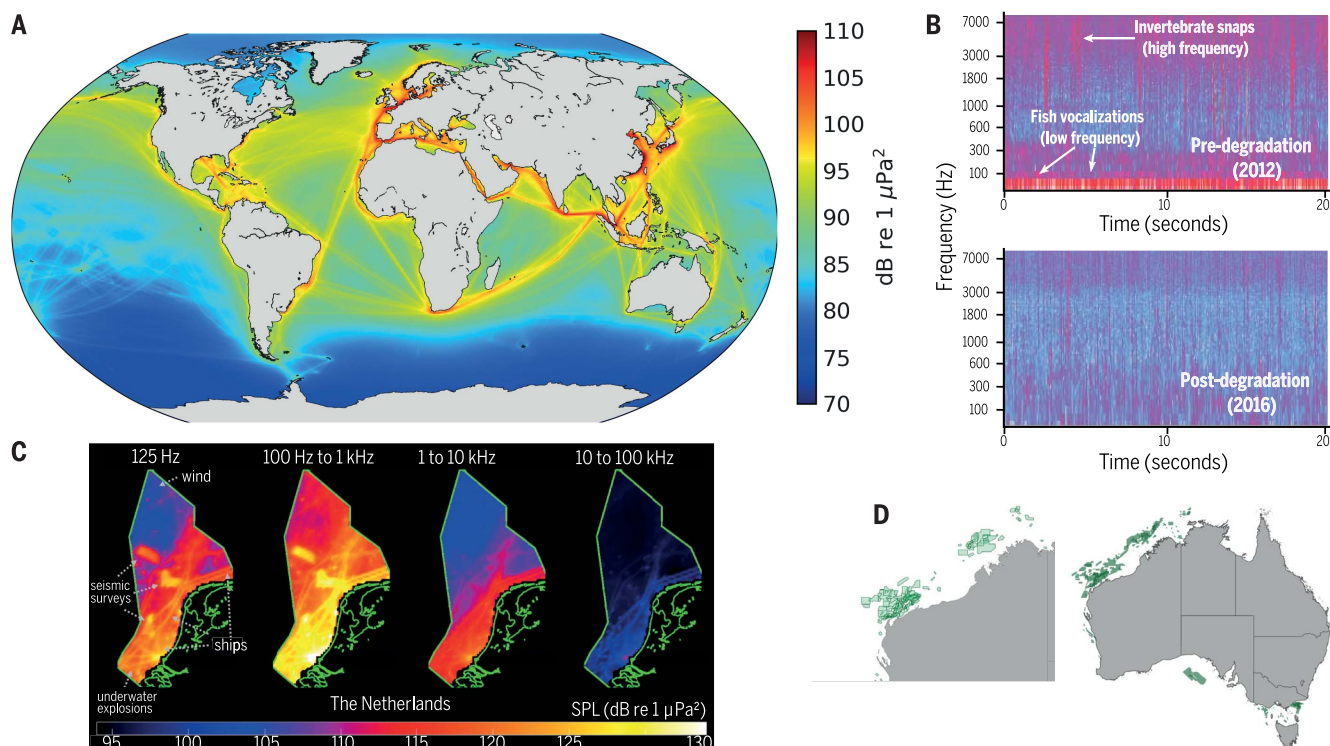


Fig. 3. Human pressures have altered ocean soundscapes at scales ranging from local to global. (A) Average sound level estimated globally from marine traffic (at 100 Hz), based on average shipping activity directed from automatic identification system (AIS) data for 2014. (B) Sound-pressure levels pre- and postdegradation at sites around Lizard Island in the Great Barrier Reef (62). (C) Sound levels in four different frequency bands in the Dutch North Sea, averaged over 2 years [adapted from (140)]. (D) Boundaries of three-dimensional seismic surveys in northwest Australia (left) and seismic lines of two-dimensional surveys in all Australian waters (right) since 1973 (data from wapims.dmp.wa.gov.au/wapims and https://nopims.dmp.wa.gov.au/nopims).

detect organisms and particles in the water column. These sensing techniques are, at times, a major component of present ocean soundscapes in many areas, especially those holding oil and gas reservoirs (49, 50), such as the continental shelf of northwestern Australia and the North Sea (Fig. 3D). Across the ocean, scientific surveys use similar tools to map the seabed and identify geological features, fishers use “fish finders” to search for schools of fish, and navies use active sonars across a range of frequencies to detect submarines and other targets.

Much of anthrophony is an unintended by-product of human activities (Figs. 2 and 3), which are intensifying across the ocean. Over the past 50 years, increased shipping has contributed an estimated 32-fold increase in the low-frequency noise present along major shipping routes (51) (Figs. 2 and 3). Vessel noise is prominent in many ocean regions even away from major shipping lanes, owing to long-range sound propagation at low frequencies, although some areas display stable or even decreasing sound levels in targeted frequency bands (52). Whereas vessel noise does not propagate as far in shallow coastal waters, the higher vessel concentration often increases noise considerably above ambient levels in coastal regions.

Further anthrophony comes as an unintended by-product of less frequent, but still common, human activities associated with coastal development and resource extraction. Traffic on structures like bridges and airplanes flying at low altitude over the ocean produce low-level, continuous noise that can penetrate under water (53). Pile-driving during the construction of offshore wind farms can substantially increase local sound levels (54), but the operational noise of turbines tends to attenuate below ambient levels of natural sound within a few hundreds of meters of wind farms (55). Similarly, construction and operation of oil and gas infrastructure (e.g., platforms, pipelines) increase anthrophony (56). The dynamic positioning systems (i.e., propellers and thrusters) used to maintain the position of offshore structures, such as drilling platforms, produce low-frequency noise (57). Technology that scrapes the bottom of the ocean—whether dredging the seafloor, harvesting minerals, or trawling for fisheries—also generates low-frequency noise (58). Dynamite fishing, designed to stun or kill reef fish for easy collection, remains a major source of blasting noise in Southeast Asia and coastal Africa, and controlled detonation of bombs dropped on the seafloor during World War II continues, more than 70 years later, to be a major source of disruptive and destructive sound in the North Sea (Figs. 2 and 3). Explosions of mines, missiles, and bombs during naval warfare or military exercises also repre-

sent a source of destructive sound. On a small scale, even coastal recreational activities—such as small motorboats, swimming, SCUBA diving, surfing, paddling, flying unmanned aerial vehicles (drones), or fireworks—contribute anthrophony to marine soundscapes (59–61).

Humans have also profoundly altered biophony and geophony in ocean soundscapes. Hunting of large marine animals, particularly highly vocal whales and pinnipeds, which began hundreds of years ago, has led to reduced and less diverse biophony in ocean soundscapes of the present. Sound levels of natural soundscapes decrease with the degradation of kelp forests, seagrass beds, coral reefs, and sponge beds, owing to fewer vocalizing animals (62–66). Biophony may also be reduced where soundscapes are heavily polluted by anthrophony as animals cease vocalizing or are displaced from ecosystems.

Climate change is increasing the number of cyclones and marine heatwaves that degrade marine habitats, which, in turn, may alter biophony. For example, degradation of coral reefs associated with these events dramatically changes ambient soundscapes, with the altered composition of the biotic community reflected in reduced overall acoustic energy and the complexity and diversity of reef soundscapes (46). Changes in the distributions of species with ocean warming also shift biophony. For example, reduced sea ice in the Arctic allows the range expansion of temperate whale species that compete for acoustic niche space with Arctic species, such as beluga whales (*Delphinapterus leucas*) (67). In addition, climate change directly affects the temperature, heat content, and stratification of the ocean, with sound traveling faster in a warmer ocean, to the extent that long-range acoustic transmissions have been used to measure large-scale ocean temperature and heat content—a phenomenon that W. Munk termed “the sound of climate change” (68). Ocean warming also affects geophony in polar areas through decreasing sea ice cover, with the soundscape of a progressively ice-free Arctic Ocean departing from that of the ice-covered Arctic Ocean of the past (69, 70). High sound levels occur during periods of ice formation, whereas polar soundscapes are very quiet in the high-frequency range during periods of solid ice coverage (71). Ice-free waters will also likely lead to increased anthrophony through greater ease of human access and activity (shipping, fishing, and seismic surveys) in a warming Arctic Ocean. An increased inflow of shallow “tongues” of warm, salty Pacific and Atlantic waters into the Arctic Ocean is also dramatically altering the acoustic environment by creating a local maximum in the sound speed profile at the depths between 100 and 200 m. This water layer acts as a strong acoustic duct, channeling sound across dis-

tances of 80 to 100 km (69), with comparable effects reported in coastal areas receiving glacial melt waters. In the tropics, climate change may increase geophony levels because of increased winds, rainfall on the surface, and waves as the energy of tropical storms increases. Greenhouse gas emissions also change sound propagation in the ocean by decreasing pH as CO₂ levels increase, which is expected to lead to a noisier ocean, owing to substantial decreases in ocean sound absorption for frequencies lower than about 10 kHz (72, 73).

Impacts of altered soundscapes in the Anthropocene ocean

Initial awareness of the impacts of the altered soundscapes of the Anthropocene ocean on marine life derived from evidence of injuries from high-intensity noise. This initial evidence focused on large iconic marine mammals (25) but has been expanded to include links between noise from military sonar, air guns, submarine explosions, and seismic surveys and hearing disabilities, mass strandings, and mortality of a number of marine animals (table S2).

Research on the ecological impacts of anthrophony has expanded to address the pervasive and prevalent impacts of chronic exposure to noise across vast spans of the ocean [table S2; (74)] and the potential impacts of anthropogenic noise on fishes (75–79), invertebrates (80, 81), and whole marine ecosystems (82). Anthropogenic noise can interfere with natural auditory signal processing by marine animals, an effect termed “masking” (83), which reduces their communication space [see (84) for marine mammals, (85) for fishes]. Indeed, anthropogenic noise overlaps with the frequency band of hearing of marine animals across increasingly broad areas of the ocean (86–88) (Fig. 2). Masking of signals from conspecifics or environmental cues indicating the presence of prey or predators may result in loss of social cohesion, missed opportunities for feeding, or failure to avoid a predator (25).

The frequency content of vessel noise (Fig. 2) overlaps considerably with the hearing ranges of marine fauna (20), particularly those with sensitivity in relatively low-frequency ranges [e.g., fishes, some marine mammals, and reptiles (20, 25, 89–91)], where most of the noise energy lies. Shipping noise has been reported to disrupt traveling, foraging, socializing, communicating, resting, and other behaviors in marine mammals (84); attenuate antipredator behavior of young fishes, leading to increased mortality and reduced ability to learn to avoid predators in future encounters (79); and impact the settlement and development of invertebrates (85). A concurrent increase in anthrophony and decrease in biophony with habitat degradation and declines in populations of marine species also likely affects onshore

larval movement patterns, and hence settlement success, across a range of species.

Given the potential for anthropogenic noise to detrimentally affect marine animals (82, 92, 93), we examined the robustness and consistency of the evidence for impacts of anthropophony and other human alterations to ocean soundscapes on marine animals through a systematic assessment of the results on this topic presented in the published literature (94). This generated a total of 538 studies that attempted to quantify the effects of anthropogenic noise and perturbations of soundscapes on marine animals. We adopted the confidence scale of the Intergovernmental Panel on Climate Change (IPCC) (95) to reflect the robustness of the evidence supporting various statements on the extent of the impacts.

There was high confidence that anthropogenic noise negatively affected marine animals (Fig. 4 and table S4). The evidence was strongest for marine mammals, for which 85 to 94% of quantitative studies found significant effects, with 82 and 81% of studies finding significant impacts on fishes and invertebrates, respectively, and the two studies available for reptiles and one of the two studies on marine birds reporting significant impacts on these animals (Fig. 4 and table S4). Noise from vessels (94.9% report significant impacts), sonars (90%), and acoustic deterrent devices (91%) negatively affects marine animals, as does noise from energy (8.23% of studies) and construction infrastructure (82.3%) and seismic surveys (74.4%) (Fig. 4 and table S4). Available data provide ample evidence that noise pollution compromises hearing ability (90.6% of studies report significant impacts), induces physiological changes (91.2%), and elicits evasive actions and displaces marine animals (83.9%) (Fig. 4 and table S4). By contrast, evidence for impacts of anthropogenic noise on mortality and fitness of marine animals is weaker, with 35.2 and 50% of studies reporting significant impacts, respectively (Fig. 4 and table S4). All quantitative studies conducted thus far provide evidence that changes in biophony reduce the settlement of marine larvae, but the number of quantitative studies testing impacts on settlement remains limited ($n = 7$; table S4).

Our assessment revealed that despite the large volume of literature on the impacts of anthropogenic noise on marine animals, there is a paucity of quantitative assessments for diving marine reptiles and seabirds and only a limited number of studies on pinnipeds and sirenians (Fig. 4). Likewise, the evidence supporting that changes in biophony resulting from habitat degradation reduce the settlement of marine larvae on preferred habitats was weakened by the few studies available. The evidence for impacts on animals exposed to multiple sources of anthropogenic noise was

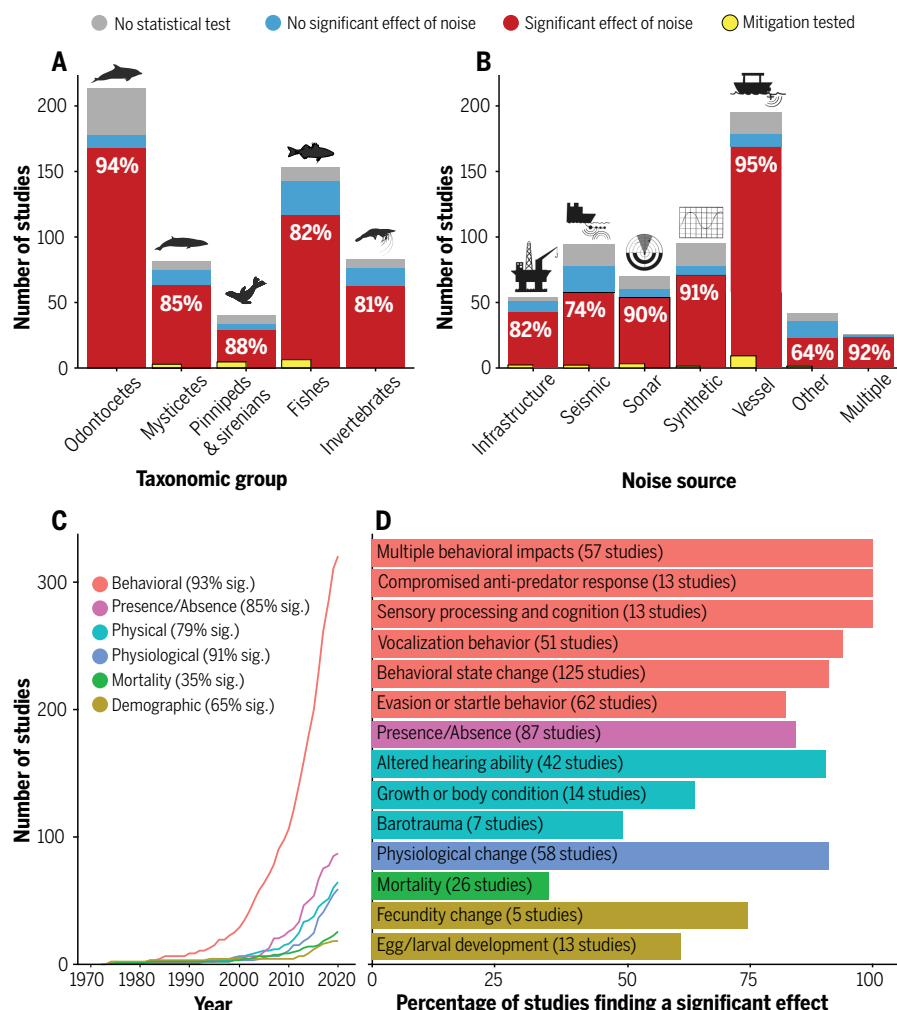


Fig. 4. Synthesis of the negative impacts of noise pollution on marine animals present in the literature.

The estimates provided here derive from a systematic literature review [(74), compare supplementary materials]. (A and B) Total number of studies found, split by (A) taxa (excluding birds and reptiles, which together accounted for only six studies) and (B) noise source. Colors indicate the proportion of different statistical outcomes (red, significant negative effect of noise; blue, no significant effect of noise; gray, no statistical test) and the proportion of studies that seek to directly test the impact of noise-mitigation strategies such as bubble curtains and altered engine types (yellow). White numbers indicate the percentage of studies with a statistical test (red plus blue) that find a significant effect of noise (red). (C) Cumulative frequency curves over time of all studies, split by effect category. Searches were carried out from 1900 to 2020, but no records that met the criteria were found before 1973. (D) The percentage of studies in each subcategory that found a significant effect of noise, calculated as a fraction of the total number of studies with a statistical test.

also small, limiting the assessment for cumulative impacts. In addition, we found a very limited number of studies testing the effectiveness of mitigation measures, which makes it difficult to provide confidence on their performance. This may preclude these mitigation measures from being adopted by national and international policies aimed at reducing the impacts of anthropogenic noise on marine life. The gaps identified in our systematic review underscore areas where research efforts should focus to provide a comprehensive understanding of the impact of anthropogenic noise on marine animals, integrate these impacts to

assess population-level consequences from chronic exposure to anthropogenic noise, and deliver effective mitigation measures.

In addition to controlled experiments, global disruptions offer an opportunity for serendipitous observations of the effect of anthropogenic noise on marine life at scale. For instance, reduced ship traffic in the Bay of Fundy, Canada, after the events of 11 September 2001 resulted in a 6-dB decrease in underwater noise, particularly at frequencies less than 150 Hz, with some evidence suggesting that this reduced stress in right whales (*Eubalaena glacialis*) (96). Likewise, strategies to combat

COVID-19 infections, which involved confinement of about 58% of the global human population, have also provided ample evidence of an unusual expansion of the movements of marine mammals and sharks to what were previously busy, noisy waterways, such as harbors and coastal urban areas, where they are not regularly seen (97). This unusual behavior has been linked to reduced anthropogenic noise during human confinement (98, 99).

Marine animals may recover from and cope with intense anthropogenic noise through avoidance behavior or habituation (100, 101). The former behavior is a common response of marine animals to potentially damaging or disruptive levels of anthropophony but may displace species from important foraging grounds (100) and is not always possible for species that have high site fidelity and small biogeographical ranges, such as the critically endangered Maui dolphin (*Cephalorhynchus hectori maui*) (102), or slow-moving species, like benthic invertebrates, which have a limited scope to avoid noise. When hearing damage occurs from loud noises, fish may recover better than marine mammals because hair cells regrow in fish but are unlikely to regenerate in mammals (103). Avoidance behavior by fish in response to the approaching sound of fishing vessels is well documented (103). However, this may also be induced by sounds from recreational boats, resulting in flight responses and interruption of foraging, reproductive, or vocalizing activities (104). Conversely, it is possible that some predatory marine mammals and large fishes may use the sound of vessels as a “dinner bell” alerting of opportunities to depredate catch from fishing boats (105, 106). These examples provide evidence for behavioral plasticity or acclimation but do not provide evidence for evolutionary adaptation, which requires observational time scales that have not yet been achieved in soundscape ecology.

Marine mammals may adapt to anthropophony, but the long life span and large home ranges of many marine mammals render assessment of adaptations to noise challenging. For instance, some mammals—such as killer whales (*Orcinus orca*), right whales (*Eubalaena* spp.), and Guiana dolphins (*Sotalia guianensis*)—and fishes have been shown to alter the source level or frequency of vocalizations in order to be heard, a phenomenon known as the Lombard or cocktail party effect (107–110). Habituation, in the form of increasing tolerance, has been demonstrated for some species of marine mammals and fishes (101, 111). In some situations, habituation may be considered a reduced response to stimuli that have no biological importance on the individual being observed (112), although disturbance involving a sensory modality that is so fundamental to most

marine animals would not often be considered inconsequential.

Although our assessment shows that anthropogenic noise detrimentally affects marine animals, a lack of global syntheses of data has resulted in it being typically ignored in reviews of cumulative and/or global impacts of anthropogenic stressors on marine life (3, 5, 6, 113) and consequently by the high-level policy initiatives (e.g., UNCBD, UNCLOS, UN SDGs) that these analyses inform. For instance, the draft of the UN Law of the Sea “BBNJ” Agreement on Biodiversity in Areas Beyond National Jurisdiction (114) does not mention noise among cumulative impacts, despite mandating an environmental impact assessment of activities in the high seas and the fact that anthropogenic noise was discussed at its 19th session of the process in June 2018. The last assessments of climate change impacts by the IPCC (115) have yet to acknowledge the impacts that climate change has on ocean soundscapes, whereas the recent IPCC report on oceans and the cryosphere acknowledges noise only in the context of increased human operations in the Arctic Ocean (116). Our review of existing evidence (Fig. 4) shows that anthropogenic noise should be included in assessments of cumulative pressures on marine ecosystems. Encouragingly, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) assessment acknowledges the role of shipping noise as a pollutant affecting marine life (117), but it makes no attempt to rank its contribution compared with other human impacts in the context of multiple stressors in the marine environment.

Pathways to healthy ocean soundscapes

Most anthropophony is “noise” in a biological sense, because it is an unnatural and unwanted signal. The evidence reviewed here shows that the impacts of human alterations to ocean soundscapes are pervasive across all ocean areas and detrimentally affect marine life (Fig. 4 and table S4). Anthropogenic noise is thus a pollutant that cannot be ignored and must be addressed in policies to mitigate human impacts on the oceans. This is particularly urgent given the growing focus on the ocean-based economy, which is forecasted to double its contribution to global gross domestic product by 2030 (118). This economy includes many new industries, such as deep-sea mining, that may be major sources of underwater noise. A “business-as-usual” development of the ocean-based economy will inevitably lead to ever-increasing noise from more shipping, coastal development, seismic surveys, military operations, dredging, pile driving, and deep-sea mining, likely contributing to increasing impacts on marine biota (Fig. 4). Yet, the High Level Panel for a Sustainable Ocean

Economy (www.oceanpanel.org) has not considered anthropogenic noise in either of the Blue Papers addressing different dimensions of actions required to achieve SDG14 (www.oceanpanel.org/blue-papers), including that on integrated ocean management (119). The postponement, owing to COVID-19, of the UN Oceans Conference to 2021 provides an opportunity to consider the evidence summarized here, showing that the contribution of noise pollution to the declining status and health of ocean ecosystems is likely substantial [Fig. 4; (120)]. This is particularly timely, given that 2020—and now, because of COVID-19, 2021—is the International Year of Sound (sound2020.org). There are, however, solutions that can lead to healthier ocean soundscapes in the context of a sustainable ocean economy.

Improved human stewardship of ocean soundscapes requires regulatory frameworks designed to manage sound within exclusive economic zones and the high seas and promote the deployment of available technological solutions to reduce noise introduced by human operations in the marine environment. Because species-sensitivity distribution models (120) have not yet been generated, alternative approaches for the regulation of anthropogenic noise must be developed. However, unlike other sources of pollution, anthropogenic noise is not persistent in the environment once sources are removed. Consequently, legislative actions to reduce anthropogenic noise and incentivize the deployment of existing technological solutions can have near-immediate, positive effects.

It may be easier to instigate noise reduction of activities that produce sound as a by-product (e.g., shipping, construction), rather than intentionally (e.g., seismic surveys, military activities), through technological and/or regulatory measures, as demonstrated by recent progress in the shipping industry. In 2014, the International Maritime Organization approved voluntary guidelines for reducing underwater noise from commercial ships (www.imo.org/en/MediaCentre/HotTopics/Pages/Noise.aspx). These guidelines focused on design features that could reduce the primary sources of underwater noise, namely the propellers, hull form, and on-board machinery. Following these guidelines, in 2015, Maersk underwent a retrofit of five large container ships and found that reducing propeller cavitation decreased low-frequency sound pressure levels by 6 to 8 dB while improving fuel efficiency (121). In addition, the growing use of advanced materials, such as fiber-reinforced polymer composites, which have good dampening properties and are also lighter—thereby requiring less energy for propulsion—can also help to reduce ship noise. Another potential noise-reduction method is the use of electric motors which, with the development of solar power and

battery storage, are increasingly installed on larger vessels (122). Although such technological improvements are promising, it is the ship-building companies, not necessarily the shipping companies, that need to adopt them, and there is currently no regulatory mechanism to incentivize a transition (123).

The cross-boundary nature of marine ecosystems and some sound sources (e.g., shipping) means that international cooperation is key. Yet, a review of 10 major international agreements that address noise (124) showed that all but one are voluntary in nature or offer both binding and nonbinding options for member nations; the exception is the European Union's Marine Strategy Framework Directive (MSFD), which explicitly includes noise as a stressor and mandates that European Union member states monitor and mitigate noise pollution as part of their efforts to obtain "good environmental status." A likely reason for the noncommittal nature of international agreements that address marine noise is the absence of a compelling assessment of the evidence of impacts, which we now provide (Fig. 4). Therefore, we hope that the strong evidence summarized here will increase the ambition of national and international policies that regulate marine noise to achieve soundscapes conducive to healthy oceans across exclusive economic zones and the high seas.

Meanwhile, regulating the speed and routes of ships can help reduce noise and/or divert impacts away from biologically sensitive areas. For example, reducing steaming speeds for noisy vessels in the major shipping route(s) in the eastern Mediterranean from 15.6 to 13.8 knots led to an estimated 50% reduction in the broadband noise from these vessels between 2007 and 2013 (125). A recent assessment estimated that half of the total noise radiated by the shipping fleet comes from just 15% of the ships, particularly those with source levels above 179 dB re 1 μ Pa at 1 m [i.e., relative to the reference pressure of 1 μ Pa root mean square (126)]. Thus, a targeted approach with focused incentives could substantially reduce shipping noise. Marine construction, particularly for offshore wind farms, is achieving rapid advancements in noise-dampening technology. Acoustic barriers like bubble curtains and noise-abating sleeves have been introduced in some European wind farms and can reduce sound from pile driving by up to 15 dB (127). Indeed, both the European Union's MSFD and the U.S. National Marine Fisheries Service encourage the use of such technologies. Finally, the E&P Sound and Marine Life Programme, funded by a number of oil and gas companies, has invested in developing alternative technologies to seismic air guns (www.soundand-marinelife.org/). Marine vibrators ("vibroiseis") produce sounds that are nonimpulsive and more narrow band in frequency than typical

seismic air guns, potentially removing some of the more harmful acoustic attributes. Several companies are developing prototype vibroiseis technology to be mounted on submarine vehicles that would roam the seafloor. These vehicles will use hydraulic systems to generate force waves that penetrate the sediments and deliver the required data while avoiding impacts on animals in the water column (128). As environmental constraints and impacts of deep-sea mining are discussed, there is an opportunity to design instruments and procedures that avoid impacts from noise before commercial operations begin (128).

Mitigating climate change in accordance with the most ambitious goals set by the Paris Agreement (<https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>) will also help reduce further impacts from climate change on geophony and biophony. However, the recent IPCC assessment of climate change impacts on oceans and the cryosphere indicates that sea ice will continue to decline, affecting soundscape features, and coral reefs will continue to degrade even if those climate goals are met (116), affecting biophonic components.

Sound is a fundamental component of the sensory environment of marine ecosystems, with animals across a broad range of taxa—from jellyfish to marine mammals—perceiving and using sound throughout their life history. Global industrialization of the ocean has led to the rise of anthrophony, whereas human impacts on marine species and ecosystems and the climate system have led to a decline in biophony and alterations to geophony. Substantially modified ocean soundscapes, in turn, have widespread impacts on the ecology of the Anthropocene ocean. These impacts are pervasive, affecting animals at all taxonomic and trophic levels, and compounded with impacts from other stressors, such as ocean warming, acidification, habitat loss, and overfishing. Changing ocean soundscapes have become the neglected "elephant in the room" of global ocean change. In an era when societies increasingly look to the "blue economy" as a source of resources and wealth, it is essential that ocean soundscapes be responsibly managed to ensure the sustainable use of the ocean. Solutions to mitigate anthropogenic noise, both in terms of policy and technological measures, are becoming available but remain challenging (123, 124). Incorporation of these solutions in internationally binding conventions would pave the way for ocean soundscapes that support healthier ecosystems under a sustainable ocean economy.

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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/371/6529/eaba4658/suppl/DC1

Materials and Methods

Fig. S1

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MDAR Reproducibility Checklist

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The soundscape of the Anthropocene ocean

Carlos M. Duarte, Lucille Chapuis, Shaun P. Collin, Daniel P. Costa, Reny P. Devassy, Victor M. Eguiluz, Christine Erbe, Timothy A. C. Gordon, Benjamin S. Halpern, Harry R. Harding, Michelle N. Havlik, Mark Meekan, Nathan D. Merchant, Jennifer L. Miksis-Olds, Miles Parsons, Milica Predragovic, Andrew N. Radford, Craig A. Radford, Stephen D. Simpson, Hans Slabbekoorn, Erica Staaterman, Ilse C. Van Opzeeland, Jana Winderen, Xiangliang Zhang and Francis Juanes

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DOI: 10.1126/science.aba4658

An anthropogenic cacophony

Sound travels faster and farther in water than in air. Over evolutionary time, many marine organisms have come to rely on sound production, transmission, and reception for key aspects of their lives. These important behaviors are threatened by an increasing cacophony in the marine environment as human-produced sounds have become louder and more prevalent. Duarte *et al.* review the importance of biologically produced sounds and the ways in which anthropogenically produced sounds are affecting the marine soundscape.

Science, this issue p. eaba4658

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