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Understanding the Impact of Underwater Noise to Preserve Marine Ecosystems and Manage Anthropogenic Activities

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Abstract: Policy makers require a knowledge-based support to identify effective interventions for the socio-economic sustainability of human activities at sea. When dealing with anthropogenic impacts on marine ecosystems, we deal with a complex and faceted system which has high variability in terms of environment, regulation, governance, industrial activities, and geo-political scenarios. We analyzed the conceptual scientific framework adopted to address underwater noise as a polluting component of the marine environment. We identified the scientific paths that can provide useful contributions towards comprehending the impacts on the native ecosystem. In order to furnish relevant clues towards the properties of the interconnection of signals, we briefly reviewed an example from a different discipline (helioseismology). We describe a new approach on how acoustic energy in the sea could be detected and analyzed to understand its role in the functioning of the ecosystem. We propose a change of perspective in the observation strategy of underwater noise, promoting a knowledge transfer from other disciplines, which in turn will enable a better understanding of the system. This will allow researchers and policy-makers to identify feasible and effective solutions to tackle the negative impacts of underwater noise and the conservation of the marine ecosystem.

Keywords: underwater noise; signal analysis; ecosystem approach; observation systems; environmental sustainability; complexity; support to policy

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1. Introduction

The impacts of human activities on the environment have historically been framed within two main aspects: economic sustainability and the protection of the ecosystems. Scientists are often asked to support policy decisions, and different disciplines are contributing, seldom competing, to provide an inclusive and coherent knowledge-based analysis of the scenarios. The end goal is to foresee the different dynamics of the interaction between humans and the environment in order to assess the different options and provide guidance for interventions.

In recent decades, we have faced global challenges which are showing some peculiar characteristics: (1) they are linked to complex systems, involving a huge diversity of interconnected aspects in terms of environment, sectors, stakeholders, and responsibilities; (2) they should be dealt with via cooperation and agreement at the transnational level, thus avoiding single countries offering solutions in isolation [1,2].

The marine environment is adding another aspect which, in turn, increases the complexity and difficulty in tackling challenges. Seas and oceans do not have physical boundaries imposed by political decisions: the boundaries of a human-driven problem (e.g., pollution) are identified by the dynamics of the environment, but human-driven solutions are indeed strongly dependent on the boundaries identified by countries [3]. In this context, understanding the dynamics of the interaction between human activities and the native ecosystem is crucial to identify the impacts and the essential aspects to guide sustainable and beneficial activities at sea [4]. Historically, the effects of anthropogenic noise have been conducted for many decades on terrestrial animals [5]. In this context, the disturbances on humans have been deeply analyzed, especially in the context of the protection of employees and insurances' aspects [6,7]. Acoustic noise is, in fact, usually associated with unwanted sound considered loud, unpleasant or disturbing. From a physics point of view, there is no distinction between noise and desired sound: both are signals detected as vibrations through a medium. Underwater noise includes the signals both from a natural environment (e.g., linked to thermal and seismic sources, etc.) and those introduced by human activities.

Marine scientists are considered the main reference community for "understanding" the processes which drive the dynamics of seas and oceans. Nevertheless, analogously to what occurred within the Intergovernmental Panel on Climate Change (IPCC) for addressing global climate change and the CO_2 balance in the atmosphere, and where different disciplines and experiences were included to tackle such a complex challenge, a similar approach should be adopted for marine pollution.

In this paper, we address underwater noise as one of the polluting factors of the marine environment, mainly focusing on how to understand its impact on the behavior of marine fauna and how to approach the design of an adequate observation strategy. Acoustic signals are probably much easier to detect than many other pollutants (e.g., chemicals), and comprehending their propagation is also supported by a comprehensive theoretical framework. However, when approaching the impacts on the ecosystems, it seems that observations are not designed to feed a fully fledged model and that we observe what we can and not what we need.

We identified experiences and clues from another discipline (helioseismology) which address similar conceptual frameworks. Then, we concluded with a call for changing the approach to observation strategies and signal analysis, promoting the investigation of the role of synchronism in communication and functioning within ecosystems.

2. Underwater Noise as an Economic-Political Issue

Noise-generating anthropogenic activities in marine habitats require the careful evaluation of possible effects on fauna, since these activities could potentially impact individual fitness and population health [8]. Marine populations play key roles in their ecosystems: from primitive organisms to marine mammals, they are also of primary importance against climate change through CO_2 capture and mineralization that results in carbon being stored in marine sediments and rocks [9]. Therefore, it is essential to regulate underwater noise emissions in order to preserve marine life and its economic value.

This situation is of increasing concern to the EU, since marine life cannot be replaced. In 2010, the European Commission (EC) instituted the Marine Strategy Framework Directive, MSFD, (EC Decision 2010/477/EU) with the aim of assessing, achieving, and maintaining the good environmental status (GES) through 11 descriptors. Underwater noise should be "at levels that do not adversely affect the marine environment" (Directive 2008/56/EC) and it is considered in Descriptor 11: "Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment" (EC Decision 2010/477/EU). Furthermore, two indicators were identified: 11.1. for "distribution in time and place of loud, low and mid frequency impulsive sounds" and 11.2. for "continuous low frequency sound".

During the 1980s, the International Maritime Organization (IMO) began its work on the impact of noise on humans aboard ships. A code regarding noise levels on ships was adopted by the Maritime Safety Committee in 2012. In 2014, following that, IMO began to acknowledge underwater noise in correlation with shipping as an issue raising concern. Therefore, it was agreed that it must be mitigated in order to reduce its effect on marine life. The Guidelines for the reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life are mostly meant to inform stakeholders on this problem and are not mandatory (IMO MEPC.1/Circ.833).

The political attention to achieve a sustainable management of activities at sea, mainly referred as the Maritime Spatial Planning (Directive 2014/89/EU), is also a consequence of the awareness of the costs of their possible impacts on ecosystem services. Quantifying the ecological cost of underwater acoustic pollution for societies is challenging, especially because we should consider not only the impacts on individuals or single species, but those that can result in disruptive changes on populations, on ecosystems and on the food web. Moreover, the cost of enforcing mitigation measures should also be computed and taken into consideration [10]. In the case of uncertainty, the precautionary principle could be applied and mainly depends on the culture and objectives identified at the political level. In the European Union, this principle has been applied in many cases [11].

The benefits of reducing underwater noise can be considered in terms of reducing damage for society, that is preserving ecosystem services that are useful for some economic sectors and the equilibrium of the environment as a whole. However, it is difficult to build a quantitative comprehensive model able to calculate its cumulative impacts on different sectors. This has been recently expressed in terms of the damage on marine ecosystem services that can be introduced also via a cascading effect. If acoustic pollution hampers the health of marine taxa (e.g., apex predators or preys), all linked fauna will be potentially affected, leading to a negative impact on the entire ecosystem [12,13]. Moreover, marine life's well-being influences the health and wellness of human populations. On the other hand, mitigation measures that should be implemented to reduce impacts on marine fauna could economically affect stakeholders (e.g., on fishery due to the depletion of fish stocks). This might result in a cost increase and can be approached by abating the source, carrying out restrictions regarding location and time, setting suitable operational parameters, mitigation equipment, and procedures. This whole process, however necessary, might prove expensive [10,13]. When interventions are designed and eventually adopted, it is often difficult to estimate their effectiveness in the long-term and broad scenario, since other aspects can arise, and collateral issues are introduced in different economic sectors or ecosystems. Therefore, the cost in relation to ecosystem services needs to be considered. In this regard, the Enhancing Cetacean Habitat and Observation (ECHO) Program in British Columbia, Canada, is a good example. After having identified underwater noise from vessels as a major concern for their Southern Resident Killer Whales (SRKW) population, between 12 July and 31 October 2018, the Vancouver Fraser Port Authority coordinated a voluntary slowdown of ships in a key feeding area [14]. A total of 87 per cent of ships participated in the slowdown, transiting through the feeding areas at 15 knots or less. The median reduction in underwater noise intensity levels during the slowdown showed an estimated 29 per cent [15]. However, this project was developed to tackle a very specific situation for a localized area and the endangered SRKW were considered a key endangered species. In the "Summary Findings" of the program, the Vancouver Fraser Port Authority states that an application for a CAD 500 stipend was open to all ships transiting the area, since it was recognized that all the vessels could incur direct and indirect costs while participating in the trial. However, due to the short period and non-mandatory participation, it was not expected that shipping operators would incur high economic costs [16].

The problem of underwater noise has become more of a political issue. Very recently, commitments to tackle the challenge of underwater noise resulted in the launch of a joint action funded by EU member states [17]. Moreover, revised guidelines for the reduction in underwater noise from commercial shipping have been agreed on by the IMO Sub-Committee on Ship Design and Construction [18]. In addition to the voluntary vessel slowdown programs implemented in the Vancouver port and the Northwest Atlantic areas, at the European level, rerouting and ship quieting measures are being tested by the projects ECHO-JOMOPANS and SATURN [19]. Building on the need to increase underwater noise mitigation measures, several international monitoring projects for continuous and impulsive noise have been funded by the EU [19]. The increasing number of research and monitoring programs established to fulfill the MSFD are shedding light over the impacts caused by acoustic pollution; however, the target to assess the GES has not been reached.

3. The Impacts of Underwater Noise on Ecosystems

3.1. The Scientific Approach

Oceans are very noisy. Sound travels more than four times faster underwater than in air and absorption is lower compared to air. Underwater sounds are the result of biological sounds produced by animals, physical processes (such as waves, undersea earthquakes) and anthropogenic sources, and are mainly continuous (such as shipping noise) or impulsive (such as seismic sources) [20–22]. See Figure 1 for a comprehensive sketch in the frequency domain. Underwater ambient sound can span from 10 Hz (mostly due to shipping) to 100,000 Hz, where thermal noise, which is due to the random motion of water molecules, dominates [23].

In the research field, sound generation can be used as a tool for investigation (e.g., seismic prospecting) or it can be a by-product of the activity itself (e.g., shipping noise) [24].

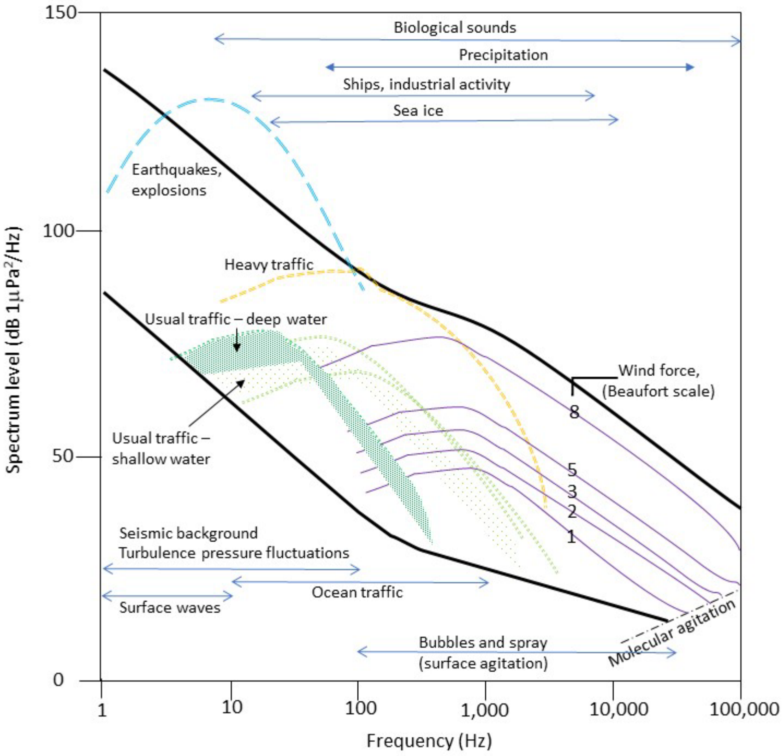

Figure 1. Wenz curves diagram of noise spectra pressure spectral density levels of common anthropogenic and natural sources in the marine environment. Picture inspired from [25].

On the other hand, many aquatic organisms use sound to accomplish their biological functions [20,26]. Therefore, since sound is far ranging, activities generating it underwater can create synergistic and cumulative effects, thus hampering their behavior and, consequently, their role in the ecosystem's function. Noise alters animal behavior and fitness in many ways; for example, it might be merely detectable—if emitted at low levels—or it might interfere with animal communication at high levels. In addition, it might mask acoustic signal detection and potentially affect the vestibular, reproductive, and nervous systems of the animals [27]. Because noise is so pervasive, it is not clear whether marine fauna and ecosystems can adapt to its slight increases or whether it will affect populations that are already stressed by other forms of pollution [28].

3.2. Impact on Marine Fauna and Ecosystems

Sound intensity decreases as one moves away from the source and impacts lessen, as depicted in the 'zone of influence model' by [29], as can also be seen in Figure 2.

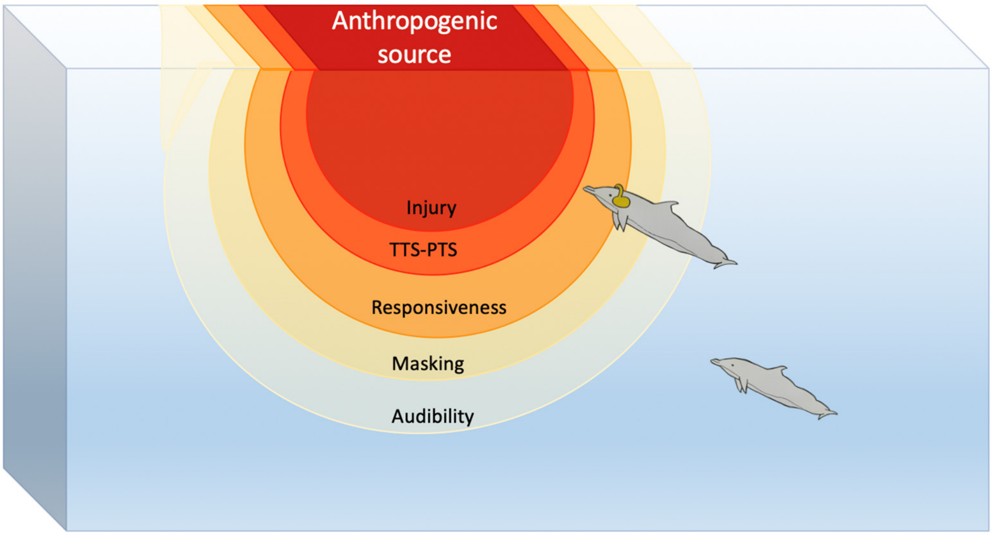

Figure 2. Zone of influence model for organisms: this simplified model mainly shows the isotropic propagation of the intensity of the signal to describe the possible spatial effects of acoustic signals. Moving away from the source, the intensity of the produced sound decreases. TTS and PTS stand, respectively, for temporary threshold shift and for permanent threshold shift.

Figure 2 presents a simplified model for a single interaction between an organism and an acoustic signal, considering only its characteristics of intensity and homogeneous isotropic propagation. Indeed, a context-dependent framework is needed when dealing with the interconnection between the sources, propagation, and sensing of the signals when investigating the effects on the whole ecosystem [30]. The spatially extensive outer zone in Figure 2, the zone of audibility, depends on the hearing range, on the sensitivity of the taxa, and on the local conditions. This level of complexity probably drops closer to the organism, but many aspects are interconnected.

In Figure 3, we show a schematic representation for the different aspects which need taking into account. This general approach also includes what is usually referred to as the masking effect, that is, when an acoustic disturbance from the "masker" can interfere with the detection of biologically relevant signals degrading them and altering the "native" expected feedback [27]. Predicting masking is difficult. There are a multitude of factors that need to be accounted for, such as the combination of sender, environment, and receiver characteristics, and models are still struggling to provide a general approach [8]. A signal may be barely audible when at a low signal-to-noise ratio (SNR), while, at a higher SNR, the functioning of the communication becomes more effective. There are two main mechanisms which lead to lower masking thresholds for signal detection [31]. One is the "comodulation masking release" (i.e., "improvement in the detection threshold of a masked signal that occurs when the masker envelopes are correlated across frequency)" [32], which leads to the improved detection of signals over the background [33]. The signal can follow this phenomenon when it stands out more: the listener is able to link received information with its provenience [34]. Another anti-masking strategy is "spatial unmasking": sounds appear to come segregated from the source and are perceived at different times, since sound levels and phases depend on the ear that the sound is approaching [35]. Biotic noise can also lead to inhibition; if the noise is persistent in time, the masking signals of one species might suppress the acoustic signals produced by another species [36]. The amount of masking release can be similar for creatures as diverse as humans and frogs [37,38]. As an anti-masking strategy that originates at the sender, marine mammals—for example—may modify their vocalizations in the presence of noise [39,40]. Killer whales, for example, have been shown to raise the amplitude and duration of their communication signals during vessels' presence [41,42]. The increase in features such as redundancy is itself an anti-masking mechanism because it enhances the probability of detection of the receiver. Further research is needed to assess the risk that masking might create due to various human-made activities, and the potential anti-masking strategies developed by organisms.

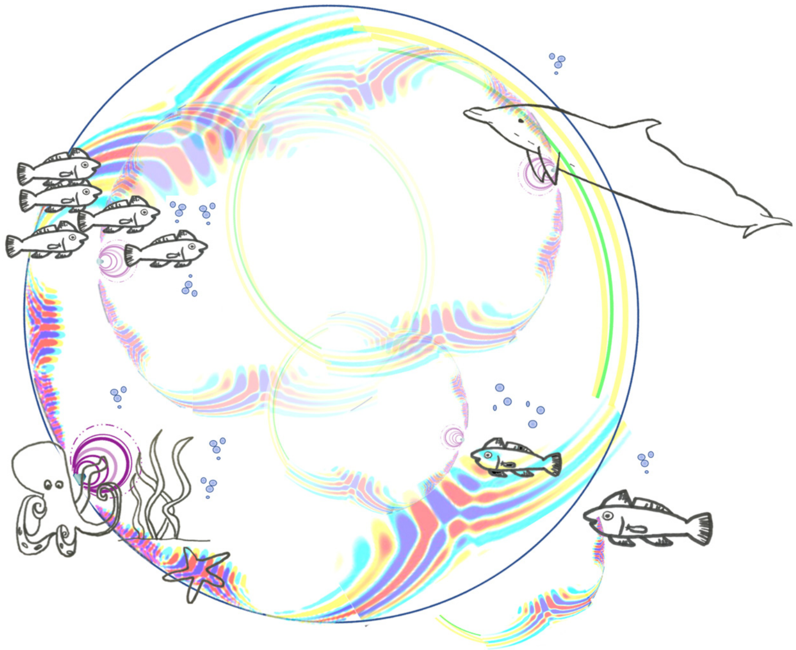

Figure 3. Schematic representation of an underwater acoustic field: a diversity of sources emits waves which are filtered through the medium and detected by the receivers. The signal emitted from the sender is modified by the medium and it arrives modified at the receiver. Colors from red to blue indicate the intensity of the pressure within the wave trains [43].

The zone of responsiveness is usually larger than the zone of audibility because an individual might choose not to respond to a barely detectable sound [44]. Animals who find themselves in this area might modify their behavior, creating cascade effects on the whole food web, such as changes in swimming direction, speed, dive, and surfacing patterns, and changes in acoustic behavior [45]. The capacity of becoming accustomed to noise—and other factors such as age, gender, and health—can influence the probability and the severity of a response. Consequences of disrupted behavior can be important for the individual but can affect fitness at the population level.

The zones of physiological effects include the temporary threshold shift (TTS), the permanent threshold shift (PTS), and injuries. A TTS varies among species and is a temporary elevation of the hearing threshold due to sound exposure, whereas a PTS is a permanent elevation of the hearing threshold that might happen at certain frequencies [22]. Furthermore, another aspect to examine when considering animal health is the duration of sounds. Longer sounds are easier to hear also due to the variability of detection thresholds.

At the center of these nested zones, we find the zone of injury. Effects experienced in this area can include lethality, the rupturing of swim bladders, bleeding of organs and tissues, and hematomas [46].

Non-auditory physiological effects, such as stress, can also be experienced. Stress is a physiological reaction that might occur when an unknown source is detected, or after masking, and involves the release of adrenalin, leading to an increase in heart rate: the animal is getting ready for a fight-or-flight response [47]. This repetitive or prolonged stress can negatively affect health [48].

Finally, many of these effects can be influenced by one another. For example, noise can induce a fight-or-flight response in deep diving animals, propelling them to quickly surface and experience decompression sickness and death [48]. Chronic stress can impinge upon mating and nursing and, hence, the survival of the population. In addition, other human-induced pressures such as habitat degradation, climate change, and chemical pollution might make it harder for marine fauna to cope with stress and vice versa [24,28].

3.3. The Other Side of the Coin: Stochastic Resonance

We have seen that underwater noise can be harmful to animals; however, as discussed in relation to the problem of masking, in some situations, an optimal level of noise can contribute to the conveyance of information, playing a constructive role. Many habitats are equipped with their own typical pattern of ambient noise, and a uniform level of noise may serve as a baseline upon which sounds can be distinguished [49]. This is made possible by "stochastic resonance", a phenomenon which, among others, allows the detection of weak sound stimuli when added to a uniform (white) noise in nonlinear systems. The frequencies of the original signal will resonate and amplify just the signal, not the white noise, increasing the signal-to-noise ratio. If the system overcomes a sensory barrier in order to perform its task, stochastic resonance can be implemented, in hearing, through a source of low-intensity noise and a weak coherent input. The impact of stochastic resonance on hearing can hinder a variety of taxa, such as humans [50], other mammals [51], and fish [51]. Due to the complexity of ocean systems, ambient noise variations are usually nonstationary and nonlinear [52]. Therefore, detecting weak acoustic signals can be challenging [53]. In order to comprehend problems related to underwater communication, the sender with the acoustic characteristics, the medium, and the receiver should be investigated (see Figure 3). The sender emits a call—with certain spectral characteristics at a given source level—that travels through the marine habitat, undergoing propagation losses, scattering, and absorption. The listener perceives the sound in different ways depending on the reverberation effects [8,54].

It is worth reflecting on the fact that the acoustic environment is embedded in marine fauna's life, becoming a constituent of the ecosystem itself. This acoustic environment has huge variability and complexity. Sources (anthropogenic or biological), receivers, and the medium are the fundamental components we should focus on when addressing underwater communication: the dynamics of the three are closely interconnected and cannot be treated in isolation.

3.4. Communication and Cognition within the Ecosystem

The use of signals is usually tied to background noise because its propagation is limited by the decrease in the signal-to-noise-ratio [55]. Solutions to this problem may involve evolutionary changes in signal features leading to long-term adaptations, or the individual adjustments of traits [56]. Animals usually adjust their vocalizations by modifying amplitude, duration, pitch, and timing. The level of interference depends on the degree of overlap between noise and signals for certain frequencies [57]. Synchronized signals may sometimes play a role in emphasizing acoustic details or draw attention to the sound of the associated source [58]. This depends on the capacity to focus on one of the auditory streams and it is important for auditory scene analysis and the ability to perceive details in other auditory streams. An example of this can be inferred from fish: for them, noise can serve as an 'illumination source', enabling them to obtain an acoustic image of their surroundings [59]. An animal can also have the ability to focus on perceiving a specific signal in a noisy environment, experiencing the "cocktail-party effect", that is the phenomenon of the cognitive systems that allows individuals to focus their attention on a particular stimulus while filtering out a range of other stimuli [60,61].

The receivers have a range of sensory adaptations in their auditory system that can be used together to obtain signals against background noise while the sounds overlap and enter the auditory system. In addition to changing position in relation to the source, recipients can also improve their audibility by moving their heads or ears. Shifting their body or head positions after hearing a sound may benefit signal recognition due to the signal–ear transmission pathway optimization [62]. In addition, when a receiver moves through its habitat, this movement will affect the characteristics of both perceived signals and noise.

Access to information is one of the major benefits animals acquire from social interactions [63]. The problem-solving skills of animals are linked to their mental capabilities; indeed, cleverer animals may undergo more awareness of a problem [64]. Furthermore, the phenomenon known as "wisdom of crowds" can be experienced when the sharing of information in ecologically relevant situations is improved for individuals or for the group [65–67]. Knowledge can be built up by individual interactions, and therefore, bigger groups have a greater probability of containing wise and capable individuals. This is known as the 'pool-of-competence' effect and the modality with which collective future decisions are made could depend on it. However, we do not know how much previous generations pass on to the new ones or just how groups arrive at solutions thanks to the number of animals involved. When making a decision, individuals base their movement on pieces of information that can be assembled locally, such as position and motion. The decision-making process in most animal species stands on an adaptation of the collective response based on the negative or positive feedback gained [68,69]. If this piece of information gained does not improve certainty, the animal can benefit from an accumulation of information on a longer time scale. In fact, a fast decision is not always recommended because it can lead to a loss in accuracy due to individuals making sequentially arbitrary decisions [68,70]. For example, if the group helps to reduce predatory risks, which can be one of the major drivers for evolution, individuals can devote more of their cognitive resources to other tasks [71,72].

All living organisms base their lives on cognition (*sensu lato*), that can be defined as the detection of the environmental conditions, and on communication. Communication leads to the exchange of information carrying a functional message among other individuals implying a language and semantics. The main problem in the communication field deals with the ability of the receiver to identify a specific message generated by the source and decrypt the characteristics of the signal. Messages have meaning; animals can choose to hear a select message out of a pool of potential ones. Communication is crucial in the cultural social learning [73,74] of some marine mammal species, for example. In fact, some marine mammals experience cultural transmission. Elder individuals teach the youngsters how to use vocal signals, which occurs in bottlenose dolphins (*Tursiops truncatus*), killer whales (*Orcinus orca*), sperm whales (*Physeter macrocephalus*), and humpback whales (*Megaptera novaeangliae*). Furthermore, killer whales [75] and sperm whales [76] have dialects that differ from pod to pod and from region to region. In addition to this, bottlenose dolphins use signature whistles for identifying individuals [77,78].

4. SEAS-Mology: A Lesson Learnt from Helioseismology

Our telescopes are able to probe further and further into the depths of space but the interior of the Sun and the stars seems less accessible to scientific investigation than any other region of the universe. Nowadays, we probably know the Sun's interior better than our ocean, even if no sensor has ever been installed on its surface or in its interior.

In the 1960s, solar light was sampled using a narrow passband filter centered on its spectrum's absorption lines [79]. The continuum spectrum of the Sun is in fact absorbed when atoms are reconnected, forming an absorption line whose height depends on the density and temperature of the plasma. If the plasma moves, the wavelength of its absorption line shows a Doppler effect, allowing it to detect the Doppler oscillations of the Sun's surface, which are mainly centered at a period of 5 min. The frequency distribution of these 5 min oscillations shows a specific trait that was interpreted as the signature of acoustic waves' resonance in the Sun's interior: acoustic waves travel through its interior and some of these are trapped inside the Sun and form resonant oscillation modes [80].

In practice, the Sun plays like a drum, driven by continuous explosive events that produce pressure and temperature disturbances that propagate. By measuring the travel times and frequencies of transients and waves, a lot of information can be obtained on the conditions in the interior, and with seismology, we can infer properties of the Earth's composition [81,82].

Today, we can retrieve solar velocity fields in the order of a few millimeters per second and investigate a wide variety of phenomena inside the Sun [83,84]. Moreover, solar physicists introduced new tools to study the dynamical behavior of a complex system such as the solar atmosphere [85,86], clarifying many characteristics of the different typologies of waves (acoustic resonant or propagating, gravity, Alfven, etc.), and their heat transfer and anisotropic propagation [87,88].

A relevant aspect of these new tools of analysis consists of investigating phases and coherence between different waves at different heights in the atmosphere, and the frequency distribution of these variables. This means that the cross-spectrum of different time-series needs to be built before performing the power spectrum. In order to make this approach effective, different samples of the waves must therefore be acquired: in the case of the Sun, an absorption line in the light spectrum is formed at one height in the solar atmosphere, and the simultaneous observation of different wavelengths allows a scan over the depth. A multi-line observation on the solar spectrum can be considered as a network of moorings deployed on the Sun and equipped with many hydrophones.

These advances in acquiring useful information from the Sun were possibly due to a monitoring strategy designed and implemented to provide long-term continuous observations at different heights of the atmosphere, creating a sort of tomography of the upper layers and the validation of the models for the interior [89].

The lesson learnt from helioseismology is that we cannot limit our investigation to the study of frequencies but we need to acquire time-series at different heights and apply correct data analysis to understand the processes that embed the environment. This approach is based on a well-known scientific framework that has proved to be fundamental for extracting relevant data clues [90].

5. Reflections

The use of the term noise has historically been associated with a negative human perception of what is identified as a disturbance in useful information [91], as in Spitzer 1945. The concept of noise is not limited to acoustics, and it is described with a flat, or almost flat, frequency distribution, introducing energy which can hide the signal or distract from those of interest. Indeed, many techniques for the recovery of a signal embedded in noise have been developed [92]. On the other hand, noise can be used as a meaningful tool to detect information. In marine science, a negative impact is then defined when the anthropogenic inputs change the physiology or the behavior of marine organisms, inducing a transformation of the ecosystem that can be localized or systemic [93]. This latter case addresses the possibility of the complex marine system facing a tipping point which can abruptly disrupt its sustainability.

To date, we have looked at a few general concepts concerning research on underwater noise:

- Research to date has demonstrated that underwater noise has an impact on marine ecosystems, even though it is still difficult to quantify the problem.
- Different methodologies for the analysis of signals are used: spectrograms, correlations, counting of impulses, and waveform analysis.
- When the influence of noise on the behavior is investigated, we are not focusing on the disturbances introduced in the meaning of the message.

We identified the main challenges we have to tackle in order to understand the impacts of anthropogenic noise on the marine ecosystem and the interactions in this complex environment. Experiments and observations of animal behavior were carried out mainly with the use of hydrophones, sometimes coupled with other sensors such accelerometers, cameras, and magnetometers. Notwithstanding the increase in studies on this topic, we believe that we face a lack of understanding of the tuning of the signals for the functioning of the ecosystem itself, and the role of communication and exchange of energy between the different components of the system (including organisms).

The analysis in the frequency domain is widely used, due to the historical military tradition and experience, and its relative simplicity for detection. However, it provides a limited point of view because the "semantics" of the signals is the crucial aspect to be investigated [94–96]. In this regard, we may mention the deluge of scientific results on brain activity, the functioning of brain waves, and neuronal chip developments which indicate the need to also analyze signals in terms of transients and their context dependency in a complex environment [97–99]. A thorough description of the reality should be promoted with a reasoning for change in the overall properties and indicators. The main issue is the synchronization between different signals, the phase relations between sources and receivers, and the way to reach a state of equilibrium of the system, not just of the single components. In fact, the state of the whole system can be very sensitive to the space–time dynamics of energy and information [100–102].

While the study of synchronism has focused on the stability and order of the systems, recent theoretical research on the climate has also provided new findings on the aspects which can induce instabilities. Noise-induced and rate-induced examples have been reported for tipping points in open systems [103]. All these results suggest that not only the intensity fluctuation and spectral signature of a signal are crucial in generating a systemic change but also the speed of the change. Therefore, we should focus on investigating what happens at the right time, in the right place, with the right intensity, and with the right shape, keeping in mind that the frequency domain has to be accompanied by phase and coherency between the different components of the network in the system [104,105].

In this setting, a conceptual general reflection on the meaning of noise and the way it is observed and analyzed is fundamental to understand the impacts of human activities on the ecosystem, and consequently to devise interventions for its conservation. Despite the difficulty in understanding the more complex facets of this topic, the economic interests in modeling and forecasting tipping points and irreversible paths are huge [106,107]. In fact, precautionary approaches are usually not properly welcomed by the industrial sector, which demands more detailed studies, thresholds, and specifications to be included in legislation and insurance contracts. In turn, the scientific community should strive to provide accurate and robust models to understand the interaction between the underwater acoustic field and the ecosystem. These results would support policy decision, satisfy the diversity of stakeholders, and aid in the adoption of effective interventions. This challenge should be tackled through a multidisciplinary process which involves different expertise; moreover, science should contribute as a neutral, coherent, and effective actor.

The observation of the solar system is comparable to installed moorings at more than 150 million kilometers far from Earth. Moorings in the oceans are non-intrusive and ideal instruments to evaluate acoustic impact and study communication between organisms. Measurements from a ship can provide a snapshot of the environmental conditions along the route: moorings are indeed Eulerian observation sites that could provide long-term information at fixed locations, simplifying any cross-spectral analysis between different signals. Undoubtedly, they play a key role in assessing acoustic pollution at large spatial and temporal scales [26,108].

At present, the networks of observing stations in the ocean and satellites are available with different spatial and spectral resolutions. However, research ships are often a common tool used to collect data. While measurements from ships provide a snapshot of the environmental conditions along the route, moorings are used in the oceans as Eulerian observation sites that could allow for real-time data gathering and continuous and long-term information at fixed locations [109]. They are ideal instruments to simplify any cross-spectral analysis between different signals, evaluate the acoustic impact, and study communication between organisms, playing a crucial role in assessing acoustic pollution at large spatial and temporal scales. In addition, hydrophones could be added to fixed stations that have already been deployed for oceanographic purposes, such as the Global Ocean Observing System (Figure 4, top right). This solution could reduce the cost of new deployments and serve in the forms of multidisciplinary, multipurpose infrastructures.

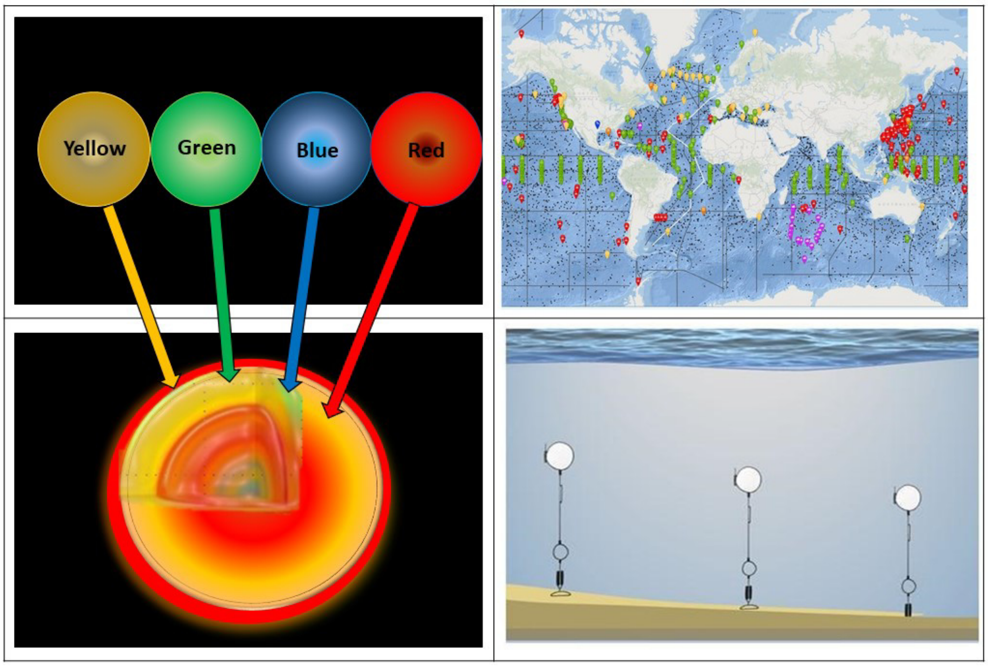

Figure 4. A comparison of observing strategies to acquire a tomography of the acoustic field of the Sun (**left**) and of the ocean (**right**) is shown. Upper left: solar full-disk images at different wavelengths (i.e., colors) can sample different heights of the star since the absorption lines of the electromagnetic spectrum are formed within different densities and temperatures in its atmosphere. The heights indicated by the arrows (**bottom left**) are not representative as the absorption lines are formed in the upper layers of the atmosphere and not in the interior of the Sun. Right: the spatial distribution of the moorings on Earth (**upper** panel, green = fixed sites, yellow = local array, orange = regional array, purple = ship survey, blue = satellites, red = sea floor, black = ARGO, transects = GO-SHIP, figure from [110], license CC BY 4.0) and a sketch of possible sampling capacities at different depths in the ocean (**bottom** panel).

Navies and governmental agencies usually deploy underwater networks which have the great advantage of continuously registering real-time data and covering vast areas.

Implementing techniques for passive acoustic monitoring on cabled deep-sea platforms and moored stations is not cheap. However, although challenging, an investment in this direction could allow us to move towards the understanding of the ecosystem. For example, in real-time monitoring, a seafloor observatory equipped with a range of oceanographic sensors as well as low- and high-frequency hydrophones (0.1 Hz–200,000 Hz) from Ocean Network Canada can be used, and will have a cost of approximately CAD 750,000. Moreover, the buoy and other equipment, deployment, and maintenance cost will be far greater than the cost of the sensor. On the other hand, research vessels management deals with many operational daily costs: for example, depending on the vessel size, the crew can cost 40–60% of the total budget, and fuel will be around 20% of the total budget for open water vessels (up to 40% for the Polar class). The remaining 25% is due to maintenance, insurance, and other expenses. Thus, ocean research vessels can cost from CAD 10,000 to more than CAD 40,000 a day to operate.

These amounts imply that one month of an operational vessel campaign approximately accounts for the deployment of one fully equipped fixed platform, which will provide long-term monitoring. New opportunities are arising for underwater acoustics. Instead of deploying one or several hydrophones, with an approximate cost of CAD 8000 each, optical fiber sensors can be used to perform real-time, multiple-point sampling. This new technology would allow for a fine-grained sampling, using the optical fibers of km length. Optical fibers are very cheap, robust, fast-responding, and immune to electromagnetic interference [111]. The overall cost will depend on (home-made or commercial) electronics, detectors, sensors, and delivery, arriving at approximately USD 10,000 for a number of sensing points ranging from 5 to 10.

6. Conclusions

The preservation of biodiversity has gained attention at political debates, but there is a controversial argument on whether to give priority to cost-effective actions or focusing on the most endangered species [112–115].

When entering the scientific approach to the challenge of understanding the anthropogenic impacts on the environment, the complexity of the system and the data analysis are struggling with partial and short-term observations. This is a well-known problem in ecology, which limits the models to remain phenomenological, focusing on the short-term dynamics (e.g., snapshots) and on pattern analyses [116]. Since the study of isolated states rather than the trajectories connecting them is inappropriate to capture the dynamics of the complex system, the analysis of different snapshots will make the support to decisions mostly depend on statistics and not on understanding.

Dealing with acoustic signals, we identified helioseismology as one of the research lines that has proved an effective strategic approach to the observations, allowing an unexpected understanding of the processes through a multi-layer sampling of the solar atmosphere and the adoption of state-of-the-art analysis techniques. We also compared the costs of such an installation to the use of research vessels and reflected on the opportunity to adopt a cost-efficient approach to gather data, extract information, and validate models that can better understand the processes governing the system.

Although the need for passive acoustic ocean monitoring from cabled platforms and moored stations is broadly understood and implemented in some areas, we call for action in designing and adopting observing strategies enabling unprecedented data analysis. Networks of fixed platforms can now take advantage of cheaper new technologies and allow more appropriate analysis techniques (e.g., phase analysis) to deal with the dynamics of interconnected factors. These networks will constitute augmented observatories in specific locations of the planet that will provide clues towards understanding the complexity of the marine environment that floats or research vessels cannot provide.

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