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Review

Trade-offs and synergies in the management of environmental pressures: a case study on ship noise mitigation☆,☆☆

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ABSTRACT

Underwater noise from shipping is increasingly recognized as a significant pollutant that can have a range of detrimental effects on marine organisms. However, ships impact marine life in more than one way. From a management perspective, a holistic approach could provide a more successful way to minimize the impact of ship traffic than sequential, single-pressure mitigation. In this paper, we assess how other shipping pressures are affected by six noise mitigation measures: ship speed restriction, rerouting, convoying, frequent hull/propeller cleaning, ship-quieting technologies, and incentivising fewer, larger ships. Here, we present and apply a framework to evaluate the synergies and trade-offs in the implementation of mitigation measures to better consider cumulative effects and advance effective, and holistic management. Using expert judgement and peer-reviewed literature, we evaluate each of the proposed mitigation measures to determine whether they are likely to have synergistic or trade-off effects on the impacts from other shipping pressures, the scale of the effect, and the strength of the evidence. Overall, speed reduction has mostly synergies with only weak trade-offs in the other shipping pressures. Frequent hull and propeller cleaning has fewer synergies, but also very few trade-offs, whereas convoying is expected to be the measure with the most trade-offs with other pressures. Re-routing and the incentivization of fewer larger ships have mostly unclear outcomes, because this will depend on the circumstances of implementation. We conclude that carefully considered and thoughtfully implemented mitigation measures can lead to multiple benefits across shipping pressures.

1. Introduction

In the past century, there has been a rapid increase in anthropogenic activities at sea, from fishing and aquaculture, to tourism, transport and energy production. This industrialization of the sea is expected to further increase in the near future, as the number and size of ships in the

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global fleet is forecasted to grow (Kaplan and Solomon, 2016; DNV, 2021). Human activities, like shipping, can affect the environment through multiple pathways and pressures; pressure refers to the mechanism whereby an activity impacts the ecosystem (Patrício et al., 2016). The occurrence and interaction of overlapping pressures in space and time necessitates a multiple pressure or cumulative effects framework approach (the terminology differs across research fields) (Orr et al., 2020). Also in marine management, there is a broad consensus that a holistic view is needed for an ecosystem-based approach (Knights et al., 2013; Pedreschi et al., 2019; Haugen et al., 2024), to resolve spatial competition for human use of the sea (Coccoli et al., 2018; Queirós et al., 2021; Depellegrin et al., 2021), and to account for a lack of natural barriers or activities beyond individual national jurisdictions or management organizations (Taconet et al., 2019; Baudron et al., 2020).

With a view toward global sustainability, the world's shipping fleet has made notable management strides to reduce the risk of invasive species introductions via ships, first by ballast water discharges (IMO, 2004) and then by biofouling (IMO, 2023a). In the case of ballast water, a global convention is in place and national policies implementing the Ballast Water Management Convention have been shown to reduce the transfer and introduction of invasive species (Ricciardi and MacIsaac, 2022). To address biofouling on ships' hulls and niche areas, global guidelines are in place, and work is underway at the International Maritime Organization (IMO) and the International Organization for Standardization (ISO, 2016) to provide guidance on in-water cleaning of biofouling. These successes aside, a management approach that successively manages individual pressures one by one may not achieve the overall goals and objectives to maintain a healthy environment. For example, the ban of toxic tributyl tin (TBT) in antifouling coatings (IMO, 2001) may have reduced pollution loads but increased the transport of species on hulls with less effective coatings (Lewis et al., 2004; Dafforn et al., 2008) and increased the environmental burden of copper which was used to replace organotin (Claisse and Alzieu, 1993). Another example of unexpected side effects is the industry response to a global limit on sulfur emissions from 2020 onwards. Instead of switching to low sulfur fuels, many ships adopted Exhaust Gas Cleaning Systems (EGCS) which introduced a new toxic, acidic waste stream into the marine environment (Hassellöv et al., 2020).

The necessity of a holistic management approach is illustrated by these examples and further underscored by the identification and investigation of new pressures associated with shipping (e.g., the wide adoption of low-carbon or carbon neutral marine fuels). In addition to the discharge streams, like biological and chemical pollution (e.g. Hannah et al., 2020; Jalkanen et al., 2021), shipping can cause disturbance, and ship traffic can also emit energy (heat, light, noise, kinetic energy) to the marine environment.

Underwater noise is one example of a marine environmental pressure of urgent concern (Canada, 2018; Vakili et al., 2020). Underwater noise originates from several sources and sectors: commercial shipping, research activities, oil and gas exploration, recreational activities, construction and industrial development (Hildebrand, 2009; Vijaya Baskar and Rajendran, 2020). Shipping noise is the largest contributor, with noise produced of differing frequency and speed from the engine, propellers, and other onboard machinery (Seol et al., 2005; Widjiati et al., 2012; Aktas et al., 2016; Smith and Rigby, 2022). Among ship types, the largest contributions to global noise levels come from the large population of container ships, bulk cargo ships, and tankers (Wales and Heitmeyer, 2002; MCR, 2011; McKenna et al., 2012; Jalkanen et al., 2022). However, the noisiest ships at an individual level at high seas are fishing ships (Amron et al., 2021; Picciulin et al., 2022), while in coastal areas, recreational boats can dominate the sound scape (Hermannsen et al., 2019; Wilson et al., 2022).

In 2023, the IMO published revised guidelines for the reduction of underwater radiated noise from shipping to address its adverse impacts on marine life (IMO, 2023b). Shipping noise is a main source of anthropogenic noise and known to affect marine mammals and fishes via several pathways; through behavioural changes, physiological impacts, altered population dynamics and auditory damage (Slabbekoorn et al., 2010; Duarte et al., 2021; Kok et al., 2023). Noise pollution also affects cetacean capacity to socialize and locate prey (Tyack and Miller, 2002; Erbe et al., 2016; Erbe et al., 2019). Furthermore, noise could have significant impacts on invertebrate behaviour, physiology, anatomy, development and predator evasion (Popper, 2003; Weilgart, 2018; Vereide and Kühn, 2023). Threshold levels for the onset of physical injuries from noise are well established for marine mammals and are currently being developed for fish and invertebrates (Popper et al., 2014; NMFS, 2018; Lucke et al., 2024). For behavioural effects, safe levels have only been established for a limited set of organisms under specific conditions (see e.g. Shannon et al., 2016; Borsani et al., 2023). For example, Atlantic cod did not leave their spawning ground when exposed to noise at an SEL of 115–145 dB re 1 $\mu Pa^2 s$, while a previous study at a non-spawning site reported that cod left the area after the end of an exposure with similar sound levels (van der Knaap et al., 2021; McQueen et al., 2022). More subtle behavioural responses were observed at both sites (van der Knaap et al., 2021; McQueen et al., 2023) and behavioural responses at the spawning site were stronger for continuous than for impulsive noise (McQueen et al., 2024).

Noise production varies depending on the size, speed, level of fouling and loading of the ship, as well as engine type, propulsion system, and propeller shape and orientation (Trevorrow et al., 2008; Hildebrand, 2009; Smith and Rigby, 2022). Thus, the management and mitigation of noise impacts can take various forms as well (e.g. Lamoni and Tougaard, 2023). Although ship-source underwater noise primarily arises from ship design (hull shape, propeller, hull-propeller interaction, and machinery configuration), operational adjustments and maintenance measures are recommended as potential noise reduction methods as well (Merchant, 2019; Smith and Rigby, 2022; IMO, 2023b; Lamoni and Tougaard, 2023).

Several measures have been implemented or proposed to reduce shipping noise around the world. The most effective measures for the reduction of noise have been discussed in depth by Merchant (2019), and Lamoni and Tougaard (2023). However, in the presence of multiple environmental pressures, it is crucial for management to also assess the synergies and trade-offs such measures may present in other pressures, such as air emissions. Here, we present and apply a framework to evaluate the synergies and trade-offs in the implementation of mitigation measures to better consider cumulative effects and promote effective, holistic management. Using the mitigation of underwater noise as a case study, we evaluate each of the proposed mitigation measures to determine whether they are likely to have a synergistic or trade-off effects on the impacts from other shipping pressures.

2. Methods

2.1. Review

We conducted an expert review of published literature to assess potential effects of mitigation measures to reduce underwater noise on other pressures from ship traffic. Effects were classified as synergies if a measure that reduced noise would also reduce other pressures, while effects of measures that reduced noise, but increased other pressures were classified as trade-offs (Table 1). Effects of measures that reduced noise, but did not affect other pressures were classified as No change (Table 1). Each expert used as search terms, the combinations [UWN mitigation measure + pressure], varying the exact pressure terminology based on their background and expertise regarding the field (utilizing scholarly literature search engine(s) (s)he preferred, such as Web of Science, Google Scholar, Scopus, etc.). We screened and analyzed the articles containing relevant information regarding the potential synergies or trade-offs and wrote short reports on the findings. As the purpose of this study was to produce an illustrative example of an assessment framework, a non-exhaustive literature review was pursued

Table 1
Effect key (color and text) defining the categories used to assign the direction of the effect, the level of evidence to support the assessment, and the scale of the effect in Table 2. Other text and symbols are explained in the table text. Effects were classified as synergies if a measure that reduced noise would also reduce other pressures, while effects of measures that reduced noise, but increased other pressures were classified as trade-offs.

Strong Synergy	Strong synergy: the listed pressure (risk) is expected to decrease strongly when the mitigation measure is implemented.
Weak Synergy	Weak synergy: The listed pressure (risk) is expected to decrease slightly when the mitigation measure is implemented.
Synergy or Trade-off	In some cases, the direction of the effect could cause **synergy** or **trade-off**, depending on the circumstances or area. This is then further explained by a footnote to Table 2.
Weak Trade-off	Weak trade-off: the listed pressure (risk) is expected to increase slightly when the mitigation measure is implemented.
Strong Trade-off	Strong trade-off: the listed pressure (risk) is expected to increase strongly when the mitigation measure is implemented.
No change	No change in the listed pressure (risk) is expected when the mitigation measure is implemented.
Not applicable	There is no logical relationship between the proposed measure and the listed pressure (risk).

until the individual experts were satisfied that the direction and magnitude of potential effects had been credibly established (Fig. 1). In practice, under each pressure theme, six searches were conducted and reports written (see Suppl. Table 1 for an overview of the experts contributing to each table and Tables 2.1–2.10 for reports per pressure). We assessed the comprehensiveness of the available knowledge and any potential inconsistencies when assigning the Level of Evidence classification: 0 star – no evidence (based on expert review and judgement), 1 star - weak evidence (a single to a few papers that provide supporting evidence, or several papers providing conflicting evidence), 2 stars - moderate evidence (more than a few papers supporting an established pathway in the literature), 3 stars – strong evidence (clearly stablished pathway in the available literature with no conflicting evidence). In the end, the team discussed and jointly categorized the measure-pressure combinations and the Level of Evidence, to ensure a coherent and consistent logic throughout the summary table (Table 2).

2.2. Noise mitigation measures

We have identified and evaluated six noise mitigation methods from the literature including operational and technological command-and-control (CAC) approaches as well as incentive-based (market-based) measures (Merchant, 2019). Operational mitigation includes ship speed reduction (IMO, 2014; McKenna et al., 2013; Joy et al., 2019), rerouting away from sensitive areas (Hatch and Fristrup, 2009; Redfern et al., 2017), convoying (Heise et al., 2017; Merchant, 2019), and frequent hull/propeller maintenance (IMO, 2014). Technological measures include ship-quieting technologies (Canada, 2019; Smith and Rigby, 2022; Vard Marine Inc., 2023) and market-based measures include incentivising use of fewer, larger ships (Merchant, 2019; Lamoni and Tougaard, 2023).

The most commonly adopted noise mitigation measure has been ship-speed reduction, or slowdowns (Smith and Rigby, 2022). This has been shown to be a very effective measure, for example, Leaper (2019) suggested that a 10 % speed reduction may reduce the total global sound energy from shipping by around 40 %. Ship speed reduction is also commonly used to avoid, or reduce the severity of, ship strikes (Vanderlaan and Taggart, 2007; Conn and Silber, 2013) and reduce fuel consumption. It has been discussed whether a speed reduction would lead to a longer exposure for animals in an area, which would offset the effect of lower sound levels, but recent modelling suggests that noise exposure decreases quickly with the reduction in speed. This is because the exposure range increases quadratically, while the exposure duration only decreases linearly with increased speed (Findlay et al., 2023). Slowdowns have been implemented to reduce noise and disturbance for Southern Resident Killer Whales in the Salish Sea on the West coast of North America (Burnham et al., 2021). Bulkers, tankers, ferries, and government ships were asked to reduce their transit speed to 11 knots, and vehicle carriers, cruise ships, and container ships were asked to slow to 14.5 knots. Monitoring of the area revealed that ship slowdown caused noise reductions in the lower frequencies. In the Vancouver Fraser Port all ships were asked to reduce speed to 11 knots to reduce noise levels (MacGillivray et al., 2019). This reduced underwater noise levels significantly. Thus, speed reduction could be an effective noise mitigation measure even if some ships may produce more noise at lower speeds (McIntyre et al., 2021).

The avoidance of sensitive areas (re-routing) has been implemented in noise management since the 1980s for impulsive sounds, such as seismic surveys (e.g. Sivle et al., 2021). For continuous noise such as shipping, however, rerouting has not yet been applied as a noise mitigation measure. Rerouting has been applied to increase the distance between shipping lanes and sensitive areas to reduce other pressures with noise reductions as a result. For example, Redfern et al. (2017) found that the creation of an avoidance area around most of the Channel Islands National Marine Sanctuary in the United States to reduce groundings and pollution risks was also associated with lower noise levels. In the Salish Sea, Canada, ships were excluded from certain areas and tugs and barges were laterally displaced away from key foraging

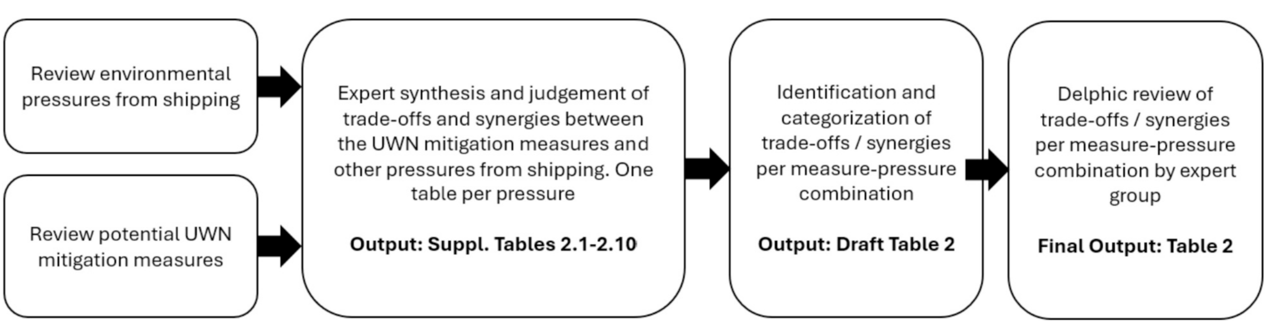

Fig. 1. Process used to review published literature to assess potential synergic and trade-off effects of mitigation measures to reduce underwater noise on other pressures from ship traffic. See suppl. Table 1 for an overview of contributing experts for each table.

Table 2
Summary of the mitigation measure-specific conclusions per each shipping pressure. The colors and the text signify whether there is a synergy or a trade-off and their strength (Table 1), and whether this effect is generic (for all areas), or site-specific. The number of stars signifies the level of evidence in the peer-reviewed literature: no evidence, * weak evidence, ** moderate evidence, *** strong evidence. For the detailed explanations with literature references, see the pressure-specific tables in the Supplementary Material.

	NOISE MITIGATION MEASURES					
PRESSURES	Ship speed restriction	Rerouting	Convoying	Frequent cleaning	Quieting technologies	Fewer, larger ships
Ship strike (1)	**Strong Synergy** Generic ★★★	Synergy or Trade-off[a] Specific[a] ★★★	Weak Trade-off Specific[b] ★☆☆	*Not applicable*	No change Generic ☆☆☆	Weak Synergy Generic ★★★
Air emissions (2)	Weak Synergy Generic ★★★	Weak Trade-off Specific[c] ★★★	Weak Trade-off Specific[d] ★★☆	Weak Synergy Generic ★★★	Synergy or Trade-off[c] Generic ★★☆	Weak Synergy Generic ★☆☆
Species introduction by ballast water (3)	Weak Trade-off Generic ★★☆	Weak Synergy Specific ★★☆	Weak Trade-off Generic ☆☆☆	*Not applicable*	Weak Trade-off Generic ★☆☆	Weak Trade-off Generic ★★☆
Species introduction by biofouling (4)	Weak Trade-off Generic ★☆☆	Synergy or Trade-off[a,c] Specific[a,c] ★★★	No change Specific[f] ★☆☆	**Strong Synergy** Generic ★★★	Synergy or Trade-off[e] Generic ★☆☆	Synergy or Trade-off[g] Generic ★☆☆
Black & grey water discharge (5)	Weak Trade-off Generic ★★☆	Weak Trade-off Generic ★★☆	*Not applicable*	*Not applicable*	*Not applicable*	Weak Synergy Generic ★☆☆
Solid waste (6)	Weak Synergy Generic ★☆☆	Weak Trade-off Specific ★★☆	*Not applicable*	Weak Trade-off[h] Generic ★★☆	*Not applicable*[i]	Weak Synergy Generic ★★☆
Light pollution (7)	Weak Trade-off Generic ★★☆	Synergy or Trade-off[a] Specific ★★☆	**Strong Trade-off** Specific ★★☆	*Not applicable*	*Not applicable*	Synergy or Trade-off Specific ★☆☆
Physical disturbance (8)	Weak Synergy[j] Specific ★★☆	Synergy or Trade-off[a] Specific ★★★	Weak Trade-off Specific ★★☆	No change Generic ☆☆☆	Weak Synergy Generic ★☆☆	Synergy or Trade-off[g] Specific ★★☆
Navigational risks (9)	**Strong Synergy[k]** Generic ★★★	Synergy or Trade-off[a] Specific[a] ★★★	Weak Synergy[l] Generic ★☆☆	Weak Synergy Generic ★☆☆	Synergy or Trade-off[e] Generic ★☆☆	Synergy or Trade-off[g] Specific ★★★
Foreign object (10)	Weak Synergy Generic ★☆☆	Weak Synergy Specific ☆☆☆	Synergy or Trade-off[a] Generic ★☆☆	*Not applicable*	*Not applicable*	Synergy or Trade-off[g] Generic ☆☆☆

Number of stars signifies the level of evidence in the peer-reviewed literature:	
☆☆☆	no evidence
★☆☆	weak evidence
★★☆	moderate evidence
★★★	strong evidence

a. Depends on the location of the new route.
b. Depends on species-specific behaviour and timing of convoys.
c. Depends on length of the new route.
d. Depends on waiting times.
e. Depends on technology and ship type.
f. May increase risk locally if convoy location is sensitive to invasions.
g. Fewer, but larger events
h. Depends on whether cleaning happens on land or in water.
i. Unless coating is changed
j. The effect of mitigation is less in open water because the original pressure is less severe.
k. Unless speed is reduced below a certain limit.
l. No evidence for open sea conditions, evidence for ice navigation only.

areas for killer whales (Burnham et al., 2021). Displacement of tug traffic reduced ambient noise, despite making up a small portion of the overall traffic in the region. In 2020, the major shipping lane in the Kattegat (Swedish west coast) was split into two and a new shipping lane, closer to the coast, was established and assigned to smaller ships (Lalander et al., 2021). An investigation of the changes in the underwater soundscape due to the shipping rerouting showed that the noise in the $^1/_3$ octave band with the centre frequency of 100 Hz increased along the coastal route by 5–6 dB in the north and 3–4 dB in the south of Kattegat. Thereby the acoustic habitat quality with respect to communication range decreased for e.g. cod, while e.g. harbour porpoises may experience a reduced ability to detect natural sounds and can potentially avoid larger areas when the new shipping lane allows for more ships in the area closer to the coast (Lalander et al., 2021).

The implementation of convoys has the potential to modify the temporal distribution of noise, leading to increased intervals of silence. However, it is noteworthy that noise levels would experience a significant surge during convoy passages (Williams et al., 2019). Furthermore, the need for additional research to comprehensively address this phenomenon has been recognized (Virto et al., 2022). Frequent hull and propeller cleaning could reduce unnecessary sources of additional flow disturbances, which could lead to both higher fuel efficiency and reduced noise levels. Ship-quieting technologies will reduce overall levels of noise without necessarily changing shipping patterns and cargo availability but can be technologically challenging. There are a range of measures that could be used (Smith and Rigby, 2022). However, a promising strategy is to focus on removing the loudest ships from the fleet, which can incentivise noise reduction technologies (Lamoni and Tougaard, 2023).

The incentivization of fewer, larger ships may lead to a smaller number, but more intensive noise events, similar to convoying. The increase of ship size has been mainly driven by improvements in energy efficiency and economy of scale (Vladimir et al., 2018), not by attempts to reduce underwater noise. However, the incentivization of larger ships for the reduction of greenhouse gas emissions is already in place (Christodoulou et al., 2019), for example through the EU Emissions Trading System for shipping (EU, 2023). Since larger ships use less fuel per tonne mile, this directive works as an incentive for the use of larger ships.

2.3. Other shipping pressures

The list of additional (non-noise) shipping pressures evaluated was derived from existing shipping conceptual frameworks (Hannah et al., 2020; ICES, 2021; Moldanová et al., 2022). In total, ten shipping-associated pressures were identified and evaluated:

1. Ship strikes (Collisions), defined as an impact between any part of a ship and a live animal, have been documented for >70 marine species, including whales, dolphins, porpoises, dugongs, manatees, whale sharks, sharks, seals, sea otters, sea turtles, penguins, and fish (Schoeman et al., 2020). Two measures have been used to reduce ship-strike risk: changing ship routes and reducing ships' speed. Measures that change ship routes, including shifting the location or configuration of shipping lanes or establishing areas to be avoided, are used to reduce the co-occurrence of animals and ships. Measures that slow ships are used to reduce the risk of lethal ship strikes because the probability of a lethal strike increases with ship speed (Vanderlaan and Taggart, 2007; Conn and Silber, 2013). Slower speeds may also allow animals and ship operators more time to engage in avoidance behaviour (e.g., Vanderlaan and Taggart, 2007; Gende et al., 2019). The IMO adopted nine proposals between 1997 and 2009 to reduce the risk of ships striking large whales (Silber et al., 2012).
2. Air emissions include all emissions related to fuel combustion, including pollutants such as CO_2, sulfur oxide, nitrogen oxides, particulate matter volatile organic compounds, carbon monoxide and black carbon (Eyring et al., 2010). The emissions released depend mainly on the fuel type, engine, and engine maintenance and efficiency (Bouman et al., 2017; Johansson et al., 2017) for most ship types. However, in fisheries, route decisions when searching for fishing grounds can have more impact on emissions (Granado et al., 2021) as well as trade-offs with bycatch of other species (Goikoetxea et al., 2024). These emissions impact both the climate and local air quality, which lead to human health effects. Air emissions affect the marine environment directly through the deposition and dissolution of gases, and indirectly via forcing effects on the climate (Endres et al., 2018). In addition, they can cause eutrophication and contamination.
3. Species introductions by ballast water were defined as the unintentional translocation of non-native species from their native habitat to a new location via ship's ballast tanks: within the ballast water, ballast sediments or solid ballast materials (Bailey et al., 2020). Non-native species introductions may negatively affect ecosystems, economies, or human health through predation, competition or degradation of resources (e.g., Pyšek et al., 2020; Cuthbert et al., 2021) as well as control costs (e.g., Fernandes et al., 2016). Ballast water management activities aim to reduce this translocation of species through open ocean exchange of ballast water and, more recently, the treatment of ballast water with filtration, and chemical or UV systems (IMO, 2004; Gollasch et al., 2015).
4. Species introductions by biofouling was defined as the unintentional translocation of non-native species from their native habitat to a new location as organisms attached or in association with the ship's hull and other submerged surfaces (Bailey et al., 2020). Non-native species introductions may negatively affect ecosystems, economies, or human health through predation, competition or degradation of resources (e.g., Cuthbert et al., 2021; Pyšek et al., 2020) as well as control costs (e.g., Fernandes et al., 2016). Antifouling systems (AFS), defined as a coating, paint, surface treatment, surface, or device that is used on a ship to control or prevent attachment of unwanted organisms (IMO, 2023a), are used to reduce biofouling to improve fuel efficiency.
5. Black and grey water, and food waste include the discharge of sewage, leftover food, food processing waste and wash water. These discharges originate from the kitchen, laundry and passenger spaces and may contain nutrients and detergents. Most sewage treatment plants used onboard ships are not able to remove all of the nitrogen and phosphorus which end up in the sea if discharged from ships' tanks. The impacts of additional biological material and nutrients on the marine environment can include eutrophication, oxygen depletion, an increased risk of harmful algal blooms (Sellner et al., 2003), and reductions in community biodiversity (Kroon et al., 2020).
6. Solid waste can be discharged accidentally or operationally from commercial ships, either as macrodebris or microplastics. Examples of macrodebris include discarded food products, mismanaged garbage or recycling, and lost cargo of varying types (World Shipping Council, 2011). The natural breakdown or physical disturbance of a ship's antifouling coatings during hull cleaning can also release microplastic particles (Earley et al., 2014; Oliveira and Granhag, 2020; Tamburri et al., 2022).
7. Light pollution is electromagnetic energy (light) emitted from lighted structures, running lights, and navigational aids on commercial ships. Light disturbance, also called Artificial Light at Night (ALAN), from moving ships or at-sea support structures can both attract and repel marine organisms, and thereby alter the composition of ecological communities (Marangoni et al., 2022). Since it is mainly a sensorial pollution, it can trigger behavioural changes and collisions leading to a reduction in fitness, injury and mortality. Artificial lighting can affect the fitness of a wide range

of ecological components, including marine mammals, birds, fish, invertebrates, and plants (Montevecchi, 2006). Birds are attracted to light and are considered to be at risk of collision with lighted structures (Arctic Council, 2009; Hodgson et al., 2013; Huntington et al., 2015). Normal working-light from a research ship may disrupt fish and zooplankton behaviour down to at least 200 m depth across an area of >0.125 km^2 around the ship (Berge et al., 2020).

8. Physical disturbances from shipping refer to any pressure causing an energy-related impact on the marine environment. The pressures considered in this assessment were ship-induced turbulence, erosion, and incidental disturbance, including ice displacement, but not disturbance from anchoring. The turbulent ship wake may cause unnatural mixing in stratified waters, with potential effects on nutrient dynamics and biogeochemistry (Nylund et al., 2021; Nylund et al., 2023). Ship-induced waves and wake wash contribute to coastal erosion (Parnell et al., 2008; Rapaglia et al., 2015; Gabel et al., 2017; Zaggia et al., 2017) and sediment resuspension (Clarke et al., 2015; Craig et al., 2023).
9. Navigational risks, such as collision, grounding and accidental spills are potential hazards that ships may encounter when navigating. Typical accident types are collisions with other ships or objects, and groundings, caused by technical or/and human errors (e.g. Bye and Aalberg, 2018; Fu et al., 2021). Such accidents can pose a threat to environmental safety. For example, even relatively small leakages of cargo or bunker oil to the sea may have serious impacts on coastal ecosystems (Helle et al., 2020).
10. Foreign object is a pressure introduced by the presence of the ship itself. The introduction of a foreign object or obstacle, such as a ship, anchor or mooring system, can affect or alter a habitat due to its physical presence (Hannah et al., 2020). The presence of a ship may hinder the movement, feeding or other behaviours of mobile biota. Floating objects are known to attract fish, as the fish-aggregating device (FAD) effect (Dempster and Taquet, 2004). Floating objects may act as barriers to migration for marine animals (Hazel et al., 2007).

2.4. Evaluation framework

Each shipping pressure was evaluated for effects of the implementation of each noise mitigation measure. The direction, evidence, and scale were qualitatively assigned after review of the scientific literature and by expert opinion, with review by the entire expert group for consistency and consensus, according to the key in Table 1. The direction (synergy, trade-off, no change) and magnitude (strong or weak) of the effect of the noise reduction measure on the pressure, the strength of evidence for the effect in the peer-reviewed literature (rated low (*), medium (**), or high (***)), as well as the scale of the effect (Generic or Site Specific) were assigned. Comments on the complexities and uncertainties were recorded in footnotes. Details of the reasoning and scientific evidence for each cell are given in the Supplementary Material.

3. Results

Below, we summarise the main synergies and trade-offs with other pressures for each noise mitigation measure. More detailed explanations on the rationale and implications are provided with literature references in the Supplementary Material. Notably, there is no single noise-reduction measure with solely positive, synergistic effects across all other ship-related pressures.

3.1. Ship speed restriction

Ship speed restriction is already commonly used as a measure to avoid lethal ship strikes for marine mammals, and additional synergies occur for air emissions (especially CO_2), physical disturbance through wake-effects, and navigational risks. Speed reduction may also reduce debris due to a lower risk of accidental spills and reduce the effects of the ship as a foreign object, giving mobile animals more time to navigate around it. Within the range of typical slowdowns (2–4 knots), a reduced speed allows more time for ship personnel to react, make evasive manoeuvres and warn others, and leads to lower collision energy and smaller damages.

Weak trade-offs occur because speed reduction may lead to more concentrated discharges of ballast, black and grey water into receiving waters. An increase in the risk of species introductions could occur if ballast water exchange or discharge occurs in a smaller geographic area, concentrating the discharge of organisms, however, organism survival in ballast tanks may decrease with longer voyage length. For black water, grey water, and food waste, ship speed restrictions will increase the time spent on board which also increases the amount of waste generated because these are connected to the number and the time people spend onboard. However, these discharges may be stored onboard if tank capacity allows it, or processed in advanced treatment plants, although the treatment systems rarely remove nutrients. Light pollution may also increase if ships spend more time on the water. Lower speed increases the biofouling species introduction risk for ships using antifouling paints that rely on greater speed to slough off biofouling layers.

Whether a ship will introduce more or fewer species due to biofouling with a lesser speed will depend on when and where the species settle and are released. A slower speed may lead to increased settlement of hull fouling species on the ship, but also to fewer introductions due to a lower shedding rate. Overall, the sum of these effects may lead to a weak trade-off for this pressure, as well.

3.2. Rerouting to less direct route

Rerouting to avoid sensitive areas could have strong synergies for the area that is protected, because the avoided area would experience a decrease in all shipping related pressures. Especially for direct effects such light pollution this will have strong synergistic effects for the sensitive areas that are avoided. However, the overall effects will be very dependent on the length and location of the new route, so for most of the pressures it will depend on the location of the new route whether there will be synergic or trade-off effects. For example, physical disturbance depends on water depth, so if a route is changed from a deepwater area that is sensitive to noise to shallow water, this pressure will increase.

Rerouting can increase the voyage duration and therefore reduce survival of ballast water organisms and support greater treatment efficacy with longer holding times. If rerouting significantly increases voyage time, there would be lower survival and reproductive output of certain fouling species and hence a lower risk of species introductions from ballast water. However, if the new route leads to connections to new geographical locations, the risk for species introduction may also increase locally. Rerouting may also shift the environmental pressure of sewage, grey water discharge and food waste releases to a different area and increase the volume if voyage duration is increased. Increased voyage duration and length would also increase fuel consumption and thus air emissions, and the discharge of black, grey and ballast water, leading to a higher risk of species introductions and pollutants.

The effects of rerouting on navigational risks are strongly dependent on the specific characteristics of the old and potential new routes: their ambient environmental conditions, ecological sensitivity, the density of animals, and traffic parameters. For example, to have a positive effect from rerouting, the new route must either be less sensitive or less affected by physical disturbance (e.g. deeper waters, further from land, or a less sensitive habitat). Re-routing could also expose species in the new route to pressures for which they are not acclimated. The new route should, therefore, be chosen with care to consider maritime spatial planning, avoid increases in ship strikes, navigational risks, light pollution, and physical disturbances.

3.3. Convoying

Convoying has a single synergistic effect on navigational risks. In the context of ice navigation, the overall accident risk is found to be lower compared to independent navigation, especially for convoys led by an icebreaker. However, there is no such data for open water, and due to the proximity of the ships in a convoy, collision risk may increase, and more course corrections may be necessary.

While little research has been done on the effect of convoying on ship-strike risk, we assigned a weak trade-off for this noise reduction measure because of observed behavioural responses of blue whales to approaching ships (McKenna et al., 2015) and the potential for limited ability for ship personnel to manoeuvre to avoid a strike. Specific effects will depend on the density of marine mammals in the convoy area and the timing of the convoy relative to time spent at the surface by marine mammals. Convoying through sensitive areas may increase erosion and the impact of ship-induced turbulence, if the area has shallow water or is close to shore. Convoying has negative effects from the presence of the ship itself, as convoys present as a much larger object increasing the barrier to movement.

Convoying would effectively lead to fewer, but higher intensity disturbance events for noise and light pollution, physical disturbance, and the effect of a foreign object. Especially for light pollution, a single high pulse of light in otherwise dark night could be a strong attractant to sea birds, which would lead to an increased risk of mortality. The combination of waiting times and increased navigational effort could lead to an increase in air emissions. Convoying could have negative effects on the risk of species introduction if ballast water exchange activities overlap in space and time, allowing cross-contamination of ballast tanks (i.e. one ship picks up the coastal-sourced ballast discharged by another ship, rather than fully oceanic water). Operating ship convoys may have small negative effects on black water, grey water, and food waste discharges, if a significant amount of time is spent waiting to form a convoy.

Convoying is not likely to affects the risk of species introduction by biofouling, unless the turbulence from other ship dislodges biofouling species at a specific location that is sensitive to introductions.

3.4. Frequent hull/propeller cleaning

Frequent cleaning with suitable methods and tools has a moderate to strong synergy with three of the 10 listed pressures, a single weak trade-off and no effects on the other pressures. There is a strong positive effect for frequent hull cleaning and biofouling as maintaining a clean hull significantly reduces species introductions of biofouling species. It is important that in-water cleaning activities use methods and tools that minimize release of non-native species and pollutants into the area where cleaning occurs. Biofouling increases friction and resistance, potentially decreasing the ship's manoeuvrability and energy efficiency. Thus, more frequent propeller and hull cleaning are advantageous from the viewpoint of navigational safety and air emissions.

The only potential trade-off identified was an increase in waste discharge if hull and propeller cleaning is conducted in water and the resulting debris, which can include biofouling, pollutants, and microplastics, is not fully captured.

3.5. Ship-quieting technologies

The effect of ship-quieting technologies will strongly depend on the type and specific design of the technology. Quieter ships may attract fewer biofouling species or species that are taken up with ballast water, if these are attracted to ship noise. Ship-quieting technologies have been shown to decrease physical disturbance in terms of erosion and ship-induced turbulence, but there are few available studies investigating these effects and they are likely limited.

A general potential trade-off, on the other hand, may be that a more silent ship may be harder to detect and thus increase the risk of ship strike for some species. In addition, quiet ships may experience slightly increased survival of larvae in the ballast water, which could increase the risk of species introductions. This could, however, be remedied by effectively treating the ballast water before discharge. Biofouling extent (and the associated risk for species introductions) could increase if the quieting technology increases the complexity (i.e., adds niche areas where organisms can settle and be protected from shear forces) or roughness of the hull surface (facilitating stronger attachment of biofouling organisms in comparison to a smoother surface).

The developed and existing ship quieting technologies are diverse, as are their potential effects on navigation safety. Some solutions may to some extent negatively affect ships' manoeuvrability or structural strength, whereas some also enable high manoeuvrability. Similarly, some quieting technologies will increase efficiency, and thus, air emissions, while others will decrease efficiency.

3.6. Fewer, larger ships

The incentivization of fewer, larger ships is particularly dependent on the circumstances. Four of the 10 pressures examined could have either synergies or trade-offs depending on the resulting changes in number and size of the ships, as well as the area of implementation.

Using fewer, larger ships is likely to reduce the navigational risks of accidents, including lethal ship strikes, because it will reduce the amount of ship traffic. These gains could be somewhat offset if larger ships are harder to avoid or to manoeuvre, which would make it more difficult for ship personnel to take actions to avoid a strike. However, safe navigation with a very large ship requires more space and depth and the spill volume in a supertanker accident may be very large. Larger ships have larger ballast volumes, increasing the abundance of organisms released and therefore increasing the risk of establishment. For solid waste, gains come mainly from the reduced surface area of fewer, larger ships translating into reduction in microplastic release from certain types of antifouling coatings. Replacing many small ships with fewer, bigger ones may help in controlling the sewage treatment performance.

Incentivising fewer, larger ships would lead to fewer–but stronger–disturbance events for light pollution, physical disturbance, the effect of a foreign object, and biofouling. The effect of fewer larger ships could go either direction for these pressures. For example, larger ships have a greater wetted surface area to support larger inoculation events but there would be fewer events and biofouling management across a smaller population of ships might be easier. Modelling would need to be attempted to understand the effects of fewer larger ships on these pressures. Because so many of the synergies and trade-offs are dependent on how many fewer and how much larger ships will be, the effects should be modelled before implementing incentives.

4. Overall results

Overall, speed reduction has more synergies than trade-offs, with only weak trade-offs in the other shipping pressures. This is an operative measure that does not require installation of new equipment. Moreover, it can be applied to the existing fleet with a short lead time. Frequent hull and propeller cleaning has fewer synergies, but also very few trade-offs and even fewer trade-offs if cleaning happens on land. Therefore, this is a measure that may be relatively simple to implement.

Re-routing and the incentivization of fewer larger ships have mostly undecided outcomes, because trade-offs will be dependent on circumstances. Rerouting will have strong synergistic effects for the specific area that is avoided, but new areas may be more sensitive to other pressures than noise. New routes therefore have to be carefully chosen. Incentivising fewer, larger ships also has uncertain consequences for many pressures and modelling the effects of this change in the fleet would be required before implementation.

From this analysis, convoying is expected to be the measure with most potential trade-offs with other pressures. Convoying can lead to strong pulses of disturbance (noise, light, turbulence, erosion), increased air emissions, non-indigenous species introductions, and risks of collisions with other ships or animals. However, in extreme navigational conditions, such as in ice-covered waters, the positive overall effect of convoying on navigational safety may override these trade-offs by decreasing the risk of environmental hazards remarkably.

The consequences of ship-quieting technologies are relatively uncertain as it is dependent on the method applied. Therefore, further evaluation of each specific technique across pressures would be required before implementation.

5. Discussion

When viewed across the full range of shipping pressures, the implementation of any single mitigation measure becomes more complex. Our results illustrate the need for consideration of synergies and trade-offs across pressures in the implementation of mitigation measures. However, there are clear indications which pressures should be taken into account in the decision process for each noise mitigation measure. When considered holistically, decision-makers have access to a comprehensive view of impacts and can identify solutions with broader positive impacts and potentially mitigate unintended consequences. Here, we used underwater noise mitigation as an exploratory example, but the approach can be adapted to any set of mitigation measures.

Overall, there was no single noise mitigation measure with synergies across all the other shipping pressures. In this case study, speed reduction, frequent cleaning and ship rerouting had the most synergies with mostly weak trade-offs in the other shipping pressures. Speed reduction and rerouting are in fact the two measures that are the most commonly implemented around the world (e.g. Burnham et al., 2021; Lalander et al., 2021), even if the other shipping pressures were not systematically and holistically examined as we have demonstrated here.

The primary goal of this paper is not to elaborate whether we should or should not try to decrease the impacts of underwater noise, but rather, to identify benefits and trade-offs that need to be acknowledged to avoid the parallel increase of the level of other environmental pressures. The framework we developed and applied can reduce the possibility of unintended consequences, seek out options that bring multiple benefits across pressures, and support fully informed decisions.

We have demonstrated that the proposed framework can be used to evaluate synergies and trade-offs of other pressures and mitigation measures in a qualitative, integrated way in accordance with ecosystem-based management (EBM) of the marine ecosystem. Adoption of EBM requires full consideration of the human activities and their associated pressures (Knights et al., 2013; Knights et al., 2015; Halpern et al., 2019; Pedreschi et al., 2019). This requires a big data and information fusion process which collates, harmonises, and integrates data and information from different sources and different granularities to provide continuous and complete data for analysis and modelling (Castanedo, 2013; Hu et al., 2014).

Here the case study was evaluated at a global scale with a theoretical application. The same framework could be applied to a specific region with defined management objectives. The framework could be advanced to quantify the trade-offs, add socio-economic trade-offs in specific regions considering their specific active fleets (Eguíluz et al., 2016; Taconet et al., 2019) and ecology (Pompa et al., 2011; Erauskin-Extramiana et al., 2023). The framework could be extended to a semi-quantitative assessment where the color codes could be converted into index values representing the locations on the synergy - trade-offs continuum and the stars could be transformed into numerical values indicating the level of evidence available, as in risk assessments (O et al., 2015; Tulloch et al., 2022). The framework presented could also be extended to a fully quantitative evaluation by transforming the schema to a common metric, such as in cumulative effects assessments (e.g. Murray et al., 2021) and scenario modelling (Jalkanen et al., 2023).

6. Knowledge gaps and research priorities

The treatment and presentation of uncertainty is crucial in the decision-making process (Polasky et al., 2011). In addition to the synergies and trade-offs, the framework explicitly evaluates the evidence and scale of the outcomes of mitigation measures. In doing so, the evaluation of the underwater noise case study highlighted several knowledge gaps that could direct future research. For example, rerouting and the incentivization of larger but fewer ships should be carefully modelled for the specific area before introduction of these measures. The effects of convoying in open sea conditions are largely unknown and the body of evidence on convoying in ice may not extrapolate to other situations. Finally, the rapid advancement of ship quieting technologies and their effects on the other pressures is dependent on the technical specifications and needs careful research. There were also several pressures where the direction of the impact was uncertain and dependent on the specific application of the mitigation measure. For example, the location of hull cleaning (on land or in water) determines whether species introductions would be expected to increase and the level of pollutants and microplastics released. The relative effectiveness of the mitigation measures to reduce the pressures was not taken into account here but can be taken into account in future iterations.

Even if mitigation measures decrease the environmental impact of shipping, these measures, such as re-routing, have a cost to industry that has not been taken into account in this work (Anaxagorou et al., 2015). They can also have cost-saving opportunities not foreseen (Fernandes et al., 2016; Granado et al., 2024). No consideration of socio-economic synergies and trade-offs was included in this case study, and we did not evaluate the costs of implementation to the shipping industry nor consider possible alternative responses of industry to management incentives (e.g. development of different more noisy screws in response to speed restrictions). There may be unforeseen industry responses to environmental measures, such as the development of scrubber technology in response to measures to reduce sulfur emissions (Hermansson et al., 2023) but the framework could be applied to any new mitigation measure under consideration. As evidenced by the diversity in the author list, the application of the framework is highly dependent on interdisciplinary expertise, which can be convened in a working group or workshop setting.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary data

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Data availability

Data is included in the supplementary

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