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ORIGINAL ARTICLE

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A synthesis to understand responses to capture stressors among fish discarded from commercial fisheries and options for mitigating their severity

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Abstract

Discarding non-target fish from commercial fisheries is controversial and has been a persistent concern for fisheries managers globally. Discard management strategies typically begin by understanding mortality rates among discarded fish, a challenging task given the dynamic, highly context-specific nature of fisheries. An alternative is to develop our knowledge of how stressors operate by first understanding the causes of mortality that drive this context dependence. Particularly relevant to mitigation efforts is an understanding of how fish respond to the physical factors of fishing, such as the gear itself and methods of fishing and handling the gear. We provide a synthesis of how commercial fishing methods may influence discard mortality and outline means by which capture-induced stress and injury can be mitigated for common commercial gear types, emphasizing method variants or alternatives during capture, handling, and release that could improve survival. This synthesis identifies exhaustion and injury as the most detrimental and ubiquitous stressors experienced by discarded fish, with few options for mitigating their effects. Trawls and hanging net fisheries are identified as the most harmful gears for by-catch, characterized by high stress regardless of method variants and limited options for mitigation. Irrespective of gear type and type of stressor, minimizing durations of capture and handling and encouragement of good handling behaviour (e.g., during landing and sorting) will reduce the magnitude of stress and injury in fish, and ultimately increase survival.

KEYWORDS

air exposure, by-catch, fish handling, injury, mortality, physiology

1 | INTRODUCTION

The occurrence of by-catch (defined as any part of the catch caught incidentally; Alverson, Freeberg, Pope, & Murawski, 1994) in commercial fisheries is a persistent management concern globally (Halpern, Selkoe, Micheli, & Kappel, 2007). It is widely acknowledged that the loss of marine life due to commercial fisheries discard constitutes a waste of resources and contributes to the depletion of marine biodiversity (FAO, 2011; Kelleher, 2005). By-catch also occurs in inland (freshwater) systems, though has been comparatively less studied (Raby, Colotelo, Cooke, & Blouin-Demers, 2011). A large quantity and diversity of marine and freshwater fauna, including aquatic mammals, birds, turtles, fish and invertebrates, are captured as by-catch (Hall, Alverson, & Metuzals, 2000). There have been numerous types of gear modifications that attempt to reduce by-catch (e.g., turtle/juvenile fish exclusion devices, shrimp sorting devices), as overall prevention of non-target species capture is certainly the best way to avoid fisheries-related mortality

(Broadhurst, Uhlmann, & Millar, 2008). However, such modifications are not 100% effective, are often size and/or species-specific and are not found in all fisheries. Therefore, by-catch remains a proportion of catch in most fisheries.

While some by-catch is retained, the majority is discarded (Hall et al., 2000), and fishes, the focus of this review, compose the greatest biomass discarded from commercial operations in both marine (Alverson et al., 1994) and freshwater (Raby et al., 2011) systems. By-catch can be further categorized according to the animal's fate following capture. Although many fish are dead prior to discard (i.e., immediate capture-induced mortality), others are discarded alive, some of which will die after release (i.e., post-release mortality). Here, we outline the causes of mortality attributed to various fishing methods among fishes captured in commercial fisheries, with the aim of informing mitigation options and management decisions on how to minimize the negative effects of capture.

Discarding fish is controversial from ecological, economic and ethical standpoints. Discarding occurs due to regulatory measures for conservation, licence or sharing agreements, market considerations, or, less commonly, logistical constraints (e.g., lack of appropriate storage); Hall, Gilman, Minami, Mituhasi, and Carruthers (2017) provide a thorough review of by-catch situations and why they occur. Often body size will inform discard decisions. Size selectivity can be employed to increase yields, either by allowing individuals to reach sexual maturity for at least one reproduction event (Hall & Mainprize, 2005; Halliday & Pinhorn, 2002) or by protecting older individuals, particularly females, that typically demonstrate the highest fecundity in the population (Birkeland & Dayton, 2005). Size selectivity can also take the form of "high grading," where fishers only retain high-value fish, a practice that can lead to substantial discarding (Gillis, Peterman, & Pikitch, 1995). Conversely, some by-catch has such little economic value that there is no incentive for retention, a cause of discarding that some argue is unnecessary, as most fish can be used to produce marketable products such as fish meal and oils (Blanco, Sotelo, Chapela, & Pérez-Martín, 2007). Indeed, in small-scale fisheries in food insecure areas, nearly all fisheries products are retained and consumed.

A Code of Conduct for Responsible Fisheries developed by the United Nations Food and Agriculture Organization (FAO) provides international principles and standards for the sustainable use of aquatic ecosystems. The voluntary guidelines call on signatory countries to adopt "to the extent practicable, the development and use of selective, environmentally safe, and cost-effective fishing gear and techniques" (Alverson et al., 1994). Despite widespread endorsement, there is growing concern that fish discard mortality continues to threaten long-term sustainability of many marine and inland fisheries (FAO, 2011). There is also an argument opposing by-catch discard, suggesting instead balanced exploitation practices where fishing pressure is distributed across the widest possible range of trophic levels, sizes and species in proportion to their natural productivity (Garcia et al., 2012; Zhou et al., 2010). Some nations (e.g., European Union countries, Chile, Norway and New Zealand) have begun to introduce partial or complete discard bans in marine waters, forcing affected fisheries to land non-target catch (Borges, Cocas, & Nielson, 2016)—a major change not without criticism (Heath, Cook, Cameron, Morris, & Speirs, 2014; Sardà, Coll, Heymans, & Stergiou, 2015). For certain taxa and situations, however, live-release may represent a simple, cost-effective measure to achieve discard management objectives without complete discard bans (Benoît, Hurlbut, & Chassé, 2010).

A major limitation to any discard management strategy is that accurately defining the effect of fisheries on stock status is limited without population dynamics modelling. However, these models are only as accurate as the estimates of population demographics and total mortality for the species in question (Magnusson & Hilborn, 2007). In particular, total mortality, which encompasses natural mortality in addition to fishery-induced mortality across all gear types and fisheries encountering the species, is often not available in detail (Magnusson & Hilborn, 2007). A prescriptive approach of establishing mortality estimates for each species, fishery and area is likely unachievable due to the dynamic, highly context-specific nature of fisheries. Moreover, large species-specific differences exist in response to capture stressors and mortality estimates generated from one context cannot be easily extrapolated to another (Benoît, Hurlbut, Chassé, & Jonsen, 2012). In his seminal paper, Davis (2002) calls for researchers to first enhance current fundamental knowledge of stressor action to understand *why* fish die. Such an approach encompasses the context-dependency of discard mortality and provides a general understanding of how fish respond to a fishery encounter under varying scenarios (Patterson, Robinson, Lennox, et al., 2017). The knowledge garnered can, for example, inform methods of estimating fishing-related incidental mortality rates (as in Patterson, Robinson, Raby, et al., 2017), assist management decisions regarding retention or release and support best practice recommendations and mitigation efforts; the latter is the focus of this paper.

Particularly relevant to mitigation efforts is a focused assessment of how fish respond to the physical factors of fishing (i.e., gear and handling), yet such synthesis is currently lacking from the primary literature. A better understanding of the mechanisms of mortality as they relate to fishing factors will advise mitigation efforts and provide the scientific information required to inform management decisions. Herein, we identify potential mechanisms of mortality among discarded fishes from various capture and handling scenarios in commercial fisheries; rather than attempting to quantify mortality, we take a broad and fundamental view of the potential causes of mortality. We amalgamate research relevant to considering the effects of commercial capture on discarded fish that is based on an understanding of the fish's experience during capture, handling and release.

1.1 | Approach and objectives

The objective of this literature synthesis is to inform how fishing method, including gear type, deployment and handling methods, influence probability of survival of fish discards from commercial fisheries through an examination of the resulting fish responses. While environmental (e.g., temperature, sea/lake/river conditions) and biological (e.g., life stage, size) factors (Davis, 2002; Veldhuizen, Berentsen, de Boer, van de Vis, & Bokkers, 2018) are important when considering how a fish responds to a stressor, understanding the effects of various fishing methods has potential to steer mitigation efforts because gear and method variations can be more directly controlled. This is neither a review of the magnitude of fish discards among commercial fisheries (as done by Harrington, Myers, & Rosenberg, 2005; Davies, Cripps, Nickson, & Porter, 2009), nor a review of discard mortality rates observed in commercial fisheries (as done for recreational fisheries in Bartholomew & Bohnsack, 2005)—the findings presented here are in the context of mitigation and improving the condition of discarded fish.

Our objective was to provide a synthesis of the information available to help mitigate and minimize capture-induced stress and injury for the most common commercial gear types that discard fish. To this end, we first review the general stress responses in fish invoked by capture, regardless of method (Section 2), as well as the stressors and injuries common among commercial capture methods (Section 3; Figure 1). We then describe the severity (i.e., magnitude, duration and likelihood) of identified stressors and injuries resulting from each of the selected gear types (Section 4; Figure 1). Finally, the implications for fisheries management and by-catch mitigation are synthesized and discussed, emphasizing methods that could lead to improved condition of fish discarded in commercial fisheries (Section 5; Figure 2).

2 | FISH STRESS PHYSIOLOGY IN THE CONTEXT OF CAPTURE

Regardless of capture method, fish discarded from commercial fisheries are exposed to multiple acute stressors. The initial contact with

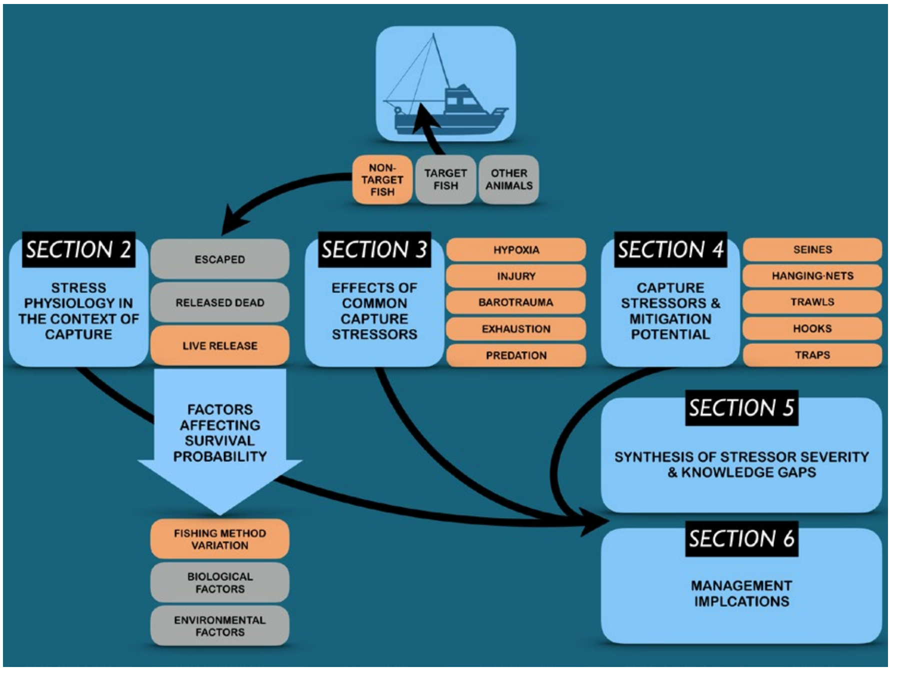

FIGURE 1 Conceptual diagram outlining the structure and extent of the presented literature synthesis. This synthesis, inclusive of all topics within black boxes, aims to assess how fishing methods influence the probability of delayed mortality or reduced fitness among non-target fish discarded alive from commercial fisheries. Topics displayed in grey boxes are beyond the scope of this synthesis. For example, the synthesis does not include fish that do not survive the capture event (released dead) or are not landed (escaped) and is limited to understanding the effects of fishing method variation. Text under each section heading outlines the paper structure [Colour figure can be viewed at wileyonlinelibrary.com]

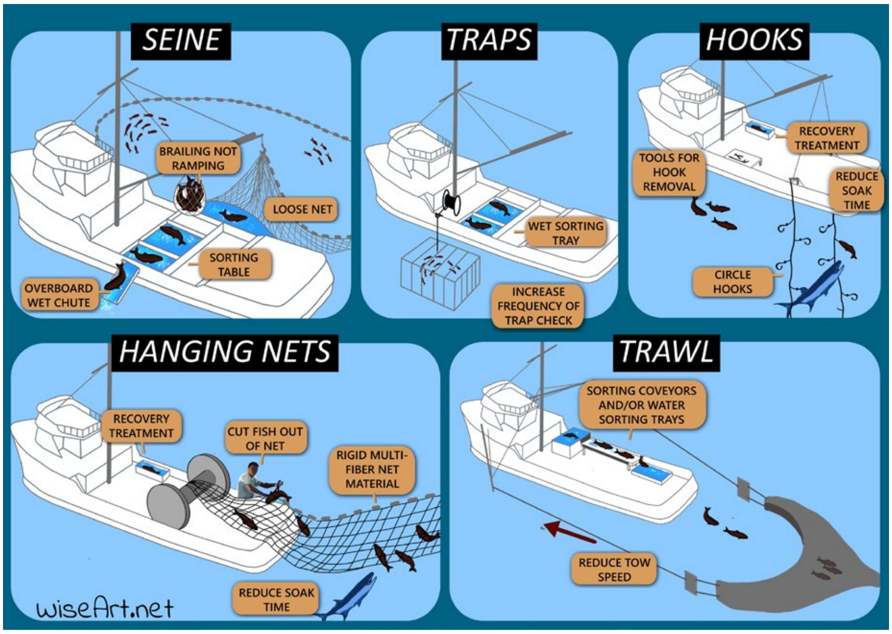

FIGURE 2 Mitigation measures for each commercial gear type covered by this review that would be the most effective in reducing the severity of stress experienced by discarded fishes, and that could also be practically employed in many fisheries [Colour figure can be viewed at wileyonlinelibrary.com]

fishing gear may lead to entanglement, physical trauma and/or confinement. Attempts to escape can lead to exhaustion during both capture and handling and, when on-board, fish are often air-exposed and face additional trauma (e.g., crushing, mechanical injury).

The general stress response has been described in detail for fish (Barton, 2002; Mommsen, Vijayan, & Moon, 1999; Wendelaar Bonga, 1997). Adaptive neuroendocrine responses are initiated the moment a stressful encounter is perceived and physiological adjustments are required at all levels of biological organization, from the molecular level to changes affecting whole-organism function (Kassahn, Crozier, Pörtner, & Caley, 2009; Wendelaar Bonga, 1997). Barton (2002) categorized this progression of responses as primary, secondary and tertiary; primary responses encompass the initial neuroendocrine changes, secondary responses relate to tissue-level adjustments (e.g., changes to respiration, osmoregulation, immune function and cellular processes), and tertiary responses involve aspects of whole-animal performance.

Acute stress in fish initially causes a rapid release of catecholamines and activates the hypothalamic–pituitary–interrenal (HPI) axis, which culminates in an increase in circulating concentrations of glucocorticoid hormones (Barton, 2002; Wendelaar Bonga, 1997). These immediate hormonal changes then mobilize the energy required for secondary responses (Barton, 2002). Increases in glucose and lactate are observed along with decreases in tissue glycogen, and changes to ion concentrations and haematological features (Barton, 2002; Wendelaar Bonga, 1997). At this stage, the innate immune system can also become activated, increasing lysozyme activity and antibody production (Tort, 2011). At the cellular level, concurrent molecular damage initiates a cellular stress response that enables the individual to temporarily tolerate or counteract the stress and shifts energy allocation from cellular growth to cellular repair (Kassahn et al., 2009). Tertiary stress responses extend to both the organismal- and population-level. A stressed animal will modify its behaviour, and lasting changes to growth, performance, reproductive potential and disease resistance can occur (Barton, 2002). This complex cascade of processes is considered an adaptive mechanism that facilitates escape from challenging situations, promotes immediate survival and enables the reestablishment of a homeostatic state (Wingfield et al., 1998).

For fish discarded from fisheries, behavioural impairment due to stress and/or a failure to recover from the stress event can have fitness effects both directly (e.g., increased probability of predation; Raby, Packer, et al., 2014; Raby, Packer, Danylchuk, & Cooke, 2014) and indirectly (e.g., impaired foraging or swimming abilities; Gregory & Wood, 1999). Extensive comparative physiology research has established that the duration and magnitude of physiological disturbance following acute stress, such as a capture event, are proportional to the severity of the stressor (Chopin & Arimoto, 1995; Cook, Hinch, Watson, et al., 2018). Therefore, the type and duration of a stressor have consequences for the severity of response exhibited by the fish and recovery time required (Kieffer, 2000). Ultimately, mortality results when the magnitude and duration of the stressor overcomes the adaptive stress-coping mechanisms available to the individual.

3 | EFFECTS OF COMMON CAPTURE STRESSORS

Understanding the effects of stressors experienced by discarded fish will better establish connections between fishing method and probability of survival, and can inform mitigation. In this section, we outline the fish responses to, or effects of, individual stressors common to commercial capture, handling and release methods.

It is important to note that many factors can exacerbate the response to individual stressors. While each stressor experienced during capture may independently elicit a general stress response, there is real potential for effects to be interactive (Chopin & Arimoto, 1995; Crain, Kroeker, & Halpern, 2008), the cumulative effects of which are beyond the scope of this paper. Additionally, we have not provided an exhaustive list of all stressors potentially influencing discarded fish. Environmental conditions (e.g., water temperatures) and fish characteristics (e.g., size, life stage), not included in this overview of stressors associated with fishing method, are exceptionally important to survival outcomes for discarded fish and will influence the magnitude of each of the stressors chosen for this review.

3.1 | Hypoxia/air exposure

Air exposure is often unavoidable in commercial fisheries and causes acute hypoxia, a deficiency in oxygen reaching the tissues. Although air exposure is most frequent during sorting, hypoxia may also occur if ventilation is restricted (i.e., the operculum cannot move), or with localized oxygen depletion in crowded nets/traps (as observed in Raby, Packer, et al., 2014). Gill lamellae, the respiratory organs responsible for gas exchange, collapse during air exposure, ceasing aerobic respiration (Ferguson & Tufts, 1992). An oxygen debt develops and carbon dioxide accumulates, decreasing pH (i.e., extracellular acidosis; Ferguson & Tufts, 1992; Arends, Mancera, Munoz, Wendelaar Bonga, & Flik, 1999). The longer the duration of air exposure, the longer it takes for fish to recover from these effects (Arends et al., 1999) and the higher the probability of mortality (Cook, Lennox, Hinch, & Cooke, 2015).

Durations of air exposure during capture and handling are variable, ranging from seconds to over an hour depending on method. Other variables, such as environmental conditions, species or life-history stage, can all influence air exposure tolerance (Cook et al., 2015). Although some species can tolerate prolonged air exposure, most notably demersal fishes (Davis & Olla, 2002; Haukenes & Buck, 2006), a difference of just 10 seconds was enough to influence fecundity measures in Atlantic salmon (*Salmo salar*, Richard, Dionne, Wang, & Bernatchez, 2013). When air exposure is combined with other forms of acute capture stress (e.g., exhaustion; see Section 2.4), the combined effect can influence an individual's vulnerability to hypoxia.

3.2 | Injury

All capture scenarios will cause some level of injury to a fish, but the type of physical damage and the magnitude of effect will be a function of fishing gear, method and fish characteristics (e.g., body size and shape, skin characteristics). In all fish however, longer fishing durations are associated with more external injuries (Veldhuizen et al., 2018). Severe crushing injuries, exsanguination and puncture wounds to major organs can easily be traced back to capture and/or handling events and can result in immediate or short-term mortality. Less obvious injuries, such as damage to the integument, are more difficult to attribute to fisheries encounters but can still lead to delayed mortality.

The most ubiquitous fisheries-induced damage is the loss of protective mucus layers that cover skin, scales and gills through physical contact with gear or other fish. Integral to the immune system, mucus contains lysozymes and antibacterial proteins, creating the first defence against pathogens; thus, the removal of mucus can increase the potential for infection (Svendsen & Bøgwald, 1997). Fish will typically increase mucus production during a stressful encounter, potentially reducing the physical damage and latent infection risk associated with capture and handling (Fast, Sims, Burka, Mustafa, & Ross, 2002). Mortality associated with damage to the next line of defence, the skin and scales, is also typically latent. Fish with deciduous scales are most vulnerable to scale loss (Suuronen, Erickson, & Orrensalo, 1996; Suuronen, Lehtonen, Tschernij, & Larsson, 1996). Extensive scale loss and skin damage can disrupt osmoregulatory abilities (Olsen, Oppedal, Tenningen, & Vold, 2012; Zydlewski, Zydlewski, & Danner, 2010), from which recovery times increase with injury severity (K. V. Cook, Unpublished data).

Bruising, crushing and constriction injuries, which tend to occur in gears that crowd fish together (Broadhurst, Uhlmann, & Millar, 2008; Ryer, 2002; Veldhuizen et al., 2018), may not be immediately apparent upon capture, are harder to quantify and are therefore not as well studied. Constriction injuries, such as those typical of gillnet encounters where the girth of the fish is squeezed during entanglement, may induce fatal damage to the circulatory system (Kojima, Ishii, Kobayashi, & Shimizu, 2004) and/or internal organs (Broadhurst, Millar, Brand, & Uhlmann, 2008). Most severe injuries include the puncturing of organs, which can occur by deep hooking or when fish interact with non-smooth deck surfaces and/or other captured organisms, especially those with sharp appendages (Kaimmer & Trumble, 1998; Suuronen, Perez-Comas, Lehtonen, & Tschernij, 1996; Suuronen, Lehtonen, et al., 1996). Perhaps more common, and equally severe, are injuries to the gills that can lead to severe bleeding from which recovery is unlikely (Kaimmer & Trumble, 1998; Muoneke & Childress, 1994). Gill injuries can occur from puncture and crushing, but also tearing during net removal (e.g., from gill nets; see Section 3.2). Additionally, injuries such as ruptured swim bladders, exopthalmia and haemorrhaging can be caused by rapid changes in pressure (i.e., barotrauma; see Section 2.3). Upon release, capture-induced injuries can also influence schooling behaviour (Olsen et al., 2012) and increases probability of migratory delay (Bass, Hinch, Patterson, Cooke, & Farrell, 2018; Cook, Hinch, Drenner, et al., 2018). Injuries can serve as a potential entry point for opportunistic bacteria or fungal microbes, increasing the latent mortality risk associated with infectious diseases (Miller et al., 2014).

3.3 | Exhaustion

There is substantial inter- and intra-specific variation in how fish respond to exhaustive exercise (Kieffer, 2000). However, in all cases, exhaustion from excess physical activity can cause a build-up of metabolites that exceed the physiological capacity to be cleared from the muscle tissue in a timely manner. This leads to serious ion imbalances and potentially acute death, but latent mortality can also occur from the inability to fully recover from exhaustion (Black, 1958; Kieffer, 2000). Fish that do survive the physiological imbalances can lose equilibrium (Danylchuk et al., 2007) and exhibit impaired swimming abilities (Jain & Farrell, 2003), both of which increase susceptibility to predation (See Section 2.5; Brownscombe et al., 2013; Raby, Packer, et al., 2014).

3.4 | Barotrauma

Fish captured at depth can experience rapid decompression during ascent. This change in pressure can cause barotrauma, an internal build-up of gas that can result in potentially severe internal physical damage. Barotrauma is generally observed in fish captured below 20 m depth but can be observed from capture depths of 5 m (Rudershausen, Buckel, & Williams, 2007). Conspicuous evidence of barotrauma in fish includes everted stomachs, bloated abdominal walls and bulging eyes, while less conspicuous tissue damage includes ruptured swim bladders, blood embolisms and internal haemorrhaging (Humborstad, Ferter, Kryvi, & Fjelldal, 2017). Physoclistous fishes, those with a discrete swim bladder, are more vulnerable to barotrauma, whereas physostomous fish, those that still retain a direct connection between the swim bladder and gut, can de-gas quickly during rapid ascents. Elasmobranchs, such as sharks and rays, are the least vulnerable to barotrauma given the absence of a swim bladder.

Although barotrauma can result in immediate mortality, latent and indirect mortality is more common. With the loss of equilibrium and buoyancy control upon release, fish are more vulnerable to predation (including avian predation) and suboptimal surface conditions (e.g., elevated water temperatures), and it may take an extended time (i.e., days) before fish can return to depth (Midling, Koren, Humborstad, & Saether, 2012; Nichol & Chilton, 2006). Damage to eyes, blood embolisms and everted stomachs can also impact foraging behaviour, increase stress levels and potentially increase infection risks resulting in latent mortality.

3.5 | Predation

Predation can occur during capture or after release. Predation is a crucial factor in any fishery where fish are held vulnerable for extended periods. For example, in hook fisheries, fish dragged behind trolling vessels are exposed to highly mobile predators (Weise & Harvey, 2005; Zollett & Read, 2006) and the passive counterpart, longlines, can be deployed for long periods of time, holding fish vulnerable to a number of predators (Nishida & Shiba, 2005). Fish held captive in hanging nets can also be highly vulnerable to predation. Upon release from any gear type, fish are especially vulnerable to predators if discarded in a state of decreased responsiveness and mobility. Not surprisingly, predators have learned to associate fishing vessels and gear with opportunistic feeding on weak or incapacitated fish (Weise & Harvey, 2005).

Predation during capture or after release is exceptionally difficult to monitor (Raby, Packer, et al., 2014). However, it is reasonable to assume that predation will vary extensively depending on the condition of the fish and abundance and consumption rates of predators in proximity to the fishery. For example, discarded fish not able to equilibrate due to severe exhaustion or barotrauma are increasingly vulnerable to avian predators (Campbell, Tolan, Strauss, & Diamond, 2010), while decreased ability to maintain shoaling behaviour, commonly observed in stressed individuals, influences predator evasion abilities (Ryer, 2002).

4 | CAPTURE STRESSORS AND THEIR MITIGATION POTENTIAL BY FISHING METHOD

The severity of stress associated with commercial fishing is directly related to gear type, fishing method and handling of captured fish. Mitigation strategies need to consider how the capture process can be modified to minimize the magnitude, duration or likelihood of stress and injury experienced. Here, we outline the stressors characteristic of each of the most common commercial gear types and present mitigation options to reduce the impact of stressors experienced by non-target fish during capture, handling and release (summarized in Table 1, Figure 2).

4.1 | Seines

Seine fisheries are characterized by a single long net wall that is manually dragged to enclose schools of fish. Containment is achieved by drawing the net wall towards land or vessel (beach and boat seine, respectively), or by cinching the bottom of a cylindrical containment area as the ends of the net are closed (purse seine). Fish are then sorted either on the shore (beach seine) or vessel deck. Fish discarded from seine fisheries will typically experience confinement stress, exhaustive exercise during crowding and sorting, crushing and tissue damage from capture and handling gear, and hypoxia throughout on-board sorting. Fish are progressively corralled into a smaller volume of water during containment; avoidance behaviour and exhaustive exercise increase as the net becomes more constricted, as do forced physical interactions with both the gear and other captured organisms. Dissolved oxygen levels can decrease during crowding, and in some cases result in hypoxic water conditions (Raby, Packer, et al., 2014). However, these low oxygen conditions can also reduce activity and potentially prevent some struggling-related injuries (Schurmann & Steffensen, 1994), though this has not been tested in the context of seine fisheries.

During removal and on-board sorting, bouts of exhaustive exercise will likely continue, and any exposure to air during handling or hypoxic water conditions will accelerate physiological disturbances. Mucus sloughing, scale loss and tissue damage commonly result from the forced physical interactions of a typical seine fishery encounter (Marçalo et al., 2010). The catch size and composition (e.g., body

TABLE 1 For the most common fishery-induced stressors experienced by fish discarded from various commercial gear types, an assessment of the level of concern was conducted based on the severity of fish responses, as well as a feasibility assessment for mitigating each stressor. Assessments were conducted by gear type during both capture (i.e., time from initial encounter to gear retrieval; shaded) and handling and release (time from gear retrieval to release; not shaded). For stressor severity, categories are low, variable or high and are based on magnitude, duration and likelihood of a given stressor. Categories for mitigation feasibility include feasible, variable or impractical. Feasible mitigation strategies have demonstrable support in the literature and are practical; those classified as "variable" either have no direct scientific support and/or a fishery constraint; and those labelled "impractical" have obvious limitations. A synopsis of the mitigation feasibility assessment is provided. For each stressor and gear type, a situation of high concern is where high stressor severity is combined with unlikely mitigation potential. When high stressor severity is coupled with feasible mitigation potential, this is a clear area where action can be taken

		Capture					Handling and release				
		Hypoxia	Injury	Exhaustion	Barotrauma	Predation	Hypoxia	Injury	Exhaustion	Barotrauma	Predation
Seine	Stressor severity	Low	Variable	Variable	Low	Low	High	Variable	High	NA	Variable
	Mitigation potential	Impractical	Variable	Impractical	NA	Impractical	Feasible	Feasible	Feasible	NA	Variable
	Synopsis	Mitigation during capture is limited, but matching mesh size to size of discarded fish may reduce injury. Mitigation options during handling and release include: keeping the net loose to reduce hypoxia and injury, brailing instead of ramping and using overboard wet chutes to reduce air exposure, injuries and exhaustion. Although there are no known methods to directly reduce predation, improving fish condition through changes to handling would enhance avoidance abilities. Barotrauma is not a concern									
Hanging nets	Stressor severity	Variable	High	High	Low	High	High	High	High	NA	Variable
	Mitigation potential	Impractical	Variable	Impractical	NA	Variable	Variable	Variable	Variable	NA	Variable
	Synopsis	Reducing soak times would reduce extent of predator exposure and operculum restriction. Though severe injuries, suffocation and exhaustion can occur rapidly. Practicality of soak time reduction is variable, but could improve product quality. To reduce injury, matching mesh size to size of discarded fish and/or modifying net materials/tension can be effective. Electrifying nets and/or adding light deterrents can reduce predation. Cutting non-target fish out of nets (injury mitigation), in-water removal (air exposure mitigation) and recovery treatments (exhaustion mitigation) during handling could be feasible in some small-scale fisheries. Barotrauma is not a concern.									
Trawls	Stressor severity	Variable	High	High	High	Low	High	High	High	NA	High
	Mitigation potential	Impractical	Variable	Impractical	Impractical	Impractical	Feasible	Variable	Impractical	Impractical	Impractical
	Synopsis	Most mitigation options during capture are impractical. Reducing tow times and/or catch size would reduce air exposure, injury and severity of exhaustion at the cost of reduced catch-per-unit-effort (CPUE). Reducing ascent rates to minimize barotrauma is also impractical. Reducing tow speed to reduce injury may be feasible, but effectiveness rarely tested. Reducing handling times is feasible with automated sorting conveyors and/or water sorting trays (injury and air exposure reduction). Procedures to reinvigorate exhausted fish or minimize barotrauma effects are labour-intensive and impractical given the magnitude of by-catch. Improved handling may improve fish condition, but not to a degree such that released fish could effectively evade predation (i.e., full recovery treatments would be required but are impractical).									
Hooks	Stressor severity	NA	Variable	High	Variable	High	Variable	High	High	NA	Variable
	Mitigation potential	NA	Variable	Impractical	Impractical	Variable	Variable	Variable	Variable	Variable	Variable
	Synopsis	Most means to mitigate injury and exhaustion during capture are unlikely given potential impacts to CPUE [e.g., matching hook size to non-target fish size and using certain hook types (injury mitigation), reducing capture times (exhaustion mitigation)]. Effects of hook design to CPUE are context-dependent; such strategies may be effective in some fisheries. Reducing soak and fight times would reduce predation, with the added incentive of not losing target catch. For barotrauma, slowing ascent rates is impractical and may increase predation. During handling and release, tools to facilitate hook removal can reduce air exposure, injury, exhaustion. Slowly releasing fish to depth to allow barotrauma recovery is possible in some fisheries. Recovery methods to revive exhausted fish may be an option with low by-catch numbers.									

(*Continues*)

TABLE 1 (Continued)

		Capture					Handling and release				
		Hypoxia	Injury	Exhaustion	Barotrauma	Predation	Hypoxia	Injury	Exhaustion	Barotrauma	Predation
Traps	Stressor severity	Low	Low	Variable	Variable	Variable	Variable	Variable	High	NA	Low
	Mitigation potential	Variable	Feasible	Variable	Impractical	Variable	Feasible	Feasible	Variable	Variable	Variable
	Synopsis	Checking traps more frequently could reduce injury and predation during capture, though may increase CPUE. Fewer fish captured per haul could also mitigate effects of air exposure, exhaustion, and injury during sorting. Selecting trap netting to ensure non-target fish is not entangled or gilled can also reduce injury. For barotrauma, slowing ascent rates is likely impractical. During handling and release, using chutes or sorting trays would reduce air exposure and exhaustion. Slowly releasing fish to depth may be possible to mitigate barotrauma in some fisheries. Improving fish condition through efficient sorting could reduce predation, but fish are generally released in good condition unless suffering from barotrauma.									

size, species), mesh type and relative mesh size also influence the degree and severity of entanglement and injury (Chopin & Arimoto, 1995). The injury experienced during handling can be exacerbated by severe crowding during pursing, crushing during ramping, contact with non-smooth deck surfaces, prolonged air exposure and high activity levels of the fish brought aboard.

4.1.1 | Mitigation options

Reducing capture durations would directly benefit fish condition upon release by limiting exhaustive exercise, though large resistance to this recommendation is expected given the time required to set large seine nets and bring catch aboard. Reducing handling times is the most practical means to improve survival through a reduction in air exposure and exhaustion. Prioritizing by-catch during sorting (Poisson, Séret, Vernet, Goujon, & Dagorn, 2014; Raby, Packer, et al., 2014) or before brailing (with larger by-catch species; Hutchinson, Itano, Muir, & Holland, 2015; Hall et al., 2017) to expedite their release can be effective. Having the vessel equipped with a canvas sling is a similar solution for the safe release of large by-catch species reducing risk of injury (Poisson et al., 2014). Although not tested, aerating the water has been proposed to improve survival of discards if there are concerns of severe hypoxia due to crowding (Chopin & Arimoto, 1995; Gilman, 2011). However, reducing net constriction while holding fish for brailing is perhaps a simpler means to reduce hypoxia and crowding, and has been shown to improve fish condition (Cook, Hinch, Watson, et al., 2018). Injury reduction can be achieved through changes to mesh size (depending on size of non-target fish) and employing brailing methods rather than ramping the catch, which increases crushing injuries (Farrell et al., 2000). Brailing small groups of fish will reduce the individual sorting times, and thus air exposure times. Other means to expedite sorting and reduce exhaustion, air exposure and injury potential include the use of overboard wet chutes, which are employed in some commercial purse seine fisheries either voluntarily (e.g., Pacific salmon; Watson, Cook, Young, & Hinch, 2018) or by regulation (e.g., tuna; Poisson et al., 2014), conveyor belts, or by providing shade and/or water spraying (Hall et al., 2017). Efforts to improve the design and efficiency of on-deck sorting systems will improve the condition of fish passing through them, but there has been little published research to substantiate these claims. As a novel means to eliminate brailing (and crushing injuries) in tuna purse seine fisheries, Hall et al. (2017) describe fish pumps that deposit live fish on deck for sorting.

4.2 | Hanging nets

Hanging nets, including gill, tangle and trammel nets, hang vertically in the water column as a translucent wall of netting (He, 2006; Uhlmann & Broadhurst, 2015). Gill nets capture fish trying to pass through the netting by snagging their opercula (fish become "gilled"), preventing both their advancement and retreat. Tangle nets are similar, but have a smaller mesh size so that fish are captured by the snout rather than by the gills (Vander Haegen, Ashbrook, Yi, &

Dixon, 2004). Trammel nets consist of two or three layers of netting: a loosely-strung small mesh and an inner layer between two outer layers of large mesh within which fish will entangle. Hanging nets are all fished passively, and they may be "set nets," fixed by means of anchors or stakes, or "driftnets" which are free to drift with the current.

Hanging nets are typically associated with high rates of incidental mortality among discarded fish. Injuries resulting from entanglement and incurred during removal are of particular concern, and have been associated with reduced longevity and hampered reproductive development (Baker & Schindler, 2009). The severity and nature of injuries are dependent both on how the individual is entangled in the net (e.g., loosely netted by the teeth, gills entangled and/or compressed, enmeshed around muscular tissue or bagged in net) and how it is removed from the net (e.g., pushed through or disentangled; Veneranta, Pakarinen, Jokikokko, Kallio-Nyberg, & Harjunpää, 2018). In particular, injuries to the gills, potentially leading to exsanguination, and constrictions and bruising around the body due to net encirclement have been linked to fatal outcomes for fish (Kojima et al., 2004; Ng, Fredericks, & Quist, 2015).

The amount of time a hanging net is deployed, soak time, can have serious implications for both survival probability, and exposure to predation (Bell & Lyle, 2016; Uhlmann & Broadhurst, 2015). Severe exhaustion can also result from the need to maintain position in the hanging net (Farrell, Gallaugher, Fraser, et al., 2001; Veneranta et al., 2018). Fish can be experience hypoxia not only during removal from the net, but also during capture if opercula are covered by netting, thereby suffocating fish.

4.2.1 | Mitigation options

Reducing soak times may be the most effective mitigation option for most hanging net fisheries, but reduced catch-per-unit-effort (CPUE) will often result (Buchanan et al., 2002; Frick, Reina, & Walker, 2010; Uhlmann & Broadhurst, 2015) and some species may suffer high mortality regardless of soak duration (Bell & Lyle, 2016). Shorter deployments may be favoured in some fisheries given improved catch quality (Uhlmann & Broadhurst, 2015), but in others, the level of damage incurred may be so high that reducing soak times would not sufficiently improve catch quality (Savina et al., 2016). With the increased effort required to retrieve nets more frequently, shorter deployments are unlikely to be readily accepted in a commercial setting unless product quality, and value, is improved.

Changes to net mesh size, material and tautness are potential mitigation options in net-based fisheries. Matching mesh size to size of fish to be discarded to ensure non-target fishes are tangled and not gilled can substantially reduce injuries (Patterson, Robinson, Lennox, et al., 2017; Vander Haegen et al., 2004). This is a difficult balance; even a slight difference in fish size can affect the extent of physical damage and subsequent mortality, as well as CPUE (Broadhurst, Millar, & Brand, 2009; Broadhurst, Millar, et al. 2008). Net material is a further consideration. Tissue damage may be exacerbated by monofilament gillnets compared with multifilament gillnets (Bettoli & Scholten, 2006), while stiffer materials and/or increased tension can decrease the severity of entanglement. For example, Thorpe and Frierson (2009) experimentally modified a gillnet by increasing mesh tension and observed a reduction in entanglement severity among fish by-catch, a method that was adopted because it also resulted in less damage to nets. Some gillnet fisheries are experimenting with the use of high-powered electric or magnetic fields to reduce predation on entangled fish (Forrest, Cave, Michielsens, Haulena, & Smith, 2009; Rigg, Peverell, Hearndon, & Seymour, 2009).

In gillnet fisheries, removing by-catch from the net quickly and under-water could reduce dermal injuries and degree of anaerobic activity (Teffer et al., 2017). Additionally, fish can be extracted by cutting the mesh around the fish to avoid the dermal injuries associated with forcing fish through the netting (Veneranta et al., 2018), but this practice means the fisher will later need to repair or replace the net. The use of revival boxes shows promise in hanging net fisheries where non-target catch is often exhausted and would benefit from being protected during recovery (Farrell, Gallaugher, & Routledge, 2001); the challenge for adoption, especially in large-catch fisheries, is the on-board revival capacity relative the number of non-target fish caught.

4.3 | Trawls

Trawling is typically a demersal capture method in which fish are concentrated in a catch ball in the back of the net (the codend) by a continuous forward movement of the gear. The inherent poor selectivity of trawl gears combined with their broad spatial deployment results in the discarding of large numbers of fish, especially juveniles and/or undersized fish (Bahamon, Sardà, & Suuronen, 2006; Broadhurst, Suuronen, & Hulme, 2006). Substantial physical damage occurs in trawl fisheries as fish are crowded and pushed against the codend mesh and/or other captured organisms, leading to injury and potentially anoxic conditions. In a beam trawl by-catch study, ~70% of flatfish experienced scale loss and bruising, the severity of which was associated with delayed mortality (Kaiser & Spencer, 1995).

Observational studies demonstrate fish within trawls will burst swim to maintain position within the gear until exhaustion, finally falling to the back of the net, increasing susceptibility to injuries (Suuronen, Lehtonen, & Wallace, 1997). Additionally, trawling can occur at depths >1,000 m, causing barotrauma as fish are brought to the surface, especially in physoclists (Hall & Mainprize, 2005).

The process of catch sorting is also a concern for trawl fisheries. Injuries can result during sorting through interactions with the deck, conveyors or other catch, particularly if crustaceans, benthic invertebrates or fishes with sharp appendages are captured (Depestele, Desender, Benoît, Polet, & Vincx, 2014). Fish are also typically air-exposed during sorting, and with large catches, sorting times can exceed 60 minutes, during which time fish may also be exposed to elevated air temperatures (Davis & Parker, 2004).

Trawls are conspicuous both above and below water as they are generally large and cover substantial distance. Predators may become concentrated around trawls, resulting in intensive predation pressure relative to other fisheries (Ramsay, Kaiser, & Hughes, 1998). Fish are also typically released in a state of reduced vitality (e.g., unable to maintain equilibrium, achieve neutral buoyancy), and are therefore less likely to escape predators (Ryer, 2002, 2004).

4.3.1 | Mitigation options

Survival probabilities of non-target fish captured by trawls are so low that most mitigation focuses on means of improving gear selectivity (reviewed for beam trawl fisheries by Wade, Revill, Grant, & Sharp, 2009), rather than fish condition following capture. For non-target fish that are brought aboard, total catch mass, catch composition, haul duration, individual fish behaviour and handling have been identified as factors affecting trawl discard survival (Depestele et al., 2014; Neilson, Waiwood, & Smith, 1989; Uhlmann et al., 2016). Catch mass increases compression in the codend, and researchers have suggested that there is a threshold catch volume after which potentially fatal damage will increase (Depestele et al., 2014; Enever, Revill, Caslake, & Grant, 2010; Mandelman & Farrington, 2007). Identifying such thresholds, if they exist, could be important for mitigation efforts, but would certainly be fishery- and species-specific. Reducing tow times and speed is another potential means to reduce mechanical damage to non-target fish. Though a reduction in overall CPUE would be expected (Uhlmann et al., 2016), the quality, and thus value, of target fish may increase (Wade et al., 2009).

Although barotrauma is a concern in trawl fisheries, current methods available to reduce the effects of barotrauma (e.g., reducing ascent rates and weighted descent upon release) are impractical for large commercial operations handling large volumes of by-catch. Minimizing handling time may be the most feasible option to improve survival of discards (Beardsall et al., 2013; Neilson et al., 1989), given there is limited opportunity to mitigate the effects of the capture method for most trawls fisheries. Automated sorting conveyors can expedite the sorting process and reduce air exposure (Chilton, Urban, Krygier, & Stoner, 2011), and conducting sorting in water (Broadhurst, Uhlmann, & Millar, 2008) may decrease discard mortality if air exposure could be eliminated. Some trawlers are equipped with seawater hoppers, tanks on the trawler deck that are filled with seawater, into which the catch is spilled at the end of each trawl for holding (Heales, Brewer, & Jones, 2003). The catch is removed from the bottom of the seawater hopper by a conveyor belt, reducing air exposure durations during sorting.

Given the reduced responsiveness typical of fish released from trawls, predation is a concern, but there is little that can be done to directly mitigate it. The only exception would be to be increase the vitality of discarded fish through reductions of other stressor would help reduce rates of predation (Ryer, 2002).

In recent years, electric pulse trawls have replaced conventional trawls. In pulse trawls, the mechanical stimulation is replaced by electrical stimulation, immobilizing the fish until it enters the net. With reduced fuel consumption and ecosystem impacts, the use of electric pulse trawls will likely increase (De Haan, Fosseidengen, Fjelldal, Burggraaf, & Rijnsdorp, 2016). The injuries resulting from this form of capture among some non-target fish (e.g., haemorrhages, spinal fractures) are a cause for concern and cannot be mitigated per traditional methods. However, recent research purports that this new method will not cause higher discard mortality rates than observed previously (De Haan et al., 2016; Van Marlen, Wiegerinck, van Os-Koomen, & van Barneveld, 2014).

4.4 | Hooks

Trolling and longline fisheries consist of multiple hooks suspended on a mainline that are fished either actively in trolling, trailed behind vessel or passively in longline fishing, where a main line with multiple branching hook sets is suspended stationary. Trolling fisheries are considered to be relatively selective with minimal by-catch, as fishers can target species by varying hook size, lures, bait, troll speeds and habitats (Alverson et al., 1994). In comparison, longline fisheries are passive and relatively non-selective, leading to by-catch of numerous species.

Physical injuries associated with hooking in these fisheries are similar to those of recreational angling, which have been extensively studied in the context of catch-and-release (reviewed in Brownscombe, Danylchuk, Chapman, Gutowsky, & Cooke, 2017). There has been considerable research on effects of various aspects of hooks (e.g., size, type) and other terminal gear (e.g. bait, lures) to discarded fish. Hooking injuries in soft tissues such as the gills, tongue and oesophagus are the most consistent and significant predictors of mortality in recreational fisheries (Muoneke & Childress, 1994) and have similarly been noted in commercial trolling fisheries for salmonids (Wertheimer, 1988).

Commercial hook fisheries typically deploy numerous lines simultaneously, each with several hooks, increasing durations of capture and retrieval. Although no literature has explicitly researched hook time in commercial operations, retrieval time is important for mortality outcomes in recreational fisheries due to the positive relationship with exhaustion (Cooke & Schramm, 2007); physiological perturbations consistent with extreme exhaustion have been observed in commercial troll-caught Pacific salmon by-catch (Farrell, Gallaugher, & Routledge, 2001). Predation is a crucial factor in most hook fisheries, but the duration that a fish is hooked and exposed to potential predators varies. Predation in longline fisheries by sharks and marine mammals can indeed account for most observed mortality. For example, predation rates in Japanese tuna longline fisheries were as high as 18% (Nishida & Shiba, 2005) and ranged from 2.5 to 100% per set in longline fisheries off the coast of Brazil (Dalla Rosa & Secchi, 2007).

4.4.1 | Mitigation options

Varying the terminal line, hook and bait is the main mitigation methods available in hook-based fisheries. A promising option for the release of large by-catch such as sharks and/or rays is the use of nylon or monofilament leaders that will break and release large animals (Favaro & Côté, 2015; Poisson et al., 2016). For by-catch species that are not able to break through line, bait selection has good potential to increase selectivity for target species. Gustatory responses can differ between target and non-target fish (Davis, 2002; Løkkeborg, Siikavuopio, Humborstad, Utne-Palm, & Ferter, 2014) and, in recreational fisheries, artificial baits are less likely to cause deep hooking than natural baits (Bartholomew & Bohnsack, 2005). While not yet considered a viable alternative for high-volume commercial fisheries (Aneesh Kumar, Pravin, & Meenakumari, 2016), additional research on selective bait types could provide meaningful strides in by-catch reduction for some hook fisheries. Adoption of circle hooks over straight-shanked "J" hooks has been shown to decrease deep hooking, reduce hooking in soft tissue and increase survival in several species in both troll and longline fisheries (reviewed in Serafy et al., 2012). However, there exists species-specific variation in CPUE between circle hooks and J-hooks (Serafy et al., 2012); for circle hooks to be readily adopted in commercial fisheries, there would need to be minimal change to CPUE. Similarly, using hooks that are easily removed (e.g., barbless) could greatly expedite unhooking and reduce injury, but because barbless hooks can also decrease landing success, they are also unlikely to be widely adopted in commercial operations (Alos, Palmer, Grau, & Deudero, 2008). Using corrodible hooks could reduce long-term health effects and probability of infection if bitten off the line or cut from the line (Poisson et al., 2016).

Modifications to fisher behaviour are more general across hook fisheries. Reducing air exposure and handling time is critical for by-catch survival in hook fisheries. Easy improvements to handling include the use of dehookers, mouth openers, and in cases where by-catch species are deeply hooked, using remote line cutters rather than attempting to remove the hook (Hall et al., 2017; Poisson et al., 2016; Tsuboi, Morita, & Ikeda, 2006). While slowing ascent rates is not feasible and would increase predation rates, slowly releasing fish to depth to allow for barotrauma recovery is possible in some fisheries.

4.5 | Traps

Traps represent a suite of passive containment gears that retain fish until retrieved by a fisher (Hubert, 1996). Traps have a variable volume of water in which fish can theoretically swim and even eat without physically touching the gear. This of course does not imply that capture is not stressful, nor that capture does not cause injury. The characteristics of the trap, the biology and behaviour of captured species, environmental conditions and fisher behaviour all influence the potential outcome for discarded fish. Compared to active fishing methods, traps discard less biomass and cause less habitat disturbance, and are therefore thought to be more environmentally-benign (Chuenpagdee, Morgan, Maxwell, Norse, & Pauly, 2003; Jenkins & Garrison, 2013; Meintzer, Walsh, & Favaro, 2017).

Depending on trap material and mesh size, some fish can become gilled or entangled, especially small fish or those with prominent dentition. However, most trapped fish are funnelled into a retention area where they are held until the trap is tended to. If fish behaviour while trapped results in significant interaction with the trap material, dermal abrasion or other injuries may occur (Colotelo, Cooke, et al., 2013; Colotelo, Raby, et al., 2013). Depending on abundances, effectiveness of the gear, and frequency of trap tending, fish density can become such that interactions are forced, or local oxygen depletion occurs (Renchen, Pittman, & Brandt, 2012). Retention may also be associated with reduced food intake or starvation, dependent on feeding behaviours of trapped fish and the presence of preferred prey. With protracted trap deployments, conditions will worsen as densities within the trap increase.

As traps are removed from the water or brought to the surface, interactions among captured fish and with the trap are forced, causing both minor and major injuries (Rudershausen, Baker, & Buckel, 2008). Barotrauma is also a concern if traps are brought up from depths quickly (Uhlmann & Broadhurst, 2015). During sorting, fish are often air-exposed and will engage in high levels of activity that lead to exhaustion (Colotelo, Cooke, et al., 2013; Colotelo, Raby, et al., 2013; Hopkins & Cech, 1992).

4.5.1 | Mitigation options

Traps are a common in small-scale fisheries in developing countries where discard mitigation initiatives may be irrelevant because all captured animals will be harvested (Welcomme et al., 2010). The best method of improving the condition of any fish discards is to check gear frequently. However, longer deployments do not necessarily result in greater mortality (Uhlmann & Broadhurst, 2015), and these relationships have rarely been tested (Barber & Cobb, 2007). Becoming gilled within the trap material can be an issue for certain species regardless of deployment duration (e.g., Dieterman, Baird, & Galat, 2000); it is therefore important to choose a mesh size that minimizes mortality to non-target species while not affecting CPUE. Where barotrauma is of concern, reducing ascent rates when retrieving traps may reduce effects of barotrauma, but this is not a practical solution for most commercial operations (Stewart, 2008).

To improve the condition of discarded crustaceans, some trap fisheries slide catch down angled chutes instead of directly onto the deck for sorting (Tallack, 2007), or modify drop height (Grant, 2003). Though not tested for fishes, any methodology that results in gentler handling would likely reduce discard mortality. Cole et al. (2003) used a water tray for sorting to improve flesh quality of trapped fish for harvest, which would also be effective in reducing mortality among discarded fish. Assuming air exposure is minimized, and fish are discarded rapidly, mortality of fish discarded from traps may be low.

5 | SYNTHESIS AND KNOWLEDGE GAPS

There are many context-specific factors at play that influence the severity of a stressor in a fishery encounter. The stressors described herein are not the only stressors that discarded fish are exposed to during capture, but are the most common. These stressors will interact with one another, as well as with others not encompassed by this review. For instance, fishery encounters are linked with decreased energy availability in fish, which is exacerbated in warmer waters (Patterson, Robinson, Lennox, et al., 2017). Decreased disease resistance is yet another potential outcome, as fish injured and stressed from a fishing encounter may face immunosuppression, where temperature too plays an exacerbating role (Miller et al., 2014; Teffer et al., 2017). It is quite clear from previous work that biotic aspects of a fisheries interaction (e.g., fish size, health, precapture stress state, species/population, maturation state, etc.) all have the potential to modulate the effects of fisheries interactions (Raby et al., 2015).

The preceding sections reviewed the consequences of air exposure, injury, barotrauma, exhaustion and predation to fish discarded from commercial fisheries, of which injury and exhaustion, inherent to all capture methods, are the most ubiquitous (Table 1). Although magnitude and duration are quite variable among gear types, the likelihood of experiencing injury and/or exhaustion is high in all capture scenarios. Similarly, some degree of air exposure is likely to occur during handling and sorting in most fisheries, though the duration is variable (Table 1). Conversely, barotrauma and predation do not occur in all fisheries but in specific scenarios where fish are physiologically and spatially susceptible.

Tolerance and susceptibility to fishing-related stressors are dependent on both context (e.g., species, water temperature, size), and magnitude of exposure. Investigations of thresholds (i.e., the duration of stressor exposure after which the physiological condition is irreversible and the individual will die) and contexts influencing these thresholds would be very informative. There are currently several good examples of such research [e.g., species-specific exhaustion in trawls (Olla, Davis, & Schreck, 1997); variable air exposure tolerance with size (Davis & Parker, 2004), life stage (Davis & Olla, 2001), and species (Broadhurst, Uhlmann, & Millar, 2008)]. Expanding this research area to include more species of commonly discarded or at-risk fish would allow for further comparative assessments and refinement of mitigation strategies. Where fish are discarded in a state of severe exhaustion or where exposure to hypoxia is unavoidable, experimentation to elucidate thresholds would be most informative.

With respect to fishing-induced injuries, there is currently little known regarding the capacity for wild fishes to heal (Mateus, Anjos, Cardoso, & Power, 2017; Schmidt, Andersen, Ersbøll, & Nielsen, 2016). New research is just beginning to unravel the complex and interactions between stress, injury severity, disease and environmental context (Miller et al., 2014; Teffer et al., 2017). These are areas of research need, especially in the context of a rapidly changing climate, as evidence suggests elevated water temperatures negatively affect recovery and healing following a fishery interaction (Teffer et al., 2017).

Rates of predation are unknown in most fisheries, although it is often visually apparent that wildlife surrounding commercial fisheries are taking advantage of concentrated numbers of prey and discarded fish (Zollett & Read, 2006). The exception is longline fisheries, where the static nature of the fishing gear allows some predation events to be recorded. Understanding the extent and nature of predation occurring both during capture and after release can provide important inputs into risk assessments for fisheries. Understanding predation rates [e.g., With newly developed predation tags that can detect when a fish has been eaten (Halfyard et al., 2017)], as well as testing net methods to repel habituated predators (e.g., Schakner, Götz, Janik, & Blumstein, 2017) are fruitful areas of research that would greatly benefit our understanding of predation and post-release mortality. Probability of recapture following release and the factors influencing recapture similarly remain unknown, and relatively unstudied, for commercial fisheries. This is important when considering stressor action as effects to individual fish may be cumulative with every capture event.

Ultimately, the severity of a fisheries encounter within each gear type is context-dependent. However, reducing the overall encounter time, catch size and/or density (e.g., in the net) will generally reduce severity of injury, exhaustion, predation and air exposure (Patterson, Robinson, Raby, et al., 2017; Table 1). Specific to exhaustion, recovery treatments have shown great promise to revitalize fish following commercial capture and are consequently employed in some commercial fisheries, where practical (Farrell, Gallaugher, & Routledge, 2001). However, recovery treatments may cause further stress in vigorous fish and it is still unknown whether recovery benefits vigorous but physically-injured fish (Nguyen et al., 2014). Reductions in air exposure and the encouragement of gentle but efficient handling behaviour similarly translate to improved condition upon release. Simple tools like conveyor belts, water sorting tables and chutes can be very beneficial, and affordable in many fisheries (Figure 2).

It is widely understood that the successful adoption of any mitigation measure will require support from the fishers involved. Acknowledging this, Poisson et al. (2014) developed a manual of best handling practices for tuna purse seine fisheries to safely discard elasmobranch by-catch that can be applied on a case-by-case basis; most global commercial fisheries would benefit from such guidelines. In general, methods that require minimal cost and alteration to traditional gear and practices increase the likelihood of fisher acceptance (Watson et al., 2018). However, there is also a notable lack of research on incentives for fisher uptake (Campbell & Cornwell, 2008). Factors such as the economic costs associated with new technologies and increased work burden or risk when operating more complex gear, either perceived or real, serve as deterrents to fisher uptake (Sigurdardóttir et al., 2015). Most binding conservation and management measures fall short of gear and technology best practices, and compliance is probably low due to inadequate surveillance and enforcement (Gilman, 2011).

Of the fishing gear discussed, trawls and hanging nets present the highest stressor exposure risk, and least opportunity for practical mitigation measures (Table 1). Although reductions in tow or soak times could reduce stressor severity, such changes are impractical given likely effects to CPUE. Conversely, traps serve as a gear type that is regarded generally as being low impact. Trap-based fisheries have been shown to produce less by-catch compared to other fisheries, and because captured fish are free swimming within a protected space, injury and predation rates are typically low (Favaro, Rutherford, Duff, & Côté, 2010). Traps also require less travel by fishers and thus have lower overall emissions compared to other gear types (Suuronen et al., 2012). As a more sustainable extraction method, many trap fisheries are eligible for certification by sustainability agencies and can consequently be sold at higher market prices (Blomquist, Bartolino, & Waldo, 2015). As a result, trap fisheries are being explored as alternatives to more destructive methods (e.g., trawls, gillnets) for harvesting demersal fish species (e.g., Meintzer et al., 2017), and their use is likely to increase in response to rising fuel prices, environmentally-conscious consumers and management reforms (Suuronen et al., 2012).

The practicality and efficacy of potential mitigation measures must be explored and tested for individual fisheries. Although it is often assumed that mitigation measures will negatively effect CPUE or create additional workload and costs to fishers, these trade-offs are rarely explored. These investigations are especially worthwhile if mitigation measures could provide benefit to fishers, in the form of, for example, increased product quality/value or reduced predation to both target and non-target catch.

6 | MANAGEMENT IMPLICATIONS

Knowledge of where mitigation options are most feasible and, equally important, most unlikely, is key to prioritizing management resources. For example, although air exposure during handling and release is a considerable and extended stressor in most fisheries, there are feasible options to reduce the effects of air exposure in every fishery (e.g., brailing small batches of fish in seine fisheries; spraying fish during sorting in trawl fisheries; Figure 2). Conversely, for barotrauma, methods available to mitigate these effects are likely impractical for any commercial operation despite some successes in the recreational sector. Certainly, some fisheries are more amenable to mitigation than others. Understanding the dynamics of stressor severity and mitigation potential can speak to whether to employ mandatory retention or mandatory release. Those fisheries imposing severe stress with a limited scope for mitigation (e.g., trawl fisheries) are perhaps more suited to be selective in terms of space and time, avoiding discard encounters.

Determining when it is best to keep vs. discard fish is an increasingly controversial issue. For instance, discard bans have been put in place to eliminate discarding and ameliorate fisher behaviour through increased incentive for better species selectivity (Condie, Grant, & Catchpole, 2014). But many critics of this approach claim this policy is inappropriate given that (a) for species with high probabilities of survival post-release, retention may increase fishing-related mortality; (b) discards have become important food sources; thus, discard bans export useful energy away from aquatic systems; and (c) such policies can generate new markets for species that were previously discarded, increasing demand for and fishing pressure on less-exploited species (Heath et al., 2014; Sardà et al., 2015). There could also be additional economic drawbacks to discard bans, such as fishers being forced to land products with little value, and the need for costly monitoring and enforcement programs. Again, fisher acceptance is a critical for the success of any of these measures (Campbell & Cornwell, 2008) because while support for gear technology research and development has generally been strong, political will to achieve broad uptake of best practices has been lacking (Gilman, 2011).

There are fundamental knowledge gaps hindering the development of policies to reduce discard mortality. Even when mitigation strategies are developed, a lack of performance standards, inadequate observer coverage, and incomplete data collection, can hinder assessing their efficacy (Gilman, 2011). Data available on rates of discard mortality and of the sub-lethal effects of capture are limited and largely focused on North American and European fisheries, with very limited available data on developing, artisanal or small-scale fisheries. Moreover, the bulk of the research available, and consequently reviewed herein, is concentrated on fisheries operating in marine systems, whereas the fate of fishes discarded from freshwater (inland) commercial fisheries remains understudied. Likewise, although this review was limited to the most common commercial gear types, other methods exist that while not common, could be exceptionally damaging to non-target fish if not retained (e.g., the use of grappling, wounding or stupefying devices and harvesting machines or pumps). Nonetheless, similarities exist among the stressor experience of fish released from such unconventional methods as those encompassed by this review.

Given the wide range of reasons for and against discarding, the context-specific nature of fisheries (Raby et al., 2015) and the significant species-specific differences in responses to capture events (Davis, 2002), there is unlikely to be a single unifying management solution to address this issue. Rather, discard management measures need to be tailored to the specific management objectives for a given fishery considering impacts to both target and non-target species if they are to be effective (Rochet, Catchpole, & Cadrin, 2014). More comprehensive consideration across species groups is needed to identify conflicts as well as mutual benefits from mitigation methods (Gilman, 2011).

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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