Moving Up the Chain: Impacts of Noise on Marine Birds—An Indirect Pathway Through an Important Forage Fish

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Abstract

Noise can have a variety of impacts on marine organisms and systems. However, most of the research to date focuses primarily on single species responses rather than trying to examine the effects of noise on multiple species in a system or the species community as a whole. One reason this may often be unaddressed is that system-wide studies are difficult to do. However, by choosing a focal species that serves a particular role in their ecosystem (e.g., as predator or prey), and focusing on how noise affects that role, scientists can better understand the indirect effect

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of noise through a community. In this chapter, the authors use forage fish and their relationship with their avian predators to examine how noise affects not only one species, but how it can indirectly impact others that they interact with.

Keywords

Predator · Prey interactions · Indirect effects · Anthropogenic noise · Ammodytes · Alcidae

Introduction

Global trade has increased approximately 3% annually over the last few decades, with a brief pause during COVID-related restrictions after which it resumed a 3% increase, and over 80% of this trade relies on maritime transport (UNCTAD 2019, 2023). Increased background noise levels associated with vessel traffic have been documented in several regions of the world (Erbe et al. 2019), along with increases in underwater exploration (e.g., seismic surveys; Peng et al. 2015), construction (e.g., pile driving; Peng et al. 2015), and machine operation (e.g., wind farms; Peng et al. 2015). This growing list of potential impacts of noise has raised concerns about how noise may be affecting not only individual marine species, but the marine ecosystem and species communities within, and by extension ecosystem services (Peng et al. 2015). Animals are negatively impacted by anthropogenic noise in marine environments in a myriad of ways, from injury and death, to subtle changes in behavior (Kok et al. 2023; Cox et al. 2018). While some of these changes may not appear to have major impacts on an organism or its community at first glance (e.g., changes in swimming depth), these subtle changes may impact interspecific relationships, leading to system-wide consequences. For example, noise pollution may impact predators negatively (e.g., marine birds) by altering the availability, catchability, and quality of important prey (e.g., forage fish; Kunc et al. 2016).

Forage fish are small schooling fish that play a pivotal role in marine ecosystems by concentrating and transferring energy from primary and secondary production to upper trophic levels, supporting large biomasses of predators (Smith et al. 2011; Pikitch et al. 2014). They also play a key role as top-down control of lower trophic levels and downward recycling of nutrients (Rice 1995; Bakun 2006). Due to their central role, noise-associated changes in the behavior and physiology of forage fish that affects their availability, catchability, or quality can have far-reaching implications, including impacts on predatory populations that depend on them. This mechanism provides indirect pathways where noise can affect predator species. In this chapter, the authors will examine the potential ways in which anthropogenic noise can have system-wide impacts by examining how the effects of noise on a forage fish could directly impact their availability, catchability, and quality as prey, thereby indirectly impacting the predators that rely on them.

Marine piscivorous birds (e.g., Alcids such as marbled murrelets, *Brachyramphus marmoratus*) often rely heavily on forage fish as a major source of food year-round, and this is reliance is emphasized during the breeding season when chicks need to grow quickly in order to increase successful fledging (Bertram and Kaiser 1993; Hedd et al. 2006). Many diving piscivorous marine bird species could be considered suitable indicators of impacts of noise on forage fish, providing an opportunity to explore how noise can impact species/species communities indirectly. First, these marine bird species are conspicuous and easily monitored. Second, they are reliant on forage fish, and hence, impacts from anthropogenic noise on forage fish ought to be detectable in these bird species through changes in their predator–prey relationship. Third, the relationship between piscivorous marine birds and their prey is similar to many other species who rely on forage fish, making detected indirect impacts of noise on birds exemplary of potential impacts to other marine predators. Finally, marine birds are only exposed to anthropogenic noise underwater briefly when diving (though they may still be exposed to above water noise). This restricted exposure to noise reduces the likelihood of noise directly impacting marine birds, and allows the authors to explore indirect affects stemming from noise impacts on forage fish, reducing the conflation of direct and indirect effects of noise on these marine predators.

Pacific Sand Lance

Pacific sand lance, *Ammodytes personatus* (PSL), are a quintessential forage fish as they serve as an important resource for a wide range of taxa in the Northeast Pacific including marine birds (e.g., gulls and terns; Suryan et al. 2002), mammals (e.g., porpoises; Aydin et al. 2007), and piscivorous fish (Robards et al. 1999a; Gunther et al. 2024). PSL have an extensive range and are commonly found in near-shore habitat from southern California to Alaska. They are a small elongate (<200 mm) and short-lived (max 6 years) fish species that lack a swimbladder, pelvic fins, projecting lower jaw, and spines in dorsal and anal fins (Baker et al. 2019). They are common during the summer when they are active in the water column and frequently caught by seabirds in feeding frenzies. In the winter, however, PSL are mostly absent in the water column as they enter a dormancy phase during which they bury in sandy sediment on coastal and continental shelves for up to 5 months (Baker et al. 2019; Greene et al. 2021; Huard et al. 2022; Gunther et al. 2024).

Importance of Pacific Sand Lance to Marine Birds in the Salish Sea

Of the many species that rely on PSL, marine Alcids have been shown to be particularly sensitive to fluctuations in PSL availability and quality, especially during their breeding season (Bertram and Kaiser 1993; Hedd et al. 2006; Gjerdrum et al. 2003). PSL have features that make them an important prey for nestlings in particular. Compared to other forage fish, they may be located closer to shore, decreasing the distance individuals need to travel to catch them (Sakai et al. 2025). Although they are of similar caloric quality (energy density ~5–7 kJ/g) to other fish often fed to seabird chicks (e.g., rockfish; Harris and Hislop 1978; Robards et al. 1999a; van Pelt et al. 1997), sand lance are long, skinny, and do not easily fall apart, which allows for many fish to fit in one bill load for chick provisioning parents (Harris and Hislop 1978; Hislop et al. 1991) leading to increased calories per load (Bertram and Kaiser 1993; Robards et al. 1999a). This slender shape and high caloric quality is also important for species of birds whose chicks cannot eat deeper-bodied fish in the first week or two of life (e.g., red-throated loons; Reimchen and Douglas 1984). Higher growth rates and fledgling success of chicks are correlated with a higher proportion of PSL in chick diets (Bertram and Kaiser 1993; Hedd et al. 2006), which suggests that PSL are of particular importance to seabird populations (Gjerdrum et al. 2003). For example, rhinoceros auklet (*Cerorhinca monocerata*) arrive in the Salish Sea in May and depart in September (Bertram et al. 2023, 2025), which coincides with PSL presence in the water column. PSL breed and emerge from dormancy in May and begin to bury for increasing duration as they enter into their winter dormancy around September (Bertram pers. obs.).

Effects of Noise on Forage Fish Physiology and Behavior

Noise has been shown to affect fish in a variety of ways, from injury and death, to more subtle impacts affecting behavior or physiology (Kok et al. 2023; Cox et al. 2018). In the most extreme cases, fish exposed to very high sound levels (>196 dB re 1 **μ** Pa) can suffer injuries such as rupturing organs (Halvorsen et al. 2012; Jenkins et al. 2022) resulting in death. High levels of noise can also result in temporary or long-term hearing loss (Scholik and Yan 2001). In less extreme cases, fish can experience higher levels of stress when exposed to noise (Anderson et al. 2011) which, in some cases, may be linked to the various noise-induced behavioral changes such as alterations in movement (Vabø et al. 2002), decreased foraging success (Voellmy et al. 2014a, b; Purser and Radford 2011) and offspring survival (e.g., lower parental care; Nedelec et al. 2017), and increased mortality due to predation (Simpson et al. 2016).

PSL, like most fish, have a lateral line which serves to detect noise from the environment as particle motion (Strobel and Mooney 2012). *Ammodytes* spp. lack a swim bladder and are therefore thought to be less sensitive to sound pressure compared to other forage fish like Pacific herring (Enger 1967; Suga et al. 2005). Additionally, unlike most other forage fish, PSL burying behavior makes them vulnerable to sedimentary noise that results both from loud noises (airborne or waterborne sounds transmitting into the sediment) and vibrational sound resulting from movement/impacts within the sediment (e.g., pile driving, earthquakes, etc. Hawkins et al. 2021). There remains little experimental literature examining how PSL respond to sound, but what does exist suggests that they likely respond poorly—decreasing their energy density and weight–length relationships (Carlson et al. 2025) and altering their behavior to different types of noise (White et al.

unpublished data). However, some experiments show mixed results, either with minor behavioral changes (e.g., increased c-starting) and local but not overall changes in abundance during or after seismic surveys (Hassel et al. 2004) or some decreased condition when exposed to noise during dormancy, but not to the same degree as when nondormant (Carlson et al. unpublished).

How Noise May Affect PSL as a High-Quality Prey Species for Marine Birds

Here the authors explore the many pathways that noise could indirectly impact marine birds and discuss the potential effects of noise on PSL. The authors have chosen PSL for three reasons: (1) they are hearing nonspecialists and so represent the lower limit of anthropogenic noise impact, (2) they are important to seabird survival and reproduction, and (3) their antipredator behavior (burying) creates a binary measure which is more easy to conceptualize and well suited to this particular theoretical exploration. To examine how noise may indirectly affect seabirds the authors will focus on three main categories: prey *availability* (i.e., are the prey available in the system?), prey *catchability* (i.e., when available, are they easy to catch?), and prey *quality* (i.e., how energy dense are the prey?; Fig. 1).

Availability

Availability can be affected in a few different ways. Noise can cause changes in movement, resulting in sand lance avoiding noisy areas as seen in other fish species (Vabø et al. 2002). If these areas are the main areas where birds forage, such

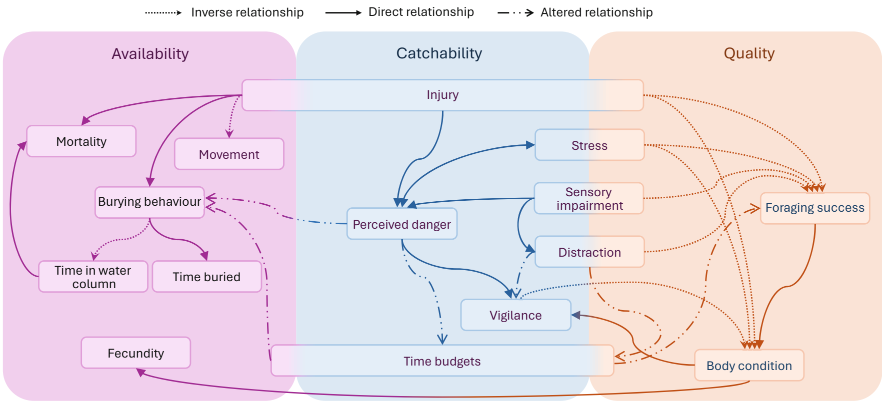

Fig. 1 Increased noise can impact forage fish availability, catchability, and quality in several ways that are often linked to one another. Line type indicates whether noise results in direct relationships (solid line), inverse relationships (dashed line), or altered relationships (dot dash line) between factors affecting availability, catchability, or quality

movement could result in a loss of accessible fish (either partially or entirely; Ronconi and Burger 2008). Similarly, if changes in noise result in increased burying behavior (as a result of stress—to avoid stress and conserve energy, increased foraging success—after meeting daily energy needs, burying to conserve energy and avoid predation, or increased perceived danger—avoid predation; Fig. 1; White et al. unpublished data), PSL availability could decrease as they would be effectively removed from areas diving birds can access. Conversely, if burying behavior decreases (Fig. 1; White et al. unpublished data) as a result of stress, decreased foraging success (not meeting daily energy needs and so remaining in the water column to forage), or altered time budgets, then fish could become more available in the water column for diving birds to access. However, increased access may lead to overexploitation by predators. Fishing pressure has been clearly associated with amplification of naturally caused collapses associated with boom-bust cycles of forage fish populations (Essington et al. 2015). Similarly, increased predation pressure resulting from increased access to forage fish may also enhance natural population declines in PSL, but to a lesser extent than amplification from fishing pressure on commercially exploited forage fish species. In addition, boom-bust population cycling has not been established in PSL as it has for other species of forage fish, and it remains unclear if there are cyclic natural declines that could be enhanced by increased predation pressure. Finally, sound can negatively impact fecundity through a variety of mechanisms resulting in population decreases, thereby reducing availability (Kok et al. 2023). Noise could decrease egg production due to increased stress and/or poor body condition as seen in other fish (van Deurs et al. 2011; Cox et al. 2018; Kuzuhara et al. 2019) or by reducing overall size of females, which would result in smaller gonads/fewer eggs in PSL as length is directly proportional to gonad size (Robards et al. 1999b; Kuzuhara et al. 2019). Exposure to noise can impact spawning through alterations in time budgets (e.g., increases in foraging time reducing time for courtship or parental care; Kok et al. 2023; Nedelec et al. 2017) or egg survival or larval growth and survival (Banner and Hyatt 1973).

Catchability

Catchability can be affected through altered antipredator responses; specifically through changes in vigilance and acute antipredator behavior. Noise can cause a decrease in vigilance, detection or appropriate response to a predator through masking predator sounds, distracting from pertinent signals (Simpson et al. 2015), or overwhelming sensory input resulting in an inability to process or respond to a signal (Hasan et al. 2018). All these cases result in increased catchability of prey (Simpson et al. 2016). However, as with availability, if predators can overexploit PSL, then the increase in catchability may only be temporary, or last until they become less available due to overexploitation. Noise can also decrease catchability by altering antipredator responses such as increased vigilance (McCloskey et al. 2020), decreased response time to predation (Voellmy et al. 2014a), or increased startling behavior (Voellmy et al. 2014b; White et al. unpublished data).

Quality

Noise has been shown to reduce both PSL energy density and weight–length relationship (Carlson et al. 2025). This reduction could be a result of increased stress (Wysocki et al. 2006) resulting in lower condition (Anderson et al. 2011), or changes in foraging success (Voellmy et al. 2014a), or altered time budgets (Voellmy et al. 2014b) as seen in other species. Stress impacts metabolism and energetic processes, often resulting in poor body condition and increased susceptibility to disease and/or parasites (Anderson et al. 2011). Noise can impact foraging success either through altering behavioral time budgets resulting in less time foraging (Voellmy et al. 2014b) or increasing foraging errors or food processing time (Voellmy et al. 2014b; Purser and Radford 2011). Although noise could also mask the use of acoustic cues to find prey, as PSL are thought to be primarily visual predators (Robards et al. 1999a), this is an unlikely mechanism.

No Effect

Finally, that noise may not affect PSL and hence will have no impact on the predator–prey relationships, and therefore, their predators must also take into consideration. While there is evidence that noise can change PSL quality and availability (Carlson et al. 2025; White et al. unpublished data), other studies have shown little to no effects (short or long-term) on other *Ammodytes* species (Hassel et al. 2004), as well as other species of fish (Cox et al. 2018), including habituation to noise over time (Nedelec et al. 2016).

Conclusion and Final Thoughts

Anthropogenic noise continues to increase in oceans, and while the scientific community's understanding of how this noise is impacting species and systems continues to grow, so does the scope and impact of anthropogenic noise necessitating further investigation on many levels. Much of the historical and current research continues to focus on direct effects on individual species or estimating intensities across entire soundscapes. Therefore, scientists continue to struggle with addressing whether these estimated impacts have relevance at the community or ecosystem levels and how they are directly and indirectly affecting species communities. To truly understand how anthropogenic noise is affecting aquatic life, researchers must look beyond single species, or even single trophic levels, and determine how noise is impacting the relationships between species to affect entire ecosystems. The authors have laid out one way of investigating these types of system-level effects: focus on species that serve a functional role in their ecosystem and target the changes to their behavior and physiology that are part of that functional role (e.g., availability as prey). In doing so, research can directly address how noise can impact species communities or ecosystem through affecting predator–prey or other key relationships among constituent species.

While the authors used PSL in this example for a variety of reasons, there are some aspects of PSL that are quite different from other forage fish species. First, PSL are the only forage fish to bury for hours to months at a time, and they are uniquely unavailable during those times (although some PSL predators such as Pacific cod and humpback whales may dig up dormant PSL; Girsa and Danilov 1976; Hain et al. 1995). However, this is similar to other species that migrate (e.g., Pacific herring; Therriault et al. 2009), and are, therefore, similarly absent during parts of the year. Second, PSL are not hearing specialists as they lack a swim bladder (Robards et al. 1999a; Suga et al. 2005), unlike most other forage fish, which means that the authors' estimates of the degree to which PSL are affected by noise is likely less than other forage fish would experience. Finally, as PSL spend time buried, they may be representative of other species that spend a large proportion of their time in or on the seafloor where they are susceptible to sound as it moves through the substrate from human activities such as pile driving (Hawkins et al. 2021).

Anthropogenic noise can affect species communities and ecosystems in several ways not only by affecting species directly, but indirectly as well through altering interspecific relationships. To understand and mitigate the potentially devastating effects of anthropogenic change, researchers need to investigate how impacts such as increased noise, temperatures, and pollution affect interspecific relationships and echo throughout communities both directly and indirectly.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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