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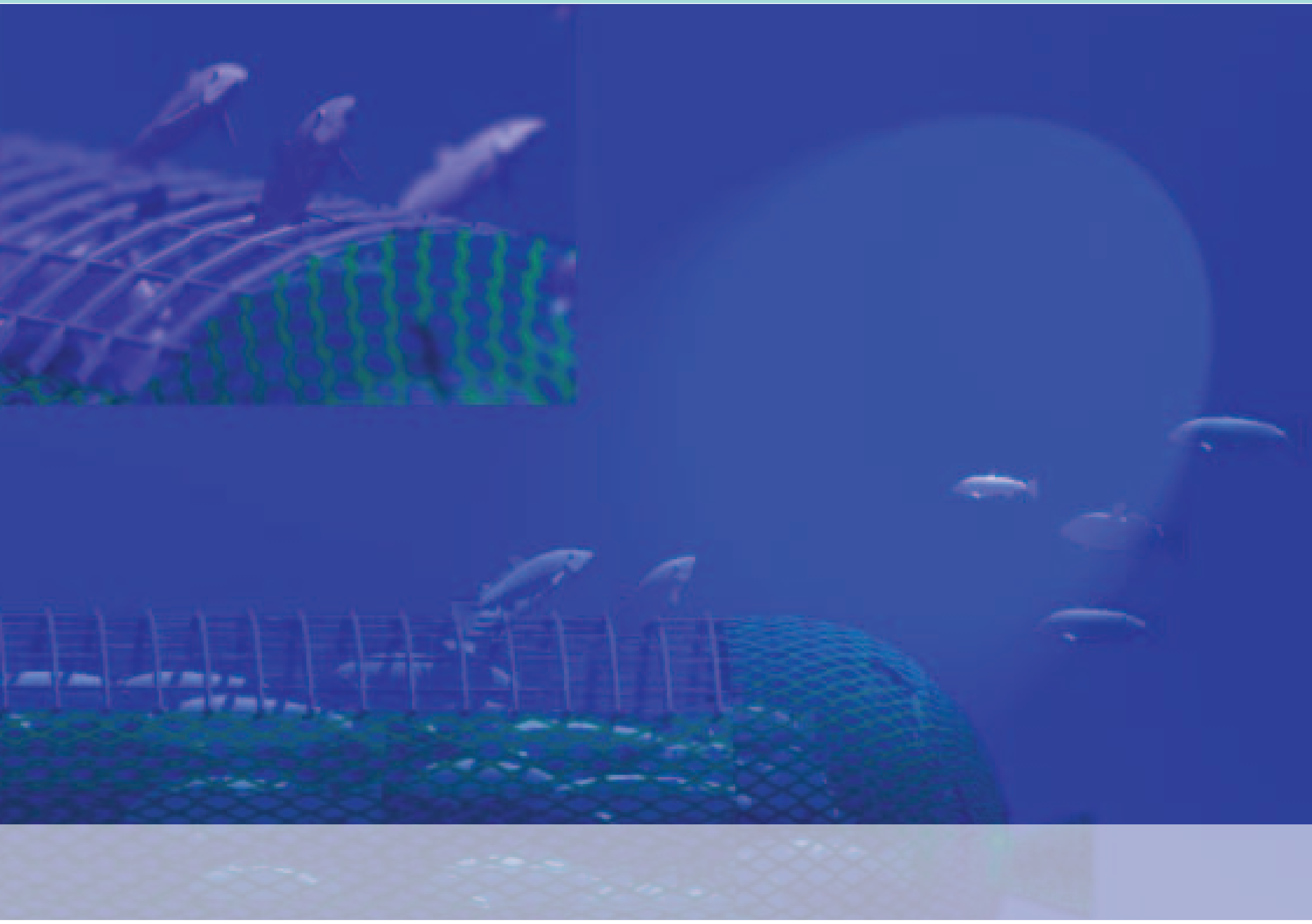

Cover illustration:
Fish escaping from a codend equipped with a square mesh panel. Courtesy of Mr Vesa Tschernij.

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by
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This study aims to assess and summarize the principal factors affecting the stress, injury and mortality of fish that arise from fishing processes, particularly when fish escape from trawl gears. Potential sources of error in the assessment of survival are identified, and improved methodological approaches and practices are suggested. Furthermore, the study attempts to evaluate the key principles for designing fishing gears and operations that reduce or eliminate the mortality of escapees. Finally, it assesses the problems associated with estimating the impacts of unaccounted fish mortality.

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Abstract

A great deal of progress has recently been made in reducing bycatch and discards through improving the selectivity of fishing gear. Selective fishing has a large potential to reduce fish mortality among non-target species and juveniles, but it can be justified only if significant numbers of escaping fish survive. This study aims to assess and summarize the principal factors affecting the stress, injury and mortality of fish that arise from fishing processes, particularly when fish escape from trawl gears. Potential sources of error in the assessment of survival are identified, and improved methodological approaches and practices are suggested. Furthermore, the study attempts to evaluate the key principles for designing fishing gears and operations that reduce or eliminate the mortality of escapees. Finally, it assesses the problems associated with estimating the impacts of unaccounted fish mortality.

Studies on the mortality of fish discarded from the decks of fishing vessels generally show high mortality rates, although the types of injuries and their severity are highly species-specific. Most fish with gas bladders that inflate after capture die because of pressure changes. The post-release mortality of other fish and aquatic organisms (i.e. those without gas bladders) is more variable and may sometimes be low. Mortality is also related to the overall fragility and physical characteristics of species. For some species, discard mortalities can be reduced through reduced exposure to air and improved on-deck handling procedures, but in many cases a significant reduction of discard mortality is difficult to achieve. Efforts should therefore be directed towards maximizing the escape of fish during fishing. This would significantly increase the likelihood of their survival.

Most scientific work on escape survival applies to towed gears, in particular trawl gears. In general, relatively high survival has been observed for many species, particularly gadoids and flatfishes, which escape from trawl codends. Substantially lower survival rates have been recorded for some pelagic species, but few studies have adequately explained the full range of stress, injury and mortality that can occur when fish escape from trawl codends under commercial fishing conditions. Moreover, survival estimates may have been affected by inferior methods of collecting, transporting and monitoring the escapees. Biases may have been significant, particularly among the smallest escapees, which are most sensitive to all kinds of handling. Substantial improvements in methodologies for assessing escape mortality rates across a wider range of fisheries and environmental conditions are suggested.

There are various options available to improve the survival of escapees. First, fish that escape from a fishing gear should do so quickly and, in the case of towed gears, should not enter into the aft part of the codend, where the risk of serious injury is greatest. Installing escape panels or other sorting devices at strategic positions in a fishing gear can enhance escape and the survival of juveniles and non-target species. Furthermore, facilitating the voluntary escape of fish through various constructional and operational solutions would increase the likelihood of their survival. The use of non-abrasive netting materials, the exclusion of debris and large objects from codends, and better design, operations and rigging of nets could improve survival. In some cases, use of other fishing methods or avoidance of areas with high densities of juveniles, non-target species and predators may be an appropriate approach to reducing unaccounted mortality associated with escape.

Improved selection means that a larger part of the fish population will escape from a fishing gear. If the survival rates of these fish are low, there may be no advantages associated with changing selectivity. In the worst case, the effect of this type of unaccounted mortality on fish stocks may be negative because overall fish mortality is underestimated. Moreover, the benefits of the change of selectivity may be largely overestimated. For many important fish species there are insufficient estimates of escape survival to conduct an assessment of the impacts on stocks and fisheries. Failure to quantify the biological impacts of this largely unknown mortality could result in biases in stock assessments and management failures.

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Contents

Abbreviations, definitions and terms

abdomen:	ventral posterior section of a fish containing the viscera (other than heart and lungs)
abrasion:	removal of the skin or mucous membrane of a fish by friction
anoxia:	lack of oxygen (causing death)
beam trawl:	a trawl with the horizontal opening maintained by a beam, usually made of metal, which may be between 3 and 12 m long; beam trawls mainly are used to catch flatfish and shrimp
benthos:	fauna and flora residing in or on the sea bed
biodegradable:	materials that are capable of being degraded by biological mechanisms
bruising:	rupture of the blood vessels in a tissue with leakage of blood into the immediate surrounding tissues (synonymous with contusion)
bycatch:	the part of the catch that is not targeted
BRD:	Bycatch Reduction Device – a physical device installed in a fishing gear that is designed to reduce bycatch
catchability:	the capability of a fishing gear to catch fish or other organism during a fishing operation
codend:	the posterior section (or bag) of a funnel-shaped fishing gear, where the catch is collected during the tow
codend selectivity:	the selection processes occurring in the codend
cover exposure:	the interaction between cover sampling time and towing speed with respect to fish swimming in the codend cover, and its effect on their survival
decompression:	a reduction in ambient pressure (synonymous with depressurization)
dehydration:	the excessive loss of water from tissues
demersal:	found near sea bed (demersal trawl = bottom trawl)
diamond mesh:	conventional rhomboid shape of meshes in sheet netting
discarded catch:	the component of bycatch returned to the sea, owing to economic, legal or other considerations
discard rate:	the proportion of total catch that is discarded
discard mortality:	proportion of discarded bycatch that dies as a result of capture, handling, injury and predation
epidermis:	the outer living layer of the skin, the epithelium, covering the body
escapee:	a fish passing through a trawl into the codend and out through the codend meshes (or through a BRD)

escape mortality:	proportion of fish that die (per unit time) as a result of stress and injury incurred when selected out of the trawl codend, prior to the catch being landed on deck (= post-selection mortality)
extension (codend):	section of netting between the trawl body and the codend; may be tapered, but the taper is much less than that of the trawl body (synonymous with codend extension piece)
fish mortality:	mortality in the population of a species generated by fishing over time; usually expressed as a percentage of the initial population
gadoid:	species belonging to the order Perciformes including several related families such as the Gadidae, Merlucciidae etc.
gas bladder:	synonymous with swim bladder
grid (sorting grid):	BRD made of parallel bars, often used to separate fish of different sizes
ground gear:	connected sections of wire or chain, protected with rubber discs or various types of bobbins, attached to and in front of the fishing line to protect the lower leading margin of the bottom trawl from ground damage while maintaining ground contact
ghost fishing:	fish mortality associated with lost or discarded fishing gears
gill:	the main respiratory and excretory organ of fish
glucose:	a carbohydrate and sugar, the main source of energy in animals; forms the basic carbohydrate component of glycogen
glycogen:	the main polysaccharide energy store of animal cells, consists of long chains of glucose units
hypoxia:	a condition of limited dissolved oxygen; below levels necessary to support most animal life
ICES:	International Council for the Exploration of the Sea
infection:	the invasion of a host by a living pathogen (virus, bacterium, parasite) resulting in a diseased state in the host (organism, organ, tissue or cells)
inflammation:	a defensive action by living tissue to injury or infection
lactic acid:	an organic acid formed by anaerobic metabolism in muscle during exercise (synonymous with lactate)
landed catch:	the portion of the catch that is landed (often the same as the retained catch)
mean retention length:	the length at which a fish has a 50 percent probability of being retained or escaping after entering the codend
MLS:	Minimum Landing Size
mortality:	rate of death in a population (of individuals)
Nordmøre grid:	a BRD comprising a diagonal deflecting grid placed in, or anterior to, a codend
osmoregulation:	the process by which fish maintain a stable electrolyte concentrations in their tissues and blood

osmoregulatory system:	the organs and mechanisms by which fish maintain stable electrolyte concentrations in their tissues and blood; includes the gills, kidneys and behavioural adaptations
otter trawl:	a large funnel-shaped net rigged with two hydrovanes (trawl doors or otter boards) that horizontally open the mouth during towing
pathogen:	any organism or substance that causes disease in a host
sampling time:	the period that the codend cover, or the collection cage attached to it, retains (samples) fish as they escape from the trawl codend
selection curve:	the percentage of fish of a particular species that are retained, for instance by the codend, expressed in graphic form against their length
selectivity:	the selectivity of a fishing gear is a measurement of the selection processes; it describes the relative retention rate of different sizes and species by the gear
sexual maturity:	the development of an individual with respect to its sexual organs (gonads)
skin damage:	damage to any of the multiple layers of fish skin, as determined by the staining of damaged tissues and/or the visual or image analysis assessment of the area of damaged tissue
square mesh:	mesh shape originating from mounting netting with 45° deviation from its normal direction so that the bars run parallel and at 90° to the trawl axis
square-mesh window:	a BRD comprising a rectangular piece of netting with square-shaped meshes, usually inserted into upper panel of a codend or extension to increase the escape of non-target fish
stress:	the adaptive physiological and behavioural changes resulting from a variety of environmental or other stimuli (stressors)
survival:	fish that do not die when selected out of the gear, such as the trawl codend (and that survive at least to the end of the monitoring period of an experiment)
SSB:	Spawning Stock Biomass
swim bladder:	an organe within the body of a fish that allows the fish to remain neutrally buoyant at various depths of water by adjusting the gaseous content of the space (synonymous with gas bladder)
target catch (species):	the intended catch of a fishing activity in terms of species or group of species
TL:	Total length of fish
trawl belly (body):	a series of tapering sections of the trawl between the lower wings and the extension
trawl selection:	the selection of fish by a trawl is considered to be the process that causes the catch of the trawl to have a different composition from that of the fish population in the area where the trawl is being used

unaccounted mortality:	the subcomponents of fish mortality that may include discard mortality, escape mortality, drop-out mortality, ghost fish mortality, avoidance mortality, habitat degradation mortality, and illegal, misreported and unreported catch
unobserved mortality:	mortality caused by encounters with fishing gear that do not result in capture

Introduction

To mitigate the problem of capturing excessive amounts of juveniles and non-target species in commercial fisheries there have recently been extensive research efforts to improve the size- and species-selectivity of fishing gears, in particular trawl gears (reviewed by Kennelly, 1995; Wileman *et al.,* 1996; Broadhurst, 2000; van Marlen, 2000; Walsh *et al.,* 2002; Valdemarsen and Suuronen, 2003; Graham and Ferro, 2004). Selective fishing has a large potential to reduce fishing pressure on non-target species and juveniles and to reduce discards. Selective fishing gears, however, can be justified only if significant numbers of escaping fish (or other organisms) survive. If most of the fish escaping from trawl codends die, conservation measures specifying minimum mesh sizes or other selective devices are of little value. In the worst case, the effect of this type of unaccounted mortality on fish stocks may be negative because the overall mortality caused by exploitation is underestimated. Hence, quantification of the survival rates of escaping fish is of fundamental importance when selectivity is improved.

The results of studies on post-selection mortality, here called escape mortality, suggest that the mortality associated with capture and escape may be relatively low for many species, particularly for gadoids and flatfishes. However, it is also obvious that not all fish survive the process of capture and escape. In many cases, escape occurs after the fish have been subjected to a wide variety of capture stressors and possible damage through contact with other fish, debris or the gear itself (reviewed by Chopin and Arimoto, 1995; ICES, 2000). Fish that do not die immediately may have their growth and reproductive capacity impaired and may suffer behavioural impairments (e.g. Davis, 2002; Ryer, 2002; 2004). The specific reasons why some fish ultimately die are still poorly understood. There is a substantial need to improve the understanding of this "unaccounted" mortality, identify its most likely sources and assess its magnitude and impact on the stocks and management of relevant fisheries. Improving the survival of escapees by using better gear modifications and operational solutions requires detailed knowledge of the basic factors affecting stress, injury and mortality of escaping fish.

Measuring the survival of fish escaping from a fishing gear under various fishing conditions is not an easy task. It is subject to high variability and methodological flaws. It is therefore not surprising that the accuracy of the escape mortalities estimated in various studies has been criticized. Until very recently, experimental methodology has been in its infancy, and historically there has been very little standardization of techniques.

It is worth noting that the fate of escaping fish is becoming increasingly important because of a recent strong tendency among fisheries management authorities to increase minimum mesh sizes and/or to use various other controls that improve selection (e.g. Halliday and Pinhorn, 2002). If mortality is high, the benefits of changing selectivity may be largely overestimated. For many important fish species there are insufficient estimates of escape survival to conduct an assessment of its impacts on stocks and fisheries. Failure to quantify the biological impacts of this largely unknown mortality could result in biases in fisheries management decision-making processes.

This study reviews the literature describing the mortality associated with commercial fishing processes and assesses the techniques used to investigate post-selection mortality. Because major bycatch problems are associated with towed fishing gears such as bottom trawls, the focus of the study is confined to these gears. Other commercial fishing gears will be dealt with only to the extent that they are relevant to the main aim of this work. In the following section, potential sources of error in the assessment of mortality are examined and identified, and appropriate methodological approaches are discussed and suggested. The paper then examines how mortality can be decreased through gear modifications and operational changes. Finally, problems in estimating the magnitude and impacts of unaccounted mortality are highlighted, and the approaches and methods by which these mortality estimates may be included in assessment and management processes are demonstrated.

This study focuses on the mortality of fish that actively escape from commercial fishing gears (termed "escape mortality"), prior to the catch being landed on deck. There is no doubt that this represents a component of total unaccounted fish mortality, but there are very few quantitative data available. Discard mortality (i.e. the mortality of fish "actively released or discarded" by fishers after capture) is a major component of overall fish mortality (FAO, 1994; 2004; Alverson, 1998). In this study, discard mortality will be addressed only to the extent useful for a general understanding of the capture-induced factors causing stress, injury and mortality of fish. Other types of unaccounted mortality, such as drop-out mortality and ghost fish mortality (see ICES, 1995; 2000; Chopin *et al.,* 1997), and the wider ecological implications of fishing (see Jennings and Kaiser, 1998; Lindeboom and de Groot, 1998; Hall, 1999; Kaiser and de Groot, 2000) are discussed only briefly. Escape and discard mortality in recreational fisheries is beyond the scope of this study, as is the mortality of by-caught marine mammals, reptiles and sea birds. A list of species (and their Latin names) mentioned in this study is presented in Annex 1.

Major factors causing stress, injury and mortality of fish escaping from trawl codends

The unaccounted mortality associated with commercial fishing has been assessed and reviewed by several authors (e.g. FAO, 1994; Chopin and Arimoto, 1995; Wileman *et al.,* 1999; Davis, 2002; FAO, 2003) and study groups of the International Council for the Exploration of the Sea (ICES, 1994; 1995; 1997; 2000). Most of these reviews have limited their scope to one particular aspect of unaccounted mortality and, in most cases, only to towed gears. By far the most detailed and extensive description of unaccounted mortality is that of the ICES Topic Group on Unaccounted Mortality in Fisheries (ICES, 2000).

Studies on the capture-related mortality of fish in commercial fisheries can be classified into two broad categories according to capture and release process: (a) survival of fish that escape from fishing gears during the capture process; and (b) survival of fish caught by fishing gears and then discarded on deck (Figure 1). This chapter attempts to review and highlight the key principles and factors that evoke stress, injury and mortality in fish that escape from a fishing gear, in particular a trawl codend. The next chapter explores the issues specifically dealing with discard mortality from trawl fisheries, followed by a review of the mortality associated with other fishing gears. This presentation does not attempt to provide an exhaustive discussion of all the potential factors causing mortality in fisheries – instead it focuses on the major factors, particularly those that can be affected.

It is notable that fish escape from many parts of the gear, and may therefore be affected differently. In the case of towed fishing gears, however, fish usually escape from the codend (e.g. Wileman *et al.,* 1996), and most survival studies have therefore focused on the mortality codend escapees. However, the zone of influence of a fishing gear is not limited to where the fish are retained and where they escape; it also includes those parts of the gear that herd and scare fish. Very little is known about the fate of fish escaping from these areas but apparently, the stress, injury and mortality induced is substantially smaller than in those fish escaping from codend.

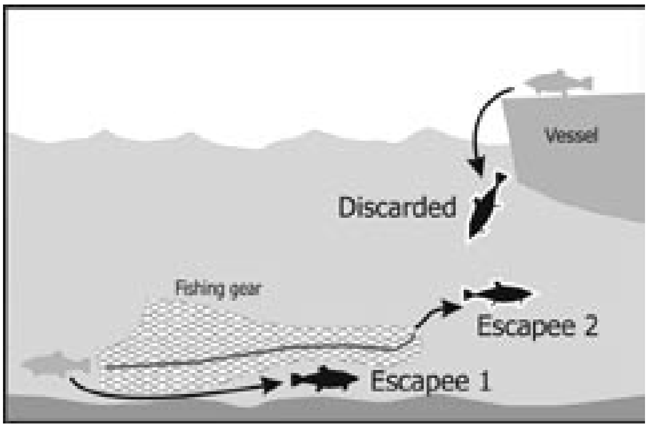


FIGURE 1

Fish may escape a towed fishing gear for instance by diving below the ground gear (Escapee 1) or by swimming through the mesh (Escapee 2). Fish that are retained by a fishing gear may be discarded from the deck of the vessel after the gear has been retrieved and the catch sorted. At each of these stages, the environmental and physical conditions that the fish are exposed to may vary considerably.

SPECIES-SPECIFIC VARIATION IN ESCAPE MORTALITIES

Most assessments of escape mortality have been made for commercially important species escaping from towed fishing gears, mainly demersal trawls. These investigations have usually attempted to compare the relative benefits of using different mesh sizes or selective devices in codends. The most studied group of fish are the gadoids, particularly haddock, whiting and cod (e.g. Main and Sangster, 1990; 1991; Soldal, Isaksen and Engås, 1993; Sangster, Lehmann and Breen, 1996; Wileman *et al.,* 1999; Suuronen *et al.,* 1996a; Ingolfsson, Soldal and Huse, 2002). Some work has also been conducted with pelagic species such as herring, vendace, capelin and walleye pollock (e.g. Treschev *et al.,* 1975; Efanov, 1981; Suuronen *et al.,* 1995; 1996b; Thorsteinsson, 1995; Pikitch *et al.,* 2002), with flatfishes (DeAlteris and Reifsteck, 1993; Robinson, Carr and Harris, 1993) and with species such as red mullet, sand whiting and yellow-fin bream (Broadhurst, Kennelly and Barker, 1997; Broadhurst, Barker and Kennelly, 1999; Metin *et al.,* 2004).

It is clear from these studies that the robustness and ability of various species to withstand physical injury and fatigue associated with capture and escape vary markedly. Generally, relatively low escape mortality has been observed in many gadoids (e.g. cod, haddock, whiting, saithe). For instance, Soldal, Isaksen and Engås (1993), Suuronen *et al.* (1996a), Suuronen, Lehtonen and Jounela (2005) and Ingolfsson, Soldal and Huse (2002) observed negligible (< 3 percent) mortality among cod escaping from trawl codends under normal fishing conditions. The observed escape mortality of saithe was at the same level as that of cod (Jacobsen, Thomsen and Isaksen, 1992; Ingolfsson, Soldal and Huse, 2002). The mean mortality of haddock and whiting escaping from a 100-mm diamond mesh codend was less than 15 percent (Wileman *et al.,* 1999).

Low mortality rates (mostly < 10 percent) have also been observed with flatfishes such as winter flounder, yellowtail flounder and American plaice (DeAlteris and Reifsteck, 1993; Robinson, Carr and Harris, 1993). Broadhurst, Kennelly and Barker (1997) and Broadhurst, Barker and Kennelly (1999) showed low mortality (< 3 percent) associated with sand whiting and yellow-fin bream that had past through the square mesh panels of a trawl codend. It is notable, however, that some of these species have also shown relatively high mortalities.

Substantially larger escape mortalities (of as much as 70 to 100 percent) have been observed in small-sized pelagic species such as Baltic herring (Suuronen *et al.,* 1996b), although almost opposite results have also been reported with the same species (Treschev *et al.,* 1975; Efanov, 1981). Medium levels of mortalities have been recorded with some pelagic species such as walleye pollock and vendace (Suuronen *et al.,* 1995; Pikitch *et al.,* 2002). In most studies, survival has been shown to depend on size.

Although clear species-specific differences in survival have been observed, one of the main findings of these investigations is the high variability in survival, even with the same species in the same experiments (e.g. Suuronen *et al.,* 1996b; Suuronen, Lehtonen and Jounela, 2005; Wileman *et al.,* 1999; Ingolfsson, Soldal and Huse, 2002). This variation has not yet been explained adequately. Moreover, mortality estimates have not usually been estimated with confidence intervals; typically only a range of mortality observations is given.

EFFECTS OF MESH SIZE AND SHAPE

It is generally considered that increasing codend mesh size will automatically reduce the injury and mortality of escaping fish. It is assumed that the larger the mesh opening, the easier it is for fish to pass through, and consequently the less damage that occurs. Indeed, an inverse correlation between mortality rates and increasing mesh size has been reported in several investigations (e.g. Main and Sangster, 1991; Sangster, Lehmann and Breen, 1996; Lowry, Sangster and Breen, 1996; Wileman *et al.,* 1999). Lowry, Sangster and Breen (1996) demonstrated that fish escaping through a larger

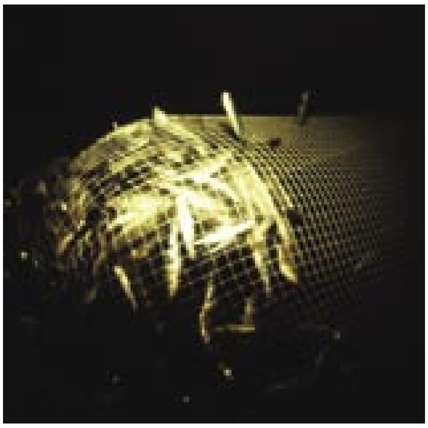


FIGURE 2
Young vendace escaping from a square mesh codend. Many fish escape through open square meshes more easily, and apparently with less injury, than through conventional diamond meshes.

mesh may sustain less skin and scale damage than fish escaping through a smaller mesh. However, some studies have suggested that codend mesh size has less influence on the survival of escaping fish (e.g. Suuronen *et al.,* 1996b; Wileman *et al.,* 1999). Clearly, the positive effect of an increase in mesh size on the survival of codend escapees has not yet been demonstrated conclusively. This does not mean, however, that mesh size does not play any role in survival; it is potentially important, but many other important factors affect survival simultaneously.

There are indications that mesh shape may play a more important role than mesh size in reducing the mortality of escapees. For example, haddock and whiting escaping through a square mesh codend were reported to have lower mortality than those escaping from a traditional diamond mesh codend of the same mesh size (Main and Sangster, 1990; 1991). Apparently, many fish may escape through open square meshes with less injury than through conventional diamond meshes because the latter may become almost closed owing to net tension during tow (Figure 2). In some investigations, escape through a special sorting device, such as a grid (Figure 3), has shown to result in lower mortality than mesh sorting (e.g. Suuronen *et al.,* 1996b; Ingolfsson, Soldal and Huse, 2002), but this has not yet been demonstrated adequately. Intuitively, it would appear that survival should be greater when escape is easier. This may be true to some extent, but the passage of a fish through an open mesh or other selective device is not the only factor that can inflict fatal injuries. A potential advantage of square mesh panels and special sorting devices is that they can be placed in front of the actual codend so that escapees do not have to enter the rear part of the codend, which is probably the zone with the highest mortality for escapees. Clearly, effects of a selective device, whether it is a netting mesh or a sorting grid, on injury and mortality of escapees are complex and relatively poorly understood; many factors have

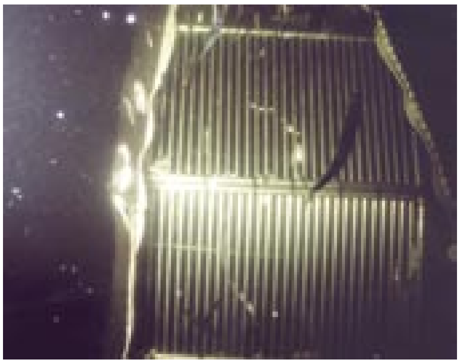


FIGURE 3
Young Baltic herring escaping through a sorting grid placed in front of the codend of a pelagic trawl. Note the large number of herring scales in the water. Herring lose scales as they scrape against the trawl belly and codend extension, prior to entering into the codend.

to be considered when developing selective gear modifications and bycatch reduction devices that also guarantee a high survival rate for escapees.

EFFECTS OF FISH SIZE

Studies have been somewhat inconclusive regarding the relationship between escape mortality and fish size (length), but the general observation has been that escape mortality decreases with increasing fish length. For instance, Wileman *et al.* (1999) observed that the mean length of haddock that died after escape was significantly lower than that of surviving haddock, i.e. survival increased with increasing mean length. Similar length-related mortality has been described in many other studies conducted on gadoids (e.g. Lowry, Sangster and Breen, 1996; Sangster, Lehmann and Breen, 1996; Pikitch *et al.,* 2002; Ingolfsson, Soldal and Huse, 2002) and species such as Baltic herring (Suuronen, Erickson and Orrensalo, 1996).

On the other hand, a significant increase in injury and death rates would seem likely in groups of fish whose passage through a mesh or grid is made difficult by their physical size (i.e. in the largest escapees). For example, fish that have a transverse morphology that is similar in size to the maximum mesh opening could be expected to sustain more injury than smaller individuals that can pass through meshes with less contact. However, very few investigations have documented a marked increase in injury and mortality among the largest escapees (Efanov, 1981; Ingolfsson, Soldal and Huse, 2002).

Many investigations have shown an inverse relationship between skin injury and the size of the escaping fish (e.g. Soldal *et al.,* 1991; Soldal, Isaksen and Engås, 1993; Soldal and Isaksen, 1993; Suuronen, Erickson and Orrensalo, 1996; Breen and Sangster, 1997; Ingolfsson, Soldal and Huse, 2002), i.e. the smallest individuals show the highest injury rates. This supports observations that the smallest escapees often suffer the highest mortalities. Apparently, smaller fish with poorer swimming ability are less able to avoid injury when swimming within the gear and during escape. They may also have less physical strength to make active escape attempts, and may therefore stay longer inside the gear before escaping. The smallest fish are generally also more delicate than larger individuals, and are therefore more susceptible to all types of capture-induced injury. Their high vulnerability may be the result of a combination of exhaustion and injury. It is notable, however, that several studies have been inconclusive regarding the relation between skin injury and fish size (e.g. Lowry, Sangster and Breen, 1996; Sangster, Lehmann and Breen, 1996; Suuronen *et al.,* 1996a; 1996b; Suuronen, Lehtonen and Jounela, 2005; Pikitch *et al.,* 2002).

The mortality of escapees may also be at least partly a function of fish age. There is some evidence that in a particular year class the smallest haddock and whiting, i.e. those fish that have grown more slowly, are more susceptible (e.g. Lowry, Sangster and Breen, 1996; Sangster, Lehmann and Breen, 1996; Wileman *et al.,* 1999). Hence, in a fish population, the fittest individuals from age group 1 may survive better than the less-fit individuals from age group 2. Therefore, the age and fitness of a particular size of fish, and not only its length, may play a vital role in its ability to survive codend escape.

In conclusion, there are complex relationships between the size of fish and their injury and mortality due to capture and escape. Owing to their sustained swimming ability, larger fish generally appear to suffer less injury and lower mortality than smaller fish. It is notable, however, that the methods used in the experiments may have seriously biased these estimates. In particular, the smallest fish may be highly sensitive to collection and handling (e.g. Suuronen *et al.,* 1996b; Breen *et al.,* 2002). Hence, results describing the relationship between the size of fish and their injury and mortality should be considered with great caution. Better techniques and more work are required in this area.

CAUSES AND EFFECTS OF SKIN INJURY: POTENTIAL HEALING

It is well demonstrated that the skin of fish performs a number of functions that are important to their survival and well-being. These include mechanical protection, osmoregulatory control, protection from pathogenic invasion, communication, sensory reception, and capture and predator avoidance. Depending on its severity, damage to the skin could result in the loss of one or all of these vital functions.

The abrasive qualities of netting materials suggest that fish may sustain severe injuries during the tow, especially in the codend where individuals are exhausted and crowded together. In a number of studies, gear-induced injuries have been observed in fish that escaped from a trawl codend (e.g. Borisov and Efanov, 1981; Main and Sangster, 1990; 1991; Suuronen *et al.,* 1996a; 1996b, Wileman *et al.,* 1999). During the escape, fish may sustain injury when they exhibit the common behavioural pattern of thrashing their tails in an attempt to swim while still confined by the mesh (e.g. Glass and Wardle, 1989; Main and Sangster, 1990). Fish can also sustain injury at other times; using video, Suuronen *et al.* (1996b) observed that Baltic herring scraped against the trawl netting along the trawl belly and codend extension prior to entering into the codend, which resulted in major scale loss and skin injury. Apparently, herring were not able to avoid contact with the trawl netting. Similar observations have been reported in vendace trawl fishery (Suuronen *et al.,* 1995). Moreover, several studies have suggested that the proportion of other abrasive objects, such as spiny fish species, crustaceans and broken shells, in the codend may also injure escaping fish (Treschev *et al.,* 1975; Main and Sangster, 1991; Wileman *et al.,* 1999). Bublitz *et al.* (1999) demonstrated that many walleye pollack escaping from trawl meshes were bruised to some extent, and this bruising was correlated with subsequent mortality.

Most assessments on capture-induced skin injury have been conducted on gadoids and herring. Farmer, Brewer and Blaber (1998) assessed the scale loss of several tropical fish species escaping through trawl codend meshes. Scale loss was significant in all the species studied; the heaviest losses were observed for species with deciduous scales, such as perforated-scale sardine, pearly finned cardinal fish and sunrise goatfish. It is notable that escapees from a 45-mm square mesh codend were generally less damaged than those from a 38-mm square mesh codend.

To determine the potential injury to fish passing through netting meshes or other selective devices (e.g. sorting grids), some studies have attempted to simplify the observation process by conducting simulated laboratory (tank) experiments. Species studied include cod, haddock, saithe and sand whiting (e.g. Soldal, Engås and Isaksen, 1989; Soldal, Isaksen and Engås, 1993; Engås, Isaksen and Soldal, 1990; DeAlteris and Reifsteck, 1993; Jónsson, 1994; Broadhurst, Kennelly and Barker, 1997; Broadhurst, Barker and Kennelly, 1999). In most cases, mortality was indistinguishable from that of the control fish, which supports the view that the simple passage of a fish through a netting mesh or other selective device does not necessarily inflict fatal injury. However, results obtained in laboratory conditions cannot usually be directly extrapolated to the more complex nature of a commercial fishing process (see e.g. Soldal, Isaksen and Engås, 1993).

Clearly, while many studies have demonstrated that skin damage, particularly scale loss, among fish escaping from trawl codends is often the prevalent injury, it is not conclusive that this is the primary cause of mortality. The scientific literature provides few clues about the physiological mechanisms associated with skin injury and mortality (see the review of Smith, 1993). Skin injury may not account for all of the observed mortalities that typically occur within the first day after escape, but it may expose fish to secondary infections that significantly increase their longer-term mortality (e.g. Roberts, 1989). Mellergaard and Bagge (1998) observed a high occurrence of skin ulcerations in Baltic cod caught in the vicinity of the Danish island of Bornholm. The ulcerated fish were mainly 24 to 28 cm in length, and most of the ulcerations on the trunk occurred bilaterally. There were strong indications that the skin ulcers were induced by the trawl gears that are used in the area. Mellergaard and Bagge (1998) suggested that these fish had escaped from trawl codends and that many of them were likely to die of secondary bacterial septicaemia during the summer months of increasing water temperatures. Jones (1993) reported on gear-induced cuts, scrapes and scars on hoki caught from the New Zealand fishing grounds. He suggested that the presence of net-damaged fish provides evidence that hoki are injured by coming into contact with trawl gears. He also suggested that the absence of an epidermal layer in the gear-induced wounds of some hoki may indicate that re-epithelization by epidermal migration (see e.g. Bullock, Marks and Roberts, 1978) cannot cover the relatively large area of these wounds. Clearly, long-term observations are required to understand the role of skin injury in determining mortality.

Very little is known about the potential healing of gear-induced injuries. Although minor injuries may heal completely, and open skin lesions be replaced by scar tissue within a few weeks after injury (e.g. Engås, Isaksen and Soldal, 1990; Sakanari and Moser, 1986; Bell and Bagshaw, 1985; Jones, 1993), there may be secondary infections from potentially pathogenic bacteria and fungi (e.g. Bullock and Roberts, 1980; Copland and Willoughby, 1982; Roberts, 1989). Particularly at warmer temperatures, such infections may exacerbate the lesions and the fish will succumb to osmotic distress or septicaemia if the infection becomes generalized (e.g. Mellergaard and Bagge, 1998). On the other hand, Roberts (1989) showed that the healing of dermis may be slower in very cold water. Clearly, more work is required in this field.

EFFECTS OF SWIMMING EXHAUSTION

The overall effect of capture-induced stress and exhaustion on the mortality of escapees is not clear. Stress response enables fish to avoid or overcome potentially threatening or harmful situations (e.g. Pickering, 1993; Chopin and Arimoto, 1995). How a fish reacts to a particular stressor will depend on the species, as well as the type of stressor and its severity. The type of stressors that fish are subjected to during capture by commercial fishing gears depends on the fishing method. In the case of towed fishing gears, stresses include confinement, overcrowding and severe exercise. Suuronen *et al.* (1996a) and Tschernij and Suuronen (2002) observed Baltic cod swimming in front of a demersal trawl until they became fatigued, after which they turned and were overtaken by the trawl. Xu, Arimoto and Inoue (1993) showed that small pollack became severely fatigued during the trawl-capture process, and Beamish (1966) suggested that muscle fatigue alone could cause mortality. Young vendace subjected to a trawl capture and escape process exhibited strong symptoms of exhaustion (Turunen *et al.*, 1996); this may contribute markedly to the high mortality of escapees (Suuronen *et al.*, 1995). Likewise, the dramatic reduction of liver glycogen of small (7 to 11 cm) Baltic herring escapees after forced swimming inside the trawl may have increased their susceptibility to stress, thereby contributing greatly to their high mortality (Suuronen, Erickson and Orrensalo, 1996).

Swimming exhaustion may be an important factor contributing towards mortality, at least in some specific cases, although very little direct scientific evidence exists. It is notable that haddock and cod survived severe swimming exhaustion and muscular fatigue in tank experiments (Soldal, Isaksen and Engås, 1993). It is likely that the towing speed has an effect on fish's swimming capacity within the trawl and during escape from the trawl, and thereby on mortality. However, there are no published data on the effect of towing speed on survival. The interactions between towing speed, fatigue, water temperature, the escape process, injury and survival are likely to be very complex. More work is needed to assess the importance of stress and swimming exhaustion on the survival of escaping fish.

EFFECTS OF CODEND CATCH

It is generally assumed that increasing the catch size increases the likelihood of injurious mechanisms within the codend, owing to increasing the abrasive contacts with other fish, netting, debris and turbulent flow patterns. In survival experiments, however, no significant relationship between codend catch size and escape mortality has been demonstrated (e.g. Wileman *et al.,* 1999; Pikitch *et al.,* 2002; Suuronen, Lehtonen and Jounela, 2005). However, owing to the many methodological constraints, most survival studies have been conducted with small catches that typically do not reflect commercial situations. It is also notable that the effects of catch size and catch composition may be highly confounded by such variables as the towing time and environmental conditions.

It is notable that codend catch weight may reduce the selectivity of the codend owing to mesh blocking (e.g. Dahm, 1991; Dahm *et al.,* 2002; Suuronen and Millar, 1992; Lowry, Sangster and Breen, 1996; Erickson *et al.,* 1996). Therefore, the overall number of the fish escaping would decrease and the escape would become more difficult, leading to higher mortalities. However, it has also been demonstrated that as the codend fills with catch, the meshes in front of the catch bulge become more open and fish may therefore escape more easily. In fact, a codend may have poorer selectivity with smaller catch sizes, and selectivity may improve substantially as the catch starts to accumulate in the codend (e.g. Lowry, Sangster and Breen, 1996; O'Neill and Kynoch, 1996; Dahm *et al.,* 2002; Campos, Fonseca and Henriques, 2003; Herrmann, 2005). The risks of abrasive injury during the passage though a mesh may be reduced, at least in certain catch sizes. Clearly, the effects that codend catch size and composition have on mortality require further study.

EFFECTS OF SEA STATE

Fishing vessels roll, pitch and heave in response to waves and winds. Sea state is generally known to affect trawl codend selectivity (e.g. Wileman *et al.,* 1996; O'Neill *et al.,* 2003), so it can be assumed that increased sea state and vessel motion may also affect the survival of fish escaping from trawl codends. Trawl "surging" associated with increased sea state may alter the water flow within the gear and make it difficult for fish to orient towards selective panels or sorting devices. Fish may become stressed, meshed and injured but increased sea state may also cause increased escape during towing and haul-back (e.g. Engås *et al.,* 1999). Wileman *et al.* (1999) demonstrated that the survival of whiting escaping from trawl codends decreased with increasing sea-state. However, no significant effects were observed in other experiments where greater changes of sea state occurred. More work is needed in this area.

EFFECTS OF ESCAPE DURING HAUL BACK

Depending on the vessel, its operation and the design of the gear, a trawl codend may be under heavy tension during towing. Codend meshes may be almost totally closed during the capture process, and fish are not able to escape until the codend is at or near the surface during haul back (e.g. Tschernij and Suuronen, 2002). As a result of decompression problems, many fish may suffer injury to their swim bladders. Fish with ruptured swim bladders often have gas in their abdominal cavities and are trapped on the water surface. After escape, these "floaters" may be subjected to high predation by birds. Moreover, various mechanical forces on a codend floating at the surface can be extremely high, particularly in rough seas. Catch may become compressed in the aft part of the codend, and fish may become crowded, resulting in oxygen depletion, abrasion and injury. These fish may have been subjected to substantial differences in temperature, salinity and pressure. While there is little available information on the fate of fish escaping from codends near the surface, these factors suggest that the probability of survival would be quite low. Clearly, escape should take place during fishing and not during hauling.

EFFECTS OF WATER TEMPERATURE

Water temperature influences the physiological processes and behaviour of fish (e.g. He and Wardle, 1988; Özbilgin and Wardle, 2002), and so probably affects their escape and subsequent survival. Nevertheless, relatively little direct fieldwork has been done to quantify the effects of water temperature on the survival of escapees under commercial fishing conditions. Most observations on temperature effects are by-products of research in which other factors have been the main interest. Suuronen, Lehtonen and Jounela (2005) observed low mortality (circa 3 percent) in Baltic cod escapees at ambient (< 10 °C) water temperatures. At higher temperatures (> 15 °C), a substantially higher mortality (up to 75 percent) was observed, but there was high variation between hauls. Fish that are caught at greater depths or in cool waters by a towed fishing gear may be exposed to substantially warmer water temperatures for instance when gear is towed to shallower ground or during gear retrieval. If escape occurs at relatively higher temperatures, the stress, injury and mortality of escapees could be increased.

In laboratory studies, the mortality rates of sablefish, lingcod and Pacific halibut increased with increasing seawater temperature for fish that were first towed and then exposed to increased temperature, with 100 percent mortality at 16 °C for sablefish, 18 °C for Pacific halibut and 20 °C for lingcod (Davis, Olla and Schreck, 2001; Davis and Olla, 2001; 2002). Although there were substantial species-specific differences in mortality rates, these results demonstrate the marked effect of temperature. An abrupt temperature increase of several degrees induced high mortality in adult sablefish (Olla, Davis and Schreck, 1998). Exposure to warmer temperatures results in increased core body temperature, with smaller fish warming more rapidly. Davis, Olla and Schreck (2001) argued that the additional stress and mortality resulting from the interaction of capture, escape and exposure to increased temperature may be common in fisheries during warmer seasons of the year, or in areas where fish are caught in cooler deeper water.

Low water temperatures may also affect fish's behaviour and sensitivity to various capture stresses. Fish's swimming speed and endurance generally decreases at low temperatures (e.g. He and Wardle, 1988). Reduced swimming speed and endurance may influence the herding effect of various gear components and the ability of fish to escape from trawls. Davis (2002) argued that deficits in swimming performance and orientation in a trawl associated with low temperatures could cause fish to be injured more frequently. In conclusion, water temperature plays a critically important role in the mortality rates of escapees, and may magnify the effects of other stressors.

EFFECTS OF TIME AND AMBIENT LIGHT

Vision plays an important role in the response of many species to trawls (e.g. Glass and Wardle, 1989; Olla, Davis and Schreck, 1997; Olla, Davis and Rose, 2000). Olla, Davis and Rose (2000) observed that there was a clear difference in the orientation and swimming behaviour of walleye pollock when the light level fell below that necessary for vision-mediated swimming. In darkness, captured walleye pollock swam less, passed along the trawl faster and did not orient to the long axis of the trawl. However, other field studies show that some species are able to orient in a trawl during dark hours, indicating that senses other than vision may play an important role (e.g. Engås and Ona, 1990).

Ambient light conditions may have a significant effect on fish's behaviour and ability to escape from codends. The available light may not always be adequate for visual mesh detection because fishing operations are commonly conducted in relatively deep waters, often at night and in turbid water. There is some evidence that loss of orientation and swimming ability under dark conditions may result in reduced ability to escape through trawl mesh and increased injury and mortality. Suuronen *et al.* (1995) observed that young vendace escaping a pelagic trawl codend at night sustained significantly higher mortalities than fish escaping during daylight hours. Apparently, fish were not able to orient towards the gear and the open meshes, and so incurred greater injuries. Laboratory experiments on walleye pollock towed in a net under light and dark conditions demonstrated that in light conditions fish could see the net and were able to swim up to three hours with no resulting mortality, whereas fish in dark conditions were not able to see and respond to the net and became pinned against net meshes, ultimately resulting in mortality (Olla, Davis and Schreck, 1997). Clearly, developing effective gear modifications to improve selectivity and the subsequent survival of escapees requires a good understanding of how fish react to gear under various light conditions; reactions both under light and dark conditions must be considered.

It is worth noting that the whole aft section of a bottom trawl is often surrounded by a sand or mud cloud stirred by the otter doors and the ground gear (e.g. Pikitch *et al.,* 1996; Tschernij and Suuronen, 2002). It is likely that this makes visual detection of open meshes or other selective devices difficult or impossible, even during the day (in light conditions). Very little is known about the potential effect of this on survival.

EFFECTS OF TOW DURATION

It could be assumed that towing time has a strong effect on stress, injury and mortality because a longer tow is likely to produce more catch, crowding, abrasion and swimming exhaustion, as well as more blocked meshes. However, Wileman *et al.* (1999) observed no clear effect of trawl towing time on the escape mortality of haddock and whiting. Treschev *et al.* (1975) reported that tow duration had an effect on the survival of Baltic herring, but the results they presented are not very convincing. The length of time that escaping fish spend inside the trawl is not generally known, and there may be substantial variation depending on the conditions, species and sizes. The general rule may be that fish that escape do so very soon after reaching the codend. For these fish, the length of trawl tow is not necessarily the most important factor affecting their subsequent survival. Those fish that do not manage to escape rapidly will soon become exhausted and be piled up in the catch, from where they are carried out with the trawl. Some of these fish may manage to escape later, particularly during the hauling when tension on the codend netting is reduced. They are likely to exhibit very different mortality rates compared with those of fish that escape immediately. The effect of tow duration on escape mortality should be explored in more detail. It may be influenced by the codend catch size and composition, the towing speed, the netting material of the gear, and hauling and handling processes.

The effect of towing duration on the survival of fish has been explored in greater depth in discard mortality studies (see page 21). However, it is important to realize that discarded fish have probably spent, on average, longer in the trawl gear than escaping fish have, and will have experienced additional stress owing to gear retrieval and on-deck handling processes. Hence, tow duration may be an important factor in determining discard mortality.

EFFECTS OF SEX

Few studies have investigated the effect of sex on the mortality of escaping fish. Wileman *et al.* (1999) showed that sex had no effect on the survival of sexually immature haddock and whiting. However, sex may be an important factor for adult fish, at least near and during spawning time, when females have a wider transverse morphology than males of the same length. Notwithstanding this, the issue may not always be relevant because selective fisheries usually attempt to sort out only young immature fish. It is notable that the survival rates of trawl-caught and discarded Norway lobster were found to be significantly lower among females than males (Wileman *et al.*, 1999).

PREDATION MORTALITY

Marine predators are known to follow trawls during towing, and consume fish that escape from the codend meshes (e.g. Broadhurst, 1998). Under laboratory conditions, Ryer (2002) showed that walleye pollock subjected to capture and escape stress were more likely to encounter predators than a control group was. Ryer, Ottmar and Sturm (2004) emphasize that even a relatively small change in predator detection, avoidance, schooling and shelter seeking could have profound implications for survival. Clearly, increased vulnerability to predation may be an important, yet largely unobserved, source of mortality for fish escaping trawl gears. By not accounting for predation, many survival experiments may have underestimated mortality values. Moreover, fish may be transported for significant distances in front of and inside the trawl. When they escape, they may be in a very different environment (sub-optimal or inappropriate habitat), where they may be more vulnerable to predators. This may further reduce the effectiveness of innate behavioural responses to predators, make it more difficult to find shelter and food, and reduce shoaling and swimming. The influences of such effects are poorly understood and require substantially more investigation.

EFFECTS OF REPEATED ESCAPE AND THE POTENTIAL ROLE OF LEARNING

Very little is known about the effects of repeated capture and escape of organisms from trawls (but see Broadhurst *et al.*, 2002). In grounds where fishing activity is high, young fish may repeatedly encounter trawl gear. If stress and injury are cumulative, fish may eventually die when they experience several escape processes within a short period, without sufficient time for adequate recovery between the events. This hypothesis clearly requires further investigation. Moreover, learning may play some role here. A fish that has been captured and passed through the meshes of a fishing gear may be capable of escaping more easily on subsequent encounters, and may thereby also have a higher probability of survival than a naive fish. Özbilgin and Glass (2004) provided experimental evidence that haddock can modify their behaviour based on prior experience; one mesh penetration tended to increase the probability of penetration in the next encounter. Özbilgin and Glass (2004) also emphasized, however, that the true nature and effect of the learning abilities of fish in codend mesh penetration behaviour during commercial fishing operations remain to be investigated.

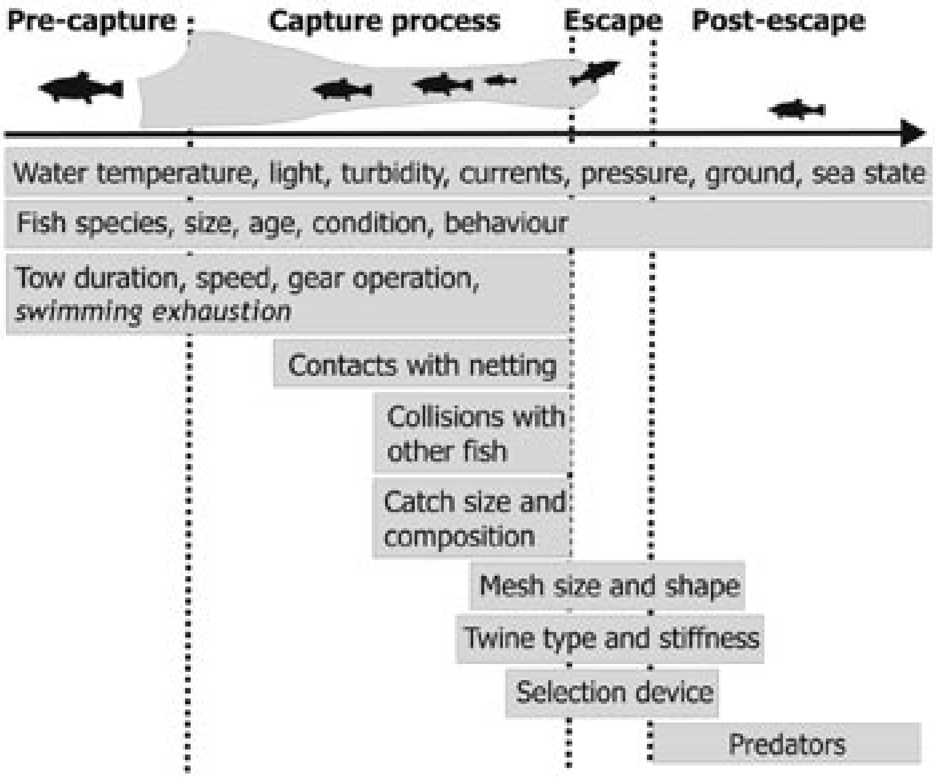
EFFECTS OF COLLISIONS WITH THE GROUND GEAR

There has been an overall trend towards larger and heavier ground gears in the demersal trawl fisheries, although in some fisheries the current trend is towards lighter or modified ground gears to reduce sea bed impacts (see Valdemarsen, 2004). During herding and capture, fish may collide with the ground gear (e.g. Walsh and Hickey, 1993; Tschernij and Suuronen, 2002). Very little is known of the magnitude of such collisions, although there is likely to be substantial variation in the type and degree of injuries sustained by fish. In Norway, scientists measured a high level of under-gear escape among young cod, and a significant number of these fish exhibit external injuries caused by collisions (Aud Soldal, personal communication). However, it could be assumed that in some cases a fish would have a better chance of survival when escaping through the free space between the rollers of a ground gear than when entering into a trawl and escaping through a codend mesh. In fact, for some fish species, such as cod, escape under modified ground gear could become an alternative to codend selectivity (see page 46).

CUMULATIVE EFFECTS

It is evident that the damage and mortality incurred by fish during their capture and escape from trawls are often caused by a multitude of factors (stressors), and can only rarely be ascribed to a single cause. Some stressors are connected to ambient factors

FIGURE 4
A schematic description of potential factors that may affect fish behaviour, endurance, stress and injury during the capture and escape process. The effects of these factors may be cumulative.



such as water temperature, light conditions, currents, pressure, fishing ground and sea state. Others are capture stresses such as crushing and wounding against trawl netting, collisions with other fish, sustained swimming until exhaustion, and the final passage through a mesh or selective device. Lack of oxygen in a towed fishing gear packed with fish could lead to conditions of anoxia. Finally, there are biological attributes such as fish species, size, age, behaviour and predators. The effects of all these stressors may be cumulative and lead ultimately to mortalities. For instance, while moderate damage to the skin is unlikely to induce initial mortality, injury may provide a sufficiently large physiological stress to – in combination with exhaustive swimming – induce the death of fish (e.g. through metabolic acidosis or osmoregulatory failure). Figure 4 summarizes some of the main factors that may affect a fish captured by and subsequently escaping from a trawl gear.

CONCLUSIONS

The results of experiments conducted on post-trawl mortality suggest that for many species it is relatively low, although among some species groups, such as small-sized pelagic fish, mortality may be high. Few studies, however, have adequately and quantitatively explained the full range of mortalities that can occur when fish escape from fishing gears under commercial fishing conditions. A number of mechanisms may cause injury, stress and mortality in escaping fish; the passage through a mesh or a selective device is not the only potentially damaging factor. Fish escaping from fishing gears may suffer immediate as well as delayed mortalities owing to physical injury, exhaustion, disease and predation. Moreover, changes in water temperature, pressure and light conditions may strongly affect the fate of escaping fish. The robustness and ability of various species to withstand the physical disruptions and fatigue associated with the process of capture and escape vary substantially. The smallest escapees often appear the most vulnerable. Until the effects on mortality of various critical factors and their interactions are better understood, there will be a lack of confidence in generalizing escape mortality results to a wider range of fishing conditions, gear designs and operations and fish species. Further work is required to identify the damaging mechanisms that cause injuries.

Research on the mortality of fish escaping from fishing gears has tended to focus on the mortality of fish kept in a sheltered environment such as a sea bed cage, for a relatively short time. Factors such as predation on injured fish and the ability of a fish to recover fully from its injuries or stress are more difficult to monitor, and are therefore poorly understood. The fate of fish after multiple encounters with fishing gears is largely unknown. Moreover, the cumulative effects of all stressors are likely to have a strong influence on the probability of long-term survival. These areas clearly require more investigation.

Methods for assessing escape mortality rates across a wide range of fisheries and environmental conditions are not yet adequate. It is necessary to develop appropriate methodologies, collect more realistic data and obtain a better understanding of the main sources of injury, stress and mortality under various conditions. It should be borne in mind that, owing to natural variation in environmental parameters and in the general condition of exploited fish, there will always be some variability in mortality estimates between experiments, tows and years. Detailed records of relevant environmental parameters and condition indices of target stocks should be collected routinely during survival experiments.

Major factors causing mortality of trawl-caught and discarded fish

Although this study focuses mainly on the fate of fish that escape from trawl codends during the capture process, it is useful for an overall understanding of the factors causing capture-induced stress, injury and mortality to take a brief look at studies conducted on the discard mortality of trawl-caught fish. Many of the factors that affect discarded fish are similar to those affecting escapees, but discarded fish have experienced additional stress and injury resulting from lifting on to the vessel deck, on-deck handling and air exposure, as well as the eventual discarding process.

It is well demonstrated that discarding is a widely applied practice in commercial fisheries and that there are many reasons for discarding (reviewed by FAO, 1983; 1994; 1997; 2004; Hall, 1996; Alverson, 1998; Hall, Alverson and Metuzals, 2000). It is also clear that not all of the discarded fish and other organisms survive (e.g. ICES, 2000; Davis, 2002). In fact, discard mortality represents a large source of uncertainty in estimates of overall fish mortality rates, and is a potentially important issue in fisheries management worldwide.

Most of the work conducted on discard mortality has concentrated on the survival of fish caught by trawls (otter trawls, beam trawls, shrimp trawls). A few studies include other gears such as longlines, gillnets and trap-nets (see page 25). Most discard mortality studies conducted in the field have focused on capture- and handling-induced stressors. Davis (2002) pointed out the important role of environmental factors, size- and species-related sensitivity to stressors, and interactions among stressors, all of which increase the mortality of discards. This chapter addresses those factors that are important for a general understanding of stress, injury and mortality associated with trawl capture processes. The discussion includes not only fish, but also other animals (in particular invertebrates) affected.

MAIN FACTORS AFFECTING THE FATE OF DISCARDED FISH

The main factors affecting the stress, injury and mortality of discarded fish are related to capture stresses, fishing conditions and biological attributes (Davis, 2002). Capture stressors include such factors as net entrainment, crushing, wounding, sustained swimming until exhaustion, and changes in pressure. Fishing conditions include towing time and speed, light conditions, water and air temperature, anoxia, sea conditions, time on deck, and various handling procedures. Biological attributes include behaviour, size and species. In addition, there are factors such as seabird predation near the surface and fish, mammal and invertebrate predation in the whole water column.

Although a discarded fish may survive the discarding process and immediate predation, a rapid fall to the sea bed may result in death owing to the physiological effects of increased pressure. Moreover, the disruption of schooling behaviour and the attraction of predators by visual, olfactory and mechanical cues from injured fish may significantly increase mortality (Ryer, 2002; Ryer *et al.,* 2004). Delayed mortality of discards may represent a significant source of unobserved mortality. Clearly, a large number of factors affect discarded fish; many of these factors are the same as those that affect the mortality of fish escaping from fishing gear, but there are also several additional factors involved in discard mortality.

PRESENCE OF GAS-FILLED ORGANS AND OVERALL FRAGILITY

The types and extent of injuries caused by discarding are species-specific (ICES, 2000; Davis, 2002). While some species are highly sensitive to capture and discarding, others are capable of surviving these traumas. Fish with gas bladders and other organs that inflate after capture because of pressure changes may easily become "trapped" near the surface after discarding, and may therefore suffer complete mortality. Hence, it is not surprising that bottom dwelling round fish such as cod, haddock and saithe generally do not survive the discarding process well (e.g. Thurow and Bohl, 1976; Hokenson and Ross, 1993; ICES, 2000; Davis, 2002). It is worth noting that these fish may have at least three types of reactions to decompression:

(a) the swim bladder may become overinflated but remain intact;
(b) the swim bladder may be ruptured, but gas is kept in the abdominal cavity; or
(c) the swim bladder may rupture and gas be released through the ruptured abdominal wall.

In the last case, a fish that dives downwards may have a better chance of survival. Nevertheless, regardless of the level of damage to gas-filled organs, it is clear that the most effective way of reducing the mortality of such species would be to use selection measures that allow them to escape before being lifted to or near the water surface.

In some cases, these fish might benefit from the removal of excess gas from their swim bladders or abdominal cavities (e.g. Lee, 1992), but such measures are unlikely to be applicable in commercial situations. It is apparent that fishing conducted in shallow waters may result in somewhat lower discard mortality than deeper water fishing. In fact, Jurvelius *et al.* (2000) observed that mid-water trawling was far more lethal to trawl-caught and released pike-perch than trawling near the surface. It is also apparent that decompression speed affects the survival of discarded fish.

For fish that do not have gas bladders (e.g. sablefish, lingcod, flatfishes) mortality after release is more variable (e.g. FAO, 1994; Erickson *et al.,* 1997; Erickson and Pikitch, 1999; Davis, 2002). Several species of flatfish, for example, appear to have relatively good chances of survival (e.g. Kelle, 1976; 1977; Neilson, Waiwood and Smith, 1989; Van Beek, Van Leeuwen and Rijnsdorp, 1989; Robinson, Carr and Harris, 1993; Pikitch *et al.,* 1996), although relatively high mortalities have also been observed (e.g. Robinson, Carr and Harris, 1993; Lindeboom and de Groot, 1998). It is obvious that improved deck handling measures can be used to reduce further the discard mortality of these species.

The discard mortality of fish is related to the fragility and physical characteristics of each species. For instance, some fish species lose scales easily and may therefore suffer substantially higher mortality than species with more robust skin structures. If the catch consists of a mixture of species with hard parts, spines, shells and carapaces, and other more fragile species, the mortality of these latter species may be substantially greater than when only soft-bodied individuals are present. It is also notable that flatfish (e.g. Pacific halibut) may be more sensitive than round fish (such as walleye pollack, sablefish and lingcod) to suffocation in nets from pressure on the operculum (Davis, 2002). In addition, fish size may affect discard mortality. Smaller fish are generally weaker and more sensitive to capture and handling stress.

The average survival rate of undersized plaice, sole and dab in the German shrimp trawling was substantially lower than that of larger individuals (Kelle, 1976). The body size of trawl-caught and discarded Pacific halibut significantly affected mortality (Pikitch *et al.,* 1996). The increased sensitivity of smaller fish may be caused by fatigue from the swimming forced by the gear and by abrasion and crushing injury. Smaller specimens may also be more sensitive to increased water temperature at the surface, as well as to all kinds of handling on board. These effects have not yet been investigated thoroughly enough to make any quantitative evaluations.

ON-DECK EXPOSURE TIME AND AIR TEMPERATURE

On-deck handling time and air temperature are among the most important factors potentially influencing the survival of discards. Exposure to air is almost unavoidable when the catch is brought on to the deck. Exposure times can range from a few minutes when catches are small to several hours when catches are large or handling is inefficient. Exposure may occur over a wide range of air temperatures.

Higher survival is associated with short air exposure times and low air temperature on deck (e.g. de Veen *et al.,* 1975; Thurow and Bohl, 1976; Kelle, 1976; Pikitch *et al.,* 1996; Nielson, Waiwood and Smith, 1989; Erickson and Pikitch, 1999). Direct sunlight on deck may markedly increase the mortality of discarded fish (e.g. Kelle, 1976; Pikitch *et al.,* 1996). Any changes in fishing practices that reduce handling time and exposure to air would reduce discard mortality (assuming that lethal stress level has not been encountered).

It should be noted that freezing temperatures on deck may also contribute to discard mortality. However, very few scientific studies exist on this subject. Although handling time and air exposure are undoubtedly very important factors, it is obvious that the general handling process of discarded fish also plays an important role in determining their fate. It is also likely that sea state affects discard mortality. For instance, the haul back of trawl gear and the handling of catch on deck may take substantially longer in rough sea conditions, thereby increasing the likelihood of injury and mortality.

WATER TEMPERATURE

Water temperature affects the survival of discarded fish. There are marked species-specific differences in temperature sensitivity. Erickson *et al.* (1997) observed very high mortality (> 95 percent) for trawl-caught and discarded sablefish when surface water temperatures were high (18 to 20 °C). Mortality was substantially lower when surface water temperatures were 12 to 15 °C (Erickson and Pikitch, 1999).

Laboratory studies have shown similar results. Exposure of sablefish held at 5 °C to a range of seawater temperatures between 12 and 16 °C in the laboratory resulted in loss of feeding and increased physiological stress and mortality (Davis, Olla and Schreck, 2001). Mortality occurred after towing fish in a net at 5 °C and then exposing them to 12 °C. Exposure to 16 °C resulted in complete mortality for sablefish. Similarly, mortality rates increased with increasing seawater temperature for Pacific halibut and lingcod that were towed at 5 and 8 °C and then exposed to increased water temperatures, with 100 percent mortality reached at 18 °C in Pacific halibut and at 20 °C in lingcod (Davis and Olla, 2001; 2002).

Hyvärinen, Heinimaa and Rita (2004) exposed brown trout to an abrupt cold shock (10 min exposure to ice water in a chilling tank) after forced swimming that simulated swimming in a trawl. This treatment caused temporary unconsciousness of the fish. The cold shock seemed to be a stress factor, but the results did not indicate any permanently damaging effects on the fish. However, fish discarded in an unconscious state would certainly be highly vulnerable to predation by birds and predatory fish. Moreover, a longer exposure to cold water would likely be substantially more damaging.

TOW DURATION AND CATCH QUANTITY

Pacific halibut are frequently caught as bycatch by demersal trawlers in the Alaskan groundfish fishery (Figure 5). This bycatch must be released (discarded) back to the sea. Pikitch *et al.* (1996) estimated the mortality and physiological condition of trawl-caught and discarded Pacific halibut in the Gulf of Alaska.

Tow duration (of one to three hours) was among the factors that significantly affected halibut mortality. Similarly, the mortality of trawl-caught and discarded sablefish increased with longer tow durations (Erickson and Pikitch, 1999). These

FIGURE 5
Pacific halibut are frequently caught as bycatch by demersal trawlers in the Alaskan groundfish fishery. Regulations do not allow the retention of trawl-caught Pacific halibut; instead, this bycatch must be released (discarded) back to the sea. Some of the discarded halibut do not survive.

studies suggest that tow duration can be a significant factor affecting the survival of discarded fish. On the other hand, it is generally not known how long discarded fish have spent in the trawl. The duration of towing did not have a significant effect on the stress and mortality of undersized brown trout released after the haul (Turunen, Käkelä and Hyvärinen, 1994). Catch abundance, on the other hand, was a significant factor in causing stress.

Clearly, the effect of tow duration might be connected to codend catch size and catch composition, as well as to towing speed. It should be noted that catch volumes are rarely very large in experimental tows, so this variable is likely to come out as non-significant. Both longer tow duration and larger catch quantities increased the mortality of undersized discarded plaice (Kelle, 1976).

The effect of towing time on discard mortality is complex and should be explored more carefully. Nevertheless, for some species, shorter tows would probably increase the chances of survival. It is also likely that catch composition has an effect on discard mortality. Higher mortality may be assumed when the catch consists of spiny species and rubbish/trash. The amount of sand mixed in with the catch may also affect survival (Pikitch *et al.,* 1996).

MORTALITY OF TRAWL-CAUGHT AND DISCARDED INVERTEBRATES

Hill and Wassenberg (1990) studied the survival of fish and invertebrates discarded in a prawn trawl fishery operating in Torres Strait, Australia. They found that none of the crustacean floated, and about half of them survived. All crabs survived the 12-hour monitoring period. Twenty-six percent of cephalopods floated, with a survival rate of only 2 percent. The majority (88 percent) of starfish survived the 12-hour monitoring period.

Wassenberg and Hill (1993) concluded that the major factors determining the fate of discards from shrimp trawlers are whether or not the animals were alive when discarded and whether they sank or floated. It is noteworthy that these authors later suggested that their previous assessment of survival rates for animals discarded from prawn trawlers may have been optimistic because they monitored for only 12 hours. They argued that longer experiments would have led to substantially lower survival figures, particularly for crustaceans. In many studies the estimated discard mortality of crustaceans has been high (e.g. Wileman *et al.,* 1999) or very high (e.g. Harris and Ulmestrand, 2002). After being kept in tanks for two days, the average mortality for king and Tanner crabs captured as bycatch in commercial sole trawls in the Eastern Bering Sea was 78 to 79 percent (Steven, 1990). However, Lancaster and Frid (2002) estimated that about 80 percent of undersized brown shrimp survive the capture and discarding processes in the Solway shrimp fisheries (United Kingdom).

Harris and Ulmestrand (2004) demonstrated that nearly all discarded Norway lobsters in the Skagerrak-Kattegat Norway lobster fishery died because they were discarded through a low salinity surface layer. The authors underline the need to switch from discarding-based size-sorting lobster trawling methods towards ones that are size-selective. Norway lobsters escaping from a trawl codend have a relatively high likelihood of survival (Wileman *et al.*, 1999).

In most cases, shelled molluscs and echinoderms appear to survive capture and discard processes relatively well (e.g. Hill and Wassenberg, 1990). The survival of trawl-caught Patagonian scallops subjected to 30 minutes of aerial exposure on board was also high (Bremec, Lasta and Hernandez, 2004). Sea urchins, on the other hand, may suffer high mortality in beam trawling (e.g. Kaiser and Spencer, 1995).

It is likely that the on-deck handling processes will affect the later survival of discarded invertebrates. For instance, the instant and delayed mortalities of trap-caught snow crab increased substantially with increased drop height on deck (Grant, 2003). Climatic conditions may have a strong impact. Smith and Howell (1987) assessed the mortality of trawl-caught American lobsters that were exposed to sub-freezing (-9.5 °C) temperatures for periods of 30 to 120 minutes. The mortality of lobsters reached 100 percent at 120 minutes exposure.

CONCLUSIONS

Generally, fish do not survive discarding processes well. However, the mortality of discards varies considerably according to species, size and environmental conditions, as well as with fishing and handling procedures. Air exposure on deck clearly affects stress and mortality. Higher survival rates are associated with short air exposure and low air temperature on deck. Exposure times are a function of handling times on deck, and can range from a few minutes to several hours, occurring over a wide range of air temperatures.

A number of other factors have also been shown to affect the mortality of discarded fish. Extreme sea surface temperatures were shown to have a significant impact on the mortality of discarded fish and invertebrates; hence, when possible, fishing seasons should be established to exclude extreme water (and air) temperatures. Smaller individuals are generally more sensitive to capture and discard-induced stressors and may therefore show greater discard mortality than larger specimens.

For species that do not have gas bladders that inflate after capture, discard mortality can be reduced through improved on-deck handling procedures and other operational improvements. Any changes in fishing practices that reduce handling time and exposure to air are likely to reduce mortality. For many species, however, it is difficult to obtain a significant reduction of mortality through improved handling processes.

To improve the survival of these fish, they should escape before they are landed on the vessel deck, preferably at the depth of capture. This would significantly increase their likelihood of survival. The use of selective fishing gears is a potential approach to reducing the mortality of these fish.

Mortality associated with fisheries other than trawling

All major fishing gear types involve some degree of injury to fish through internal and external wounding, crushing, scale loss and hydrostatic effects, with the severity of the injury depending on the gear type and its operation. Susceptibility to injury varies with species and type of stressor. The aim of this chapter is to explore briefly the general factors that are important for an understanding of stress, injury and mortality associated with capture processes with fishing gears other than trawl. The discussion includes not only fish, but also some other animals affected by contact with fishing gears.

MORTALITY ASSOCIATED WITH BEING HOOKED AND RELEASED

There have been several investigations on the survival of fish released from the hook in various longline fisheries. Generally, it appears that hook penetration depth, hooking location and the technique used to remove fish from the hook have major impacts on subsequent survival. A swallowed hook may induce a substantially greater injury than a hooked mouth (e.g. through the jaw, lips or operculum).

Fish removed from hooks automatically (e.g. by a crucifier or gaff) experience a significantly higher mortality than fish removed manually (e.g. Kaimmer, 1994; Milliken *et al.,* 1999). Huse and Soldal (2002) showed that the mortality of undersized haddock released from a hook by means of a gaff was markedly higher (53 percent) than that of those that were torn off by means of a crucifier (39 percent).

Both release methods inflicted severe injuries to the mouth parts of the fish. Fish that were released by a gaff suffered also from punctures to the body wall and damage to the abdomen and intestines. It is worth noting that the gaff can be used to remove the hook without handling the fish, and this is likely to reduce the injury.

Hooking mortality is variable and is affected by many factors, for example, the size and shape of the hook. Trumble, Kaimmer and Williams (2000) conducted a large-scale tagging experiment on Pacific halibut released from longline gear; halibut experienced lower mortality following release from small circle or autoline hooks than from large circle hooks. Neilson, Waiwood and Smith (1989) studied the survival of Atlantic halibut (< 81 cm in size) caught by longline (16/0 circle hooks, at 210 to 300 m). They found that 77 percent of the longline catch survived more than two days in on-board tanks.

The mortality of handline-caught and discarded undersized Atlantic cod was significantly higher in deep water (54 percent) than shallow water (32 percent) (Pálsson, Einarsson and Björnsson, 2003). Parker and Black (1959) and Parker, Black and Larkin (1959) estimated delayed mortalities of 40 to 86 percent for troll-caught chinook salmon, and of 34 to 52 percent for coho salmon.

Wertheimer (1988) measured the mortality of chinook salmon released from commercial trollers. Fish length, injury location and lure type were the three factors influencing post-release mortality (9 to 32 percent). Chopin, Arimoto and Inoue (1996) observed no mortality in released sea bream captured by hook and line, although the fish sustained various types and levels of stress from the capture process.

Fish behaviour during capture included initial flight response, successive struggles of decreasing magnitude, reverse swimming, and finning to maintain position. Struggle activity reduced as the period of capture increased. Chopin, Arimoto and Inoue (1996) argued that hook and line-caught fish were able to exhibit an adaptive response to capture; the cessation of struggling resulted in the captured fish regaining their normal swimming positions and allowed them to recover. This reduced the probability of mortality.

In conclusion, hook-caught fish may suffer a range of injuries, stresses and mortalities depending on the species, size of fish, water temperature, depth of capture, hook type and size, bait type and size, site and depth of hook penetration, and how the fish are released.

MORTALITY ASSOCIATED WITH GILLNETTING

It is commonly assumed that many bycatch fish might be injured and die during the capture process in gillnets or immediately after release from a net. Thompson *et al.* (1971) recorded mortality of 80 to 100 percent for gillnet escapees (chinook salmon, coho salmon). Thompson and Hunter (1973) separated scale damage mortalities from those associated with combined physical injuries and physiological stress. They suggested that scale damage alone resulted in mortalities of 40 percent, while scale damage and stress accounted for 80 percent of mortalities among salmon escaping from gillnets.

The material of the net is likely to have a substantial effect on the injury and subsequent survival (Van der Haegen *et al.,* 2004). It is worth noting that Suuronen, Ikonen and Siira (2004) observed on average of only seven percent mortality among adult Atlantic salmon released from large floating trap-nets moored along the northern Baltic coast.

Hay, Cooke and Gissing (1986) collected Pacific herring passing through a 57-mm monofilament gillnet with a fyke net attached to the net. The fish were then transported to a cage and monitored for nine months. Mortality was low (< 2 percent) during the first two weeks, but rose afterwards (partly owing to high water temperatures at the cage site). Large herring had severe scale loss of up to 40 percent. Chopin, Arimoto and Inoue (1996) observed relatively high stress levels and mortality of sea breams captured by trammel net. The gill covers of fish were often held closed by the net. The degree of entanglement and constriction caused by netting around the fish's bodies did not reduce as a result of struggling.

Generally, gillnet fishery appears to cause substantial damage to fish, and fish released from a gillnet may suffer high mortality. Post-release mortality caused by gillnet injuries is variable, and is clearly species- and fishery-dependent.

Other factors that are likely to affect the post-release mortality of gillnet-caught fish include water temperature and fish size and condition. It is also notable that gillnet mortality may continue long after the end of the eventual gillnet fishing season. Gillnets are frequently caught on the bottom and subsequently lost. Trawl gears also drag and cut into pieces the nets. Depending on the conditions, lost gillnets may continue to catch fish several months or even years before they gradually disintegrate (e.g. Tschernij and Larsson, 2003). "Ghost fishing" mortality caused by lost gillnets is an important issue in many fishing grounds. This problem can be partially addressed by the use of biodegradable materials that deteriorate easily or other means to disable unattended gillnets, and by facilitating the quick recovery of lost nets.

MORTALITY ASSOCIATED WITH LOST POTS

Fishing with pots generally results in catches that are alive and uninjured, so in most cases unwanted bycatch organisms can be released with a good chance of survival, although factors such as on deck injury and air exposure, and decompression or thermal shock, may jeopardize the survival of released organisms. However, pots are frequently lost in many types of crab and lobster fisheries (e.g. Smolowitz, 1978; Breen, 1987; Godoy, Furevik and Stiansen, 2003).

The head-line or hauling line may break during hauling, drifting ice may carry the pots away from the set location, the propeller of a vessel may cut the line from the buoy, or strong currents may force the buoy below the surface. The traditional materials used in the construction of pots do not deteriorate easily. Concerns have therefore been expressed as to whether lost pots continue to catch various commercial and non-commercial species, thereby contributing to unaccounted mortality.

Vienneau and Moriyasu (1994) and Hebert *et al.* (2001) found high mortality among snow crabs trapped in conical pots. Godoy, Furevik and Stiansen (2003), on the other hand, observed relatively low mortality in king crabs from lost pots; crabs escaped from the pots relatively easily.

These authors speculated that this difference may simply be connected to the fact that a snow crab is much smaller than a king crab, and may therefore find it more difficult to escape through the top entrance. Clearly, the overall pot design and the entrance size and shape influence the viability of escaped crabs, and thereby the mortality rates caused by lost pots. To prevent extensive ghost fishing, many pot fisheries are regulated to include galvanic timed releases or biodegradable materials that deteriorate easily.

MORTALITY ASSOCIATED WITH PURSE SEINE OPERATIONS

Purse seining is generally known as a non-selective fishing method. Sometimes the catch, or part of it, is released from a purse seine during the haul-back process. Lockwood, Pawson and Eaton (1983) investigated the effect of crowding on mackerel during purse seine operations. They found that the mortality rate was related to fish density and duration in the net before slipping.

Attempts have been made to improve the selection in purse seining by using sorting grids. However, relatively high mortalities (> 40%) were measured in mackerel that escaped through a sorting grid with a bar spacing of 40 mm attached in a purse seine (Beltestad and Misund, 1996; Misund and Beltestad, 2000). Mackerel suffered severe stress and skin injuries during the selection process.

Misund and Beltestad (2000) concluded that the size-selection process in mackerel purse seining causes too high a mortality rate to allow it to be recommended for commercial fishing. Misund and Beltestad (1995) investigated the survival of Atlantic herring after simulated purse seine bursts. Their results indicated that there may be high mortality among herring connected to the net burst, which caused severe scale loss that may have resulted in mortality owing to severe osmoregulation difficulties.

MORTALITY ASSOCIATED WITH (SCALLOP) DREDGING

Caddy (1973) estimated that between 10 and 17 percent of scallops died in the Gulf of St. Lawrence as a result of damage and predation associated with scallop dredging. McLoughlin *et al.* (1991) in Bass Strait, Australia, assessed dredge damage on dense beds of scallops, and estimated indirect mortality of scallops at 88 percent (owing to bacterial infection spreading through the residual population), which suggests a very high unaccounted post-harvest mortality. The authors estimated that 14 days after dredging, there were still more than 30 percent of the original number of live scallops on the sea bed, but this had decreased to less than 1 percent after 300 days.

Currie and Parry (1999), on the other hand, observed that the proportion of scallops damaged by dredging was generally low in Port Phillip Bay, southeastern Australia. The highest percentage (20 percent) of dead scallops was observed on the firmest (hardest) sediments, where scallops were occasionally trapped beneath the passing dredge skids. Messieh *et al.* (1991) reported that on the eastern Canadian continental shelf, scallop dredging destroyed (e.g. by crushing) about the same quantities of scallops as were caught by the dredges. Mortality of uncaught clams ranged from 30 to 92 percent.

The density of animals in fishing grounds was reduced by roughly 40 percent immediately after dredging, but returned to its original levels within ten months

(Messieh *et al.,* 1991). Within one hour of fishing, fish and crabs were attracted to the dredge tracks in densities that were three to 30 times greater than those observed outside the tracks. It is clear that the long-term mortality caused by dredging operations can be very high.

It is worth noting that bycatch may be another problem for dredge fisheries. For instance, dredging in southeastern Australia periodically catches spider crabs as bycatch (Currie and Parry, 1999); the mortality rates of discarded spider crabs average more than 50 percent.

CONCLUSIONS

All major types of fishing gear involve some degree of injury to fish. Stress response and injury vary according to gear type and mode of action. The likelihood of survival for fish that have been released from a hook varies. The injuries caused by a demersal gillnet are different from those caused by a trapnet, where fish can swim without any contact with the gear.

Gears deployed in surface waters do not include the effects associated with depth. Susceptibility to injury varies with species and stressor type. Survival ultimately depends on how well the fish are able to adapt to capture (and release) conditions. Clearly, differences in injury among gear types is an important aspect when considering the most appropriate and sustainable fish capture methods.

Methodologies and techniques used in escape survival experiments: general guidelines for field experiments

When investigating the survival of fish escaping from a fishing gear under commercial fishing conditions, it is necessary to collect the escaping fish and then either hold them captive for a specific period of time, or tag and release them (preferably at the deph of capture) for later recapture. For the latter approach, very little adequate technology is available, so escapees are usually held and monitored in cages near the fishing ground where they were captured. It is noteworthy that most escape-survival experiments carried out so far have not fully simulated commercial fishing conditions in terms of tow duration, depth, catch size and season. Hence, these experiments may not reflect the full range of possible sources of injury and mortality encountered by trawl codend escapees under normal commercial fishing conditions.

Typically, the mortalities of codend escapees have been assessed in relatively shallow waters during summer months, and under relatively short trawl tows and low catch rates (e.g. Main and Sangster, 1990; 1991; Soldal, Isaksen and Engås, 1993; Lowry, Sangster and Breen, 1996; Sangster, Lehmann and Breen, 1996; Suuronen *et al.,* 1996a; 1996b; Wileman *et al.,* 1999). This chapter focuses on potential ways of improving techniques for reliably assessing the survival of fish that escape from trawl codends across a wider range of fisheries and environmental conditions. Laboratory methods for assessing various types of capture-induced injury and physiological stress are beyond the scope of this discussion.

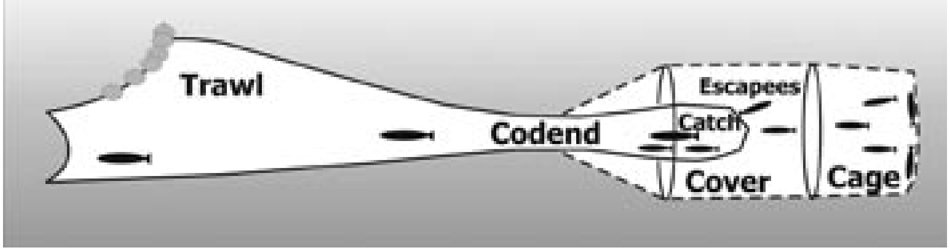
POTENTIAL FLAWS IN METHODOLOGY

Investigations conducted in the field have revealed that survival can be markedly affected by methods of collecting, transporting and monitoring the escapees. For instance, the sampling of escapees in the collection cover may cause them substantial damage and stress (Sangster, Lehmann and Breen, 1996; Suuronen *et al.,* 1996b; Wileman *et al.,* 1999; Breen *et al.,* 2002), thereby resulting in overestimates of escape mortality. Suuronen *et al.* (1996b) observed that small Baltic herring that had escaped from a trawl codend were soon lying against the rear netting wall of the collection cover. The fish had been exposed to a continuous flow of water inside the cover, and were apparently unable to sustain the swimming speed necessary to maintain their position within it. Hence, they were forced against the rear wall of the cover (Figure 6), where they were highly vulnerable to skin abrasion, scale loss and suffocation. Similar observations were made by Breen *et al.* (2002) on young haddock captured in a cover. The authors suspected that, depending on the length of time spent in the cover ("cover exposure time"), such entrapment against the cover may cause serious injury and fatalities among fish.

Although many cases have shown that the use of codend covers may lead to overestimates of escape mortality (see above) – unless the necessary precautions are taken – it may also result in underestimates. Breen *et al.* (2002) demonstrated that the water flow around a codend with a typical cover was significantly lower (by circa 80 percent) than that observed around a normal uncovered codend. The reduced flow means that the codend experiences less drag, and thereby the netting forming the

FIGURE 6

Traditional technique to collect escapees into a cage attached to the aft part of the cover. Observations of fish in covers have revealed that smaller fish struggle to maintain position and are often forced against the netting at the back of the cover. The period for which the escaping fish are forced to swim behind the trawl can effect their subsequent survival.



codend will be under less tension. As a result, the passage of a fish through the meshes of a codend may be easier and perhaps less injurious. The passage may be less hazardous also because of reduced water flow outside the codend. Clearly, the presence of the cover around the trawl codend may protect escaping fish from the injurious forces that are normally experienced during passage through a trawl codend. This mechanism means that the cover may contribute to the underestimation of true escape mortality.

Moreover, under normal commercial fishing operations, codend escapees are free to swim away into their normal environment to recover. Enclosure in a cage, often with other damaged fish and in non-favourable environmental conditions, is likely to cause additional stress that may further contribute to mortality, possibly also through cross-infection. Hence, it might be argued that the recovery of a damaged fish is hindered by captivity (for further discussion, see Main and Sangster, 1990; 1991). However, it could also be argued that fish within the cage are protected from predators and other potential hazards. Therefore, great caution is needed when interpreting past and present results. Clearly, in a survival experiment, a fish may die of causes other than capture and escape-related damage. The key issue in assessing the survival of escaping fish is to ensure that the collection and monitoring methodology does not induce stress and injury in the fish that are subject to investigation. Experimentally induced stress and injury should be eliminated to the extent possible. It is important to realize that controls cannot account for all the potential errors and flaws in experimental methodology and design. General standardized methods and protocols to generate reliable estimates of escape mortality rates in a wide range of fisheries and conditions are not yet available. The ICES Topic Group on Unaccounted Mortality in Fisheries (ICES, 2000) provided the following general principles, which should be adopted in survival studies:

- The capture and maintenance of specimens should take place without any additional stress or injury to them.
- During the transfer from the site of capture to the site of captivity, specimens should experience a minimum level of environmental change.
- Conditions in captivity should be stable and mimic as closely as possible the ambient conditions in the wild.
- The effects of captivity should be closely monitored; ideally this should involve a suitable control group of specimens.
- A full description of any mortality occurring within the experiment must be made in terms of all possible explanatory variables, both experimental and environmental.

These principles are still highly relevant and should be followed to the extent possible. The following sections give suggestions and practical recommendations for putting these principles into practice.

COVER EFFECT AND SAMPLING DURATION

The first critical task in a survival study is to find (or develop) a method for collecting the fish escaping through trawl codend meshes or other selective devices. Collection should be done without causing any extra stress and injury to the fish. There are many technical variations for capturing escaping fish. Until the early 1990s, the most common method was a traditional codend cover, in which the rear part was designed as a holding cage (Figure 6). The cover was closed at the beginning of the tow and released at the end, when the codend was at the surface. Therefore, escaping fish were sampled throughout the entire haul.

To reduce the effects of cover exposure on escapees, the haul duration was often limited to periods that were much shorter than those used in normal commercial practice (e.g. Suuronen *et al.,* 1996b). However, sampling durations were in most cases too long from the escapee's point of view (owing to cover exposure effects). For example, the smallest escapees tended to become trapped against the rear netting wall of the cover, sometimes only a few minutes after escape from the codend (e.g. Soldal, Isaksen and Engås, 1993; Suuronen *et al.*, 1996b).

Breen, Sangster and Soldal (1998) and Breen *et al.* (2002) demonstrated that the period during which escaping fish are sampled and forced to swim in the cover (or in the cage attached to the cover) may have a significant effect on their subsequent survival. "Cover-induced mortality" is linked to many stress-inducing factors, among which the swimming ability of the fish is one of the most important. Hence the high mortality seen in some investigations, particularly among the smallest escapees (e.g. Suuronen, Erickson and Orrensalo, 1996), could be at least partly the result of cover-induced mortality. Small fish may become too weak and exhausted by the capture process to have enough energy left to swim within the cover; the water flow then forces them against the cover wall.

To reduce cover-induced mortality on young Baltic herring escapees, Suuronen *et al.* (1996b) reduced the sampling (and trawl towing) time to only a few minutes. The relevance of such an approach, however, should be questioned because it does not reflect commercial fishing conditions. Moreover, such a reduction of the sampling (and towing) time means that insufficient numbers of the target species are often caught and collected in the sample, particularly when working with groundfish.

Clearly, such approaches and techniques have not been adequate for assessing the survival of escaping fish under commercial fishing conditions. A sampling method is needed in which the duration of the tow is not restricted by the method used to collect escapees.

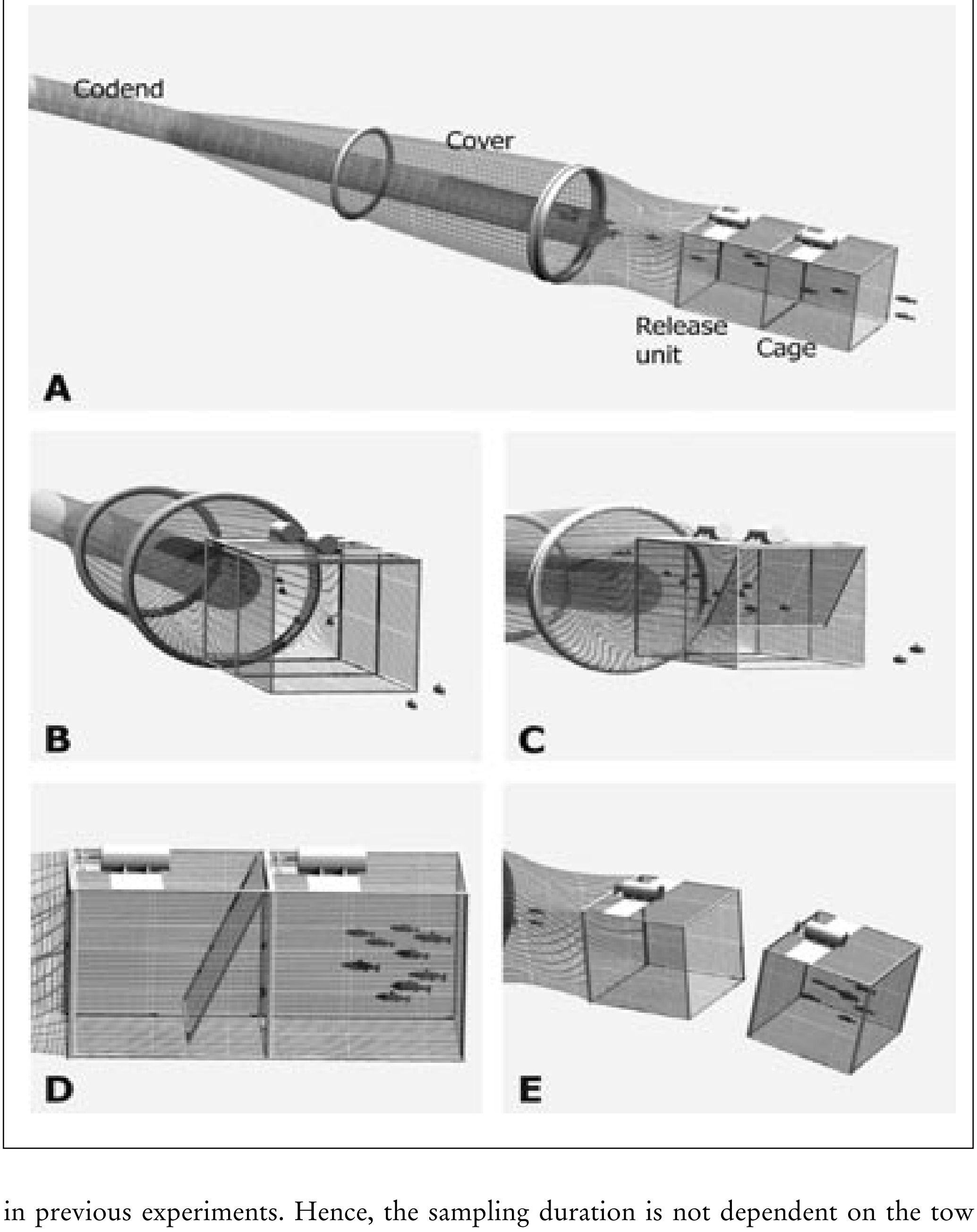
METHODS FOR COLLECTING ESCAPEES

To avoid decompression injury and temperature shocks to the escapees, Soldal, Isaksen and Engås (1993) used acoustic, and Suuronen *et al.* (1996a; 1996b) mechanical, releasers to close and release the cages from the cover remotely (at the depth of capture). Nevertheless, these systems still had the problem that sampling of the escapees was possible only at the beginning of the tow; collection was limited to the very first part of the tow. To minimize injury from cover exposure and simultaneously permit realistic tow durations, later designs allow the sampling of escaping fish at any moment of a haul (e.g. Lehtonen, Tschernij and Suuronen, 1998; Erickson *et al.,* 1999; Wileman *et al.,* 1999; Ingolfsson, Soldal and Huse, 2002).

The system developed by Lehtonen, Tschernij and Suuronen (1998) has the following principle (Figure 7): the collection cage attached to the cover has two gates that can be closed separately during the tow to conduct the sampling. The collection cage can then be remotely detached from the cover with the captive fish contained within. With this technique, sampling can be conducted at any moment of a haul, and the sampling period can be controlled precisely and kept substantially shorter than

FIGURE 7

A cage technique by which a sample of escaping fish can be collected during any moment of a haul. During the trawl tow, the gates of the collection unit are initially open so any fish escaping from the codend are allowed to swim freely through the cage into the open sea. Collection of a sample begins when a pre-set timer activates the closure of the rear gate. After an appropriate sampling time, the front gate is closed using a second timer, confining sampled escapees inside of the collection unit. A third timer activates the separation of the collection unit from the release unit. The collection unit then drops to the sea bed containing captive fish (modified from Lehtonen, Tschernij and Suuronen, 1998)



in previous experiments. Hence, the sampling duration is not dependent on the tow duration. Likewise, the haul duration is not affected by the sampling process.

Survival can be assessed for short and long tows, and for small and large catch quantities. Cover exposure time (i.e. sampling time) can be kept short enough to avoid cover-induced injury, but long enough to provide adequate numbers of escapees. Suuronen, Lehtonen and Jounela (2005) successfully applied the system developed by Lehtonen, Tschernij and Suuronen (1998) to assess the survival of Baltic cod escaping through various trawl codend meshes (Figure 8).

FIGURE 8
The cage-unit attached to a codend cover is being lifted on a vessel deck. Note that both gates of the collection cage (on the left side) are closed. This design allows the collection cage to be closed and released remotely so that escaped fish can be sampled at any time during the tow, thus allowing a short sampling period while not affecting the haul duration. The collection cage can be detached from the cover system with the captive fish contained within.

A relatively similar technology using a double set of acoustic releasers was developed by Wileman *et al.* (1999). However, instead of using a door to close the rear part of the cover, their experiments used a rope to close the rear part of the cover netting. This technique was further developed into a solid door system (Ingolfsson, Soldal and Huse, 2002). Erickson *et al.* (1999) further modified the technique of Lehtonen, Tschernij and Suuronen (1998) when investigating the survival of Alaskan pollock escaping through a square mesh upper panel. They used an underwater camera to monitor the cover and the collection cage during the tow.

The collection of escapees began only after an adequate catch had been accumulated in the codend. When there were adequate numbers of escapees in the cage, it was remotely closed and released. Hence, the sampling period was restricted to the time that was required to collect the sample. No additional stress and injury was caused to fish. When there is high variation in fish density, a compromise often has to be made between sampling time and sample size.

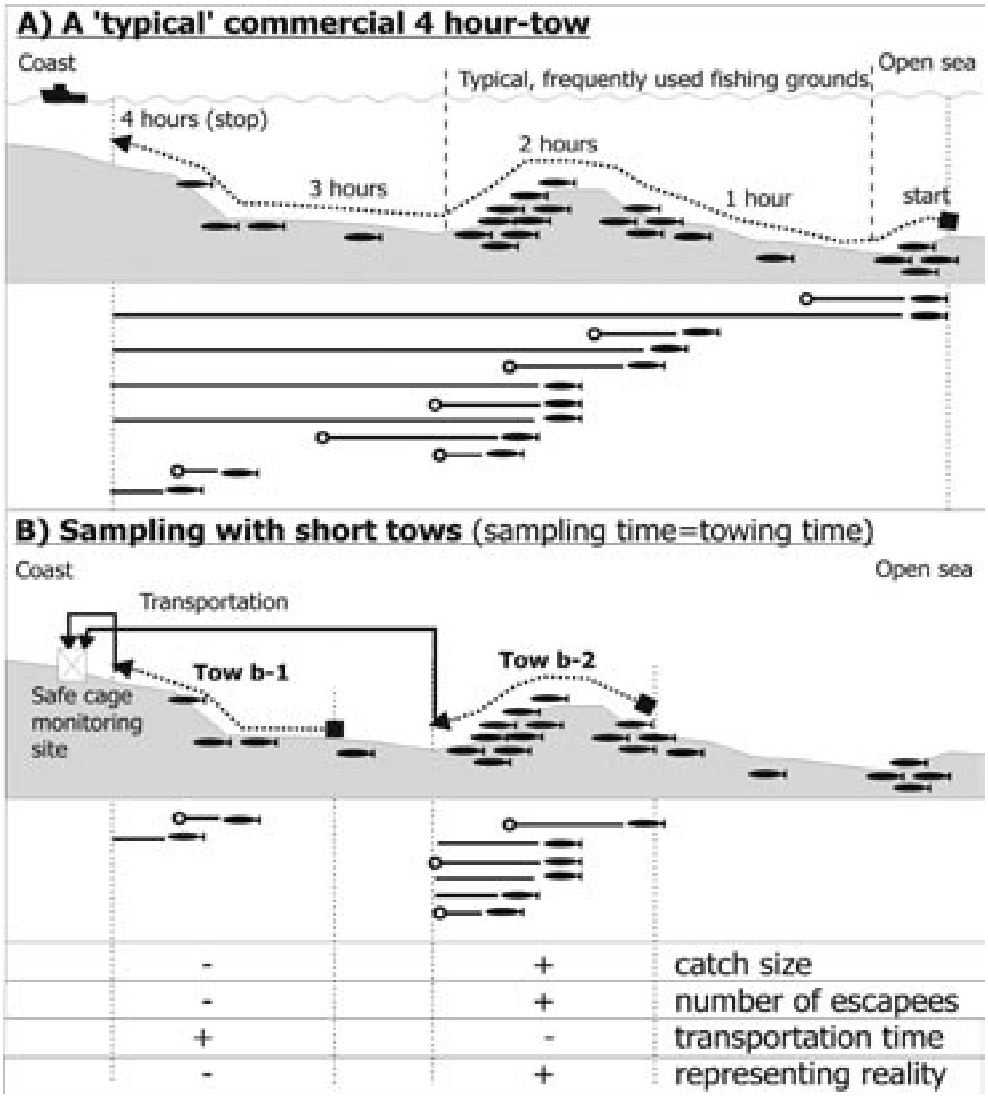
COLLECTION STRATEGIES

It is largely unknown how long individual fish swim in trawls and when they escape. Some may swim within the gear throughout the tow duration, while others may escape immediately after capture. It is possible that the survival of fish escaping at the beginning of the haul, when there are fewer abrasive objects within the codend and when fish have spent only a short time within the gear, is higher than that of those escaping at the end of tow, when the codend may be full of debris, fish and other substances, and when the flow patterns may be less favourable for controlled and oriented swimming. Moreover, fish escaping at the end of the tow may be more exhausted than those escaping earlier. Therefore, it is important to assess and understand when and where during the tow the escapees should be sampled.

Figure 9 demonstrates a typical four-hour commercial demersal trawl tow (upper figure, A). Fish are captured along the path of the tow. The amount of time spent inside the gear varies considerably among individual fish. Some fish escape almost immediately, while others may swim for a long time within the gear before escaping. The lower figure (B) demonstrates two sampling approaches that have generally been used in survival experiments. Tow b-1 presents a sampling approach where the tow ends over a shallow bank so that the collection cage can be released on to a sheltered site. Therefore, the experimental haul is conducted near the shore in an area where fish density is typically relatively low. Owing to methodological restrictions, fish are sampled during the entire tow, i.e. sampling time is the same as towing time. The advantage of this technique is that it does not require the transfer of cages and escapees after release. The disadvantage is that the catch rates may be small and the tow does not represent a typical commercial trawl

FIGURE 9

The upper figure (A) demonstrates a typical four-hour commercial demersal trawl tow. Fish are captured along the path of the tow. Some of these fish swim for longer periods within the trawl, while others escape almost immediately. The lower figure (B) demonstrates two sampling approaches generally used in survival experiments. In tow b-1 the experimental haul is conducted near the shore where fish density is relatively small. In tow b-2, escapees are sampled in areas where fish density is high, and the escapees are then transferred to the cage site.



tow regarding catch size, number of escapees and capture depth. This type of approach has commonly been applied in survival experiments (e.g. Suuronen *et al.*, 1996a).

Tow b-2 (Figure 9, B) presents the other typical approach used by experiments to collect escapees from trawls. In this approach, escapees are sampled in areas of high fish density and where a commercial fishery is typically operated. The sampling time is the same as the towing time (e.g. it is restricted to 30 minutes to minimize additional stress and injury to escapees from cover exposure). After the collection cage has been released, it may be transferred to a more sheltered cage site. The sample of escapees in this approach is likely to be more representative than that of Tow b-1, but the potential stress and injury induced by the cage transfer process may cause difficulties in the final interpretation of the results.

FIGURE 10

A more advanced sampling approach when technology is available to collect a sample of escapees at any point and for any length of time during a commercial tow. The sample can be taken at the beginning, the middle or the end of the tow. This approach allows a more realistic assessment of mortality

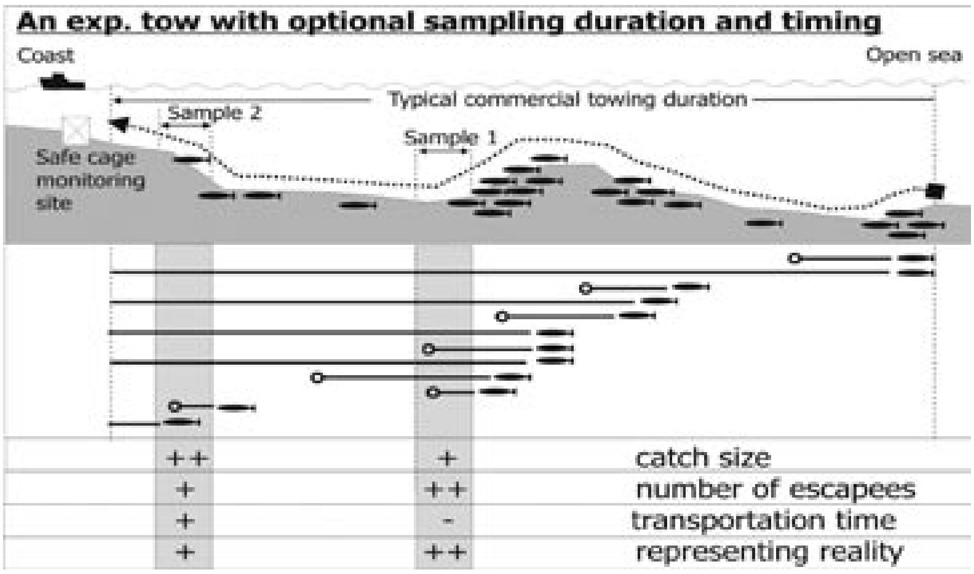


Figure 10 demonstrates a more advanced approach where technology is available to collect a sample of escapees from any point and for any length of time during a commercial tow (e.g. the technology developed by Lehtonen, Tschernij and Suuronen, 1998). The sample can be taken at the beginning, the middle or the end of the tow. Clearly, this approach allows a more realistic assessment of mortality. However, when Suuronen, Lehtonen and Jounela (2005) applied it in their Baltic cod survival experiments, they sampled fish during only the last 20 minutes of the tow in order to release the cages at a sheltered cage site. This approach was chosen because these authors did not want to have to transfer the cages after release. If the cages could have been left at the site of release at any point along the trawl path, samples could have been taken at any moment of the tow (and without the transfer of escapees after cage release). However, this would have made the daily monitoring of cages difficult because of the long distances, and would have required an area in which no other trawl towing was conducted (because the cages could easily have been damaged or lost as a result of other fishing activity). Nevertheless, if technically and logistically possible, this last approach would be highly recommended. Using the methodological approach presented in Figure 10, it is possible to assess the potential difference in survival of escaping fish at any particular moment of the tow.

DURATION OF SAMPLE COLLECTION AND SIZE OF SAMPLE

A statistically adequate sample of fish from various sizes groups should be collected in each cage – a goal that is not always easily accomplished. The number of fish collected depends on the escape rate and sampling duration. A compromise is usually needed between sample size and sampling duration (which should be as short as possible). The escape rate is not normally known and has been quantified in only a few cases. In addition, it is likely to vary substantially within the same tow and between tows. The escape rate depends on numerous factors such as fish species and size, fish density, catch size and composition, geographic location, time of year, water temperature, amount of available light, and selectivity of the experimental gear.

Pilot tows are often necessary in order to predict escape rates before experiments are initiated, and they may provide some idea of potential escape rates and appropriate sampling times. Generally, relatively high escape rates have been encountered in pelagic fisheries; it is not uncommon to have several hundred escapees in a period of only one minute (e.g. Suuronen *et al.,* 1996b; Erickson *et al.,* 1999; Pikitch *et al.,* 2002). This may occur, for instance, when a large school enters a trawl; between schools there may be no escapes. On the other hand, groundfish fishery escape rates may be somewhat more constant, but may be of only very few individuals per minute (e.g. Sangster, Lehmann and Breen, 1996; Suuronen *et al.,* 1996a). Occasionally, however, high escape rates have been encountered with groundfish (e.g. Soldal, Isaksen and Engås, 1993). Adjusting the sampling time according to the escape rate with the help of an on-line underwater video camera and remote-operated cage closure and release mechanisms is an alternative that deserves attention (see Erickson *et al.,* 1999; Pikitch *et al.,* 2002; Ingolfsson, Soldal and Huse, 2002). With such a technique, it is possible to collect a statistically adequate number of escapees in each cage. This would reduce the number of "invalid" tows to close to zero.

CONSTRUCTION OF THE CODEND COVER

As described in previous sections, most survival assessment techniques use some form of codend cover to collect escapees. The cover (and the collection cage attached to it) should be designed so as not to induce skin injury and other damage to escapees. It should be made of soft knotless material to minimize abrasive injury, and have relatively small mesh size to retain small fish and prevent the meshing of fish. It is also necessary to restrict the water flow inside the cover. A supporting hoop or frame system (Figure 11) may be necessary to prevent the cover from collapsing against the codend (see e.g. Sangster, Lehmann and Breen, 1996; Wileman *et al.,* 1996; 1999). Alternatively, special kites can be used to keep the cover open (Madsen, Hansen and Moth-Poulsen, 2001**).** There must be adequate space between the cover and the codend in the area where escapees are collected. The cover affects water flow in and around the codend (e.g. Wileman *et al.,* 1996; Breen *et al.,* 2002; Madsen and Holst, 2002). This may have a substantial effect on the behaviour and survival of escaping fish (see above). Therefore, the flow in and around the codend should approximate that of actual commercial situations, where there is no cover around the codend or selective device. In particular, the design should ensure that the water flow inside the cover, outside the codend, is as close as possible to a commercial tow, and that there is no flow in the rear part of the cover, where fish may recover from exhaustion. Water flow patterns can be affected by constructional details of the cover. The twine thickness and the mesh size of the cover, as well as the towing speed, should be carefully considered in each particular experiment. In addition, the visual contrast between the cover netting and the surrounding water may affect the escape behaviour of fish swimming in the codend.

Generally, the visual contrast of the front and middle parts of the cover should be minimized in order to obtain escape behaviour that is reflective of commercial conditions. Furthermore, the cover must be large enough in all dimensions. Erickson *et al.* (1996; 1999) showed by video observations that walleye pollock escaped along the entire length of the escape panel to 18 m in front of the catch bulge. Hence, for this species, a cover installed only a few metres ahead of the codend would not collect those fish that escape from the front part of the codend. Such fish may show different mortality from those escaping from the aft part of the codend. Therefore, if the experiment is supposed to study the overall mortality of escapees, the codend cover should be installed to cover the whole length of the codend and other potential selection devices (i.e. the whole selective area). It is also important that the collection process and the proper performance of the cover and collection unit are monitored with underwater camera; there is always a possibility that some critical gear component becomes twisted or blocked, preventing normal performance.

FIGURE 11
Setting out the trawl, codend cover and collection cage-unit from a trawler. The cover around the codend is supported by two hoops. The timers of the release-unit can be seen on the surface.

TRANSFER OF ESCAPEES TO CAGE SITE

Once the specimens have been collected in the cover or the collection cage, they usually have to be transferred into a sheltered and stable environment where they can be held without large risks of additional damage and be monitored efficiently. However, the transfer process can be risky (e.g. Lowry, Sangster and Breen, 1996; Erickson *et al.*, 1999). Clearly, transfer should involve minimum environmental changes and stress for the escapees. Abrupt changes, for instance in water temperature, hydrostatic pressure, salinity, water flow or ambient light level, may affect the stress and survival of fish (e.g. Olla, Davis and Schreck, 1998; Wileman *et al.*, 1999). Hence, all changes in environmental parameters should be avoided during transfer. Transporting should take place at a slow speed avoiding excessive water flow, and fish should be monitored throughout the transfer process. Fish should arrive at the cage site in good condition. To overcome some of the common problems of underwater fish transport, the collection cover/cage may be placed in a protective container for the towing process (Lowry, Sangster and Breen, 1996; Sangster, Lehmann and Breen, 1996). A rigid container can be towed far more easily and quickly to the cage site, while fish inside the cover are protected from excessive water flow. However, this method has several practical difficulties and can be very labour-intensive (see Lowry, Sangster and Breen, 1996). Controlled decompression protocols should be used if the transfer involves a marked change of fish depth. If the depth has to be changed, there is a risk of fish's gas bladders being overinflated to the point of rupturing as a result of depressurization. Erickson *et al.* (1999) ensured that cages remained continuously deeper than 10 m, and transferred them by using constant video surveillance and monitoring of the cage and environmental parameters (see also Pikitch *et al.*, 2002).

LOCATION AND DESIGN OF MONITORING CAGES

The conditions where the fish are monitored should mimic as closely as possible those experienced by that species in its normal life (after escape). On the other hand, the monitoring site should be sheltered and practical for observing the cages and the fish inside. It is almost inevitable that some compromises have to be made in terms of normal natural (commercial fishing) conditions and practicability. To overcome, or at least mitigate, the stress induced by confinement in a cage, many field experiments keep the sampled fish in or close to the area where they were caught but in a specific cage site (e.g. Ingolfsson, Soldal and Huse, 2002; Suuronen, Lehtonen and Jounela, 2005). At cage site, fish are transferred from the collection cage to the separate larger monitoring cages (e.g. Main and Sangster, 1990; Suuronen *et al.*, 1996b), or the collection cages are serving as monitoring cages, i.e. there is no transfer of fish from one cage to other (e.g. Suuronen *et al.*, 1995; Suuronen, Lehtonen and Jounela, 2005). Fish can be held

FIGURE 12
After escaping from a trawl codend, Baltic cod are held in a monitoring (collection) cage on the sea bed. Fish are swimming calmly in a loose school format.

in cages that are suspended in the water column or placed on the sea bed (Figure 12). Suspended cages are best used with pelagic species (e.g. Suuronen *et al.*, 1995; 1996b) but have also been used with demersal species (Jacobsen, Thomsen and Isaksen, 1992; Soldal, Isaksen and Engås, 1993; Suuronen *et al.*, 1996a; Ingolfsson, Soldal and Huse, 2002). The major disadvantage with pelagic cages is that they are highly vulnerable to changes in environmental conditions.

Wave action and strong currents can force the cage to move considerably, causing additional stress to fish. Moreover, vessel traffic may cause severe problems by cutting off the mooring ropes of cages, sometimes dragging them for distances along the vessel. The use of pelagic caging with demersal species is questionable. Strictly, demersal species may need the sea bed for at least part of the day, and are likely to find much of their food there. Isolation from the sea bed could lead to additional captivity-induced stress. Sea bed cages are usually more stable in terms of environmental conditions. There are several critical choices to be made regarding cages and cage sites. Sea bed cages should be able to stay freely at the bottom; therefore, a rectangular shape is most suitable. A rigid frame is usually needed. Pelagic cages can be cylindrical and can be suspended; therefore, they can be constructed of hoops and netting, i.e. have a simpler construction. Cages should be large enough to allow a large sample of escapees to be held without any additional stress and injury. Some assessment should be made of the average number of fish to be held in cages and the amount of water required per fish. Netting for the cage should be as soft as possible, to avoid abrasions, and of relatively small mesh size, to avoid meshing. Environmental conditions, as well as fish behaviour, in cages should be constantly monitored. Abrupt changes in water temperature, salinity and quality should be avoided as much as possible by careful location of the cage site (see Suuronen, Lehtonen and Jounela, 2004). Fish held in cages should be offered suitable food regularly.

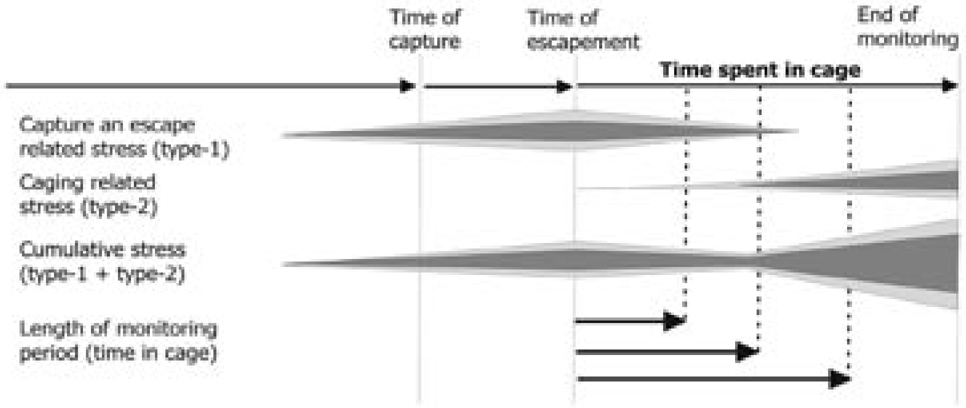
DURATION OF MONITORING

When a fish that has escaped from a trawl codend survives for a certain period in a monitoring cage, it has obviously recovered from its traumatic experience. If it dies during the monitoring period, there is often uncertainty about the cause of death. That is, fish held in monitoring cages may have died of causes other than capture and escape-related damage. The duration of the period for which escapees are monitored may have a large influence on the observed mortality (Wassenberg and Hill, 1993; Suuronen *et al.*, 1996b; Pikitch *et al.*, 2002).

Mortality has generally been shown to peak in the first two to three days after escape, the highest mortality usually occurring during the first day (e.g. Wassenberg and Hill, 1993; Chopin *et al.*, 1996a; Sangster, Lehmann and Breen, 1996; Suuronen *et al.*, 1995;

FIGURE 13

General illustration of potential stress components in a survival study. Capture and escape-related stress is at its highest during the escape, and then decreases slowly. Captivity-related stress starts to increase after escapees have spent a few days in a cage. Total stress, which may be highly cumulative, is presented in the lowest graph – suggesting that total stress may increase substantially when the duration of caging is extended. This suggests that cage monitoring may not be a suitable technique for the long-term evaluation of mortality.



1996b; Wileman *et al.,* 1999). The rate declines with time, usually reaching a minimum after one or two weeks. Mortality assessments over only a few hours may not be adequate for measuring short-term capture and escape-induced mortality. On the other hand, observation periods longer than one to two weeks may not be useful because of secondary infections and the stress connected with captivity (Figure 13). Interpretation of results may become more difficult the longer the experiment continues. Delayed deaths in monitoring cages are often correlated to the onset of various skin infections and other problems (e.g. deteriorated caudal fins, lesions and sores).

These types of secondary infections have been described for many species (e.g. Main and Sangster, 1990; Soldal, Isaksen and Engås, 1993; Suuronen, Erickson and Orrensalo, 1996; Erickson *et al.,* 1999). In fact, for many fish speces, cage methodology may be suitable for studying only primary mortality. Clearly, assessing long-term mortality caused by secondary infections and predation may require other technologies (tagging, etc.).

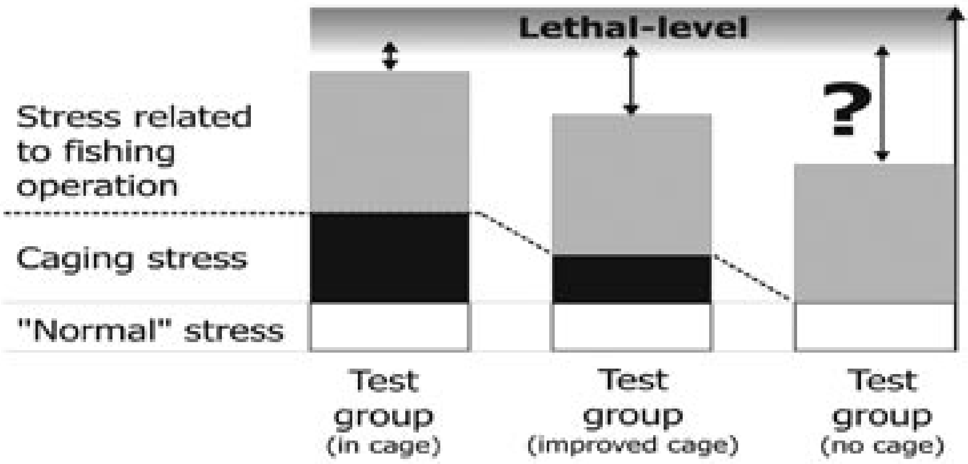
CONTROL SAMPLES – WHAT THEY SHOULD REPRESENT

The potential effect of captivity on escapees during the monitoring period can be assessed through the use of adequately captured and held controls. That is, a representative group of fish of the same species and size are held in captivity in similar cages and in the same area as the escapees, and their survival is assessed in the same way. If captivity has no lethal effect on the captive fish (over a specific period), there should be no observed mortality in the control group. When there is mortality among controls, it is important to know why they died. Death may be due to captivity stress, but it may also at least partly be due to natural mortality over that period, or to stress and injury from the capture of control fish. This must be known when interpreting the mortality for escapees held in cages. The equation in which "control mortality" is subtracted from "trawling mortality" to derive "escape mortality" may not always be quite true.

One of the major difficulties with controls is the question of what aspect of the experiment they are supposed to be a control for. The control fish should represent as closely as possible the population of fish that are in the test groups (treatments),

FIGURE 14

There are at least three sources of stress in a typical survival experiment: "normal" baseline stress of the fish; stress related to fishing operations (capture and escape); and stress caused by captivity in a cage. If fish suffer significant stress from captivity (left column), the high mortalities observed in treatments may be interpreted incorrectly as capture and escape-induced. To be able to make firmer conclusions of the observed mortality of treatments, the stress and injury induced by caging should be minimized to the extent possible (centre column), or totally eliminated (right column).



except regarding the test variable(s), i.e. the capture and escape process. Usually, control fish have not experienced all of the aspects of the experiments, such as capture and confinement in the cover and collection cage and transfer to the cage site. In fact, in order to be able to measure the potential mortality caused by the collection and transport of escapees, there should be at least two different types of controls: those that determine the effects of captivity in the holding cage; and those that determine the effects of collection and transfer to the cage site (see Suuronen *et al.,* 1996b; and Wileman *et al.,* 1999 for more details).

In a survival experiment there is always a possibility of severe cumulative effects that are difficult to detect and measure, even when there is an effective arrangement of controls. For instance, a control sample may show no mortality, although the fish may have suffered substantial captivity-induced stress. On the other hand, for escapees that have experienced substantial initial stress from the capture, escape and transfer, the additional captivity-induced stress may be the final cause of mortality. That is, these escapees may have survived if they had not been held in monitoring cages. If the controls show no mortality, these escapees would be interpreted as dying as a result of the capture and escape process, and the escape mortality would therefore be overestimated (Figure 14).

This is a particularly high risk among the smallest size groups, because small fish are usually most sensitive to handling. Hence, the stress and injury caused by captivity should be minimized or, if possible, totally eliminated by improved methodological approaches (Figure 14).

CATCHING ADEQUATE CONTROLS

Relatively little systematic work related to the capture of control fish has been carried out. In most survival studies, the capture of controls has been of secondary importance compared with the collection of treatments. However, the capture of adequate controls is one of the most important tasks in a survival study. Very often control samples are inadequate because they differ in body size from the treatment

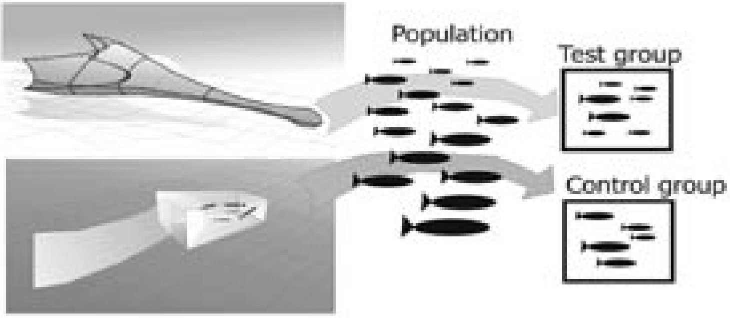


FIGURE 15
Controls should be caught by a fishing method that does not cause significant stress and injury to the fish. In some cases, a trap-net or pot may be an effective and useful capture method for collecting controls (in particular when fish swim voluntarily into the trap).

population. In particular, the smallest sizes are often missing from the control group. The lack of adequate controls has made the results of many survival studies practically useless.

Most existing capture methods are designed to catch adult fish. Young fish that are needed as controls are often more difficult to catch. Moreover, young fish are often more fragile and sensitive than adults, and are easily injured and stressed during the capture and handling process. All major fishing gears involve some degree of stress and injury to fish. The severity of these injuries depends on the gear type, the fish species and size, and environmental conditions. Contacts between the fish and the gear should be minimal. In some circumstances, trap-net, seine net or hook and line fishing may offer the most practical capture method. Fish swim voluntarily into the trap. If properly constructed, a trap-net may catch fish with relatively little stress and injury.Wounding from hooking can be reduced by using barbless hooks, and potential skin abrasion in seine fishery can be reduced by using soft netting materials.

Clearly, the choice of capture method for controls is critical. Suuronen, Lehtonen and Jounela (2005) used hook and line, gillnets and eel traps to capture control cod, but had relatively little success. Demersal pots that were baited were much more successful in the capture of control fish. Pots were also used by Ingolfsson, Soldal and Huse (2002) to capture cod and haddock, and by Erickson and Pikitch (1999) to capture sablefish. Pikitch *et al.* (2002) captured walleye pollock controls with a purse seine. No significant differences in mortality were found between experimental fish and some of the controls, but differences were noted among seining procedures. This probably caused extreme variability of "control" mortality. Pollock held in the control cage that showed the highest mortality were crowded to such an extent during the seining process that they "thrashed and boiled" on seine webbing that was unintentionally pulled tight near the surface. Although the webbing was immediately released to provide space for swimming, this action probably caused extensive skin damage and stress (Pikitch *et al.*, 2002). Seine-caught pollock held in another cage were not crowded during the capture process; mortality in this cage was only 2 percent, and almost none of the fish showed skin damage.

If technically possible, control fish should be caught through their own voluntary swimming into the control cage – various types of attraction device may be used to improve the catchability of a "cage". Modified trap-nets and pots may be applicable in some fisheries (Figure 15). The problem may be poor capture efficiency, which can be substantially improved through the use of bait. Another issue is how to transfer the fish from the trap-net to the monitoring cage without causing any extra stress. The transfer distance should be as small as possible, and in the best case there should be no need for transport, i.e. the trap-net should be in the immediate vicinity of the cage. A modified trap-net may itself also act as a monitoring cage (see Suuronen, Lehtonen and Jounela, 2005).

TAG AND RECAPTURE METHODOLOGY

The tag and recapture methodology has been used mainly to estimate the survival of discarded and released fish (e.g. Pacific halibut; Trumble, Kaimmer and Williams, 2000). This method may provide an accurate indication of long-term survival, but it does not explain much about those fish that have died (when, where and why). The methodology also suffers from being extremely labour-intensive. Tag and recapture methods may also be used when studying the survival of escapees. With current tagging technology, it is possible to mark fish with special tags that can be registered by instruments that are attached inside the trawl codend, for instance. With the help of such technology it is possible to register the passage of marked fish through the codend. Hence, by first tagging a certain number of fish within a fishing ground and then trawling in this ground it is possible to estimate how often a particular fish is captured in the trawl and how often it escapes successfully. It is likely that this type of new tagging technology will be used in the near future in many survival studies and other applications.

LABORATORY STUDIES

The wide variety of potential stressors in commercial fishing situations and the lack of controlled experimental conditions make it extremely difficult to conduct studies that systematically examine the interactions among stressors. To simplify the damaging mechanisms and repeat the treatments in a controlled environment, a variety of simulated laboratory (tank) experiments have been conducted to determine the causes of injury and death of escaping fish (e.g. Soldal, Isaksen and Engås, 1993; Broadhurst, Kennelly and Barker, 1997; Broadhurst, Barker and Kennelly, 1999; Davis, Olla and Schreck, 2001; Davis and Olla, 2001; 2002; Davis, 2002).

Laboratory studies provide a controlled means of investigating fish survival in regard to various stressors. It should be borne in mind however that the laboratory environment does not mimic the whole capture and escape process, nor does it exhibit the variability that is typically experienced in natural conditions. It is difficult, or perhaps impossible, to simulate all potential capture stressors in the laboratory. Fish that are held in laboratory conditions experience sensory-deprived environments, which can result in behaviour and stress responses that do not mimic normal responses in the field. Hence, the results of laboratory studies cannot be used to make direct conclusions about the survival of fish in commercial fishing conditions.

Nevertheless, laboratory experiments can be extremely useful and cost-effective in investigating stress responses and assessing injuries. They allow the systematic determination of the general behavioural, biological and physiological principles of stress response up to mortality in different species, and this is rarely possible in field conditions (see e.g. Davis, 2002). For instance, interactions between capture stressors (e.g. towing in a net and hooking) and temperature have been examined in laboratory conditions on walleye pollock, sablefish, Pacific halibut and lingcod using changes in behaviour, blood physiology and mortality as measures of stress (Davis, Olla and Schreck, 2001; Davis and Olla, 2001; 2002; Davis, 2002). In such experiments, researchers can focus on the mechanisms of interest and control all the others (see also Broadhurst, Kennelly and Barker, 1997; Broadhurst, Barker and Kennelly, 1999; Ryer, Ottmar and Sturm, 2004). Hence, cause and effect relationships can be established.

So far, most laboratory studies have been directed towards assessing the potential injury to fish passing through netting meshes or other selective devices, as well as assessing the exhaustion caused by forced swimming inside towed gear. The results of laboratory experiments could be used to calibrate measures of fish conditions (i.e. wounding, behavioural deficits) with mortality (see Davis, 2004).

Further observation of fish condition prior to caging in the field could be used to verify these calibrations. Estimates of the conditions of escapees and discards in the field could then be used to predict escapee and discard mortality without caging. Such an approach could expand significantly the range of fishing conditions that are studied, eliminate artefacts from caging studies and lead to more accurate estimates of unintended fish mortality. Increased mortality information could be used to develop new ways of minimizing unintended mortality in a wide range of fisheries.

INVESTIGATING FISH CAPTURE BEHAVIOUR IN THE FIELD

The development of effective gear modifications to enhance the escape and survival of escapees requires a good understanding of how fish react to fishing gear and selective devices, including in conditions where vision is limited or inoperative. Species- and fisheries-specific variability in behaviour patterns is substantial and influences the types of gear modifications that are required. Few designs have the potential for application across different fisheries; significant fish- and fisheries-specific modifications are often required. Hence, observations and measurements of fish behaviour under various conditions in each particular fishery should be carried out in order to gain more specific understanding. Unfortunately, observations under limited levels of light require special technology that is not generally available.

Various types of light-sensitive video cameras have been used in many field studies, but in most cases they are not sensitive enough for the conditions that prevail during fishing. In many cases, it is necessary to use artificial light, which may however distort the behaviour of target species. Infrared technology has been used in laboratory experiments (e.g. Olla and Davis, 1990) but has rarely been applied in the field (Olla, Davis and Rose, 2000). Other possible techniques include acoustic and laser technologies, such as dual frequency identification sonar (DIDSON) technology. Underwater observation techniques have recently been reviewed by Graham, Jones and Reid (2004).

CONCLUSIONS

Most survival studies so far have resulted in qualitative mortality estimates of limited accuracy. Survival figures have been affected by inferior methods of collecting, transporting and monitoring escapees, and no investigation has been conducted without methodological compromises. Poor replication of commercial conditions is an additional concern. Stress, injury and mortality may vary, largely depending on fishing conditions and practices, so it is not sufficient to conduct survival studies under a single set of conditions and expect that the results will be applicable to the fishery in general. A survival study should cover the full range of fishing conditions for the gear type and fish species of concern, including variations in fishing practices. Clearly, there is substantial potential to improve the techniques and systematize the procedures used in survival experiments.

Control fish are used to measure the levels of mortality occurring among captive fish either as a direct result of the stresses of captivity or owing to natural mortality over that period. The use of control fish, and the size and design of cages and their layout on the sea bed should be carefully planned to take potential problems into account and to minimize uncertainties. Experiments should describe in detail what the controls are meant to demonstrate. Different factors and handling procedures may need separate controls for the final interpretation of results. Usually, the use of controls does not exclude all the potential error factors, but many uncertainties can be minimized.

Although laboratory studies can be criticized for lack of realism, they provide a controlled way of investigating fish injury and survival with regard to various stresses. Laboratory experiments can most effectively develop knowledge of key stressors and accumulative effects. To increase understanding of and predict overall escape mortality, mortality may – at least in some cases – best be addressed through a combination of field experiments under realistic fishing conditions and controlled laboratory investigations of various key stressors.

Improvement of escape survival by technical and operational means

Efforts to reduce or eliminate bycatch and discards in (trawl) fisheries have centred on gear modifications that increase the opportunities for undersized fish or unwanted species to pass through codend mesh or other selective device. Many gear modifications and bycatch reduction devices have proved effective in guiding and sorting fish (e.g. Watson and McVea, 1977; Andrew and Pepperell, 1992; Isaksen *et al.,* 1992; Kennelly, 1995; Erickson *et al.,* 1996; FAO, 1999; Rose, 1999; Broadhurst, 2000; Graham and Kynoch, 2001; Madsen, Holst and Foldager, 2002; Tschernij and Suuronen, 2002; Walsh *et al.,* 2002; Valdemarsen and Suuronen, 2003; Broadhurst *et al.,* 2004; Graham and Ferro, 2004; Graham *et al.,* 2004; Sardà, Molí and Palomera, 2004; Valdemarsen, 2004; Fonseca *et al.,* 2005; Polet, Delanghe and Verschoore, 2005). However, relatively little consideration has so far been given to concerns as to whether or not escaping fish survive.

It is generally assumed that effective selectivity automatically guarantees good survival. In many cases, this may be a fair assumption, but it should not be an automatic presumption. If survival is in doubt, it should be assessed. Improving selectivity without reducing the damage incurred by capture and escape is not an appropriate way of protecting immature fish. When developing and improving selectivity, it is important to address the whole range of stressors caused by the capture and selection process. This chapter presents some basic design principles that may help to reduce the injury and mortality associated with fishing and sorting processes.

REDUCE THE TIME THAT FISH SWIM WITH THE GEAR

It is well established that fish captured in a trawl often undergo forced swimming and experience contacts with the netting and other fish, crowding, confinement, crushing, barotrauma and oxygen depletion. Many groundfish often swim within or in front of the trawl mouth for a long time before they are overtaken by the gear (e.g. Main and Sangster, 1981; Wardle, 1993; Tschernij and Suuronen, 2002).

Little consideration has been given to the swimming capabilities of fish entering the trawl following this potentially exhausting process. When fish finally enter into the codend, they may be exhausted and therefore have greatly reduced swimming ability. Limited swimming capability may have implications on the efficiency of selection; that is, fish may be physiologically exhausted at the time they require a positive swimming action to escape (e.g. Breen *et al.,* 2004). That is, not only may a fish's swimming ability determine its likelihood of capture by a towed fishing gear, but it may also influence the fish's escape and subsequent likelihood of survival. Moreover, the stress, exhaustion and potential injury to which fish are subjected when swimming in front of and inside the gear are probably cumulative. That is, the longer the capture process takes, the higher the likelihood of severe exhaustion and physical damage. The time between entering the fishing zone of the net and escaping should be minimized by proper gear construction and operational aspects. Greater consideration should be given to gear modifications that ensure that non-target fish are physically capable of making an active escape.

ALLOW FISH TO ESCAPE BEFORE THEY REACH THE CODEND

Fish should generally be allowed to escape before they enter into the codend, where the risk of damage is highest. This is not only because of crowding and crushing, but also because of problems caused by clogged meshes in the codend. Many investigations have demonstrated that codend meshes may become totally blocked by larger catches (e.g. Erickson *et al.,* 1996; Suuronen, Erickson and Pikitch, 1997). In such a situation, escape from a codend is difficult or impossible. Erickson *et al.* (1996) showed by video observations that escape of walleye pollock occurred along the entire length (18 m) of the square mesh escape panel in front of the catch bulge. Hence, for this species, an escape panel or selective device installed ahead of the codend would effectively sort the catch by size before fish reach the codend meshes. It would also allow undersized fish to escape, even when the codend meshes become blocked with fish.

A similar approach has been suggested for many other fisheries, such as pelagic herring trawl fishery, where blocking of codend meshes is common (e.g. Suuronen and Millar, 1992; Suuronen, Erickson and Pikitch, 1997) and the fish species in question experiences high mortality when escaping from the codend (Suuronen *et al.,* 1996b). These fish often lose scales easily, and swimming in the codend extension may cause severe damage to their skin. Fish may have lost a major part of their scales before they eventually reach the codend. For this type of fish species, escape panels and/or sorting devices should be installed as far forward as possible on the trawl, preferably in the trawl belly.

It is noteworthy that small (15 to 30 cm) gadoids (haddock, whiting, cod) excluded from a coastal shrimp trawl by a diagonal deflecting grid (Nordmøre grid) placed in front of the codend showed 100 percent survival (Soldal and Engås, 1997). Although some species can sustain stress and damage, it is always preferable to have selection in front of rear codends, where the likelihood of damage is highest.

FACILITATE RAPID, VOLUNTARY ESCAPE

Although there is little scientific evidence, it is intuitively obvious that mechanical sorting will cause more injury to fish than voluntary (i.e. active and oriented) escape from fishing gear. Voluntary escape requires that fish can detect the escape route. Vision plays an important role in the response and orientation of many fish species to trawls (e.g. Glass and Wardle, 1989), although there is evidence that some species are able to orient to the trawl under conditions of limited light (e.g. Engås and Ona, 1990). When light quantity is not adequate for visual mesh detection, fish generally have less chance of orienting properly towards a selective device (e.g. Olla, Davis and Schreck, 1997, Olla, Davis and Rose, 2000), and survival may be poorer (e.g. Suuronen *et al.,* 1995).

Commercial fishing operations are often conducted at greater depths or at night, in dark conditions. Moreover, the codend is often surrounded by a dense mud cloud strirred by the ground gear. The design of trawls to enhance bycatch escape and survival must consider reactions under such conditions. There should be elements that will guide fish to the escape route. When some light is available at the fishing depth, the contrast of critical constructions should be maximized to facilitate the herding of fish into the right direction to increase escape. Contrast patterns between netting and the surrounding water can also be used in the manipulation of fish escape behaviour (e.g. Glass *et al.,* 1995).

Management of the water flow inside the codend is an option when visibility is the limiting factor. Water flow can effectively guide at least smaller fish towards the selection panel or sorting device. Flow patterns can be managed by appropriate gear design and rigging, and through the use of various guiding and flow enhancement panels and other devices (e.g. Broadhurst, Kennelly and Eayrs, 1999; Engås *et al.,* 1999).

Flow patterns that create a vortex within the codend or near any selection devices should be avoided because fish may rotate within the vortex for long periods; this may effectively prevent them from swimming and orienting properly towards the open mesh or selective device. Clearly, flow management within trawl codends may be highly important for selectivity and survival. It is worth noting that water velocity within a trawl gear generally decreases towards the codend (e.g. Thiele *et al.,* 1997).

AVOID EXCESSIVE CATCH SIZES AND PREVENT DEBRIS FROM ENTERING THE CODEND

Operational aspects should be considered in detail when designing fishing gears that do not cause additional injury. The duration of a trawl tow and the catch size are issues that deserve particular consideration. Shorter tows with smaller catch sizes would help to maintain the selectivity properties of the codend, at least in trawl fisheries where catch rates are excessively high. On the other hand, it is notable that at very low catch sizes the selectivity of a codend may not be adequate because its meshes do not start to open properly until after the catch has built up. In demersal trawling, selectivity may gradually increase until a point is reached where it either levels out or begins to decrease as the catch quantity increases (e.g. Dahm *et al.,* 2002).

It is clear that excluding debris and large animals and objects (such as boulders) will reduce the physical damage to fish caught in the codend, thereby increasing the survival chances of those that escape. By using improved ground gear constructions, sea bed objects such as boulders can be blocked. In addition, unwanted objects (e.g. rocks) that enter the trawl can be removed through various types of exit devices and holes. Such devices should be robust, effective, inexpensive and easy to manufacture, maintain and repair. It is also evident that knotless, smooth-surfaced netting materials should be favoured over stiff, knotted nettings in gear areas where the netting is causing abrasion of escapees (Figure 16).

USE ESCAPE PANELS, GRIDS AND BYCATCH REDUCTION DEVICES

Many gear-related factors may have a measurable effect on gear selectivity and the survival of escapees. These factors include mesh size and opening, number of meshes around the codend, length of codend and codend extension, length of lastridge ropes, thickness and stiffness of twine, construction of the codend lifting bag, attachments such as chafers, protection nettings and restrictor ropes, and overall gear rigging (see page 13). Modification of these structures can enhance escape and subsequent survival. However, there are limitations regarding the extent to which these structures can be modified, and much effort has recently been given to the development of various types of selectivity panels and bycatch reduction devices (BRDs).

Square mesh panels (windows) have great potential for improving trawl selectivity (e.g. Broadhurst, Kennelly and Gray, 2002; Fonteyne and Polet, 2002; Madsen, Holst and Foldager, 2002; Tschernij and Suuronen, 2002). When using square mesh panels, it is important to install them in the proper location on the trawl. Slight variations in panel design and location can dramatically affect selectivity and survival.

FIGURE 16

A knotless, smooth-surfaced netting compared with traditional twisted knotted netting.

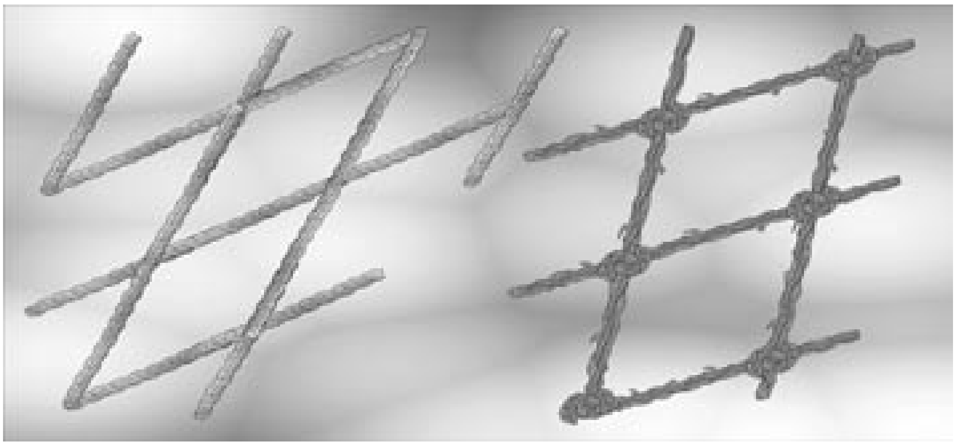
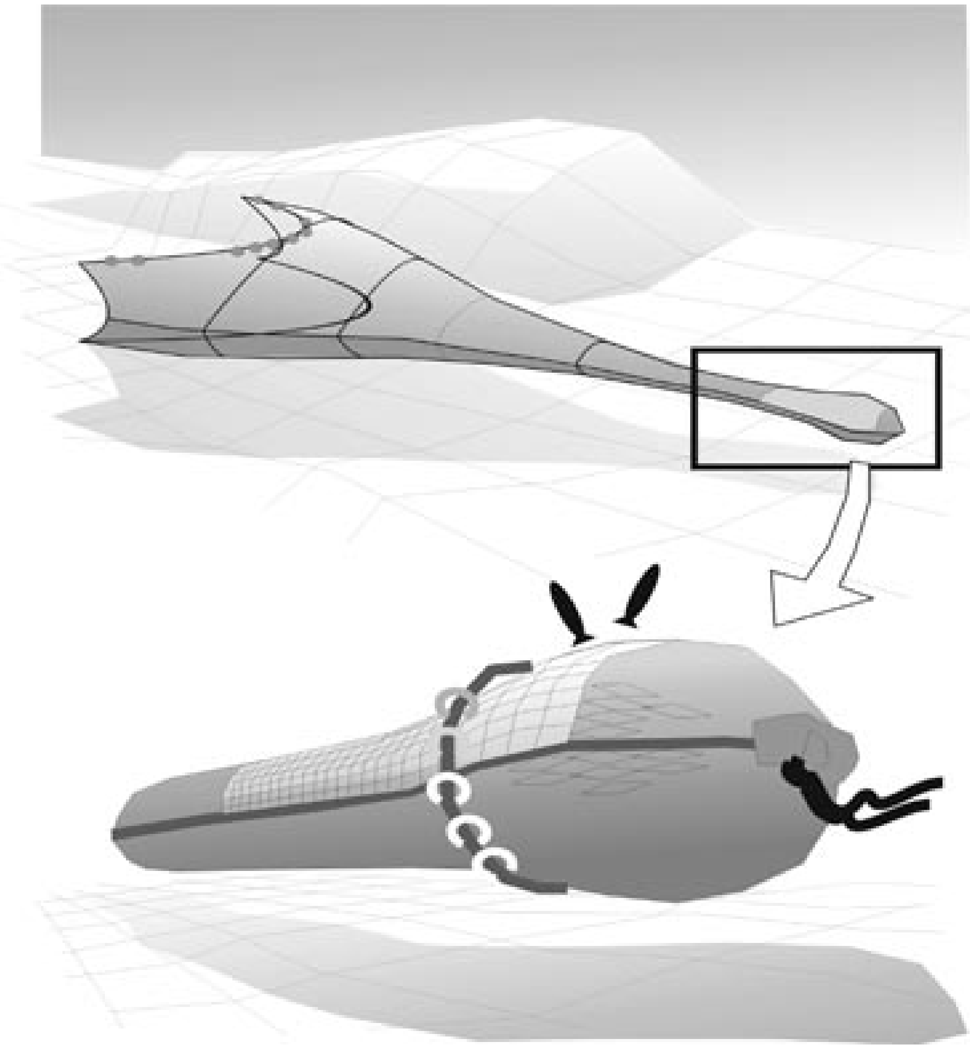


FIGURE 17

A square mesh panel (Bacoma panel) installed in the codend of a trawl gear is effective in the size selection of Baltic cod. Survival likelihood of cod escaping through this panel is high (Suuronen, Lehtonen and Jounela, 2005).



Even a very small panel may work efficiently when located in a strategically correct position. In the case of Baltic cod, the most efficient selectivity is likely attained when the square mesh panel is located in the aft most part of the codend (Figure 17). This is mainly because Baltic cod do not attempt to escape before entering the rear codend. However, it is also partly because the codend catches of cod are usually very small; if the panel were in front of the codend, the few fish swimming inside the rearmost part of the codend would not be able to see the panel. However, for most other fish species, it would be most beneficial to install the sorting panel or device in front of the codend, because many species incur most injuries while swimming inside the codend. This may require additional constructional elements that guide fish into the right position.

Selectivity and the survival of escapees may also depend on the materials used to construct the escape panels. The use of new materials such as Ulta-cross, Dyneema and composites may enhance selectivity and survival. Broadhurst, Kennelly and Gray (2002) suggest that owing to its flexibility, a composite square mesh panel fits the geometry of the codend better than square mesh panels made of plastic or metal do.

In many mixed species fishery, different species have to first be separated from each other (species selection), and can only then be sorted by size (e.g. Main and Sangster, 1982; Moth-Poulsen, 1994; Eayrs, Buxton and McDonald, 1997; Engås, Jørgensen and West, 1998; Broadhurst, 2000). Most selective devices that are intended to separate species operate by exploiting behavioural differences between different species. In order to be operative and effective, selective panels, guiding funnels and devices should be placed in strategic positions. In prawn trawls, for instance, these devices operate on the principle that fish have certain characteristic responses to towed trawls, whereas slower moving benthic invertebrates tend to show no specific, or very limited, responses (reviewed by Broadhurst, 2000). Underwater observations have shown that the majority of fish species attempt to escape in the upper part of the codend. This behaviour pattern is widely used in various bycatch reduction devices. Valdemarsen (2004) presented a new design principle in which deep water shrimp and fish are guided into separate codends by using a ring that separates the inner and outer codends. This principle is based on the observation that shrimp enter the trawl close to the bottom panels, while most fish pass into the codend at its centre. Such behavioural differences may be used to avoid fish bycatch in shrimp trawl fisheries; fish can be guided out of the trawl, and there is no need to use any filtering or sorting devices. Such mechanisms are likely to increase the survival chances of escaping fish (see e.g. Soldal and Engås, 1997).

Special guiding and sorting devices such as rigid and flexible grids can be used to effectively guide fish to an area where escape can occur, and species and sizes can be sorted (e.g. Isaksen *et al.,* 1992; Rose, 1999; Kvalsvik *et al.,* 2002; Fonseca *et al.,* 2005). Various types of grids can be used as the components of complex systems. In species selectivity, grids work best when there are large size differences among the species that are to be separated. Behavioural aspects are critically important in effective grid sorting. Grid angle, change in angle, clogging of grid, handling properties, price and maintenance are important design and operational parameters (e.g. Isaksen *et al.,* 1992; Broadhurst, 2000; Sardà, Molí and Palomera, 2004; Fonseca *et al.,* 2005).

As a size-sorting device, a grid placed in front of the codend, in its intermediate or extension section may allow effective and consistent escape that is largely independent of catch volume (Figure 18). Effective grid sorting has been demonstrated for Atlantic cod, mackerel and Baltic herring when using longitudinal grids (e.g. Larsen and Isaksen, 1993; Suuronen, Lehtonen and Tschernij, 1993; Kvalsvik *et al.*, 2002). One of the major advantages of grids is their stable performance under various conditions, particularly at higher catch rates, when conventional codend meshes tend to become blocked by the catch. However, blocking problems have also been encountered with sorting grids, and these should be taken into account in the design. There is some evidence that escape through rigid sorting grids may result in lower mortality compared with escape through a mesh (e.g. Suuronen *et al.,* 1996b; Ingolfsson, Soldal and Huse, 2002; see also section on page 13). Clearly, the use of appropriate grid designs and installations may result in reduced escape mortality.

USE SELECTIVE GROUND GEAR AND CUTBACK HEADROPE

A fish may be run over by or collide with demersal trawl gear (e.g. Walsh and Hickey, 1993; Tschernij and Suuronen, 2002). Very little is known of the possible injury sustained by fish that are run over, but it could be speculated that some fish species may have a larger chance of survival when escaping between the rollers of a ground gear than when entering into a trawl and escaping later through a codend mesh. For some groundfish species this principle might be used as an alternative to codend selectivity (Figure 19). There are likely to be many more untested design options for developing selective ground gears in demersal trawl fishing. For instance, the rolling elements of the gear may be replaced with various types of weighted plastic sheet (Valdemarsen and Suuronen, 2003; Valdemarsen, 2004). Moreover, there are another ways of separating

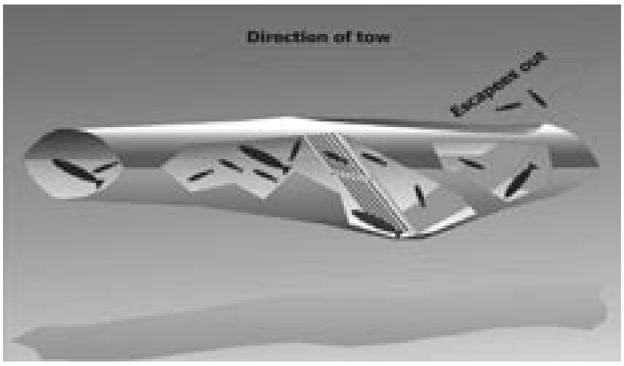


FIGURE 18

A sorting grid may be used to sort immature specimens from trawl gear. If the grid is properly constructed and installed, the survival of grid escapees may be higher than that of mesh escapees.

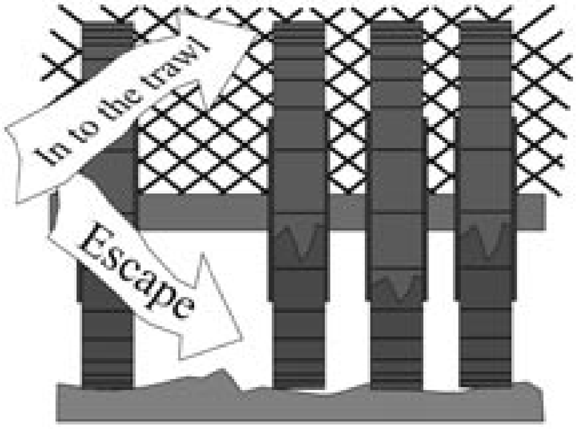


FIGURE 19

The free spaces between the rubber discs of the ground gear of a demersal trawl may offer some groundfish an alternative escape route. This could be used as a selective tool, particularly for species that tend to dive towards the bottom when disturbed.

species and sizes based on behaviour. For instance, King *et al.* (2004) describe a flatfish trawl which has a cutback headrope designed to separate out rockfish prior to their entrainment inside the trawl. This type of trawl design permits nontarget species to escape before entering into the gear and has a significant potential to reduce bycatch mortality. Clearly, there is substantial scope for development in this area.

AVOID GROUNDS WHERE YOUNG FISH OR NON-TARGET SPECIES ARE ABUNDANT

When attempting to reduce unaccounted mortality of young fish and non-target species, there are potential alternatives for the development of selective fishing gears. For instance, rather than developing techniques that enable the fish captured in a fishing gear to escape through codend meshes or other selective devices (e.g. grids), bycatches and their subsequent mortality could be reduced by preventing the fish from being captured in the fishing gear altogether. In other words, the capture of immature fish and non-target species could be actively avoided by modifying the fishing strategy (e.g. Gauvin, Haflinger and Nerini, 1996; Witherell and Pautzke, 1997). In this way, fish would not be subjected to various stressors and physical injuries that result from capture and escape processes. The recent development of navigation and gear surveillance instruments should allow a marked improvement in the avoidance of "hot-spots".

CONCLUSIONS

Although a great deal of progress has been made in reducing bycatch and discard through improving fishing gear selectivity, relatively little consideration has been given to the survival of escaping fish. Gear modifications to improve selectivity are generally based on the assumption that fish escaping from fishing gears are undamaged, minimally stressed and able to make a complete recovery. However, several studies have shown that physical damage incurred during capture and escape can result in fish mortality. Hence, evaluation of escape mortality should be an integral part of the development of selective fishing gears. Survival should ultimately be used to determine the suitability and success of new modifications.

Developing effective gear modifications that guarantee high chances of survival for escapees requires a good understanding of how fish react to gear under various conditions, including in situations when vision is limited or not operative. Clearly, immature fish that should escape from a fishing gear should stay inside the gear for as short a time as possible, and should not enter into the aft part of the codend where the risk of serious injury is highest. Installing escape panels or other sorting devices in front of the codend would probably enhance the escape and survival chances of undersized fish. It is evident that voluntary escape will cause less injury to fish than mechanical sorting. Hence, facilitating the voluntary escape of fish through appropriate constructions and operational improvements would increase the likelihood of survival. Use of non-abrasive netting materials, exclusion of debris and large objects from the codend, and use of better gear designs and riggings would further enhance the survival likelihood. It is clear that there is substantial scope for improving the survival of trawl escapees by using better gear modifications and operational solutions.

In general, measures to protect immature fish and non-target species are designed to increase the fish's opportunities to escape from fishing gears, rather than preventing or reducing their chance of encountering the fishing gear. Active avoidance of areas with high densities of juveniles and non-target species is an alternative approach to reducing unaccounted mortality.

Estimating the magnitude of escape mortality and its impact on fisheries management

Gear-related conservation measures are based on the assumption that fish escaping from fishing gears survive and live on to promote the population. Relatively little work has been done to assess the effects of selective fishing gears on reducing the overall mortality of target and non-target populations. This chapter assesses the problems associated with estimating the magnitude and impacts of escape mortality, and demonstrates the processes by which mortality estimates may be included in fisheries management decision-making processes.

INCORPORATING MORTALITY IN ASSESSMENT AND MANAGEMENT PROCESSES: CASE STUDIES

Improved selection means that a larger part of the fish population will escape from fishing gears. If escape mortality is low, the use of selective fishing gears might be assumed to bring long-term benefits. Likewise, if the mortality rates of escapees are high, there may be no advantages associated with changing selectivity. The assessment and prediction of the impacts of an increase in trawl mesh size require reliable fisheries, selectivity and biological data. These are complex tasks, particularly when fisheries involve several species and multiple gears (e.g. Macer, 1982; FAO, 1984; Kuikka *et al.*, 1999; Breen and Cook, 2002; Halliday and Pinhorn, 2002; Tschernij, Suuronen and Jounela, 2004). Escape mortality data have seldom been applied to stock assessment models or included in fisheries management decision-making processes. Moreover, for many commercially-important fish species, there are currently no sufficiently accurate and reliable estimates of survival to allow assessments to be made. The following case studies demonstrate various approaches that have been taken in evaluating the impacts of escape mortality on overall mortality.

Baltic cod demersal trawl fishery

Kuikka *et al.* (1999) assessed the potential outcome of changes in exploitation level and mesh size in the Baltic cod demersal fleet (under different environmental conditions). The assessment consisted of three steps: (a) modelling of selectivity; (b) estimation of uncertainties; and (c) decision analysis by Bayesian influence diagrams. The authors used the trawl selectivity data presented by Tschernij *et al.* (1996) to model the retention of 120-mm and 140-mm diamond mesh codends. They assumed that all escapees survive. This assumption was relatively well supported by the results of escape mortality studies conducted with Baltic cod (Suuronen *et al.*, 1996a). Their simulations suggested that the yearly loss of catch potential is significant, owing to overfishing and the non-optimal fishing pattern (i.e., poor selectivity). The average yield could be increased substantially (by 30 to 40 percent) by increasing the mesh size to 140 mm, decreasing the trawl fishing effort by 20 percent, and controlling gillnet fish mortality. The simulations also suggested that with a larger mesh size, preferred exploitation levels would become less sensitive to assumptions about future recruitment and growth levels. Increasing the mesh size to 140 mm would markedly reduce the frequency of dangerously low spawning stock biomasses and the need for very low catch quotas. A larger mesh size would be beneficial, irrespective of the assumed recruitment level.

Kuikka *et al.* (1999) emphasized that the increase in mesh size would not remove all uncertainties, but it would act as some insurance against their negative impacts. However, the authors did not fully assess several sources of uncertainty, for example: cannibalism could increase at low fish mortality rates more than they assumed, thereby reducing recruitment to the fishable stock; density-dependent effects may retard the growth of cod; and fish may migrate to other areas. Moreover, the mortality of escapees may not be zero, as was assumed. There are indications that under certain conditions the escape mortality of cod may be substantially higher, particularly if escape occurrs near the surface, where water temperature may be relatively higher (see Suuronen, Lehtonen and Jounela, 2005). Kuikka *et al.* (1999) pointed out that underestimation of uncertainties leads to overestimation of the system's controllability. As a result, managers may develop an overly optimistic perception of their potential ability to reach the desired state of the system. Nevertheless, the overall effects of a mesh size increase in the Baltic cod trawl fishery appear positive, and in the absence of additional information, this would represent an appropriate and precautionary management strategy.

Northeast Arctic cod trawl fishery

Kvamme and Frøysa (2004) used an age-length structured population model to assess the effects of changes in fleet selectivity on Northeast Arctic cod stock. They assumed that escape mortality is zero, which is a relevant assumption in the light of results of relevant studies done on Atlantic cod (e.g. Soldal, Isaksen and Engås, 1993; Ingolfsson, Soldal and Huse, 2002). Their simulations showed that there would be substantial gains, in terms of both stock size and catches, from increasing the mean retention length by 5 to 8 cm (from the present 47 cm). Catches of three- to four-year-old fish would decrease, while catches of fish of six years and older would increase within a few years. It is notable that Northeast Arctic cod reach maturity when they are six to 12 years of age and 65 to 105 cm long (Jørgensen, 1990). Hence, immature fish would be the most affected by the change in fleet selectivity.

Kvamme and Frøysa (2004) pointed out that the change in selectivity would lead to more efficient exploitation of the stock's growth potential, and more fish would have a chance of growing to mature size and spawning. This would increase the spawning biomass and result in greater and more stable catches within a few years. The total catch, however, would decrease during the first three years following implementation of a mesh size increase. Kvamme and Frøysa (2004) argued that age-length structured models (see Frøysa, Bogstad and Skagen, 2002) are highly suitable for simulating the stock effects of changing the selectivity of a fishery, because selectivity is linked to size. In age-length structured models, age at first capture will automatically be adjusted for changes in fleet selectivity by length. But for age-structured models, fleet selectivity by length has to be transformed into fleet selectivity by age, which may vary from year to year. Age-length structured population models offer versatile tools for assessing the effects of changes in the selectivity of fishing fleets. However, Kvamme and Frøysa (2004) pointed out that the estimation of natural mortality is one of the most uncertain points of their simulation.

Andreasson and Flaaten (1996) made a bio-economic analysis of the effects of using a size-selective sorting grid (55 mm bar spacing) in the harvesting of Northeast Arctic cod. Their analyses suggest that there is a great potential for economic gains by choosing an optimal selection pattern in the fishing fleet. They assumed that all escapees survive.

Northern Baltic pelagic herring fishery

Rahikainen, Peltonen and Pönni (2004) applied length-specific selection and escape-mortality functions to estimate the total quantity of escapees that die and the actual removals from Baltic herring stock in the northern Baltic Sea. Based on the results of a herring survival study conducted by Suuronen, Erickson and Orrensalo (1996), they assumed that the smallest (< 12 cm) escapees have 100 percent escape mortality and that herring of 12 to 17 cm have escape mortality of 90 percent. Their analyses showed that more ages 0 to one year of herring die as a result of escape from trawl codends than are landed. They also demonstrated that because immature herring have a fast growth rate, escape mortality follows a marked seasonal pattern. Their analyses showed that the effect of fishing-induced escape mortality decreases as a function of age and size, so that the impact on estimated recruitment and fish mortality at age one is considerable, while it is almost irrelevant at age two and older (at present exploitation pattern). The actual fish mortality at age one was estimated to be more than twice as high as estimates of fish mortality based on the unadjusted data. But, the overall effect of escape mortality on the evaluation of stock status, the stock recruitment function and reference points was minor. Rahikainen, Peltonen and Pönni (2004) emphasized that correct catch and mortality data are necessary for age-structured assessment models. Such data may be biased, for instance owing to unaccounted mortality connected to escape from trawl gears.

Kuikka, Suuronen and Parmanne (1996) studied the impacts of increased codend mesh size on the northern Baltic herring pelagic trawl fishery with an age-structured population model. The long-term effects of an increase in trawl codend mesh size (from 20 to 36 mm) on catch weight, catch value per recruit and the stock biomass of herring in the northern Baltic were assessed. The high escape mortality (85 percent) of herring (from Suuronen *et al.,* 1996b; Suuronen, Erickson and Orrensalo, 1996) was incorporated into the analysis. The length-based trawl codend selection curves (from Suuronen and Millar, 1992) were transformed into curves that described codend retention by age. It is known that the annual growth rate of herring varies, and consequently retention by age also varies from year to year. Therefore, yearly estimates of growth rates from commercial catch sample data for the years 1974 to 1992 were used in the analysis. By using age-length structured models, growth variation was handled directly. Natural mortality estimates were taken from the ICES multispecies population analysis. Kuikka, Suuronen and Parmanne (1996) also assessed the effect of mesh size increase on the economic value of the annual catches. Their results showed that under the conditions prevailing in 1974 to 1992, the increase in codend mesh size would have led to reduced catches and lower values of catch-per-recruit. The magnitude of the estimated reduction of catches varied greatly, according to the growth and natural mortality of the population. The calculation suggested that in order to make an increase in mesh size profitable for this fishery over the long term, the price of large herring processed for human consumption would have to be approximately six times greater than that of smaller "fodder" herring, or the survival of codend escapees would have to be increased to 80 percent from its current estimated level of about 15 percent (e.g. with the help of new fishing technology).

This study demonstrated that for species incurring a high mortality during capture and escape, there may be no biological or economic justification for a mesh size increase. Clearly, unless the level of escape mortality is known, the benefits of the change of selectivity could be largely overestimated. In the worst case, this type of unaccounted mortality can have a negative effect on fish stocks because overall fish mortality may be underestimated. The analyses of Kuikka, Suuronen and Parmanne (1996) answers the question of what is the adequate level of survival to justify the use of selective fishing gears; something few other analyses have attempted to address.

Hauraki Gulf snapper fishery in New Zealand

Harley, Millar and McArdle (2000) presented a modelling approach using estimates of selectivity to estimate discard and escape mortality, and applied their model to the

Hauraki Gulf snapper fishery off the northeast coast of New Zealand. In their model, discard and escape mortality can take any value between 0 and 100 percent and can also vary with fish length. Their approach represents an extension of the work of Casey (1993), who provided a theoretical basis for estimating discard-at-age mortality. Casey, however, assumed that all discards die and all escapees survive. This does not allow examination of the trade-off between discard and escape mortality that occurs with towed fishing gears. By allowing escape mortality to be greater than 0 percent, the trade-off between escape and discard mortality relating to mesh size regulations can be examined. The method presented by Harley, Millar and McArdle (2000) requires certain specific information such as estimates of catch by year and fishing gear, selectivity at length, and the probabilities of mortality for fish that are discarded and those that escape from gears. The authors obtained estimates of escape mortality from the reviews of Muoneke and Childress (1994) and Chopin and Arimoto (1995). They included interannual growth variability in their analysis and assumed mean recruitment. Natural mortality was assumed to decrease with fish length among pre-recruits and to be constant for all mature fish. Fate diagrams provided a graphic representation of how the different components of fish mortality affect the population. Harley, Millar and McArdle (2000) found that escape mortality may not be a significant component of total fish mortality, although there are large numbers of escapees in fisheries conducted with towed fishing gears. They emphasized, however, that a large number of individuals just below the minimum landing size die as a result of discarding. The reasons for this type of heavy discarding practice should be explored, and practices should be changed accordingly. The use of more selective fishing gears seems likely to offer one solution.

North Sea haddock

Cook (1998) proposed a calculation method for translating the escape and discard mortality rates obtained in survival experiments into mortality rates of stock and at the fisheries level, and illustrated its use in North Sea haddock assessments. His approach was based on the method presented by Mesnil (1996), which includes length-based mortality data in age-based assessments. Data from Scottish survival experiments (Lowry, Sangster and Breen, 1996; Sangster, Lehmann and Breen, 1996; Wileman *et al.*, 1999) were used to obtain escape mortality estimates by age. It was assumed that no discarded fish survive. According to Cook's analysis, the mortality of young haddock due to escape peaks at two years of age. This represents about 40 percent of the mortality from fishing at that age. However, total mortality did not differ much when escape mortality was assumed to be zero. The difference at age two was only about 20 percent, suggesting that conventional estimates of fish mortality at age two may be biased downwards by about 20 percent. This relatively small difference is mainly because the estimated escape mortality of haddock is relatively low. Cook (1998) concluded that, for North Sea haddock, the inclusion of escape mortality in the assessment does not make a perceptibly major change to the state of stock; at least not with the fishing pattern that existed during the time of analysis. However, he emphasized that the analysis was very preliminary and was performed primarily for illustration purposes.

Breen and Cook (2002) updated Cook's (1998) analysis of the impacts of selectivity on North Sea haddock assessments. Their model estimates discard mortality, escape mortality and retained catch separately using data from the ICES database. These were then transposed from length-based to age-based data using the age-length keys. Their simulation was run with discard mortality set at zero (no discards) and one (all discards die) and with varying escape mortalities (10, 25, 50 and 100 percent). The results were then partitioned into a single fish mortality value. Breen and Cook's (2002) simulation showed that including discard mortality significantly increased the fish mortality estimates, particularly for ages one (94 percent), two (63 percent) and three

(18 percent), and including escape mortality (assuming that 25 percent of escaping fish die) produced less significant but still substantial increases in fish mortality (38 percent at age one; 7 percent at age two; and 1 percent at age three). That is, their analyses showed that compared to escape during fishing, discarding has a far more profound effect on the fish mortality of haddock. Furthermore, they demonstrated that relative importance of escape mortality decreases as age increases. Clearly, the analyses of Breen and Cook (2002) provides a useful insight into the relative importance of the different components of fish mortality (landing, discard and escape mortality) with respect to the stock-assessment process. They emphasized that exlusion of escape mortality parameter estimates has the potential to introduce significant biases into the stock assessment process in particular if there are to be further increases in gear selectivity. These authors also assessed the benefits of increasing the minimum legal mesh size. Their analyses showed that this benefit is greatly reduced if, for instance, only 25 percent of escaping fish die. Significant benefits would be obtained only if most escapees survive.

North Sea mixed-species trawl fishery

It is well known that large numbers of haddock and whiting and substantial quantities of cod caught in the North Sea are discarded every year. The majority of discarded fish are smaller than the minimum landing size (MLS) (which for 23, 30 and, 35 cm TL for whiting, haddock and cod, respectively). Garthe, Campyhuysen and Furness (1996) estimated the annual quantity of fishery discards of round fish in the North Sea to be about 260 000 tonnes. Total discards equated to about 22 percent of the total North Sea catch. There are several reasons for this situation. A larger minimum mesh size alone would not provide a suitable tool for achieving maximum yield-per-recruit for each species in the North Sea mixed species fishery. Graham and Kynoch (2001) demonstrated that with a 100-mm minimum mesh size, cod, haddock and whiting of approximately 23 cm in length entering the codend would have a 50 percent chance of escaping. Almost all fish of 30 cm and larger entering the codend would be retained. Macer (1982) estimated that for the North Sea mixed trawl fishery the mesh sizes required to give optimum yields are approximately 250 mm for cod, 140 mm for haddock and 90 mm for whiting. A minimum mesh size of 100 or 120 mm would be too small for cod and haddock, but too large for whiting. Requiring one mesh size to catch these three species inevitably results in discarding and/or high catch-losses. Nevertheless, an increase in the average mesh size would increase the average age-at-first-capture, and would therefore improve the overall situation, increasing the long-term total yield from the fishery even if a precise optimum were not achieved. This case study demonstrates the common problem faced in almost any mixed species trawl fishery. To attain marked improvements, there should be a selectivity system in which the different species are first separated from each other, and then sorted by size.

Short-term effects: an example from the Baltic cod fishery

Most assessments of mesh size increases focus on the long-term effects. However, there are also short-term effects that may require attention, and the following example from the Baltic cod fishery demonstrates the importance of understanding and addressing these. In 2002, a highly size-selective 120-mm square mesh window (a "Bacoma window") was enforced in the Baltic demersal trawl fishery (Madsen, Holst and Foldager, 2002; Tschernij and Suuronen, 2002). The decision to do this was based on long-term projections that suggested there would be a substantial increase in spawning stock size and a marked reduction in discards if a larger window mesh size was enforced (Anonymous, 2000). The short-term effects of a new selectivity pattern were modelled with a stochastic size-selective simulation model (Tschernij, Suuronen and Jounela, 2004). Vessel type-dependent selectivity estimates and catch-per-unit-of-effort

(CPUE) data from the Baltic cod demersal trawl fishery were utilized to estimate the catch losses. The simulations suggested that when the window mesh size is increased by 15 mm (from 105 to 120 mm), the overall catch loss of fish of marketable size during the first month would be around 40 to 50 percent (with the same fishing effort). With a 120-mm window and a 38-cm minimum landing size, the discarding of undersized cod would decrease by about 70 percent. If fishers decided to compensate their loss in marketable catch by increasing their fishing effort, they would have to increase it by 55 to 90 percent.

Tschernij, Suuronen and Jounela (2004) suggested that fishers were unlikely to be able to increase their efforts to such a large extent. Instead, they might try to circumvent the regulations by intentionally decreasing the selectivity of their gear, i.e. by gear manipulation. In fact, widespread gear manipulation – legal and illegal – was observed in 2002 and 2003 in the main fishing grounds (Suuronen and Tschernij, 2003). Fishers were not able to adapt to heavy catch losses, which apparently were even larger than predicted by the simulations. In September 2003, the minimum window mesh size of the Bacoma window was reduced from 120 to 110 mm. This example demonstrates that even in a simple case where fishing targets almost exclusively one species, increasing the mesh size may be very complex even though the biological preconditions appear favourable. This case also demonstrates that too large an increase in selectivity is not commercially acceptable. Gears will be manipulated and rules will be circumvented if the losses are too large (see also FAO, 1984; Ferro and Graham, 2000; Halliday and Pinhorn, 2002). Clearly, short-term effects should be addressed in the management plans; it is not enough to assess only the long-term effects of a mesh size increase.

OTHER COMPONENTS OF UNACCOUNTED FISH MORTALITY

Chopin, Inoue and Arimoto (1996) and Chopin *et al.* (1997) defined fish mortality as the sum of all fishing-induced mortalities occurring directly as a result of catch (capture), or indirectly as a result of contact with or avoidance of the fishing gear. They also recognized the following sub-components of fish mortality: landed catch; illegal, misreported and unreported landings; discard mortality; escape mortality; drop-out mortality; ghost fish mortality; avoidance mortality; and habitat degradation mortality. Except for landed catch, these sub-components of fish mortality are unknown or poorly known for the vast majority of fish stocks. They are therefore referred to as "unaccounted mortalities". A significant amount of research would be necessary to estimate all the sub-components of fish mortality for any given stock, and such information is available for only a few stocks. Most of the work conducted so far in this field has been limited to two particular aspects of mortality – discard and trawl escape – as these are probably the most important components of unaccounted fish mortality, at least for trawl fisheries. Furthermore, questions about the potential negative effects of long-term size-selective fishing on the genetic composition of fished population are periodically raised. This subject, however, has remained largely inconclusive (e.g. Beverton, 1998; Law, 2000), and is beyond the scope of this study.

CONCLUSIONS

There are many problems associated with incorporating estimates of escape mortality into the fisheries assessment and management processes. Clearly, it will never be possible to predict exactly the outcome of a management decision that involves a change in gear selection, even when the escape mortality is known. It is evident that the biological and economic benefits that would be generated will always vary among species, fisheries and conditions. In most fisheries, there is a lack of suitable data and information to conduct relevant evaluations. Escape-mortality studies have been done for only a few species and in only a few fisheries. Extending investigations to other fisheries and quantifying this issue for a larger number of species would help to improve the reliability of predictive modelling. It would be particularly useful to extend investigations to fisheries where stocks are overfished or where there are large mortalities of escaping fish.

Very few studies have been able to verify their predictions with follow-up studies (after the measure has been introduced). The available analyses, however, help to provide an understanding of the general pattern. It has become increasingly clear that in many important fisheries, regulating gear selectivity alone is not enough to provide a sustainable exploitation pattern; control of the amount of fishing effort is essential also. Furthermore, it is apparent that in many fisheries the authorized mesh sizes remain too small to protect juveniles and young adults effectively, and insufficient numbers of fish survive to replace the lost spawning biomass. Moreover, density-dependent effects such as cannibalism, decreasing growth and migration of fish out of the areas exploited by the fleet may lead to lower benefits than are assumed. When escape survival is low, as it is for some small-sized pelagic fish such as herring, there are unlikely to be any biological benefits from using mesh selectivity as a management tool unless other gear modifications are concomitantly developed. Clearly, unless the level of escape mortality is known, the benefits of change in gear selectivity could be overestimated. In such a situation, the key question is what level of survival justifies the use of more selective gear. In mixed species trawl fisheries, increased selectivity should separate species first and then sort by size to account for minimum mesh sizes which differ with species.

Traditional stock assessments generally assume that all fish passing through a towed fishing gear survive the process. Few attempts have been made to incorporate escape mortality estimates into stock assessment processes. The above case studies demonstrate that ignorance of escape mortality may lead to underestimation of fishing mortality, particularly among the youngest age classes. It is evident that as the trend for using more selective gears continues, the relative importance of escape mortality on stock assessment will increase.

Further work is needed to assess adequately the true biological and economic costs of bycatch, and the benefits and costs of potential gear solutions. Technical measures such as mesh size increase are by nature long-term management measures (i.e. long-term gains are assumed when they are enforced). Substantial short-term economic losses, however, are often associated with their adoption. If short-term effects are not addressed, the assumed long-term gains may not be realized. The ecological as well as the socio-economic impacts of new measures and modifications should be comprehensively addressed before changes are implemented. In most cases, selectivity must be increased incrementally, otherwise short-term loss in commercial value for the fishery will cause fishers to not accept changes.

Conclusion

A major problem in many fisheries is that too many immature fish are caught and discarded before they have the opportunity to reproduce or reach their optimal size in terms of future yield. Many of the world's discarded fish are small juveniles of commercially-important species, which if left grow to mature size would produce significant yields. Major biological and economic losses occur as a result of bycatch, and reducing bycatch and discards has become one of the primary objectives of fishery management.

Technical measures, such as increased mesh sizes, are imposed in order to create conditions in which the capture of juvenile fish is minimized. The use of gear selectivity has a particular advantage because it provides a mechanism to reduce the mortality of younger fish while allowing the fleet to continue fishing. In recent years, there has been increasing interest in using various BRDs and gear modifications to improve the size- and species-selectivity of fishing gears. Many of these devices and modifications have reduced the levels of discarding. Traditionally, the fishing industry has been sceptical about the introduction of new and more selective gear modifications, but the deterioration of many important groundfish stocks has led to positive changes in attitudes towards the adoption of more conservative fishing methods. Real progress has been achieved in the reduction of bycatch and discards through gear modifications and operational improvements. Often, once the initial technical difficulties and resistance from fishers have been overcome, these new modifications are readily accepted.

In an ideal situation, when all escapees survive and selectivity and fishing effort are at optimal levels, the growth potential of the stock would be exploited efficiently and most fish would have a chance of growing to mature size and spawning. The spawning biomass would be high, resulting in larger and more stable catches. Fewer fish would be caught but the average size of the fish in the catch would be greater. Clearly, selective fishing has major potential for rational resource utilization. The ultimate success of selective gears, however, largely depends on fishers' willingness to accept them. Measures and techniques that increase costs and reduce earnings are unattractive to fishers. Moreover, the fishing effectiveness and practicality of new designs are important; inefficient gears will not be used or will be "manipulated". Individual fishers must not only understand the basic nature and magnitude of the problem, but must also believe that the resulting measures are effective and fair.

Fishing industries have played a crucial role in the development and implementation of most of the approaches that have been successful. Clearly, close cooperation among industries, scientists, managers and other stakeholders will be necessary throughout the development and introduction of environmentally-friendly fishing technologies. Factors that are critical to success have to be identified and determined together. A number of innovative technologies are already available, and further progress will be made. Innovative fisheries management plans offer positive incentives for the development and effective use of such fishing techniques. Proper management also stimulates the voluntary use of effective bycatch reduction practices by creating economic incentives.

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ANNEX 1

Species and their Latin names mentioned in this study

- Atlantic cod (*Gadus morhua*)
- Atlantic halibut (*Hippoglossus hippoglossus*)
- Atlantic herring (*Clupea harengus*)
- Atlantic salmon (*Salmo salar*)
- American lobster (*Homarus americanus)*
- American plaice (*Hippoglossoides platessoides*)
- brown shrimp (*Crangon crangon*)
- brown trout (*Salmo trutta*)
- Baltic herring (*Clupea harengus*)
- Baltic cod (*Gadus morhua*)
- chinook salmon (*Oncorhynchus tshawytscha*)
- coho salmon (*Oncorhynchus kisutch*)
- dab (*Limanda limanda*)
- haddock (*Melanogrammus aeglefinus*)
- hake (*Merluccius merluccius)*
- Hauraki Gulf snapper (*Pagrus auratus*)
- hoki (*Macruronus novaezelandia*)
- king crab (*Paralithodes camtschaticus*)
- lingcod (*Ophiodon elongatus)*
- mackerel (*Scomber scombrus*)
- Northeast Arctic cod (*Gadus morhua*)
- Norway lobster (*Nephrops norwegicus*)
- Pacific halibut (*Hippoglossus stenolepis*)
- Pacific herring (*Clupea pallasii*)
- Patagonian scallop (*Zygochlamys patagonica)*
- pearly finned cardinal-fish (*Apogon poecilopterus*)
- perforated-scale sardine (white sardinella) (*Sardinella albella*)
- pike-perch (*Sander lucioperca; Stizostedion lucioperca*)
- plaice (*Pleuronectes platessa*)
- red mullet (*Mullus barbatus*)
- sablefish (*Anoplopoma fimbria*)
- saithe (*Pollachius virens*)
- sand whiting (*Sillago ciliata*)
- scallop (*Pecten maximus*)
- sea bream (*Pagrus major)*
- shrimp (*Pandalus borealis*)
- snow crab (*Chionoecetes opilio)*
- sole (*Solea solea*)
- spider crab (*Leptomithrax gaimardi*)
- sunrise goatfish (*Upeneus sulphureus*)
- tanner crab (*Chinoecetes bairdi)*
- vendace (*Coregonus albula*)
- walleye pollock (*Theragra chalcogramma*)
- whiting (*Merlangius merlangus*)

- winter flounder (*Pseudopleuronectes americanus*)
- yellowfin bream (*Acanthopagrus australis*)
- yellowtail flounder (*Plueronectes ferruginea; Limanda ferruginea*)

Selective fishing has a large potential to reduce bycatch and discards, but it can be justified only if significant numbers of escaping fish survive. Many factors affect the survival of fish escaping from fishing gears and few studies have adequately explained the full range of stress, injury and mortality that can occur when fish escape from trawl codends under commercial fishing conditions. There are various options available to improve the survival of escapees. Installing escape panels or other sorting devices at strategic positions in a fishing gear can enhance escape and the survival of juveniles and non-target species. Facilitating the voluntary escape of fish through various constructional and operational solutions would increase the likelihood of their survival. In some cases, use of other fishing methods may be an appropriate approach to reducing unaccounted mortality associated with escape.

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