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Review

Jellyfish mitigation for net-based fisheries: A qualitative systematic review

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ABSTRACT

Jellyfish blooms pose significant challenges to net-based fisheries, causing economic losses and operational difficulties. This study reviews existing strategies and proposes novel methods for mitigating jellyfish for net-based fisheries. A systematic literature search identified 35 publications that specifically discussed jellyfish mitigation for net-based fisheries, which were categorised into coping, adapting, and transforming strategies. Coping strategies include relocating vessels to avoid jellyfish; manually removing jellyfish bycatch and repairing fishing gear; government subsidies; and processing facilities imposing financial penalties when receiving catches contaminated with jellyfish. Adapting strategies involve the use of Bycatch Reduction Devices (BRDs), reconfiguring nets, and using predictive models to provide advanced warnings of jellyfish blooms. Transformative strategies encompass attempts to remove medusae and jellyfish polyps from the environment and pivoting fisheries to harvest jellyfish. Most methods used by fishers to mitigate jellyfish have remained largely unchanged for many decades. Technological advancements, such as intelligent nets and real-time monitoring, however, are beginning to offer innovative solutions but may be prohibitively expensive for small-scale fisheries. The study highlights the need for collaboration among stakeholders to develop sustainable jellyfish mitigation strategies; and to resolve and forecast the causes of jellyfish blooms.

1. Introduction

Commercial and artisanal fisheries operate within complex and variable socio-ecological systems (Ostrom, 2009). Sometimes perturbations within the ecosystem due to climate change (Rogers et al., 2019), species invasions (Carrillo-Flota and Aguilar-Perera, 2017), range expansions (Tiller et al., 2017) or other factors compromise the ability of fishers to capture their target species, which may threaten the viability of the fishery. The resilience of the fishing industry to changes in the ecosystem depends on the level of impact and the industry's ability to cope, adapt, or transform (Ojea et al., 2020). Fishers cope with low level impacts by drawing on their existing skills and resources to manage the immediate challenges. As the level of impact increases, fishers adapt by using a variety of targeted actions or tools that enable them to continue fishing. At high levels of impact, however, the fishing industry may need to completely transform, for example by diversifying, (Salgueiro-Otero et al., 2022) to remain viable.

Jellyfish are a natural and essential component of healthy marine ecosystems and provide important ecosystem services (Graham et al., 2014). These include being prey (Hays et al., 2018) and providing a refuge and habitat for juvenile fish and invertebrates (e.g. Ingram et al., 2017; Kingsford, 1993), including some commercially important species (Nagelkerken et al., 2016). Jellyfish populations, (predominantly scyphozoans) are renowned for forming spectacular blooms that can be hazardous and costly for coastal industries, including net-based fisheries (Bosch-Belmar et al., 2020; Fig. 1). When caught in large numbers, the sheer weight of the jellyfish bycatch places enormous stress on fishing gear and occasionally trawlers have capsized after their nets have snagged large blooms of jellyfish (Kawahara et al., 2006). Jellyfish trapped alongside fish in the net, may sting or injure the fish. Injured fish are less appealing to consumers and attract lower prices or may be discarded (Quinones et al., 2013). The stings of jellyfish also increase mortality of discard from trawls (Broadhurst et al., 2008a), seines, and gillnets (Broadhurst et al., 2008b) and pose health risks to fishers (Kumawat et al., 2023).

The economic losses caused by jellyfish can be devastating for the commercial fishers directly affected, and the supply chain that supports the fishing industry. For example, processing plants may work at

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reduced capacity or be left idle (Quinones et al., 2013) and wholesalers and retailers may be unable to access fish to sell. Estimates of the economic costs of jellyfish on commercial fisheries are scarce but fisheries in Japan (Kawahara et al., 2006) and Korea (Kim et al., 2012) have reported annual losses of 10 s to 100 s of millions of dollars.

Most jellyfish blooms are transient events that pose short-term challenges to fishers. However, in some regions, some jellyfish species form more persistent and expansive blooms (Condon et al., 2013; Lynam et al., 2005) and introductions of non-native jellyfish species (Graham et al., 2003) and range expansions may pose new challenges to fishers (Tiller et al., 2017). In these situations, fishers need to adapt or transform their industries to remain viable. The impacts of jellyfish on commercial fisheries have been recently reviewed (Bosch-Belmar et al., 2020) but there remains a critical gap in the literature about the practical, evidence-based strategies available to commercial fishers to manage interactions with jellyfish. Moreover, there has been no comprehensive assessment of how emerging technologies, such as computer vision and drones, and ecosystem-based management approaches could be leveraged to reduce jellyfish-fishery interactions. Addressing this gap is essential to equip stakeholders with the tools and knowledge needed to build resilience in fisheries that face frequent and severe jellyfish disruptions.

Here we undertake a qualitative systematic review of approaches that net-based fishers use, or could use, to mitigate jellyfish. First, we systematically searched the scientific and grey literature to identify studies focusing on jellyfish mitigation for fisheries. We then applied knowledge of jellyfish ecology and explored technological innovations to propose novel methods that could be trialled or implemented by net-based fisheries to mitigate jellyfish.

2. Systematic literature search

We systematically searched the literature using the PRISMA-S guidelines (Rethlefsen et al., 2021). Searches were not limited by date. The Web of Science and SCOPUS were searched on 2nd-4th October 2024 using the search terms (jellyfish* OR medusa* OR polyp*) AND bloom, control, mitigat*, fisher*, net, waterjet, antifoul*, manag*. Google Scholar (which searches journal articles, books, book chapters, conference papers, theses, technical reports, and patents) was searched to identify studies published outside the peer-reviewed scientific literature using the criterion "Jellyfish AND bloom AND (control OR manage OR management OR mitigate OR mitigation OR ameliorate OR amelioration)". This search returned ~22,000 articles that were ordered by relevance as determined by the location of the publication, the author, and how frequently and recently it had been cited, based on Google Scholar's algorithms; https://scholar.google.com/intl/en/scholar/about.html. The titles of the 100 most relevant articles were reviewed and any potentially relevant articles that had not already been identified via the Web of Science or SCOPUS were retained.

The titles and abstracts of all articles were searched independently by two reviewers and those that did not present original information or did not describe a jellyfish management method were removed. Several articles were used that were not primarily written in English but contained English abstracts, figures and tables, thus enabling relevant information to be extracted. Two papers (Goto et al., 2008; Matsushita et al., 2005) were written entirely in Japanese and Korean, respectively and Microsoft Co-Pilot was used to extract relevant information from those papers. Papers were separated into those that described existing mitigation methods used by net-based commercial fisheries and those that described jellyfish management more generally (i.e. not specifically related to fisheries) and may have provided insights into potential management of jellyfish for fisheries. A forward citation search was done on each article to identify recent papers that may have cited the articles and were not identified in the original search. We then undertook general searches of the internet using Google to identify methods used by fishers to mitigate jellyfish that are not published in the scientific or grey literature.

Mitigation strategies for net-based fisheries mentioned in each article

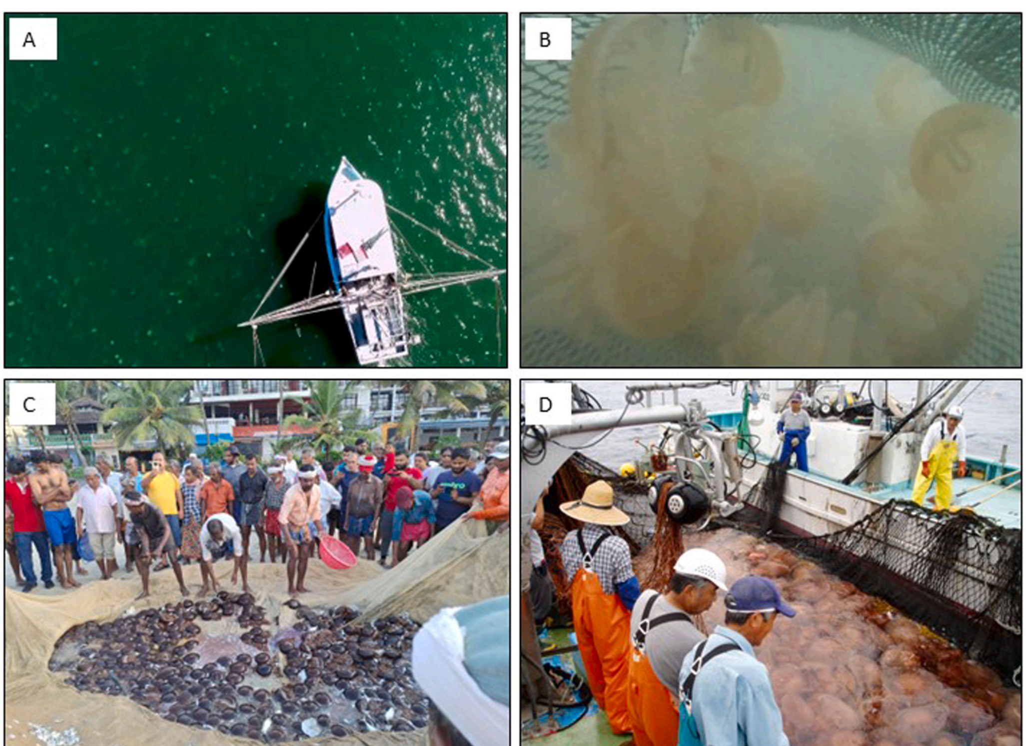

Fig. 1. Examples of jellyfish disrupting net-based fisheries. A trawler surrounded by a bloom of *Catostylus mosaicus* (A) and *C. mosaicus* entering a trawl net (B) in the Hawkesbury River, Australia; *Crambionella* sp. and *Cyanea* sp. caught in a beach seine net in Kerala, India (C); *Nemopilema nomurai* in set nets in Japan. Photo credits: A & B) Van der Neut family, C) K. Pitt, D) Shin-Ichi Uye.

were categorised as (1) coping strategies that are used to manage interactions with transient or small-scale blooms; these included categories such as relocating vessels to avoid jellyfish, repairing damaged nets, and removing jellyfish bycatch and shortening the duration of trawls, (2) adaptation strategies to mitigate larger or more persistent blooms, including use of bycatch reduction devices (BRDs), reconfiguring nets and using predictive models to avoid jellyfishes, and (3) transformative strategies that are implemented in response to permanent and large-scale shifts in jellyfish populations, including removing jellyfish from the environment and fishers pivoting their industry to harvest jellyfish. Summary details of all papers are provided in Supplementary Table 1.

3. Results and discussion

3.1. Existing methods used by fishers to mitigate jellyfish

Our systematic search of the literature identified 35 papers that discussed methods net-based fishers use to mitigate jellyfish. Of these, ten papers referred to coping strategies, twenty-two referred to adaptive strategies, and six discussed transformative strategies (some papers referred to more than one category) (Table 1; Supplementary Table 1).

3.1.1. Coping strategies

When jellyfish occur in relatively small numbers or when blooms are short-lived, fishers implement a variety of strategies to cope with the immediate problems posed by jellyfish. Coping strategies include relocating vessels to avoid jellyfish, manually removing jellyfish bycatch from nets, repairing nets and fishing gear damaged by jellyfish (Palmieri et al., 2014; Quinones et al., 2013; Tiller et al., 2015, 2014), reducing the duration of trawls or, if permits allow, temporarily using different fishing gear (such as anchored gillnets and drift nets) that are less impacted by jellyfish (Nagata et al., 2009) (Table 1). All these coping strategies incur costs that are absorbed by the fishers and reduce their income. For example, removing heavy, slimy and stinging jellyfish from nets delays fishing operations and some species of jellyfish pose health risks to fishers (Kim et al., 2012; Nagata et al., 2009; Tiller et al., 2014). Relocating vessels to avoid jellyfish may use more fuel and reduce the time available for fishing, and catches may be reduced if jellyfish prevent fishers from operating in prime fishing grounds (Kim et al., 2012). Some fishers reported fishing for longer to compensate for lost fishing time (Table 1).

Coping strategies have also been implemented by the supply chain, including fish processing plants. In Peru's purse-seine anchovy fishery, jellyfish bycatch is not separated from the target catch prior to being delivered to fish meal factories (Quinones et al., 2013). Catches contaminated with jellyfish are more difficult for factories to process and generate additional waste. To compensate for managing jellyfish, fish meal factories apply deductions to the price paid to fishers if jellyfish bycatch comprises 10–30 % of the total catch and refuse to process catches containing > 40 % jellyfish. Whilst this financial penalty helps the factories to cope with the jellyfish, it adversely impacts the fishers, and the average revenue lost by each Peruvian fisher due to jellyfish over a 35 day period was estimated to be US$5466 (Quinones et al., 2013).

Only one report was identified of government subsidies being used to help fishers cope with the impacts of jellyfish. In 2004, the European Commission provided the Slovenian fishing industry (which employed 300–400 people) with €150,000 to assist with the increased costs, reduced income and threats to employment that were incurred due to jellyfish blooms in the northern Adriatic Sea (Nastav et al., 2013). This small-scale subsidy probably provided minimal benefits and the limited use of subsidies for jellyfish mitigation reflects that they are likely not a viable long-term coping strategy.

Table 1
Summary of the coping, adapting and transforming strategies commercial net-based fisheries and processing facilities use to mitigate jellyfish.

	Mitigation Strategy	Comments	References
Coping	Relocate vessels to avoid blooms	Additional fuel costs; less time to fish	Conley Sutherland, (2015); James et al. (1985); Kumawat et al. (2021); Nagata et al. (2009); Palmieri et al. (2014); Tiller et al. (2015)
	Remove jellyfish by-catch from nets	Delays fishing operations; damages gear; health risks from stinging jellyfish	Conley Sutherland, (2015); Honda et al. (2005); Kumawat et al. (2021); Tiller et al. (2015)
	Repair fishing gear	Labour costs	Conley Sutherland, (2015); Kim et al. (2012); Palmieri et al. (2014); Tiller et al. (2015)
	Absorb lost income	Financial impact	Conley Sutherland, (2015); James et al. (1985); Kim et al. (2012); Kumawat et al. (2021); Palmieri et al. (2014); Tiller et al. (2015)
	Undertake additional net hauls or shorten duration of hauls	Additional fuel and time costs	Conley Sutherland, (2015); Kumawat et al. (2021); Nagata et al. (2009); Palmieri et al. (2014)
	Temporarily switch to fishing gear less impacted by jellyfish	Permits may be required	Nagata et al. (2009)
	Temporarily stop fishing	Lost income	Honda et al. (2005)
	Pay penalty to processing plant to process catches contaminated by jellyfish	Fishers lose income but processing plants benefit	Quinones et al. (2013)
	Government subsidies	Only reported once and seems unviable as a long-term solution	Nastav et al. (2013)
Adapting	By-catch reduction devices	Used extensively by the industry	Broadhurst, (2025); Broadhurst & Kennelly 1996; Goto et al. (2008); Holst and McDonald, (2000); Honda et al. (2005); Jenkins, (2012); Kasapoğlu et al. 2020; Kendall, (1990); Kim et al. (2008); Kogovsek et al. 2012; Martínez et al. 2014; Matsushita et al. (2005); Okino et al. (2009); Park et al. (2010); (2012); Polet et al. (2004); Sabu et al. (2013)
	Cutting device in net	Rarely reported	Kim et al. (2016)

(continued on next page)

Table 1 (*continued*)

	Mitigation Strategy	Comments	References
	Reconfigure nets	Cost-effective	Broadhurst and Sterling, (2020); Nagata et al. (2009)
	Real-time monitoring	Not implemented (to our knowledge)	Singh 2017
Transforming	Predictive models	Costly to develop but probably useful	Nishikawa et al. (2017); Uye, (2014)
	Remove medusae	Costly and not feasible at scale	Ahn 2022; Kim et al. (2015, 2016); Yokota
	Eradicate polyps	Costly and trials have had limited success	Feng et al. (2017); (2022); Yoon et al. (2018)
	Remove infrastructure inhabited by polyps	May not be practical if infrastructure is utilised	Lo et al. (2008)
	Freshets	Potential impacts on non-target species	Amorim et al. (2018); Beakes et al. (2021)
	Harvest medusae	Rarely done, probably due to logistical constraints	Gibbons et al. (2016)

3.1.2. *Adapting strategies*

When jellyfish blooms occur regularly, persist for longer, or are widespread, coping strategies are inadequate and fishing industries adapt to the regular presence of jellyfish to ensure their on-going viability. Of the twenty-two papers that referred to adaptation strategies, sixteen discussed BRDs, two discussed reconfiguring nets, one referred to adding a cutting device to nets, two discussed using predictive models to provide advanced warning of jellyfish blooms and one focused on real-time monitoring (Table 1).

3.1.2.1. Modifying nets. BRDs are the main tool used by trawl fisheries to reduce bycatch of jellyfish. BRDs for jellyfish consist of mesh panels or funnels (e.g. Broadhurst and Kennelly, 1996; Kendall, 1990; Park et al., 2012), or rigid grids (e.g. Nordmøre grids; Broadhurst and Kennelly, 1996) inserted into the net, in front of the cod-end (Fig. 2). Commercially targeted species, that are smaller than the BRD's mesh size or grid spacing, pass through the BRD while jellyfish, which are larger, are deflected out of an opening in the net (Broadhurst and Kennelly, 1996).

The first jellyfish BRDs ("jellyball shooters") were developed in the decades prior to the 1970s, by shrimpers in South Carolina and Georgia, USA, to reduce bycatch of cannon-ball jellyfishes (*Stomolophus meleagris*) (Jenkins, 2012). In the 1970s, the jellyball shooters were modified to reduce bycatch of turtles and became known as Turtle Exclusion Devices

Fig. 2. Catostylus mosaicus encountering a Nordmøre grid in the Hawkesbury estuary, Australia. Photo credit: Van der Neut family.

(Jenkins, 2012). In the 1990s, prawn fishers in New South Wales Australia began using mesh 'blubber chutes" and Nordmøre grids to reduce catches of *Catostylus mosaicus* (Broadhurst and Kennelly, 1996), and in the early 2000s, research on BRDs in Japan and Korea commenced in response to repeated outbreaks of the giant jellyfish, *Nemopilema nomurai* (e.g. Honda et al., 2005; Park et al., 2012). BRDs are generally effective at reducing jellyfish bycatch with reductions of > 80 % commonly reported, (Broadhurst and Kennelly, 1996) with minimal reductions in target species catch (Table 2). Although numerous studies have optimised the efficiency of BRDs by altering the grid/mesh size and angle of placement, BRD technology to address jellyfish bycatch for trawls has not fundamentally changed in many decades.

Changes to the configuration of the trawls may also reduce bycatch of jellyfish. In Brazil, fishers reported catching fewer jellyfish after they reduced the vertical opening of their nets, by either removing floats from the top panel, or tying the top and bottom panels together (Nagata et al., 2009). Similar reductions in jellyfish bycatch were achieved in Australia where trawls targeting penaeid prawns usually have headline ropes and footropes of similar length (termed "no-lead" nets; Broadhurst and Sterling, 2020). These trawls were modified by lengthening the footropes, which caused the top panel of the net to extend beyond (or overhang) the bottom panel of the net (termed "lead nets"). When the bottom panel disturbs shrimp in the benthos, the overhanging panel intercepts individuals that swim upwards and sweeps them into the net. Experimental comparisons of different configurations, including no-lead nets, lead nets, and "buoyed no-lead nets" (a no-lead net with a large buoy positioned in the centre of the headline rope) found that the lead and no-lead nets caught fewer (by 61 and 58 %, respectively) scyphozoan jellyfish, *Catostylus mosaicus*, than the buoyed no-lead nets, but only the lead net maintained catches of the target species (Broadhurst and Sterling, 2020). Hence, removing any buoys and lengthening the footrope to create a "lead" net would maintain catches of prawns but significantly reduce catches of jellyfish.

Jellyfish also impact purse seine (Quinones et al., 2013; Tosunoğlu and Kasapoğlu, 2019) and fixed net fisheries (Uye, 2014). Traditional stow net fisheries in Korea and set net fisheries in Japan are impacted by blooms of the giant jellyfish, *Nemopilema nomurai*, (e.g. Fig. 1D; Uye, 2014). Japanese fishers modified their set nets to reduce catches of *N. nomurai* by increasing the mesh size on the leading nets (broad wing-like panels that may extend >500 m either side of the net and direct target species into the entrance of the net) to allow large jellyfish to pass through, and by inserting interception nets within the body of the set net. The interception nets act like BRDs on trawls and allow the target species to pass through but direct the large jellyfish out an escape hole (Goto et al., 2008). Partition nets inserted at rear of the net further separate jellyfish from the target species. Following these interventions, similar numbers of jellyfish and fish were caught and catches of squid increased. However, the modifications coincided with a proliferation of jellyfish in the environment, and authors concluded that the modifications effectively reduced jellyfish catches without compromising catches of target species. The cost of modifying the enormous nets (5–10 million Japanese Yen per net) is prohibitively expensive for many fishers (Uye, 2014). The addition of conical mesh inserts in stow nets were also effective at reducing bycatch of *N. nomurai*. Stow nets rely on strong tidal flows, which caused conical mesh panels inserted in the stow nets to effectively exclude jellyfish in a similar way to BRDs in trawls (Park et al., 2012).

Purse seine nets are often used to harvest small, schooling species such as anchovies and so use small meshes that can capture large amounts of bycatch, including jellyfish (Quinones et al., 2013; Tosunoğlu and Kasapoğlu, 2019). In the Sea of Marmara, fishers fit large-mesh excluder nets in front of the "bunt" of the net (i.e. the bag containing the catch that is formed from the last section of net to be hauled aboard) to partition jellyfish from the target species. The jellyfish are then released (i.e. "slipped") from the net by rolling them over the

Table 2
Effectiveness of modifications to trawl, set, and seine nets in reducing by-catch of jellyfish and retaining target species. Where different configurations of modifications were trialled (e.g. different mesh sizes or angles at which panels were inserted) results of the most effective configuration at reducing jellyfish by-catch was reported. NS = not specified.

Type of panel	Jellyfish species	Target species	% reduction in jellyfish by-catch	% reduction in target species catch	Location	Reference
Trawl net						
Mesh	*Nemopilema nomurai*	Fish	98	62	Korea	Kim et al. (2008)
Mesh	*Stomolophus meleagris*	shrimp	78	NS	USA	Kendall, (1990)
Rigid	*Nemopilema nomurai*	Fish	89	NS	Japan	Matsushita et al. (2005)
Rigid	*Nemopilema nomurai*	Fish & squid	55	< 40	Japan	Okino et al. (2009)
Rigid	*Nemopilema nomurai*	Fish	85.2	32	South Korea	Park et al. (2010)
Mesh	NS	Shrimp	98.2	2.5	India	Sabu et al. (2013)
	NS	Shrimp	47	46	Colombia	Martinez et al. 2014
Set net						
Mesh	*Nemopilema nomurai*	Fish & Squid	0*	0	Japan	Goto et al. (2008)
Mesh	*Nemopilema nomurai*	Fish	98	17	South Korea	Park et al. (2012)
Seine net						
Mesh	NS	Fish	NS	NS**	Turkey	Kasapoğlu et al. 2020

* Catches of jellyfish did not decrease after the net was modified but this coincided with jellyfish proliferating in the environment, so the modification was deemed successful. ** The amount of anchovies lost equated to approximately 1/30th the mass of the jellyfish that were slipped from the net.

headline. Some anchovies are lost in the slipping process, but the amount lost is relatively small (approximately 1/30 the mass of the jellyfish). The effectiveness of slipping to manage jellyfish bycatch, however, still needs to be rigorously assessed (Tosunoğlu and Kasapoğlu, 2019), especially given that fish may be injured by the jellyfish during the slipping process.

3.1.2.2. Providing advanced warning of blooms using predictive models. Predictive models are used to provide Japan's set net fishers with advanced warning of where and when *Nemopilema nomurai* may impact their fishery. *N. nomurai* appear to be produced from polyps located in the Yellow and East China Sea and medusae are transported eastward by the Tsushima Current to the Sea of Japan over several months (Uye, 2014). Visual surveys from ferries traversing the Yellow, Bohai and East China Seas are used to forecast the arrival and magnitude of blooms of the jellyfish to Japan (Uye, 2014). When large blooms are forecast, numerical models predict the finer-scale spatio-temporal distributions and identify specific areas in which set nets are likely to be impacted. Forecasts, based on correlates such as salinity measurements are also being developed (Nishikawa et al., 2017). These forecasts enable fishers to either modify their nets to exclude jellyfish or, in extreme cases, to remove nets in advance of the blooms (Uye, 2014).

3.1.3. Transforming strategies

Transforming strategies involve long-term, fundamental changes to the industry or environment, to ensure the viability of the socio-ecological system. At its most extreme, transforming involves fishers leaving the industry or the fishery closing altogether, but transformations also include reducing jellyfish populations and the fishing industry pivoting to harvesting jellyfish. Of the six papers identified that specifically referred to transformation strategies for fisheries, three referred to removing medusae using trawls or robots, one discussed eradicating polyps, and two referred to harvesting jellyfish. No literature discussed fishers leaving the industry or a fishery closing, although such incidents may not have been reported in the scientific or grey literature located by our search.

3.1.3.1. Removing medusae from the environment. Relatively few attempts have been made to mitigate jellyfish by actively removing them from the environment. In Japan, fishers inserted carbon steel wire into the cod-ends of trawls to slice giant jellyfish (*Nemopilema nomurai*) and moon jellyfish (*Aurelia aurita*) (Lucas et al., 2014) that were interfering with fisheries. South Korean researchers also developed a trawl specifically designed to remove jellyfish (Kim et al., 2016). No information about the success of these attempts to remove jellyfish is available but presumably the costs of using trawlers are high. Automated robots that shred jellyfish have also been trialled as a tool for removing *Aurelia* medusae in South Korea (Kim et al., 2016). These small (~1.5 ×1.5 m) robots navigated fixed paths as they floated at the water's surface and shredded up to 25 medusae per minute and 150 kg per hour (Kim et al., 2016), however, robots only targeted jellyfish occurring in the top 1 m and large numbers of robots would be needed to manage large populations of medusae. Submersible robots that shred jellyfish have also been designed (Ahn et al., 2022; Yokota et al., 2022), although not specifically for fisheries mitigation. The robots are operated remotely from a boat via an umbilical, but field trials do not appear to have been undertaken.

Jellyfish removal programs create large amounts of waste that can be problematic to dispose of. Jellyfish that are shredded or disposed of at sea sink to the benthos where they may be scavenged or decomposed by microbes, which may alter biogeochemical cycling and cause local hypoxia (Chelsky et al., 2016; Sweetman et al., 2016; West et al., 2009). One hundred tons of *Cotylorhiza tuberculata* medusae were removed by trawling from the Mar Menor coastal lagoon in Spain to aid the tourism industry. The carcasses were disposed of in landfill, where they were estimated to leach kilograms of toxic heavy metals that had accumulated in their tissues into the environment (Muñoz-Vera et al., 2015). Hence the environmental consequences of generating large amounts of jellyfish waste, requires careful consideration.

3.1.3.2. Removing polyps from the environment. Attempts have also been made to manage scyphozoan jellyfish populations by eradicating populations of the benthic polyps that produce medusae. Larvae produced by sexual reproduction of medusae attach to the sea floor and metamorphose into tiny (~2 mm tall) polyps. Polyps multiply asexually by budding and produce juvenile jellyfish by transverse fission (strobilation). Some species of polyps can produce dozens of ephyrae during each strobilation event, and polyps of some species can strobilate repeatedly. Theoretically, each larva that is produced by a medusa could result in 100 s or 1000 s of new medusae. Moreover, whilst medusae tend to occur seasonally, polyps are probably perennial, with some polyp cultures persisting for more than a decade in captivity (Pitt pers. obs.). An extensive program to eradicate polyps of the moon jellyfish *Aurelia*, which interfere with trawl fisheries, has been undertaken in South Korea. The program appears to have been only moderately successful, as populations of medusae decreased at only one of three locations in which SCUBA divers had removed polyps by water blasting or scraping surfaces and the medusa population reestablished within 2–3 years (Yoon et al., 2018). A similar study, aimed to manage *Aurelia* in a Chinese port by removing biofouling communities (including polyps) from two large floating docks. Abundances of medusae declined by 66 % after the biofouling communities were removed, but medusae returned within five years (Feng et al., 2022). Neither of these studies compared abundances of medusae in areas where polyps were removed to control locations where polyps were undisturbed, which prevents a conclusive assessment of whether the removal of polyps caused the subsequent decline in numbers of medusae. Removing infrastructure colonised by polyps may also reduce numbers of jellyfish (Lo et al., 2008) but this will only be feasible when the infrastructure is no longer being used.

Eradicating polyps from artificial infrastructure might be feasible to manage polyp populations but regularly cleaning surfaces may also facilitate recruitment of polyps. The methods used to eradicate polyps (e.g. scraping and water blasting; Yoon et al., 2018) also remove entire biofouling communities. Biofouling communities are potential predators of jellyfish larvae and competitors of polyps (Feng et al., 2021, 2017a) and removing them could facilitate settlement of new jellyfish larvae and survival and proliferation of polyps, although the susceptibility of different species of jellyfish polyps to biofouling communities varies greatly (Feng et al., 2024). Polyps rapidly colonise "clean" acrylic settlement plates in the field (e.g. (Willcox et al., 2008) and a variety of artificial substrates in the laboratory (Feng et al., 2017b; Pitt, 2000), so surfaces where biofouling communities are removed could be quickly colonised by jellyfish planulae. Hence surfaces from which polyps are removed would need to be cleaned regularly or treated with anti-foulant chemicals (e.g. Feng et al., 2022) to inhibit recruitment of new polyps.

3.1.3.3. Harvesting medusae. Jellyfish (predominantly rhizostomes) have been harvested for food and traditional medicine in China for > 1700 years (Omori and Nakano, 2001). Growing demand for jellyfish as food, as sources of collagen (Chiarelli et al., 2023) and novel compounds with possible biotechnological (D'Ambra and Merquiol, 2022) and biomedical (Riccio et al., 2022) applications has seen fisheries for jellyfish expand into the Americas (Brotz et al., 2017), Mediterranean (Edelist et al., 2021), India (Kumawat et al., 2023), and Pakistan (Gul et al., 2015). Although it has been suggested that fisheries severely impacted by jellyfish might pivot towards harvesting jellyfish (e.g. Boero, 2013; Purcell et al., 2007; Tiller et al., 2015), there is limited evidence that this has occurred, potentially because only a sub-set of jellyfish species are commercially valuable.

The only potential example we identified of a fishery pivoting to harvest jellyfish was in Gujarat, India. At this location fishers report detrimental impacts of jellyfish on fishing operations (James et al., 1985; Kumawat et al., 2021), harvest jellyfish during the jellyfish season, and switch back to their higher valued target species once the jellyfish season is over (Kumawat, 2023). Overall, it seems that most jellyfish fisheries are initiated in response to market demand for the product and associated investment in infrastructure and declines in catches of alternative target species (Brotz et al., 2021), rather than from jellyfish interfering with traditional fisheries.

Harvesting jellyfish when their populations interfere with normal fishing operations seems sensible, but it might not be straightforward for fishers to transform their industry to target jellyfish (Gibbons et al., 2016). Although jellyfish could provide an alternative income, jellyfish usually attract a far lower price than the species normally targeted by net-based fisheries (such as prawns/shrimp and fish; but see Nishikawa et al., 2008), and the income derived from jellyfish may be insufficient to sustain fishers, particularly in regions where labour costs are high. The lower price for jellyfish means large volumes need to be harvested and this can place stress on fishing gear (e.g. nets and winches) and small vessels may be unable to store enough jellyfish in their holds. Perhaps the major impediment, is that jellyfish need to be quickly cured in mixtures of brine and alum and dried, and dedicated processing facilities are usually required. Investing in processing facilities may be risky, however, because jellyfish populations are inheritably variable, and facilities may be idle if jellyfish populations decrease, and fishers redirect fishing efforts towards more valuable species. Developing new processing protocols and/or mobile processing facilities, that could be moved among locations or that could process multiple types of products, might facilitate opportunistic harvesting of problematic jellyfish.

3.2. Possible technological and ecosystem-based approaches to mitigating jellyfishes

Our review of the literature highlighted that, with the recent exception of numerical models to predict jellyfish blooms (e.g. Nishikawa et al., 2017), commercial fishers mostly rely on mitigation methods (e.g. BRDs) that have remained largely unchanged for decades. Although some innovations, such as jellyfish shredding robots, have been trialled, they have not been adopted by the fishing industry, presumably because they are not feasible for large-scale removal of jellyfish. Rapid innovations in technology, sensors, modelling, and improved understanding of jellyfish ecology, may offer some new ways to mitigate jellyfish.

3.2.1. Intelligent nets

Computer vision is emerging as an important tool for monitoring the marine environment and could be used to reduce bycatch in trawl fisheries. Several research institutes (e.g. French Institute for the Exploitation of the Sea; New Zealand's National Institute of Water and Atmospheric Research, and the UK's Fisheries Innovation and Sustainability group) are developing "intelligent nets" that use computer vision to monitor and manage bycatch. Cameras located in the entrance of the nets monitor fish and bycatch entering the net. When unwanted species enter the net, a panel is drawn across the entrance of the codend and all organisms (including target species) entering the net are redirected out of the net via an escape chute. The cod-end can be opened and closed, as required, depending on the amount of bycatch present. Computer vision models are being built to automatically detect target and non-target species and to close the codend when the number of unwanted species exceeds a threshold, and these computer vision models could be easily trained to detect jellyfish (e.g. Martin-Abadal et al., 2020). Whilst prototypes of intelligent nets have been tested, this emerging technology may only be suitable for use on large trawlers and afforded by wealthy fishing companies. As the technology is refined and adopted more widely, it may become affordable for small to medium sized fishing enterprises and the broader fishing community.

3.2.2. Real-time monitoring of jellyfish

Technological advancements increase our ability to monitor jellyfish in real-time and could be used by fishers to avoid deploying nets in areas where jellyfish are abundant. Many jellyfish species are readily observed by drones (e.g. Choi et al., 2021; Raoult and Gaston, 2018), which could be flown ahead of a trawler at a distance that would provide sufficient lead-time to retrieve the net if jellyfish are observed. Drones are inexpensive and easily operated but only observe jellyfish near the surface and so may only be useful in shallow systems, such as coastal lagoons and when the water is relatively clear. Jellyfish are also detectable by acoustic sounders, despite their bodies being a similar density to seawater and lacking swim bladders that reflect sound in fish (Brierley et al., 2005). Sounders can detect jellyfish occurring throughout the water column, however, as they are mounted on the vessel, they are unlikely to provide sufficient lead-time to retrieve trawls when jellyfish are detected. Acoustics could be used prior to deploying nets, however, to determine whether jellyfish are present along the planned trawl path or in the general vicinity before nets are deployed. Since sounders are already used by most fishing vessels, they require no additional investment by the fisher, although monitoring the vicinity before nets are deployed takes time and resources.

Acoustic monitoring of jellyfish, in real time and at large scales (i.e. across 10s-100s of kms) has been proposed via deployment of underwater wireless sensor networks (UWSNs) (Singh et al., 2017). Such sensor networks could provide fishers with access to a 'heat map' that illustrates the spatial distributions of jellyfishes. These heat maps would enable fishers to avoid fishing in areas where jellyfish are densely aggregated. UWSNs, however, are computationally expensive, with a clear trade-off between the accuracy with which data are transmitted, and communication cost. To our knowledge, such networks have not been deployed.

3.2.3. Predicting the occurrence and distribution of jellyfish

Predictions of where and when jellyfish are likely to occur could enable fishers to avoid jellyfish or prepare for jellyfish encounters. Many jellyfish actively swim and move horizontally (Hamner et al., 1994; Hamner and Hauri, 1981) and vertically (Hays et al., 2008; Moriarty et al., 2012) through the water column. For example, in marine lakes in Palau (Hamner and Hauri, 1981) and a Canadian fjord (Hamner et al., 1994) medusae undertake extensive horizontal migrations daily. Acoustic sounders (Kaartvedt et al., 2007), miniaturised tags (Hays et al., 2008; Moriarty et al., 2012) and nets (Albert, 2010) have also been used to assess vertical distributions of jellyfish and how they move in response to tides (i.e. tidal stream transport) or time of day (i.e. diel migration). The giant jellyfish, *Nemopilema nomruai*, typically occurs within the top 40 m of the water column in the southern Sea of Japan (Honda and Watanabe, 2007; Honda et al., 2009) suggesting that nets deployed and operated below that depth may encounter few jellyfish. However, evidence for co-ordinated mass vertical migrations of jellyfish populations is rare (but see Canepa et al., 2014; Kaartvedt et al., 2007) because individuals exhibit enormous variation in swimming speeds and depth excursions that outweigh population level responses (Hays et al., 2008). Relatively few species have been studied and estuarine jellyfish subject to strong tidal flows may be ideal candidates to test for evidence of tidal migrations. Advances in underwater autonomous vehicles, tagging technologies and hydrodynamic modelling mean that it is becoming more feasible to track and predict movements in complex underwater environments. Building knowledge of where jellyfish occur and how their distributions change in relation to tides and/or time of day could enable fishers to identify places or times where they could safely deploy nets.

3.2.4. Ecosystem-based management of jellyfish populations

Jellyfish populations might be managed indirectly by manipulating environmental conditions or enhancing populations of their predators and competitors (Angel et al., 2016). Varying environmental flows in estuaries can impact jellyfish species, via sudden reductions in salinity which can kill medusae (Loveridge et al., 2021; Rippingale and Kelly, 1995) and polyps (Amorim et al., 2018), or by altering hydrodynamics (Beakes et al., 2021). Hence, sudden releases of freshwater ("freshets") in bonded estuaries have been proposed to manage problematic jellyfish populations (Amorim et al., 2018). Ideally freshets would be generated in late winter and timed to kill polyps before they strobilate but avoid impacting the spring recruitment of juvenile fishes (Amorim et al., 2018) and other organisms. Species vary considerably, however, in their salinity tolerances, and the success of this approach would depend greatly on the geomorphology of the estuary, as deep areas in the estuary may provide a salinity refuge for polyps from low salinity events (Rippingale and Kelly, 1995). Importantly, the impacts on non-target species in the estuary, would need to be considered.

Medusae are eaten by diverse predators including turtles, fish, birds, octopus, holothurians, crabs and amphipods (Hays et al., 2018) and compete with other zooplanktivores for food. Polyps are consumed by aeolid nudibranchs, caprellid amphipods, pycnogonids, decapods (reviewed by Lucas et al., 2012) and anemones (Tang et al., 2021). Enhancing numbers of predators and competitors in the environment could limit abundances of jellyfish but relatively little is known about predator/prey dynamics and whether predators can regulate populations of polyps or medusae. The most compelling evidence that predators may control polyp populations was from a combination of laboratory experiments and field observations in Gullmar Fjord, Sweden (Hernroth and Grondahl, 1985). The aeolid nudibranch, *Coryphella verrucosa* consumed up to 200 *Aurelia aurita* polyps ind^{-1} day^{-1} in the laboratory and in the field, large densities of nudibranchs (930 ind m^{-2}) occurred on settlement plates heavily colonised by polyps. Polyps (and subsequently nudibranchs) disappeared from the settlement plates and natural substrates over a period of a few weeks. The strong correlation between abundances of polyps and nudibranchs and observations that nudibranchs fed prolifically on polyps, suggests that the nudibranchs could have been responsible for reducing the polyp populations in the field. Assessing whether populations are regulated by top-down or bottom-up processes is essential for determining whether jellyfish could be managed by enhancing populations of their predators.

4. Conclusions

Net-based fisheries use multi-faceted approaches including coping, adapting, and transforming strategies to mitigate jellyfish but the methods used have remained largely unchanged for decades. Technological advancements, including computer vision, advanced tags, drones and acoustic techniques are beginning to offer innovative solutions. Some technologies, such as drones, are now affordable, but advanced solutions, such as intelligent nets, are likely to be remain too expensive for small to medium sized fishing enterprises in the short-term. Ultimately, the long-term co-existence of net-based fisheries and jellyfish requires close cooperation among stakeholders, including fishers, managers, and scientists.

CRediT authorship contribution statement

Kingsford Michael J.: Writing – review & editing, Funding acquisition, Conceptualization. **Suthers Iain:** Writing – review & editing, Funding acquisition. **Clare Morrison:** Writing – review & editing, Conceptualization. **Pitt Kylie:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kylie Pitt reports financial support was provided by Australian Government Fisheries Research and Development Corp. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107535.

Data availability

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

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