Fisheries Research 292 (2025) 107607

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Review

Seal cognition and the prospects of mitigating human-seal conflicts with deterrent devices

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ARTICLE INFO

Handled by: Shannon Bayse

Keywords:
Behavior
Conservation
Fishery
Intelligence
Management
Pinniped

ABSTRACT

The behavioural patterns and cognitive capacities of seals, along with the fast recovery of their populations in many coastal regions, have brought them into intensifying conflict with aquaculture and capture fisheries. To promote coexistence between seal populations and the fishery sector, acoustic deterrent devices (ADDs) are widely employed to prevent seals from approaching fish farms, fishing gear, coastal development sites or key areas of fish reproduction. Our literature review highlights the need for a deeper understanding of various aspects seal behaviour and cognition, such as their spatial awareness, learning capacities and problem-solving skills. Such knowledge is valuable both academically and in helping to mitigate human–seal conflicts, while minimising harm, such as hearing damage, to seals and non-target species. For instance, the current deterrent strategies often overlook behavioural and cognitive traits that may allow seals to circumvent the deterrents, thereby compromising their long-term effectiveness and causing animal welfare concerns. Our review underscores the need to understand the consequences of individual behavioural differences and environmental variability when addressing the challenges of ADDs and human–seal conflicts more generally. Such research can promote the development of more effective and ethically sound solutions to mitigate the conflict, including technical development of ADD systems that are more cost-effective, practical and align with animal welfare.

1. Introduction

1.1. Conflicts between humans and seals

Pinnipeds, particularly seals, are widely regarded as important flagship species due to their key roles in top-down ecological processes and nutrient recycling within many coastal ecosystems (Bossart, 2011; Kiszka et al., 2015; Hammerschlag et al., 2019; Nelms et al., 2021). Historically, seal populations around the world experienced substantial declines, driven by intensive hunting and, more recently, by additional threats, such as pollution, entanglement in fishing gear, coastal development and climate change (Harding and Härkönen 1999; Bowen and Lidgard, 2013; Nelms et al., 2021). For example, in the Baltic Sea, the grey seal (*Halichoerus grypus*) population was estimated at approximately 100,000 individuals in the late 1800s and early 1900s, but within a few decades, it was decimated to just a few thousand individuals (Harding and Härkönen 1999; Harding et al., 2007). This extensive hunting was mostly motivated by negative effects of seals on fisheries (Harding and Härkönen 1999).

More recently, seal hunting bans and the reduction of key environmental toxins have enabled the recovery of many seal species (Magera et al., 2013). These include, for example, the Baltic Sea populations of the grey seal and ringed seal (*Pusa hispida*) (Harding and Härkönen 1999; Harding et al., 2007; Suuronen et al., 2023; Ersalman et al., 2025), fur seal populations in Australia and New Zealand (Kirkwood et al., 2010; Berry et al., 2012) and multiple North Atlantic seal populations (Cammen et al., 2019; Bogomolni et al., 2021). While this recovery represents a notable success in animal and marine conservation, it has also amplified conflicts between seals and the capture fishery and aquaculture sectors. Many seal species have demonstrated remarkable behavioural adaptability, learning to exploit fishing activities and aquaculture facilities as reliable food sources (Machado et al., 2018; Barrios-Guzmán et al., 2024). This has led to substantial economic losses to many fishers and aquaculture operators in the Baltic Sea region (Fig. 1; Varjopuro, 2011; Waldo et al., 2020; Blomquist and Waldo, 2021; Vetemaa et al., 2021; Svels et al., 2025), North Atlantic (Gulland, 1987; Cronin et al., 2014; Houle et al., 2016; Bogomolni et al., 2021) and other parts of the world (Cummings et al., 2019; Tixier et al., 2021;

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https://doi.org/10.1016/j.fishres.2025.107607
Received 7 July 2025; Received in revised form 14 November 2025; Accepted 17 November 2025

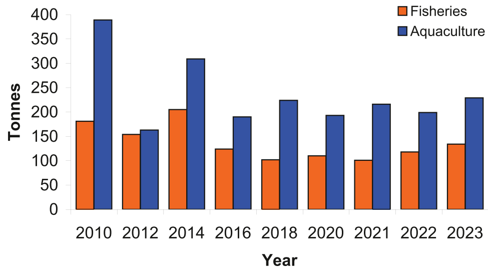

Fig. 1. The weight of fish that fishers and aquaculture practitioners reported as damaged by seals in the Finnish waters of the northern Baltic Sea (Source: Natural Resources Institute Finland / Söderkultalahti and Moilanen, 2025; Söderkultalahti and Rahikainen, 2025).

Jackson et al., 2024).

Broadly defined, human–wildlife conflicts stem from any behavioural interactions that result in negative outcomes for either humans or animals (Madden, 2004). In practice, however, the term is usually used to describe situations in which human activities are adversely affected. In the case of seals, these negative impacts—both perceived and documented—include damage to aquaculture infrastructure and fishing gear, damaged or eaten catches and farmed fish, altered fish behaviour and increased fish mortality (Baltic Sea: Kauppinen et al., 2005; Hansson et al., 2018; Suuronen et al., 2023; elsewhere: Chouinard et al., 2005; Middlemas et al., 2006; Cronin et al., 2014; Vincent et al., 2016; Olsen et al., 2018). These conflicts have also been intensified by the declining abundance of many commercially harvested fish populations, often due to overfishing and environmental change (Christensen et al., 2003).

1.2. Mitigation of the conflict

Given the human-centred perspective, traditionally the default response to the human–seal conflicts has been hunting (Bowen and Lidgard, 2013; Oksanen et al., 2014; Sellheim, 2018). However, intense culling is increasingly regarded as ethically problematic and, similarly to other major forms of human-induced mortality, may lead to unintended consequences for the target species and ecosystem dynamics (Yodzis, 2001; Scott and Parsons, 2005; Bowen and Lidgard, 2013; Nunny, 2020). Therefore, less lethal management strategies have been developed to address these conflicts. The approaches include the use of physical barriers, relocating individuals, selective removal of individuals deemed problematic, modifications of fishing gear and aquaculture structures as well as the implementation of deterrent devices (Quick et al., 2004; Suuronen et al., 2006; Hemmingsson et al., 2008).

One increasingly adopted non-lethal approach for mitigating human–seal conflicts is the use of Acoustic Deterrent Devices (ADDs), also referred to as acoustic harassment devices (Fjälling et al., 2006; Graham et al., 2009; Schakner and Blumstein, 2013; Lehtonen et al., 2022). ADDs are most often employed to protect stationary targets, such as aquaculture pens, fishing gear or, particularly in riverine environments, specific small areas (Schakner and Blumstein, 2013). These devices are designed to exploit the sensitivity of seals to underwater sound (Southall et al., 2019) with emission of noise that is sufficiently painful, discomforting or distracting to deter seals from approaching the target at which their foraging is deemed problematic (Götz and Janik, 2013; Schakner and Blumstein, 2013). ADDs are generally considered a relatively benign method to reduce the human–seal conflict (Chapter 3) and consequently widely used in the salmon aquaculture industry and increasingly also by capture fisheries and at coastal construction sites, where they keep seals, and often other marine mammals, at a safe distance for their own protection (Mikkelsen et al., 2017; Thompson et al., 2020). However, the devices have not always provided consistent or long-term deterrence of seals (Götz and Janik 2013; Schakner and Blumstein, 2013; Tidwell et al., 2021; Lucas and Berggren, 2023). In that regard, the (economic) feasibility of their application depends on seal behaviour (Chapter 2), technical characteristics of the devices (Chapter 4), the environmental conditions in which they are used (Chapter 4), and the availability of alternative solutions (Chapter 3).

This review examines the links between seal cognition and behaviour and ADDs' applicability and effectiveness as a non-lethal deterrent method. For this purpose, we synthesise research on seal cognition and behaviour that is relevant to human–seal conflicts and provide examples especially from the Baltic Sea region. We argue that, despite the growing use of ADDs, research efforts on the human–seal conflict and its mitigation have not sufficiently accounted for individual- and context-dependent variability in seal behaviour. While the behavioural responses of cetaceans, such as harbour porpoises (*Phocoena phocoena*), both as target and non-target species, to acoustic deterrents have been relatively well studied (Morton and Symonds, 2002; Brandt et al., 2013; Götz and Janik 2013; Elmegaard et al., 2023), the responses of seals have received comparatively limited attention and remain poorly understood. We expect that a better understanding of cognition and behavioural responses of seals can help mitigating the human–seal conflict, for example via deterrents' improved efficacy, ethicality and economical viability.

2. Seal cognition

Cognition is commonly defined as the set of neural processes by which animals acquire, process, and store information, to be able to act upon it (Shettleworth, 2001, 2010). It includes perception, learning, memory, decision-making and problem-solving (Shettleworth, 2001, 2010). These cognitive abilities underpin many essential behaviours, such as mate choice (Fuss, 2021), parental care (Lehtonen, Helanterä et al. 2023), predator avoidance (Evans et al., 2019) and foraging (Szabo et al., 2022). Each animal taxon operates within a unique "cognitive space", shaped by its specific sensory capabilities and perceptual biases (Greggor et al., 2014). Seals, for example, have demonstrated the ability to effectively use spatial information for decision-making during foraging and long-distance migrations (Robinson et al., 2012; Beltran et al., 2022), as well as in more localised contexts when evaluating available food resources (Iorio-Merlo et al., 2022; Maaß et al. 2022).

Besides notable spatial cognitive abilities, harbour seals (*Phoca vitulina*) have been shown to possess a well-developed sense of time, which enables them to discriminate accurately between time intervals and to utilise temporal information effectively in foraging-related decision-making (Heinrich et al., 2016). Demonstrated, sound-related cognitive skills of seals also include identification of individual calls and memorisation of the vocalisation rhythms, allowing them to adjust their responses to familiarity or identity (Lindemann et al., 2006; Robinson et al., 2015; Mathevon et al., 2017; Benson-Amram et al., 2023). However, such acoustic communication is increasingly disturbed by anthropogenic noise in coastal environments. Seals are in many areas exposed to rising levels of underwater noise originating from a variety of sources, including boat traffic, coastal infrastructure development, energy production, underwater military surveillance systems, aquaculture operations, fishing operations (e.g. bottom trawling) and the use of ADDs (e.g. Blackwell et al., 2004; Tougaard et al., 2009; Bailey et al., 2010; McKenna et al., 2012).

A key aspect of seals' cognitive repertoire is that it provides them with considerable behavioural flexibility (*sensu* Audet and Lefebvre, 2017; Lea et al., 2020), which has enabled them to cope with various sources of human-induced noise and other stimuli (Greggor et al., 2014; Samia et al., 2015; Blumstein, 2016). This flexibility, especially the capacity for rapid habituation, is highly relevant in the context of ADDs, because these devices tend to be less effective on animals capable of quick habituation or other forms of behavioural flexibility (Greggor et al., 2014). More broadly, cognitive traits, such as problem-solving, are widely recognised as key mechanisms by which animals cope with anthropogenic change and other environmental disturbances (Lowry et al., 2013; Griffin et al., 2017; Barrett et al., 2019; Lehtonen, Helanterä et al. 2023). Especially opportunistic animals, such as seals, are likely to possess such cognitive traits, which not only facilitate success in human-altered surroundings, but may also increase their likelihood of adopting behaviours that lead to the conflicts with human activities (Barrett et al., 2019; Smeele et al., 2019).

Given the cognitive abilities and behavioural flexibility of seals, it is not surprising that they exploit some anthropogenic noise sources to their advantage. Moreover, their hearing capacities both above and below water enable them to detect a wide range of sounds, which can further facilitate the formation of positive noise-related associations, when the sounds are reliably linked with food rewards. For instance, anecdotal accounts by costal fishers suggest that seals can learn to differentiate between the sounds of individual fishing boats and use this information when foraging. However, empirical research to substantiate these observations is currently lacking. Early deterrent devices were sometimes reported to function as “dinner bells” that seals learned to associate with food availability (Schakner and Blumstein, 2013). This issue has been especially apparent with pingers, devices designed to deter cetaceans from fishing gear to reduce entanglement and injury and not intended to target seals (Carretta and Barlow, 2011; Dawson et al., 2013; Lucas and Berggren, 2023).

2.1. Learning and memory

Although ADD technologies have been progressively refined (Chapter 4.2.), concerns persist that seals may possess cognitive and perceptual abilities that help in overcoming or bypassing the deterring effects (Fjälling et al., 2006; Lehtonen et al., 2022; Veneranta et al., 2024). These abilities may relate to precise timing of actions, finding weaker areas in the devices' noise coverage and remembering these details. While many ADDs emit intermittent signals that are painful to seals in the proximity, some other ADD designs have aimed to raise fear and aversion by harnessing seals' behavioural propensities (Schakner and Blumstein, 2013, 2016; Greggor et al., 2014). However, such deterrence effects may degenerate, if seals learn to overcome their prior fear and other behavioural biases over time. Indeed, learning and memory are among the core cognitive process likely to shape how seals respond to acoustic signals (Lindemann et al., 2006), including those emitted by deterrent devices (Schakner and Blumstein, 2013). Across various contexts, seals have demonstrated quick and precise learning abilities (Reichmuth and Casey, 2014; Casey et al., 2015; Niesterok et al., 2022; Benson-Amram et al., 2023), with their high reversal learning performance (ability to suppress or reverse a previously learned response: Shettleworth, 2010; Niesterok et al., 2022; Spratte et al., 2025) being particularly relevant. Such accurate learning and memory abilities underpin a range of other cognitive functions, such as categorisation, generalisation, spatial skills, innovation and problem-solving (Smeele et al., 2019; Benson-Amram et al., 2023), which may also help a seal to bypass deterrents. In this context, innovation refers to the ability to apply previously learned and memorised knowledge to novel situations, or to develop novel techniques for solving problems (Kummer and Goodall, 1985; Reader and Laland, 2003; Ramsey et al., 2007; Reader et al., 2016). This capacity can also help predators, such as seals, to expand their foraging repertoires, exploit new resources and adapt to new or changing environments (Johnson-Ulrich et al., 2019, 2022). Several seal species have exhibited such cognitive flexibility under laboratory conditions, demonstrating the ability to efficiently respond to different types of signals and to transfer the learned information across different contexts (Lindemann et al., 2006; Scholtyssek et al., 2013; Lindemann-Biolsi and Reichmuth, 2014; Erdsack et al., 2022). By contrast, field studies investigating the cognitive abilities of seals remain limited, highlighting an important direction for future research. Such research in relation to understanding how these abilities influence interactions with deterrent technologies would be particularly interesting.

Regarding ADDs, a few Finnish fishers have communicated that older grey seals may have learned to approach a fishing gear safeguarded with an active ADD by raising their heads above the water surface when near the device. However, we are not aware of any studies or formal records on these putative behavioural abilities, although related observations, such as increased surface swimming in response to ADD sounds, have been documented (Fjälling et al., 2006; Harris, 2011; Kastelein et al., 2018). Given that the sound pressure emitted by a submerged ADD is significantly attenuated above the water surface, such a behavioural strategy could allow seals to reduce their exposure to the noise, hence enabling foraging near aquaculture installations or fishing gear, despite the presence of deterrents. If confirmed, these behaviours would have important implications for the long-term effectiveness of ADDs. Therefore, we strongly encourage targeted research efforts on this topic. Such research should consider seals' cognitive capacities, particularly their abilities in learning and problem-solving.

In Finland, coastal fishers and seal hunters made notable observations regarding the memory and learning capacities of grey seals following the onset of limited hunting in late 1990s, after a ~30- year break in hunting (Suuronen et al., 2023). Hunters noted that most individuals had apparently become less fearful of humans, likely because they had never been hunted (oral communication, Jouni Heinikoski). As a result, seals were relatively easy to approach and shoot during the initial years following the policy change. However, within just a few years of relatively low hunting pressure (Suuronen et al., 2023), seals became markedly more wary of humans, which made hunting increasingly difficult (oral communication, Jouni Heinikoski). Given that this behavioural shift occurred over a short period relative to the generation time of grey seals, in the absence of high hunting mortality, and it spread quickly in the population, it is likely that learning, possibly also socially (see below), played a key role in the rapid spread of avoidance behaviour throughout the population. Finnish seal hunters also consistently report that older individuals are significantly more difficult to hunt than younger, less experienced seals (oral communication, Jouni Heinikoski). In the northeastern Pacific Ocean, harbour seals were found to respond much more strongly to the calls of mammal-eating and unfamiliar fish-eating killer whales (*Orcinus orca*) than to the familiar calls of the local fish-eating killer whale population (Deecke et al., 2002). These observations support the view that seals are capable of complex discrimination of the level of threat specific cues represent, with this information spreading through the population, indicating selective habituation by learning and experience (Deecke et al., 2002). Such cognitive capacities can have direct implications for how they respond to anthropogenic disturbance, including deterrent devices.

2.2. Social learning

Social learning—the ability to acquire information by observing others—can facilitate the spread of novel behaviours much faster than genetic change and individual learning (Danchin et al., 2004; Galef Laland, 2005; Brakes and Dall, 2016; Benson-Amram et al., 2023). Notably, such learning is not limited to conspecifics; it can also occur between species (Seppänen and Forsman, 2007; Avarguès-Weber et al., 2013; Hämäläinen et al., 2023). In seals, important links between learning and social relationships have been found for instance in the context of inhibition of potentially harmful aggression (Bishop et al., 2015; Casey et al., 2015) and when socially learned vocalisations (Reichmuth and Casey, 2014) have resulted in local call dialects (Casey et al., 2018). It is plausible that seals could learn socially also behaviours that put them into conflict with human activities, including effective ways to forage from aquaculture pens or fishing nets (Whitehead, 2010; Donaldson et al., 2012; Schakner and Blumstein, 2021).

Although certain seal species, including the grey seal, periodically gather in groups at haul-out sites (Sjöberg et al., 1999; Pace et al., 2019), their foraging is typically solitary. In these species, maternal nursing period is also brief, lasting only a few weeks, which restricts the pup's opportunity to learn foraging behaviours directly from its mother.

Therefore, it is likely that young individuals have to accomplish most foraging-related learning independently through trial and error, and opportunities for direct observation and learning from others during foraging are limited. While some social learning opportunities may nevertheless exist especially in the context of locating food sources, active foraging collaboration is unlikely. In contrast, some fur seal and sea lion species are known to forage in small groups or even cooperatively, providing a high potential for social learning in the foraging context (Gottfried, 2014; Hooker et al., 2015; De Roy et al., 2021; Hansen et al., 2023). Regarding ADDs, however, we are not aware of any documentation of seals learning to circumvent the deterrent effect simply by observing other individuals.

2.3. Limits to seals' cognitive abilities

The likelihood that a seal manages to circumvent ADDs—either through precise timing of their actions or by locating spatial weak spots in the acoustic barrier—would probably be higher if it would posses future-oriented (i.e. prospective) cognitive abilities (*sensu* Raby and Clayton, 2009; Osvath and Martin-Ordas, 2014). While the ability to act on cues about future rewards (not available immediately) are predominantly studied and observed in primates and corvids (Osvath and Martin-Ordas, 2014), such 'planning' skills might be taxonomically more broadly spread (Gallo and Chittka, 2018; Lehtonen, Helanterä et al. 2023). Hence, it is conceivable that seals would also have such cognitive skills, given their cognitive abilities in other areas (e.g. Lindemann et al., 2006; Scholtyssek et al., 2013; Reichmuth and Casey, 2014; Niesterok et al., 2022; Benson-Amram et al., 2023) and the benefits to be gained from the skills, particularly in cooperatively foraging species (Gottfried, 2014; De Roy et al., 2021; Hansen et al., 2023). However, more basic associative and problem-solving abilities may also suffice for seals to overcome the cognitive challenge.

Seals' cognitive skills are also likely to have limitations linked to their evolutionary history, living environment and niches they occupy. For instance, in some contexts, seals seem to have markedly less developed short-term memory abilities than some other marine mammals, such as bottlenose dolphins (*Tursiops truncatus*) (Smeele et al., 2019). Similarly, in visual reversal learning tasks (Shettleworth, 2010), harbour seals displayed an inferior performance compared to a range of other animals, such bottlenose dolphins, chimpanzees (*Pan troglodytes*) and pigeons (*Columba livia*), in comparable tasks (Erdsack et al., 2022). However, performance in these tasks may depend on the general setting of the task (Delfour, 2006; Aljadeff and Lotem, 2021; Erdsack et al., 2022) and the stimuli being used (Chow et al., 2022). For instance, visual cognitive abilities of seals may not be as well developed as their cognitive abilities in acoustic and spatial contexts, as suggested by a considerably better performance in a spatial than visual reversal learning experiment (Niesterok et al., 2022). Here, it is worth bearing in mind that the tasks or problems that are relevant to humans may not be relevant to seals, which is a universal challenge when examining animal cognition and communication.

2.4. Among-individual variation in seal cognition and behaviour

Pronounced individual differences in behaviour have been observed in a wide range of animal taxa (Dingemanse and Wolf, 2013; Moiron et al., 2020; Laskowski et al., 2022), including seals (Austin et al., 2004; Twiss et al., 2012). Regarding for instance sounds, vocalisation bouts among adult male leopard seals (*Hydrurga leptonyx*) were so different that researchers were able to assign them individually with a high accuracy (Rogers and Cato, 2002). Similarly, affiliative and territorial calls of Cape fur seals (*Arctocephalus pusillus pusillus*) were found to have very high levels of individual variation (Martin et al., 2021). Grey seal females, in turn, were found to differ from each other in their maternal care behaviours (Twiss et al., 2012), whereas individuals of Weddell seals (*Leptonychotes weddellii*) varied substantially in their behavioural responses to aerial devices used for observing them (Park et al., 2024). Such behavioural variation can also result in individual differences in foraging habits (Oksanen et al., 2014; Nowak et al., 2020) and success (Freeman et al., 2022).

An important driver of behavioural differences among individuals is their sex. Both data loggers and satellite telemetry show that typical movement patterns of male and female grey seals differ (Beck et al., 2003; Breed et al., 2009; Nowak et al., 2020), which is likely to affect their likelihood of being at odds with fisheries and other human activities (Oksanen et al., 2014; Greggor et al., 2016). For example, male grey seals enter trap-nets and other passive fishing gear much more often than females (Lehtonen and Suuronen, 2010; Königson et al., 2013). Therefore, males, especially young and inexperienced ones, are also more likely to be caught by, and drown in, these gears. Old grey seal females, in turn, were found to behave more boldly than younger ones (Bubac et al., 2018). Hearing deterioration with age or trauma may induce further behavioural between-individual differences that are relevant to the effectiveness of ADDs (Götz and Janik 2013; McKeegan et al., 2024).

In seals, studies have found evidence for clear differences between individuals in cognitive performance (Scholtyssek et al., 2013; Erdsack et al., 2022), including their ability to learn from past experiences (or from other individuals), which, in turn, have likely contributed to regional and individual differences in behaviour (Schakner and Blumstein, 2016; Casey et al., 2018). More generally, individual differences in behavioural coping strategies, personalities, or cognitive styles seem to be a common source of behavioural variation in many animals (Sih and Del Giudice, 2012; Griffin et al., 2015) and hence likely in seals too. Moreover, individual differences in personality and cognition seem to be linked (Carere and Locurto, 2011; Dougherty and Guillette, 2018). For instance, bolder or more exploratory individuals may also be quicker learners (Dugatkin and Alfieri, 2003; Schakner and Blumstein, 2016). Such individual behavioural variation, relevant to human–seal conflicts, may result from differences at many stages of cognitive processes, including previous experiences, perception of cues, and the decision-making stage (Sih et al., 2011; Greggor et al., 2014; Schakner and Blumstein, 2016; Goumas et al., 2020). The physical environment can also have a relevant role by altering the ability of an individual to invest in the growth and maintenance of neural tissues (Lupien et al., 2009; Buchanan et al., 2013) and hence development of cognitive abilities (Reader, 2015; Boogert et al., 2018; Pike et al., 2018). Recent research efforts have strived to unravel these links between individual differences in cognitive capacities and behavioural patterns (Boogert et al., 2018; Cauchoix et al., 2018; Goumas et al., 2020), but only initial progress has been made in this field, and therefore further research attention is needed.

From the human point-of-view, one particularly relevant aspect of individual cognitive differences is the likelihood of a seal to behave in a way that it gets categorised as a rogue or problem individual. The conflict situations between fisheries and seals have often been suggested to involve specific individuals that repeatedly forage around fishing gear or aquaculture pens (Graham et al., 2011; Oksanen et al., 2014; Freeman et al., 2022; McKeegan et al., 2024). These individuals may limit access of other ones to the food source. Such individual variation relevant to human–seal conflicts may also relate to problem-solving performance or inhibition of neophobia (fear of novelty) (Reader Laland, 2003; Boogert et al., 2018; Barrett et al., 2019; Freeman et al., 2022). Having a bolder temperament and a willingness to take risks in novel situations are also linked to the ability of an individual to start using new resources (Chapple et al., 2012; Griffin et al., 2017; Barrett et al., 2019). Similarly, cognitive capacity to innovate may increase ability of an individual to expand its foraging habits to utilising novel environments and resources available in urban or other human-modified settings (Sol et al., 2005; Lowry et al., 2013).

Individual cognitive and behavioural variation that affects the likelihood of an individual to behave and forage in ways that are regarded problematic has not always been adequately considered in human–wildlife conflict research or applications (Thornton and Lukas, 2012; Boogert et al., 2018). For instance, if a deterrent device has been designed to keep away a typical seal individual, it may still fail, over time, if particularly bold, fast-learning, or hearing impaired individuals manage to find a weakness in the deterrent system that they are able to utilise (such as weaker sound pressure zones or sound pulse patterns produced by the ADD). These individuals are then likely to be considered 'problem individuals' by fishers and aquaculture practitioners. However, further research is still needed on their specific cognitive characteristics (Benson-Amram et al., 2023), with one challenge of the technical development efforts (Chapter 4) having, thus far, been the shortage of field research on individual behavioural variation, and its consequences, in seals.

3. Animal welfare and ethical use of ADDs

3.1. Concerns of negative effects on seals and their behaviour

Animal welfare aspects are not always sufficiently included in the considerations of the mitigation measures of human–wildlife conflicts (Nunny, 2020). Regarding ADDs, potential negative impacts on seals include physical discomfort, pain, stress, temporary or permanent changes in hearing sensitivity, and behavioural changes that may decrease foraging success, well-being or fitness (Götz and Janik 2013; Schakner and Blumstein, 2013; Nunny, 2020; Branstetter and Sills, 2022). Decreased hearing sensitivity may, in turn, reduce responsiveness to the deterrent sounds, reducing their effectiveness and potentially aggravating any negative effects they have (Götz and Janik 2013). Given that many seal species (including grey seals) have wide feeding ranges (Mcconnell et al., 1999; Karlsson et al., 2005; Cronin et al., 2012; Sharples et al., 2012), deterring seals from a certain location may result in the same individuals continuing similar foraging patterns elsewhere, potentially without an overall alleviation of the human–seal conflict.

When a seal learns ways to eat fish from aquaculture pen or fishing gear, it may have less need to encage in more natural patterns of foraging. Habituation to the easy food source may then be an additional incentive for the individual to keep utilising the resource, even after it has been equipped with an ADD. If the hearing sensitivity of such an individual would decrease, it could continue to forage near ADDs while sensing less pain. Impaired hearing, in turn, could reduce long-term survival of the individual, while the frequent visits to the fishing gear or netting cage (despite ADDs) increase its likelihood of entanglement and drowning.

On the Finnish Baltic Sea coast, over the past years, seals have regularly been observed to enter areas where they were not often observed before, indicating that their foraging behaviour has changed, potentially at least partly as a response to changes in the abundance and distribution of their fish prey. For example, in the southwestern archipelago of Finland, especially in autumns (September-November), grey seals have increasingly entered shallow inner bays of the coast in search of food (Lehtonen et al., 2023). Further north, they have, in larger numbers, started to enter coastal rivers (Veneranta et al., 2024). When entering these areas, seals cause losses to local fishers and sometimes become entangled in trap-nets and gillnets. Pilot countermeasures to these changes in the foraging behaviour have included attempts to use ADDs for closing straits leading to an inner bay (Lehtonen et al., 2023) or a section of a river (Veneranta et al., 2024) during the main fishing season, thereby creating temporary zones restricted from seals. If effective, such solutions would benefit the fisheries (or safeguarded fish reproductive sites), but they could also be considered ethically questionable regarding the impacts on seals' opportunities to forage in these areas. The functionality and efficacy of this type of ADD application have thus far not been well documented and therefore require further research.

3.2. Ethical aspects supporting the use of ADDs

An ethical aspect supporting the use of effective deterrent systems is that they can advance welfare and conservation of seals by reducing their unintentional catch, entanglement and drowning. Indeed, fisheries bycatch has been one of the most serious threats to many marine mammal populations, including several seal populations (Read, 2008; Reeves et al., 2013; Hamilton and Baker, 2019). In the Baltic Sea, trap and gill net fisheries have been a major source of seal mortality (Vanhatalo et al., 2014) and therefore an animal welfare concern. Attempts to reduce such deaths by means other than ADDs (e.g. gear modifications) have had varying, and sometimes non-satisfactory, levels of success (Suuronen et al., 2006; Königson et al., 2015; Lyle et al., 2016; Kindt-Larsen et al., 2023). It is relevant to note, however, that bycatch mortality of seals has likely been decreasing with the reduction of the traditional coastal trap-net and gillnet fisheries in the Baltic Sea (partly as a response to the conflict with seals) (Suuronen et al., 2023; Svels et al., 2025).

3.3. Welfare of non-target species

Another important ethical point relates to welfare and conservation of non-target species. ADDs have potential to negatively impact behaviour, and even hearing, of other marine mammals, such as harbour porpoises, that have more sensitive hearing than seals (Morton and Symonds, 2002; Brandt et al., 2013; Schaffeld et al., 2019; Findlay et al., 2021; Elmegaard et al., 2023). In the northern Baltic Sea, the scope for such non-target effects is smaller, with the harbour porpoise being the only native cetacean, which occurs regularly only in southern parts of the sea (Viquerat, 2014). When used in riverine environments (see Graham et al., 2009; McKeegan et al., 2024; Veneranta et al., 2024) or very close to the shore, ADDs may affect the behaviour and foraging of smaller swimming mammals, such as Eurasian otters (*Lutra lutra*) in close vicinity (Stepien et al., 2024). The hearing range of most fish is clearly below the frequencies produced by the deterrent devices (Amoser and Ladich, 2005; Kastelein et al., 2008; Götz and Janik 2013; Hubert et al., 2024). More research may nevertheless be needed, because of the between-species variation in acoustic and other sensory sensitivities in fish (Mann et al., 2007; Kastelein et al., 2008; Popper and Hawkins, 2019). Similarly, not much is known about hearing in birds that are diving to catch fish, but the thus far available information suggests that they can only perceive sounds below the frequencies emitted by ADDs (Larsen et al., 2020). As a safety precaution, humans should avoid swimming and diving in the immediate vicinity of ADDs.

Large-scale use of ADDs may also have conservation concerns in terms of excluding the affected non-target animals from parts of their normal range (Morton and Symonds, 2002; Olesiuk et al., 2002; Brandt et al., 2013). Such unwanted side effects can be seen to be at odds with the European Habitats Directive (i.e. Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora) and The Marine Mammal Protection Act (MMPA) in the United States. In Scottish waters, ADDs used to safeguard local aquaculture industry have been considered to negatively impact non-target species (and potentially seals) far beyond the aquaculture sites themselves (Findlay et al., 2021, 2022; Todd et al., 2021). In a contrasting example, ADDs did not markedly affect the behaviour humpback whales around an Icelandic purse seine fishery (Basran et al., 2020).

3.4. Socio-economic aspects of the use of ADDs

Economic and social needs of professional fishers, which are in some cases compromised by the quickly recovering seal populations (Suuronen et al., 2023), could also potentially be improved by ADDs (Blomquist and Waldo, 2021; Lehtonen et al., 2022; Lehtonen, Lehmonen et al., 2023). Some researchers have suggested that the wellbeing of the small-scale fishers and local communities should be included in the ethical considerations (Arias Schreiber and Gillette, 2023; Svels et al., 2025). Humans have a high demand for healthy and climate-friendly animal protein and some small-scale fisheries and aquaculture solutions are already, or have a high potential for, producing it sustainably. Therefore, their viability could be seen as an ethical issue related to human food consumption and its consequences (Evans et al., 2023; Salmi et al., 2023). Here, it is worth noting that the small-scale fishers who potentially benefit from ADDs (or techinal approaches more generally) are unlikely to have the financial resources to acquire the ADDs needed for the implementation (Vetemaa et al., 2021; Lehtonen et al., 2022; Veneranta et al., 2024). Finally, ADDs have some potential in helping to safeguard reproduction of vulnerable fish species from seal-induced mortality and disturbance (Yurk and Trites, 2000; Tidwell et al., 2021; McKeegan et al., 2024; Veneranta et al., 2024).

3.5. Ethicality of ADDs vs. hunting

Given the current healthy state of many seal populations, it may also be relevant to consider the use of ADDs in the context of the main alternative measure to human–seal conflicts, hunting of seals. This would imply treating seals similar to the elk (*Alces alces*) and other large mammals that are considered as game animals, the populations of which are kept at lower, but (ideally) sustainable, levels by hunting. In this respect, certain remote coastal communities have been heavily affected by the strict protection and rapid population recovery of seals (Svels et al., 2025), while seal meat as a local, traditional and high-nutrition food source has been abandoned (Ziegler et al., 2021). Seal hunting has in some societies had a high societal, cultural and spiritual value (Sellheim, 2018), and its absence can result in markedly increased dependence on imported food of lower nutritional quality. It could therefore be argued that a sustainable level of hunting by locals might have fewer unfavourable side effects than ADDs, such as welfare concerns in non-target species, while it could also be economically more feasible.

4. Technical and environmental aspects of ADDs in the context of seal behaviour

4.1. Technical challenges and solutions

Key challenges with ADDs include their relatively high unit costs, which may not be covered by low profit margins of many small-scale fisheries (Vetemaa et al., 2021; Lehtonen et al., 2022), and the concerns about their long-term efficiency. As covered in previous chapters, some individuals may over time circumvent ADD effects, which would then also lower their economic feasibility. However, the studies suggesting that the efficiency of ADDs degenerates over time (Götz and Janik 2013; Schakner and Blumstein, 2013) mainly used and tested older models of ADDs, while technical improvement may help to counter balance the current high costs and temporal reduction in efficacy (Suuronen et al., 2025). One way to address the challenges arising from variation in environmental conditions and seal behaviour is to make ADD setups more adjustable by using portable and autonomous (integrated and battery-powered) units (Lehtonen et al., 2022). Another ADD solution aims to exploit the flight-associated startle reflex of seals, with initial test results having been encouraging (Götz and Janik, 2016; McKeegan, 2024). A related line of technical investigation attempts to pair a painful or startling (unconditioned) stimulus with a benign stimulus, so that ultimately the target animals would use the latter to predict the former, creating anxiety that will suffice for the desired deterrent effect (Blumstein, 2016).

More generally, harnessing seals' cognitive biases in the design of more effective and ethical (acoustic) deterrents has been considered as a promising approach (Schakner and Blumstein, 2013, 2016; Greggor et al., 2014) that is still in relatively initial stages. One primary aim of these solutions is to circumvent the target animal's habituation and learning capabilities, while avoiding the risk of hearing damage or displacement of non-target species over significant distances (Götz and Janik, 2016). The future deterrent solutions should also be able to address the context-dependency of the device efficiency, especially in relation to the local and variable environmental conditions and individual behavioural and physiological differences, both in target and non-target species (Table 1).

We also expect progress in the development of interactive ADDs that switch on only when a seal gets close to the device (and hence the object it is safeguarding from seals). If functioning with a sufficient accuracy, such devices can replace the current models that emit noise indiscriminately. By being activated by the presence of a seal, an interactive ADD with a wide deterrent sound repertoire might not allow levels of habituation that could compromise its effect. Such devices would also help to reduce human-induced underwater noise pollution. However, their current technical challenges include the fact that seals often make very little sound while foraging, as opposed to the various types of whistles or clicks of foraging cetaceans. One promising solution to this challenge is to design ADDs capable of autonomously patrolling a wider area. This approach could be particularly useful in fish farming operations that have multiple net pens located close to each other. A single mobile ADD could significantly reduce the overall underwater noise, thereby helping to address welfare concerns regarding noise-sensitive cetaceans occurring near fish farming facilities. A mobile ADD is currently under development at least at the Natural Resources Institute Finland.

Given the potential of interactive and mobile ADDs to maximise deterrent effects on seals while minimising impacts on non-target species, further development of these technologies is indeed highly warranted. The application of artificial intelligence, particularly machine learning, may facilitate the creation of additional innovative ADD solutions (Berger-Tal et al., 2024).

4.2. Environmental effects on the efficacy of ADDs

Environmental conditions can mediate the role of seal cognition in human–seal conflicts. For instance, grey seals are known to adjust their foraging behaviour to physical conditions, such as water temperature and turbidity (van Beest et al., 2019; Nowak et al., 2020). Seals have also been found to prey on food resources that are abundant or otherwise easily accessible either seasonally or locally (Cronin et al., 2014; McKeegan et al., 2024). Due to the changing environmental conditions, and seals' responses to them, the efficacy of ADDs is also likely to be affected (Lucas and Berggren, 2023). For instance, depth, bottom topography, ambient noise, turbulence and temperature stratification (e.g. Lehtonen, Lehmonen et al., 2023; McKeegan et al., 2024; Veneranta et al., 2024) may magnify irregularities in the spread of ADD sounds to the surroundings, increasing the probability of seals exploiting them (Table 1). In particular, given cognitive skills of seals especially regarding sounds, well-motivated (e.g. hungry) and persistent individuals may be particularly likely to find and utilise any spatial and temporal weak sectors in the deterrent sound coverage (Fig. 2; Table 2). To ensure their maximum efficiency, it is therefore crucial to pay attention to the specific environmental conditions in which they will be deployed (Table 1). Increasing the understanding of how environmental factors influence sound transmission and seal behaviour can help to optimise the design and application of ADDs.

The numbers of seals foraging near fishing gear or a fish farming cage could also be considered an environment-driven variable that affects the effectiveness of ADDs. Lehtonen et al. (2022) observed that a large number of seals in the proximity of a trap-net with an ADD coincided with increased levels of seal-induced catch damage. Further research is needed to verify these observations. For instance, it is possible that a larger group of seals is more likely to include an individual or individuals that have particularly high cognitive abilities, are particularly bold, or have a reduced hearing, and hence are particularly capable of finding ways to overcome the deterrent effect of the devices. The design

Table 1
Summary of environmental factors that can affect seals' responses to Acoustic Deterrent Devices (ADDs).

Factor	Effect of the factor	Optimisation of ADD use
Water depth	Water depth influences how sound waves spread underwater. In shallow areas, they may reflect of the surface and seabed, causing distortion. Deterrent sounds are most effective when sufficiently reaching the depths where seals are present, which vary depending on their foraging, migration and resting behaviours.	Water depth influences the ADD efficacy. In deeper waters, a higher number or density of deterrents may be needed, as seals have more opportunities to find gaps or irregularities in the sound 'barrier'. As depth increases, using units at multiple depths may be necessary to maintain effective coverage. The typical effective range of an ADD unit is ~40–50 m.
Bottom topography	The seafloor profile and substrate can influence sound waves and hence the devices' efficacy. An uneven seafloor may weaken or scatter ADD sounds. Seals may learn to utilise these irregularities to avoid deterrent sounds.	Seafloor topography should be considered when determining the number and configuration of ADDs. Complex or uneven seafloor conditions may require a higher number or output capacity of ADD units to ensure effective coverage.
Ambient noise	Background noise from human activities or natural sources can interfere with ADD signals. A compromised signal may reduce seals' responses to the ADD. In noisy environments, seals may become habituated to anthropogenic sounds However, in some cases sensitization to the noise may occur.	While high levels of ambient noise may mask or distort the ADD sounds, modern ADDs are generally designed to remain audible under moderate ambient noise. However, with more background noise, higher ADD output may be required to achieve the desired coverage and effect. Habituation (or sensitisation) to chronic noise may further influence ADD efficacy.
Weather and tidal conditions	Seals' movement, activity and congregation patterns are influenced by the weather and tides. Sea conditions also affect ADD signals: calmer conditions allow for greater effective ranges, whereas rough seas can scatter the sounds and reduce their effectiveness. Similarly, high tides may alter sound transmission and ADD efficacy.	Variability in local weather and tidal conditions, and their influence on the operating range of ADDs, should be accounted for in the planning of ADD placement and the design of future ADD systems.
Turbulence and turbidity	In turbid waters with high levels of suspended particles, sound waves may scatter more, reducing the effective range of ADDs. However, under these conditions, seals may need to rely more heavily on acoustic cues for navigation, foraging, and communication.	If ADDs' effective range decreases, seals may bypass them more easily. Conversely, if seals rely more on acoustic cues in turbid water, ADDs deterrent capacity may be enhanced. Thus, the sufficient ADD deployment may depend on water turbidity, but the precise effects remain to be assessed experimentally.
Season	The habitat use and migratory behaviour of many seals exhibit extensive seasonal variation. In the Baltic Sea, grey seals move into costal waters during autumn, increasing the potential for conflict with fisheries and aquaculture.	The need for ADDs can vary seasonally. During periods of lower risk of seal-related damage, their use can be reduced, helping to minimise both energy consumption and underwater noise.
Time of the day	Many seal species spend more time foraging during daylight and twilight hours, while allocating more time to resting at night.	ADDs could be programmed to operate at lower intensity (scram rate) or be switched off during night-time.
Water temperature	Temperature can influence seals' activity, behaviour, hearing sensitivity, hunger and responsiveness to sounds. The speed of sound is lower in cold water, affecting ADDs' range.	In warmer water, the physical sound range of ADDs may be higher, but seals may exhibit reduced sensitive to deterrent sounds. ADD settings should be adjusted to account for local water temperatures.
Salinity	Salinity influences underwater sound propagation and may also affect seals' hearing, with effects potentially varying by sound frequency. At higher salinities, increased water density allows acoustic signals to travel farther.	In low salinity, including brackish and river environments, increased sound attenuation can reduce the effective range and deterrent impact of ADDs. Device number and/or output levels should therefore be adjusted to local salinity levels.

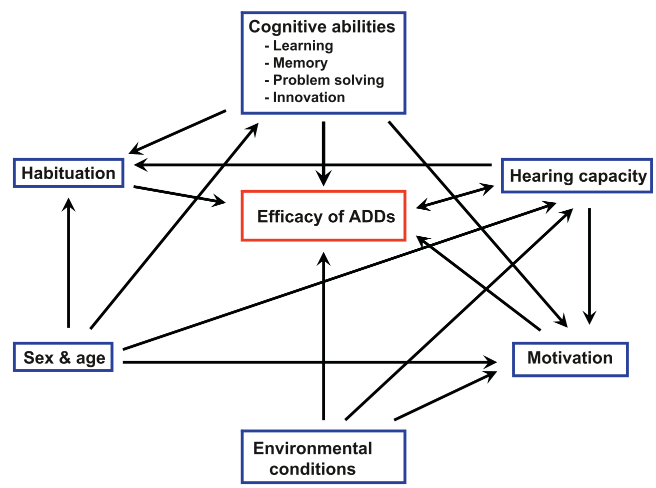

Fig. 2. Conceptual map of seal-related factors influencing the effectiveness of Acoustic Deterrent Devices (ADDs), often in interaction with the environmental variables. Further details are provided in Table 2.

and environment-dependent effectiveness of different manufacturers' ADDs is likely to vary extensively; the sound pulses of each model have distinctive patterns of frequency, amplitude, and duration. The environment, installation and settings of ADDs are likely to exacerbate these differences (Fig. 2; Tables 1 and 2). Given that the environmental effects can interact with seals' behavioural differences, the context-dependency of ADD solutions needs special attention in their technical development.

5. Conclusions and recommendations

Our review highlights critical links between cognitive capacities of seals and the utility of ADDs (Fig. 2; Table 2). Here, variation among individuals is also important. The review shows that we are currently sorely lacking data on how these sources of variation affect especially the long-term deterrent efficacy of ADDs. Indeed, future research efforts on the desired and non-desired effects of ADDs would benefit from routinely considering cognitive processes of the affected target and non-target animals, so that ADDs can provide the desired deterrence effect without compromising their hearing sensitivity or acoustic communication (Table 2). We also need more knowledge on the build up of both deterrence impact and unwanted side effects when multiple ADDs are used close to each other. If these aims are successfully met, ADDs have potential to boost the income and food security of coastal communities,

Table 2
Summary of phenotypic traits of seals that can affect the usability and effectiveness of ADDs. The summary supports the graphical presentation provided in Fig. 2.

Factor	Description of the challenge	Optimisation of ADD use
Cognitive abilities	Cognitive capacities, such as innovation, quick learning, strong long-term memory and problem solving, can enhance a seal's ability to circumvent deterrent measures. Similarly, personality traits associated with cognition, such as boldness, may cause certain seals to become regular visitors at fishing gear or net pens (even when a deterrent is present).	The configuration and settings of ADDs should be optimised to minimise weak deterrence effect areas that seals may learn to exploit. ADDs' seal detection capacities and use of greater variation in sound characteristics could reduce seals' opportunities for learning, innovation and habituation (see below), while helping to maintain neophobia.
Habituation	Seals' habituation over time to ADD sounds may decrease the effectiveness of the devices.	With the integration of AI and advanced sensory technologies, ADDs could be programmed to operate at highly varying intensities and pulse rates, reducing the potential for habituation. If an ADD unit detects the presence of a seal, it could emit sound pulses only when the animal is nearby. This approach would also lower overall underwater noise, ADD energy consumption and peak sound outputs, and the use of the most problematic frequencies.
Hearing capacity	If a seal a persistently forages at a fishing gear or net pen protected by an active ADD, its hearing may become impaired. In such cases, effectiveness of ADDs for these individuals could be severely reduced. Furthermore, older seals may naturally have significantly lower hearing sensitivity than younger ones (see below).	If ADDs can be developed to reliably detect the presence of seals (see above), exposure of both seals and non-target animals to deterrent sounds, especially at problematic frequencies, could be reduced.
Sex and age	Seals of different sexes and ages differ in their behaviour and other phenotypic traits. Such individual variation, along with individual variation from other sources, poses a challenge for effective ADD designs.	The use and design of ADDs may need to follow the precautionary principle: they should be effective across different seal phenotypes, including those that are most difficult to deter.
Motivation	Fishing gear and aquaculture facilities may offer easily accessible food sources, increasing the motivation of seals to approach them, despite the ear pain caused by active ADDs. Over time, decreased effectiveness of ADDs may result. A high or variable motivation poses a challenge to ADDs.	Users of ADDs should be provided with sufficient knowledge of the different ADD types, their settings, configurations, and environmental variables (Table 1). Proper application of ADDs can help prevent the decline of their effectiveness in long-term use, despite high motivation of seals to circumvent their effects.
Environmental conditions	Environmental variation poses various challenges that are covered in Table 1. Its effects also interact with seals' phenotypic traits.	See Table 1 for details.

by allowing continuation of aquaculture and small-scale fishing practises in waters with healthy seal populations. ADDs might also have utility in protecting critical spawning grounds or routes of endangered fish species.

ADDs nevertheless remain ethically and economically controversial. When planning their use, it is important to consider the extent to which they can mitigate negative impacts of seals, how they compare to alternative measures of alleviating human–seal conflicts, such as gear modifications or regulated hunting, and whether their use may pose significant harm or health risks to marine life.

Further research and development work will also be needed to make ADD applications more cost-effective, practical and ethically sound. We expect that the current types of ADDs will slowly be replaced by newer generations of devices that detect seal presence and probably have lower sound outputs at the problematic frequencies. More research knowledge is still needed not only on their development but also installation and application, including choosing the number and necessary features of ADDs for the size of the object or area that needs safeguarding. Similarly, users of ADD require practical guidance on selecting, installing, operating and maintaining the devices, especially near human habitats, beaches and marinas. It is also crucial to account for the environmental conditions under which the devices are deployed. For example, water temperature and depth influence both sound transmission and seal behaviour and need to be considered in the design and use of ADDs (Tables 1 and 2). To achieve these goals, we call for an improved understanding of cognitive capacities of seals, as well as for more collaboration and coordinated information sharing between researchers, technical developers, fishers and fisheries management bodies.

6. Methods

This literature review was not conducted as a systematic review. Instead, we drew on relevant literature known to us prior to the study, as well as sources identified during the research process. For the latter, we searched the Web of Science and Google Scholar databases. When further information was needed, we also examined reference lists and conducted forward citation searches using the same databases. Publications were screened hierarchically: first by title, then by abstract for potentially relevant works, and finally by full-text review for those passing the initial stages. No restrictions were placed on publication dates, although we prioritised more recent studies were when multiple sources were available. We also incorporated relevant publications suggested to us during a pre-screening by two colleagues and a peer-review process by two reviewers. Throughout the review, we favoured peer-reviewed articles over grey literature when both were available. To maintain focus, we limited the number of citations used to support any single statement to a maximum of five. When more than five suitable publications were available, we subjectively selected those that were most relevant or most recent. Using these sources, we developed a narrative synthesis around thematic areas corresponding to the chapters of the review.

CRediT authorship contribution statement

Topi K. Lehtonen: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Conceptualization. **Petri Suuronen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Olli Loukola, Pizza Chow and two anonymous reviewers for helpful comments on earlier versions of the text and Timo Myllylä for general support to this work. T.K.L. was employed by Natural Resources Finland and P.S. by International Seafood Consulting Group. This study was not supported by a specific funding.

Data availability

No data was used for the research described in the article.

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