Impacts of Anthropogenic Sounds on Reef Fish

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Contents

Abstract

Anthropogenic noise is now recognized as a global pollutant and a major threat to marine biodiversity. It affects the behavior, physiology, communication, and reproductive success of many marine organisms. However, there are several remaining gaps in its effects on certain taxa, such as reef fish. This chapter provides an overview of studies regarding the impact of noise on reef fish. Important steps to guide future research are also discussed.

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Introduction

Biodiversity is a critical functional link to key ecological processes in reef systems and the consequent quality and provision of ecosystem services (Moberg and Folke 1999). Impacts such as overexploitation, eutrophication, and climate change are some of the major drivers acting synergistically and contributing to eroding reef resilience worldwide (Hughes et al. 2017). Noise pollution, despite having been exponentially growing in the last decades (Bittencourt et al. 2020; Duarte et al. 2021), is still neglected as a major threat to biodiversity with no proper management actions.

The underwater soundscape is formed by three main sound sources: biotic, abiotic, and anthropogenic, and it is an important proxy for understanding many ecological processes (Pijanowski et al. 2011). The understanding of how anthropogenic noise affects marine ecosystems has exponentially increased in the last few years (Duarte et al. 2021). Many studies have shown the increasing contribution of different anthropogenic noise sources in marine systems (Duarte et al. 2021). However, there are still many gaps in the effects of noise on species and ecological processes. Anthropogenic noise can affect behavior (Leduc et al. 2021; Nedelec et al. 2022; Velasquez-Jimenez et al. 2020), physiology (Fakan and McCormick 2019; Mills et al. 2020; Staaterman et al. 2020), and survival (McCormick et al. 2018) of different reef fish species, and doing so can exert direct and indirect ecological effects in the dynamics of reef systems.

Sound plays a crucial role in the dynamics of different species and consequently marine environments, including reefs. Due to the efficient propagation of sound waves, hearing is a primary sense in aquatic environments (Mooney et al. 2012; Putland et al. 2019). The acoustic signature of a reef, for example, is used by larvae for guidance during settlement and habitat use (Lillis et al. 2014). These acoustic cues can also be used in intra and interspecific interactions, including reproduction, territory and nest defense, foraging, predator-prey interactions, and many others (Popper and Hawkins 2019). Low-frequency noise (below 1000 Hz) from small vessels is the most frequent source of noise impact in shallow water areas (Bittencourt et al. 2014, 2020), and can overlap the same frequency range of hearing and sound production in many reef fish species (Lobel et al. 2010; Putland et al. 2019). A detailed understanding of the effects of different anthropogenic noise frequencies on reef species is critical to elaborate management rules to minimize impacts on species and critical functional processes.

Reef fishes are a diverse and abundant group in reef systems (Parravicini et al. 2013), being a classical ecological model for understanding the effects of different anthropogenic pressures (e.g., anthropogenic noise). Reef fish, as well as all vertebrates, can hear, but the aspects of their hearing capabilities are less known. There is still a large gap in which species are vocal, and the types of vocalizations that are used (Ladich 2014). Many reef fish species use acoustic cues throughout their lifecycle, from settlement to habitat use (Gordon et al. 2018; Radford et al. 2011; Simpson et al. 2005). Damselfishes, for instance, are a great model for acoustic ecology studies, as territorial behavior makes them comparatively easy for experiments both in the lab and in the field. Also, vocalization in Damselfishes has been widely studied for territory and nest defense to reproductive interactions (Frederich and Parmentier 2016).

This chapter summarizes the main results found in the last few years regarding the effects of anthropogenic noise on reef fishes. The main topics for future research are also discussed.

Effects of Anthropogenic Noise on Reef Fish

Behavior

Anthropogenic noise affects different reef fish behavior across their life cycle, with behavioral changes usually being the first response of organisms to different environmental drivers (e.g., temperature, salinity). Looking at early life stages, Holles et al. (2013) showed primary evidence of how boat noise can negatively affect the selection of habitat by reef fish species. Later, a similar study indicated a disruptive effect of anthropogenic noise on the natural rate of settlement in reef fish larvae (Simpson et al. 2016a). The effects of noise on larvae settlement have been detected not only for tropical species but also for temperate ones (Jung and Swearer 2011). Those significant effects at early life-history stages could have detrimental effects on both populations and community levels. Survival rates are other important metrics used to evaluate the effects of anthropogenic noise on reef fishes. Recently, Nedelec et al. (2022) used both field and lab experiments to demonstrate how limited boat activity leads to greater survival rates of offspring. In "limiting-boat" conditions, the offspring of the spiny chromis *(Acanthochromis polyacanthus)* were more likely to survive, when compared to "busy-boating" conditions. The same pattern was seen for the ambon damselfish *(Pomacentrus amboinensis)* where less than one-third of recruits survived in boat noise treatments (Simpson et al. 2016b). Though, this is not always the pattern, as the survival rates of two other damselfishes did not alter after noise exposure in the laboratory (Fakan and McCormick 2019). Thus, these data suggest that more studies are needed to determine the differential effects of anthropogenic noise at earlier life stages of reef fishes.

Foraging is a crucial behavior not only for the performance of individuals but also for maintaining population dynamics since habitat use and food selection by consumers have been widely recognized to affect lower and higher trophic levels (Stephens et al. 2008). Some studies using damselfishes showed that individuals submitted to noisy conditions had lower foraging rates. For instance, a planktivorous damselfish, *Chromis chromis,* reduced its bite rates in the presence of heavy nautical traffic (Bracciali et al. 2012). The same pattern was observed for land-based (Leduc et al. 2021) and underwater noise pollution (Lessa et al., *in prep)* on the *Stegastes fuscus* foraging behavior. Leduc et al. (2021) also experimented with flight-initiation responses to predators under elevated noise conditions, and found significantly reduced fleeing distance in these same conditions. Foraging in rays was also affected by noise pollution, since boat noise induced escape behavior (Berthe and Lecchini 2016; Mickle et al. 2022).

Increased refuge behavior is a common response of some species to a threat (Cooper and Blumstein 2015). For instance, territorial species are unable to move away in the presence of a stressor, due to their limited home range and swimming abilities. In a study with the red-mouth goby *(Gobius cruentatus)* noise playback significantly increased its refuge time for short-time exposures (Sebastianutto et al. 2011). A similar pattern was detected for the domino damselfish *(Dascyllus trimaculatus)* under noisy conditions (Nedelec et al. 2016).

Acute stress caused by noise may also increase aggression levels and, therefore agonistic interactions in reef fishes. Some studies found increasing aggressiveness in the presence of noise. Mills et al. (2020) highlighted that orange-fin anemonefish *(Amphiprion chrysopterus)* increased agonistic interactions toward heterospecifics when exposed to boat noise playback in two different exposure experiments. The same pattern was observed for the spiny chromis *(Acanthochromis polyacanthus)* males guarding nests exposed to boat noise playback (Nedelec et al. 2017). Increased territoriality in the presence of noise can affect other important aspects of reef fish life cycle. If they spend more time being territorial, they have less time to spend on other crucial daily activities, including parental care and mating, which may directly affect energy budget and individuals' fitness. However, Lessa et al. (*in prep*) found that noise does not necessarily increase agonistic interactions of the dusky damselfish *S. fuscus.* Therefore, the trade-off between territorialism and other crucial behaviors (e.g., parental care and mating) during noise exposure should be investigated.

Physiology

Physiological responses, mostly associated with stress, are a central topic of discussion on the effects of noise on marine life. Noise can lead to primary (e.g., hormone release) and secondary responses (e.g., ventilation and heartbeat changes). For the first response, Armstrong-Smith (2016) observed elevated levels of corticosteroids in two reef fish species: starved green chromis *(Chromis viridis)* and spiny chromis *(Acanthochromis polyacanthus),* while Staaterman et al., (Staaterman et al. 2020) showed heightened whole-body cortisol levels of *Halichoeres bivittatus* to boat noise. Another physiological marker recognized as a stress response to boat noise was testosterone. Orange-fin anemonefish *(Amphiprion chrysopterus)* had elevated testosterone levels in short- and long-term experiments of noise exposure (Mills et al. 2020).

Noise can also have secondary physiological responses in reef fishes. An experimental study with embryos of the staghorn damselfish *(Amblyglyphidodon* *curacao)* showed that heart rates significantly increased after exposure to 2-stroke and 4-stroke boat noises (Jain-Schlaepfer et al. 2018). Interestingly, the 4-stroke had a lesser effect on heart rates than the 2-stroke engines, where the latter had more than twice the effect. Possibly because the spectral content in terms of sound pressure levels, sound exposure levels and particle acceleration of the 2-stroke powered-boats was greater, when compared to the 4-stroke engines. Similarly, Fakan and McCormick et al. (Fakan and McCormick 2019) tested whether boat noise affected the early life history traits of the cinnamon clownfish *(Amphiprion melanopus)* and the spiny chromis *(Acanthochromis polyacanthus)*. The results showed that both species had elevated heart rates with the playback of boat noise compared to ambient noise. However, when looking at morphological traits the results diverged between species.

What's Next?

Starting from Scratch

Acoustic signals are used throughout a fish life cycle for orientation and settlement, and for different social interactions, including intra- and interspecific ones (Amorim 2006; Amorim et al. 2013; Gordon et al. 2018; Lobel et al. 2010; Radford et al. 2011). However, many species do not have their hearing range or the vocal repertoire fully described. This huge gap in acoustic ecology is keeping us distant from an integrative evaluation of the impacts of noise on wildlife. Therefore, future studies must focus on basic information about reef fish bioacoustics (e.g., hearing sensitivity, acoustic signatures), rather than just using applied science to evaluate the effects of noise.

Integrative Approaches

Most studies focused on behavioral responses, nonetheless only a small number of studies explore the physiological responses of reef fishes to noise or even the interaction of both (see Mills et al. 2020). In addition to behavioral responses, physiological indicators of stress can also be used as proxies for the deleterious effects of noise. Physiology plays a vital role in understanding the mechanisms behind the effects of what we can see, such as changes in behavioral patterns. Thus, an important question may arise: how can physiological and behavioral responses be combined to address conservation efforts? Having longer experiments using combined response approaches (e.g., behavioral and physiological) is crucial to better understanding the effects of noise on wildlife. Also, it is important to evaluate the responses of key species, with different functional roles, to have a representative set of the ecological effects of noise, at both community and ecosystem levels.

Multiple Contexts

From a conservation perspective, the effects of noise under multiple stressors (e.g., overexploitation, climate change, habitat loss) are still a topic we know little about. The responses of organisms to multiple stressors can be synergistic when the effect is greater, or antagonistic when the effect is minor (Côté et al. 2016). In natural systems, where the multiple-stressor-scenario is usual, isolating the effect of a single threat is a major challenge, and that is why most studies use a single-stressor approach in the field or prefer to run lab experiments, with controlled conditions. However, these results are not always realistic, as individuals and species may vary their responses depending on different contexts (Purser et al. 2016; Radford et al. 2016). Thus, experimental designs for multi-stressor studies should be explored and conducted to have a more naturalistic risk assessment of noise and, therefore, assist in conservation efforts.

Across Scales

It is clear that there are still remaining gaps in reef fish responses to noise (Fig. 1) at different ecological and time scales. Such responses can vary with the type (e.g., low or high frequency sounds), duration, and time of exposure as well (chronic or acute, daily fluctuations) (Holles et al. 2013; McCormick et al. 2018). Although anthropogenic noise can be transient, there is an increasing number of noisy sources in the marine environment, such as ships, boats, wind farms, coastal constructions, seismic surveys, and many others (Duarte et al. 2021; Popper and Hawkins 2019). The continuous exposure to these sources may lead to habituation in some fish species, sometimes with recovering and even compensating for those stimuli (Nedelec et al. 2016; Picciulin et al. 2012). Therefore, extrapolation of short-term responses ranging from individual to population levels must be treated with caution, as some species may habituate and have different responses over time (*Pomacentrus amboinensis*: Holmes et al., 2017; *Dascyllus trimaculatus*: Nedelec et al. 2016; *Halichoeres bivittatus:* Staaterman et al. 2020).

Habituation itself is a controversial theme, as it may be associated with other unexplored topics, such as temporary and/or permanent noise-induced threshold

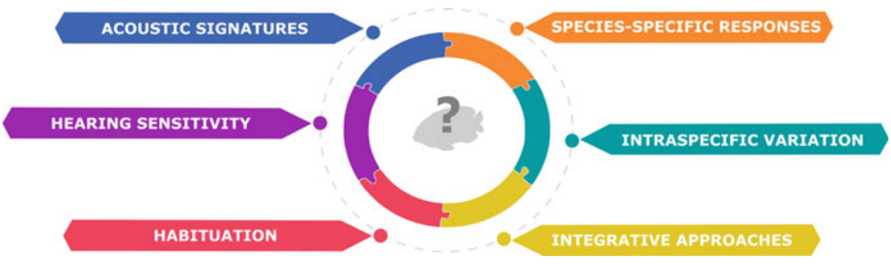

Fig. 1 Conceptual diagram of the main topics for future research

shifts. Furthermore, defining response patterns and applying them from one species to another is a very simplistic approach, as some responses may be species-specific. For instance, Fakan and McCormick (2019) showed different responses in the morphological development of two damselfish species to the same noise. In addition, intrapopulation variation should also be investigated in more detail. Individuals of the same population cannot be treated as a homogeneous unit, as they can respond differently to anthropogenic stressors, due to intrinsic and extrinsic factors (Harding et al. 2018). Further research is needed to better understand: (1) how fish responses may change over time, and (2) how those responses change inside a population and through different taxa. Moreover, (3) how those individual responses have ecological significance and are indeed affecting population dynamics.

Conclusions

Anthropogenic noise is a major concern for marine systems since noise has been recognized as a global pollutant. Despite recent efforts, the extent of knowledge on how it affects certain groups, like reef fish species, is limited. Some species can be affected by noise; however, a wide range of this impact on reef systems has not yet been determined and much work remains to be done. For instance, information about which species are more or less vulnerable to noise is crucial for management and decision-making in the future. There is also a lack of important basic bioacoustics information on reef fishes that would considerably enhance our understanding. Future research may explore the topics highlighted here for a better understanding of the range of effects of noise in reef systems.

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