Behavior of Marine Fishes

Capture Processes and Conservation Challenges

Editor

Pingguo He

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Chapter 8
Fish Behavior near Gillnets: Capture Processes and Influencing Factors

Pingguo He and Michael Pol

8.1 INTRODUCTION

Gillnets are simple and versatile gears that catch a variety of fish and shellfish. Unlike mobile gears such as trawls, gillnets do not need to be towed or moved to catch fish; unlike baited gears such as hooks and pots, gillnets do not require the addition of bait; and unlike fixed gears such as traps and weirs, gillnets do not require fixed structures and are much more easily portable. Gillnets may be one of the simplest fishing gears in design with a plain sheet of webbing salvaged to frame ropes. They are used in every region of the world and operated from small boats of a few meters in length to highly mechanized offshore vessels. On closer examination, however, greater complexity is revealed. Even small details of gillnet construction appear to affect species and size selectivity. Although gillnets are simple in design and operation, the behavior of fish during the gillnet capture process is largely undocumented and not well understood.

The history of gillnetting may be as old as that of net making, and references can be traced back to 3000 years ago in Egyptian tombs. The modern commercial gillnet fishery in the Northwest Atlantic dates to the mid-1800s when natural fibers such as cotton and hemp were used to knit the netting. Gillnetting expanded in this region after migration of hauling technology from the Laurentian Great Lakes to Massachusetts in the 1930s. Synthetic materials were tested in fishing nets in the 1950s and became very popular on both sides of the North Atlantic due to the large catch increase observed and the almost maintenance-free nature of the material (He 2006a; Pol and Carr 2000; Potter and Pawson 1991). Modern gillnet webbings are made as invisible as possible to mesh fish before they can avoid them. Fish meshing into the net are often caught behind their gills, or "gilled," and thus the term "gillnet" is used, although other methods of capture are also common in gillnets.

Gillnets and entangling nets are one of the nine basic fishing gear categories in the U.N. World Food and Agricultural Organization (FAO) classification of fishing gears (Nedelec and Prado 1990). Set gillnets, driftnets, trammel nets, fixed gillnets, and encircling gillnets are five major subtypes in this category. Some key features of these nets are listed in Table 8.1. These different types of nets or the same type of nets of different mesh sizes and rigging may be combined to form a "combination gillnet."

A typical gillnet consists of webbing and frame ropes (headrope and footrope) (Fig. 8.1). The webbing is manufactured as diamond mesh in a single piece, including a selvedge of usually double monofilament along the top and bottom. The webbing is cut to length and lashed at intervals to the headrope and the footrope with hanging line. The headrope may have internal floatation or a series of floats attached to it. Footropes are often

Table 8.1. Types of Gillnets and Their Key Features

Gear Type	Important Features
Set gillnets	Anchored/weighted to the bottom; relatively stationary; can be set on the bottom, in midwater or near the surface
Drift gillnets	Not fixed to the bottom; drift with the current; usually near surface; either tied or not tied to the vessel.
Trammel nets	Three layers of nets; a middle net with a smaller mesh size and two outer nets with larger mesh sizes
Fixed gillnets	Hung onto stakes to form a wall or "fence"; usually in tidal and shallow waters or in rivers

constructed from braided line with built-in lead ("leadline"), although a series of single weights may also be used. Typically, the gear is also anchored at both ends with solid weights or Danforth anchors using bridle lines. Buoy lines with buoys and/or highflyers are used to mark both ends of the gear at the surface. Depending on the fishing area, jurisdiction, and the type of fishery, a gillnet may require attachment of tags, pingers, weak links, breakaway swivels, radar reflectors, or acoustic gear-finding transmitters. There may be specific requirements on the size, strength, and density of ropes (e.g., NOAA 2008), as well as the maximum number of nets allowed.

8.2 CAPTURE MECHANISMS, GEAR DESIGNS, AND FISHING EFFICIENCY

Four basic mechanisms of fish capture by gillnets can be identified: gilling, wedging, snagging, and entangling (Hovgård and Lassen 2000), as shown in Figure 8.2.

- Gilling—caught with the mesh behind the gill cover
- Wedging—caught by the largest part of the body
- Snagging—caught by the mouth or teeth or other part of the head region
- Entangling—caught by spine, fins, or other parts of the body as a result of struggling

Fish may be caught by more than one of these mechanisms in the same gillnet.

Key design features of a gillnet include netting material and color, twine diameter and number of filaments, mesh size or opening, vertical and horizontal hanging ratios, and net dimension (length and height).

The mesh size of a gillnet determines to a great extent the size of fish caught in the net as proposed by Baranov (1948) in his geometric similarity theory. He predicted that the majority of fish retained by a gillnet would have their length within 20% of the optimal length (modal length). In practice, this relationship may not be that simple, considering a wide range of species, gear design features, and operational conditions (Hamley 1975). While surveying young Atlantic cod (*Gadus morhua*) in Greenland waters, Hovgård (1996) found that more cod were caught by gilling, and less by other mechanisms, as mesh size was increased. Comparative fishing trials using gillnets of 127- and 140-mm mesh size on the south coast of Newfoundland targeting redfish resulted in 3.6 times more fish caught in the smaller mesh size nets (Brothers and Yetman 1982). However, catch rates of Greenland halibut *Reinhardtius hippoglossoides* increased with larger meshes (Melindy and Flight 1992). Gillnets made of 203-mm mesh size caught 38% more fish in weight than those with 140-mm mesh size (Melindy and Flight 1992). The increase in catch rates was due to the increase in the size of fish caught for the larger-mesh nets as the average weight of fish caught in the large-mesh nets was 3.5 times heavier than those in the small-mesh nets. Comparing gillnets of 180- and 220-mm mesh sizes in the Barents Sea for Greenland halibut, Nedreaas et al. (1993) found that the modal length was 55 cm for the smaller mesh size compared with 66 cm for the large-mesh size. While regulating mesh size to reduce undersized fish has been a common management measure in many fisheries, for some species, such as paddlefish (*Polyodon spathula*), size selectivity cannot be established, perhaps due to unusual morphology (Scholten and Bettoli 2006).

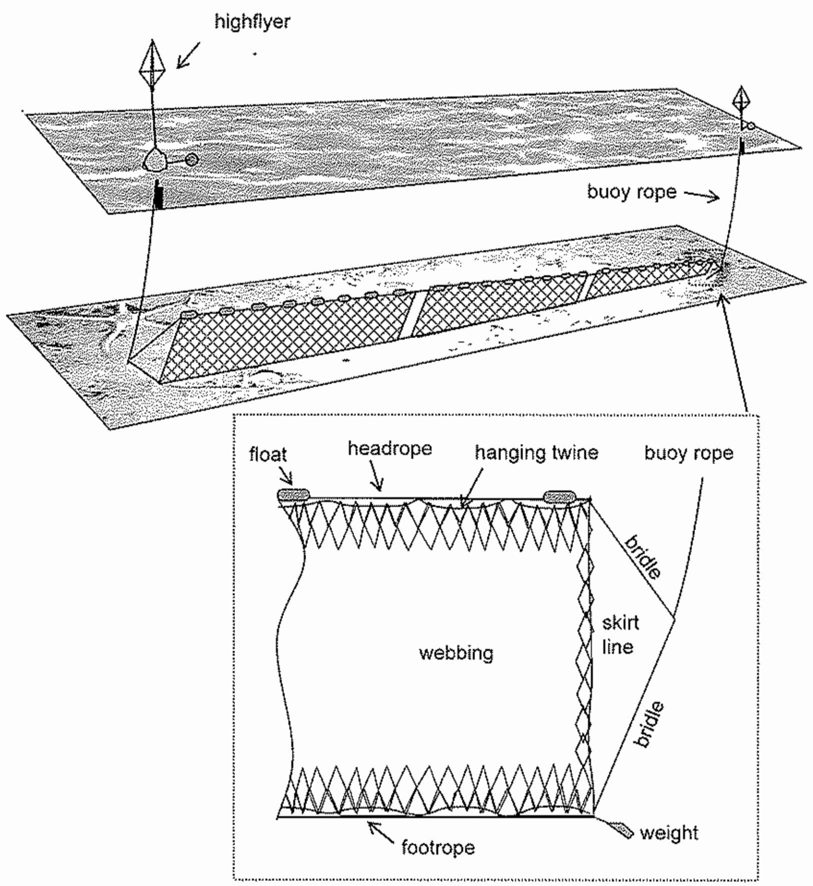


Figure 8.1. Schematic illustration of a string of gillnet while fishing. Inset: an anatomy of a gillnet with names of gear components. (He 2006a.)

Hanging ratio is another factor for design consideration. Horizontal hanging ratio is the ratio of rope length (headrope or footrope) to the stretched length of the attached webbing. Vertical hanging ratio is similarly the ratio of the skirt line to the stretched length of the webbing. Both are expressed as a decimal or percentage, with lower values indicating more "slackness" and affecting the shape of the mesh (Fig. 8.3) and resistance to penetration. Takagi et al. (2007) modeled forces acting on a bottom sink gillnet and determined that discontinuities and strong localized forces developed on the net surface. These results suggest that hanging ratios create different relative forces on the meshes, which may increase or decrease the amount of force required for mesh penetration by fish. Comparative fishing trials between gillnets of different headrope hanging ratios (0.5–0.7) indicated that the best hanging ratio for catching Atlantic cod (*Gadus morhua*) was 0.6 instead of the traditional 0.5 used by Norwegian fishermen (Angelsen et al. 1979). For European dab, nets with a hanging ratio of 0.2 caught twice as many fish as nets with a hanging ratio of 0.6 (Hovgård and Lassen 2000). Samarayanka et al. (1997) reported 40% more catch of tuna (mostly skipjack tuna, *Katsuwonus pelamis*, and yellowfin tuna, *Thunnus albacares*) and sharks with a hanging ratio of 0.5 versus 0.6. Slackly hung gillnets have been found to result in more fish becoming entangled than gilled, which results in poorer size selectivity (Angelsen et al. 1979; Hamley 1975; Samaryanka et al. 1997; Stewart 1987). When

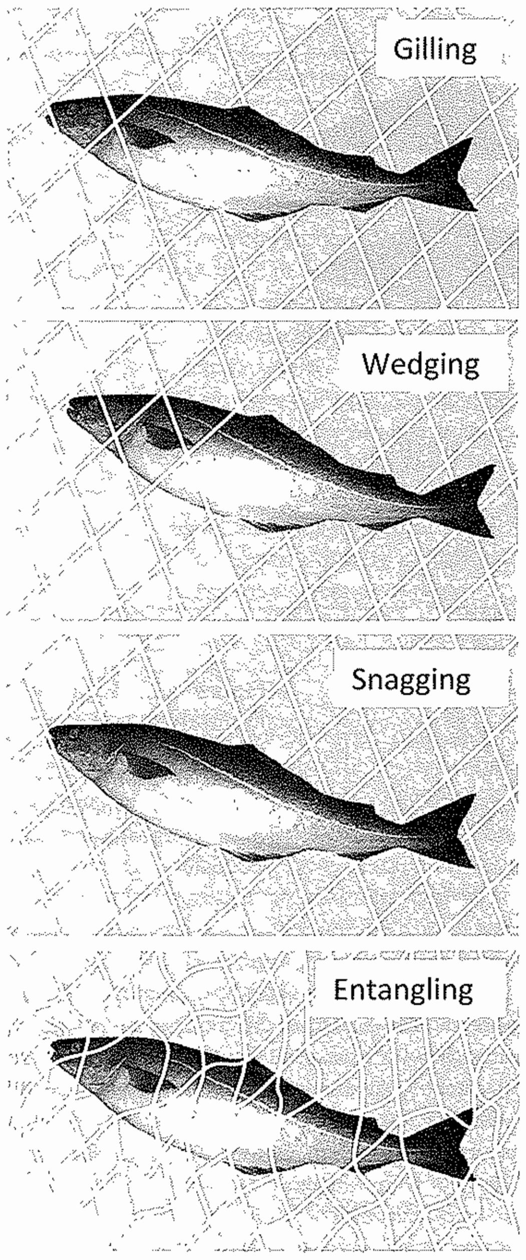


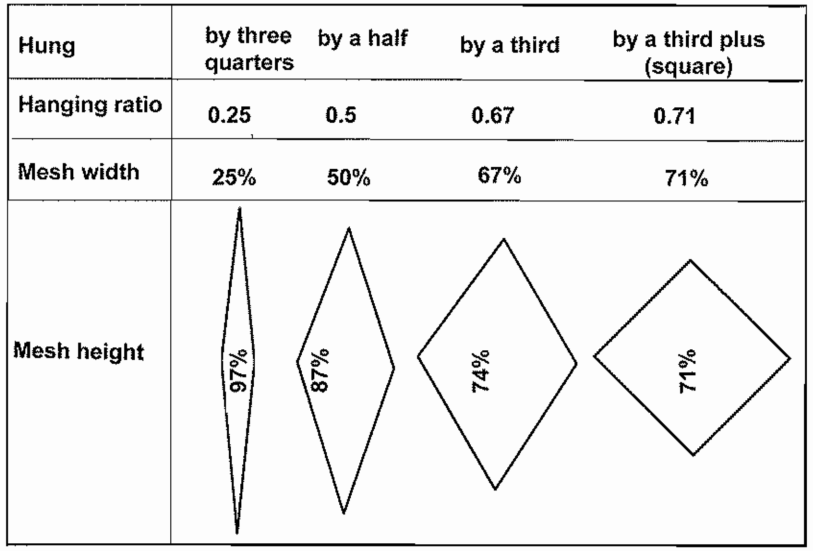
Figure 8.2. Fish capture by gillnets, illustrating four modes of capture: gilling, wedging, snagging, and entangling.

studying *Tilapia*, Hamley (1975) obtained a size range (90% of catch) of 18 to 23 cm in a tightly hung net but 8 to 22 cm in a slackly hung net. Sulaeman et al. (2000) attributed the improved catch efficiency of slackly-hung gillnets to an increase in the mesh per unit area of the net panel. However, a 25% increase in catch was observed by Samarayanka et al. (1997) even when adjusted for the increased area.

Webbing material, numbers of filaments in the twine, and twine size affect visibility of the netting in water and the "softness" of the netting, which in turn affects the mechanism of fish capture. Monofilament nets are less visible and generally produce larger catches than multifilament nets (Collins 1979; Larkins 1963, 1964; Pristas and Trent 1977). Larkins (1964) reported that the monofilament nets in a monofilament and multifilament string caught 1.9 to 4.1 times more Pacific salmon than did the multifilament nets in the same string. A larger percentage of fish are gilled in monofilament gillnets than are in nets made of multifilament and multimonofilament, which tend to result in tangling.

Thinner twines generally catch more fish (Holst et al. 2002; Hovgård 1996; Hovgård and Lassen 2000), as they are less visible and softer, but they may have poorer size selection (larger selection range) due to elongation when a fish pushes into the mesh (Hansen 1974) and ease of entanglements (Yokota et al. 2001). Turunen (1996) reported no change in size frequency but a 190% increase in catch of pikeperch (*Stizostedion lucioperca*) when comparing 0.15-mm twine and 0.20-mm twine. Hovgård and Lassen (2000) reported that monofilament nets with 0.16-mm twine caught 2 to 3 times more European dab (*Limanda limanda*) than a net with 0.28-mm twine. Holst et al. (2002) found that gillnets made of four-strand No. 1.5 multimonofilament twine (0.28-mm diameter) caught about 1.5 times that of six-strand No. 1.5 twine (0.36-mm diameter) for Baltic cod (*Gadus morhua*). Hovgård (1996) found that fishing efficiency was inversely related to the ratio of twine thickness to mesh size for a number of species in Greenland waters. However, nets made of thin twines are more easily damaged, which may result in increased costs and lost fishing time. Further, they may produce increased catch of undesired species such as crustaceans.

Net dimension (height and length) may also affect catch, although net length generally does not alter the species or size composition of catches—it



Hung	by three quarters	by a half	by a third	by a third plus (square)
Hanging ratio	0.25	0.5	0.67	0.71
Mesh width	25%	50%	67%	71%
Mesh height	97%	87%	74%	71%

Figure 8.3. Explanation of hanging ratio of a gillnet. (He 2006a.)

merely increases effort. Fish may lead along the nets, and length may affect the likelihood of striking the mesh. Net height, however, appears to alter species selectivity and affect fishing efficiency of some species. Height in gillnets is affected by a number of factors—the amount of buoyancy in the headrope, the presence of "tie-down" lines (lines connecting footrope and headrope that restrict the height of a gillnet), and the strength of currents and resistance of the webbing. In the Northwest Atlantic, Atlantic cod are targeted with nets with a great deal of buoyancy, so that they reach their maximum height. Flatfish are targeted using headropes with less floatation and with tie-down lines.

8.3 SIZE SELECTIVITY OF GILLNETS

The selection of fish by a fishing gear is the process that causes the catch of the gear to have a different composition, either of sizes or of species, than that of the population on the fishing grounds (Wileman et al. 1996). Selectivity is the quantitative assessment of this selection process. Gillnet selectivity processes, mechanisms, and analysis methods are reviewed by Hamley (1975), Millar and Fryer 1999, Hovgård and Lassen (2000), and Fujimori and Tokai (2001). Gillnet size selectivity curves are approximated as Gaussian or bell-shaped and may have two or more peaks reflecting different mechanisms of capture (discussed earlier) or multiyear class population. Bimodal curves were found to provide the best fit in several studies (Fonseca et al. 2005; Madsen et al. 1999; Moth-Poulsen 2003); in others, the normal scale curve (Revill et al. 2007) or the lognormal (M. Pol, unpublished data) provided the best fit.

Efficiency of gillnets is affected by mesh size, webbing material, hanging ratio, twine size, and fish behavior as discussed earlier. However, mesh size is likely the most important factor affecting gillnet size selectivity. Experiments confirm that larger meshes result in catches of more large fish, shifting the selectivity curve to the right as shown in Figure 8.4A; these results conform Baranov's (1948) geometry similarity rule on fish size and mesh size. If the *x*-axis is expressed as length divided by the mesh size, selectivity can be expressed as one master curve as seen in Figure 8.4B.

Gillnets generally catch larger fish compared with other gears, if the proper mesh size and netting materials are used. Comparative fishing trials have demonstrated that gillnets caught more large fish than other fishing gears. When used simultaneously on the west coast of Greenland, gillnets caught more large Greenland halibut than did longlines (Boje 1991). Although both gears caught fish of the

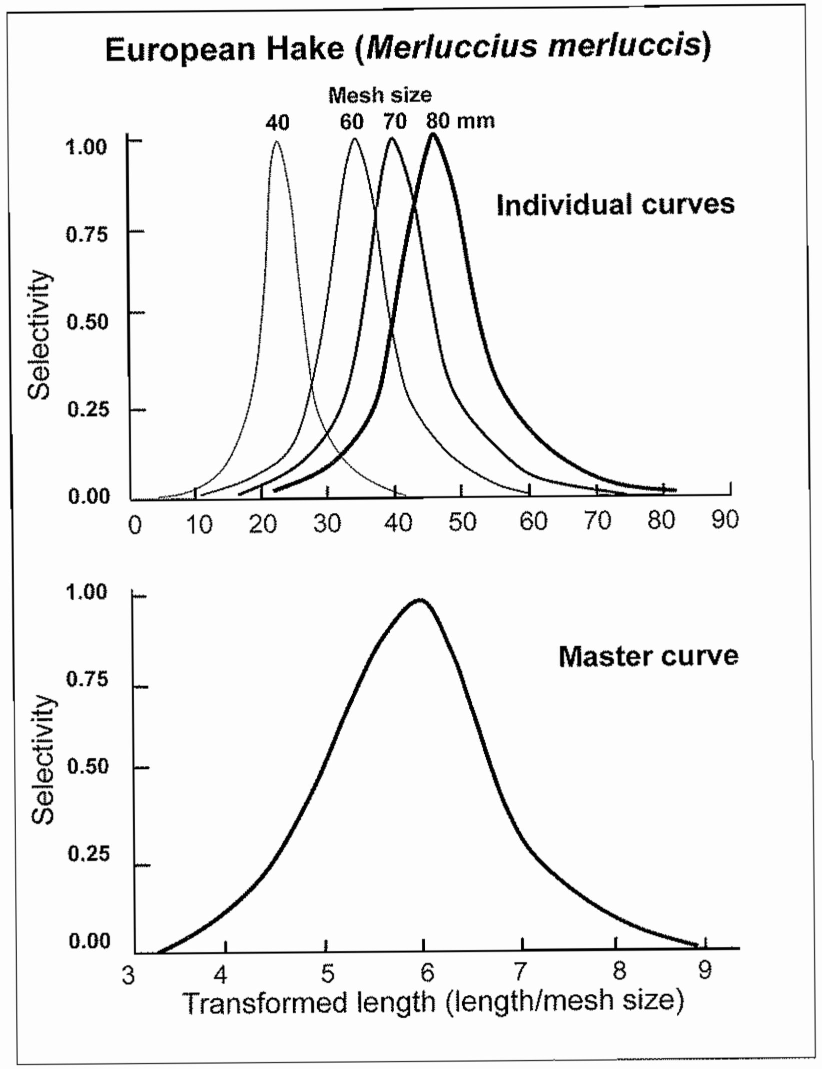


Figure 8.4. Selectivity curve of gillnets of different mesh sizes for European hake (*Merluccius merluccius*), and master curve using transformed length. (Redrawn from data in Fonseca et al. 2005.)

same peak length of about 70 cm and had a similar length range from 45 to 115 cm, longlines caught a larger proportion of fish between 50 and 65 cm, while gillnets caught a larger proportion of fish between 65 and 85 cm. Cod on the Flemish Cap in the Northwest Atlantic are fished by several fleet sectors that can be identified by gear (trawl/mesh size, gillnet, longline) and by country (Boje 1991). Portuguese gillnetters caught the largest cod with an average weight of 2.5 kg, whereas Spanish and Portuguese freezer trawlers caught the smallest cod with an average weight of 0.4 kg and 0.9 kg, respectively (Boje 1991). Lowry et al. (1994) compared gillnets and trawls with the same mesh sizes ranging from 105 to 130 mm targeting Baltic cod and found that gillnets caught fish with peak lengths 7 to 16 cm longer than fish caught with trawls using the same mesh size. Nedreaas et al. (1993) and Huse et al. (1999) compared 220-mm mesh size gillnets with a 135-mm codend mesh size trawl and No. 12/0 EZ-baiter hooks in a longline targeting Greenland halibut in the Barents Sea off northern Norway.

They found gillnet catches were composed of mostly mature females of large size, whereas the trawl and longline had a much lower percentage of large mature females. The average length of gillnet fish was 65.9 cm, the longline caught fish that averaged 59.6 cm, and the trawl caught fish that averaged 50.1 cm. Comparison of three gear types targeting cod and haddock showed similar results (Huse et al. 2000). The selection range of gillnets are also narrower than that for other gears (Erzini et al. 2003). Santos et al. (2002) compared gillnets to longlines in a hake (*Merluccius merluccius*) fishery and found gillnets had a narrower size selectivity but found the longlines yielded better-quality fish, attributed to long soak times (more than 8 h) in the gillnets.

8.4 FISH BEHAVIOR AND GILLNET FISHING

Fish availability, vulnerability, and mobility are the most important factors influencing fishing efficiency of stationary gears. Horizontal and vertical migrations are well known in many fish species. Diurnal vertical migration related to light levels and semidiurnal vertical excursions related to tide can affect gillnets set on the seabed. Increases in the rate of horizontal movement increases the probability of fish encountering gillnets. The amount of horizontal movement is especially important for set gillnets that await encounter on predicted fishing routes or foraging grounds. Fishing operators therefore need local knowledge of fish availability to set nets in the right place at the right time to be successful.

Temperature may be the most important factor affecting distribution, movement, and swimming capacity. Vertical and horizontal temperature distribution patterns can cause localized concentrations and dispersal of fish and make them more or less vulnerable to gillnets (Perry and Neilson 1988; Rose and Leggett 1989; Woodhead 1964). The fishing range (the size of fishing area) of a gillnet and encounter rate of a fish (Engås and Løkkeborg 1994; He 2003; McQuinn et al. 1988) may be reduced at lower temperatures, influencing fishing efficiency of gillnets (Stoner 2004). Swimming speed of fish in relation to temperature has been discussed by Wardle (1975, 1980) and He (1991, 1993, 2003) and in Chapter 1. In general, swimming speeds are lower at lower water temperatures (Figure 8.5). He (2003) measured the rate of movement of winter flounder (*Pseudopleuronectes americanus*) on fishing grounds using a video camera and found the rate of movement was reduced by 70% when bottom water temperature was reduced from 4.4° to −1.2°C. He (2003) further discussed how fishing areas or the active fishing space of a gillnet may be altered due to a change in water temperature and soaking durations (Fig. 8.6).

Swimming speed is also related to fish body length, as discussed in Chapter 1. Consequently, larger fish can swim faster and have larger geographical ranges than smaller fish. Gillnets (and other stationary gear) may have an intrinsic size selection property as larger fish are likely to reach the net and become available to the nets set some distance away (Fig. 8.6). This length-related difference in encounter probability in gillnets was discussed by Rudstam et al. (1984), who also applied size-related differences in encounter probability to correct abundance estimates for some freshwater species in the Laurentian Great Lakes. Other factors affecting swimming and local movement may include satiation or hunger (Robinson and Pitcher 1989) and prey density (Asaeda et al. 2001), light level (Gjelland et al. 2004), oxygen level (Beamish 1978), and spawning condition. Robinson and Pitcher (1989) found that the swimming speed of herring (*Clupea harengus*) was highest when they were hungry, presumably related to active food searching behavior. When prey species were plentiful (high prey density), swimming speed may be slowed down (Asaeda et al. 2001). Angelsen (1981) reported that more male spawning cod and halibut are caught by gillnets than are females because they are more active on spawning grounds.

Reports of underwater observations of fish behavior near gillnets in the field are scarce and limited to freshwater or coral reef environments where shallow water and good lighting conditions provided better opportunities for observations either by the naked eyes or by underwater video cameras. Laboratory tank observations of fish capture by gillnets (Potter and Pawson 1991) revealed that Atlantic

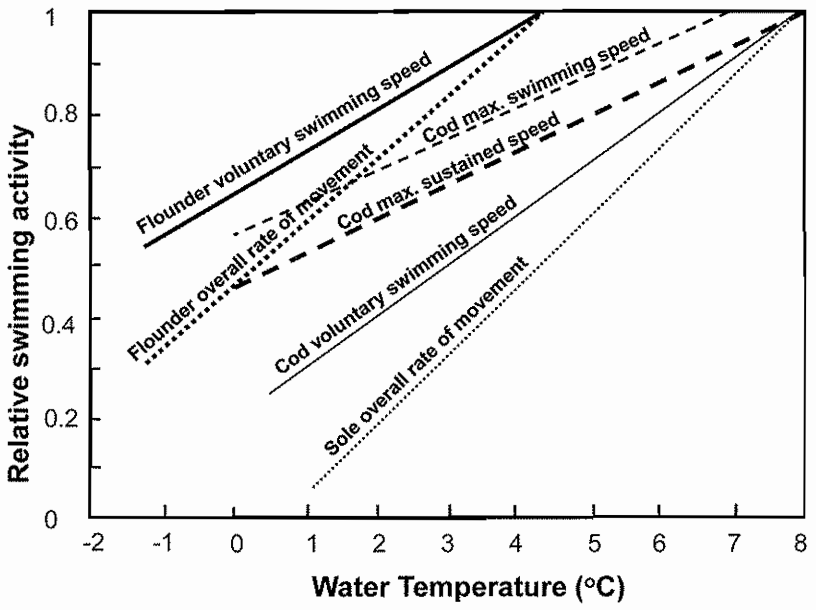


Figure 8.5. Reduction of activity and swimming capacity due to lower water temperature, assuming 1 at the higher end of temperature. (From He 2003.)

salmon (*Salmo salar*) initially struggled powerfully for less than 30 s. This powerful struggle was followed by a long period of weak activities, similar to the behavior observed in hooked fish (Bjordal and Løkkeborg 1996). Gilled fish tended to swim forward, pulling the net with them. Smaller fish may escape by squeezing through the meshes. Eleven salmon that escaped by squeezing through meshes did so in less than 25 s. Tangled fish were more likely to wrench their head or tail and to swim backward or alongside the net. The fate of capture or escape was also largely determined during the first 25 s (Potter and Pawson 1991). Fujimori et al. (1994) classified rainbow trout (*Oncorhynchus mykiss*) behavior in laboratory experiments in two ways: swimming straight into the net head-on or contacting the net with abdomen or tail.

Visibility (or invisibility) of the net is the most important aspect of gillnet design and operation. Fish vision and underwater visual characteristics of fishing gear components have also been discussed in Chapter 2. The visibility of the net is determined by the fish's visual characteristics, material of the net, light level and composition, water clarity, contrast of the net, and relative position of the fish to the net. Angelsen and Huse (1979) tested seven nets made from different materials and colors and found that monofilament nylon was least visible and multifilament nylon was the most visible at various water depths. Wardle (1989) illustrated how different shaded twines hung vertically in water had different visibilities when viewed at different angles (Fig. 8.7). White twines disappeared toward the surface, black twines disappeared near the bottom, and grey twines were least visible when viewed horizontally. Transparent monofilament lines hung vertically are almost invisible when viewed horizontally (Gabriel et al. 2005). Comparison of mesh penetration or avoidance of four types of twines of different colors by Atlantic mackerel (*Scomber scombrus*) indicated that the fish more readily penetrate the naturally colored (transparent) monofilament netting, whereas nets made from glow twine were more likely to be avoided (Fig. 8.8) (SOAFD, 1992). Faulkner (1994) discussed a "window-pane" gillnet with a highly visible large mesh in the top section and regular gillnet webbing in the bottom section. The highly visible netting on the top was believed to drive surface-swimming fish into the deep water, where

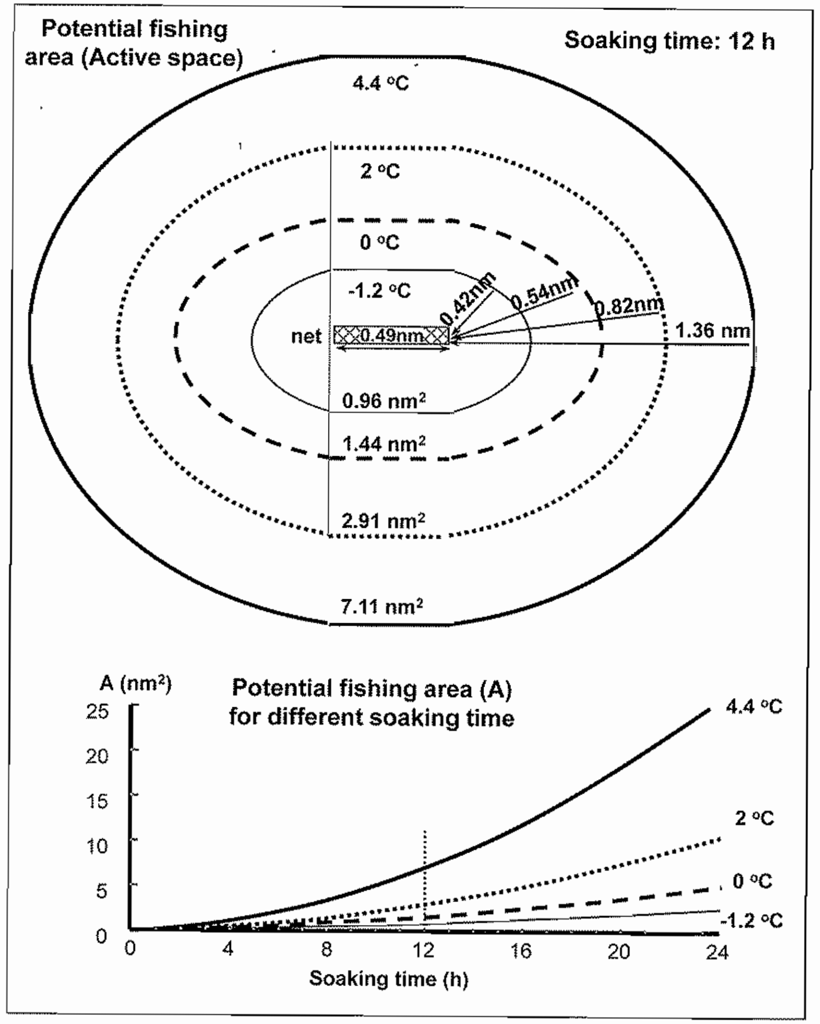


Figure 8.6. Predicted fishing range of gillnets at different water temperatures and at different soaking durations. (From He 2003.)

they were subsequently caught in the bottom part of the net.

Once the fish are in the vicinity of the net, those individuals unaware of the presence of the net may swim into it and become caught. Visibility of the net is reduced when there is low contrast between the net and its background. Smaller-diameter materials are also less visible. Nighttime hours, periods with no moon, high-latitude winter days, deep water, and turbid water (near estuaries, tidal area with muddy bottom) all contribute to lower visibility of the net. Fish are not able to detect the netting easily at lower light levels, increasing the chance of being caught by gillnets. However, lower light level conditions also cause fish to slow down (Gjelland et al. 2004), which reduces encountering probability with gillnets.

The lower visibility of synthetic nets made of thin twines may be largely responsible for the increase in catch rates compared with natural fibers (Potter and Pawson 1991). Fish may also be deterred by strong smells from preservatives used in natural fibers. Vibrations from water current passing through meshes of the netting may also make fish aware of the net (Gabriel et al. 2005). Fish seeing or otherwise detecting the net may turn and swim

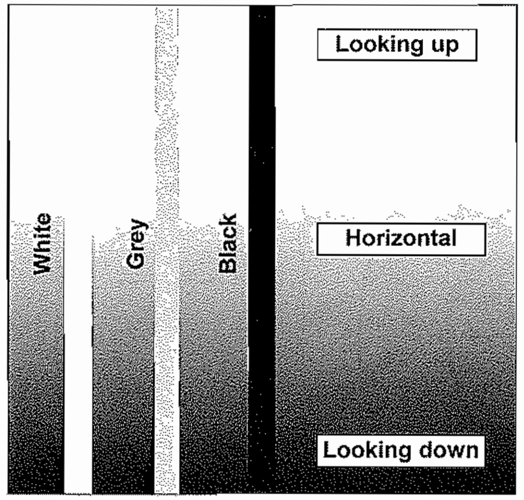


Figure 8.7. Contrast of white, grey, and black twines hung vertically in water in relation to viewing angle. (Redrawn from Wardle 1989.)

parallel to the net, similar to the behavior observed in the leader of a trap (see Chapter 7).

Acosta and Appeldoorn (1995) described observations of gillnet catch in relation to soak time and found that catch rate initially decreased after setting for 6 to 10h but increased between 10 and 20h. It was argued that the initial decline in catch efficiency may be related to reduction of fish density soon after the net was set as well as increased visibility of the net with meshed fish. Acosta and Appeldorn (1994) observed that several fish turned away after seeing a struggling fish caught in the net. The geometry of a gillnet may also be affected by the fish caught in the net, especially if it is entangled and twisted into several meshes. Grant (2002) observed walleye (*Sander vitreus*) using a stereo camera system in a shallow lake. He examined three mesh sizes and counted the number of fish blocked (turned away), passing through meshes, and caught in the meshes. Many small fish passed through meshes of large-mesh nets while many large fish were blocked by the small-mesh net, as expected. Of 147 fish observed, 35 were caught, while 46 swam through the meshes, 29 escaped after becoming temporarily wedged or entangled, and 39 were blocked (turned away) and never contacted the net. These specific numbers are important in determining catchability of specific gillnets during stock assessment surveys.

The possibility of increasing catches in gillnets through the use of additional stimuli has been investigated. Properties of fish attraction using bait are discussed in Chapter 5. Baited gillnets were tested in Norway (Engås et al. 2000; Kallayil et al. 2003). The idea of using bait in gillnets came from unexpectedly high catch rates when gillnets were set for a longer duration. It was postulated that fish caught at the beginning of the soak period might have acted as bait to attract more fish to the area (Engås et al. 2000). In some fisheries, such as the deepwater Greenland halibut fishery off Labrador, fishermen may set nets for longer than 2 weeks (Melindy and Flight 1992). In that research, however, catch rates of Greenland halibut were reduced and the amount of spoiled fish increased when soaked for a longer period of time.

Baited gillnets caught more Atlantic cod, saithe (*Pollachius virens*), ling (*Molva molva*), and Greenland halibut in a study by Engås et al. (2000) but not in one by Kallayil et al. (2003). Analysis of tagged and acoustically tracked Atlantic cod near baited and nonbaited gillnets indicated that fish spent more time near baited gillnets and have more encounters with the nets (Kallayil et al. 2003). Fish were observed to turn and make directional movements toward the bait as far away as 800m. Fish swam more slowly near baited gillnets than near nonbaited gillnets. Kallayil et al. (2003) attributed a decrease in catch rates to this slower swimming behavior despite more observed encounters. Slower swimming may give fish more time to avoid gillnets. The presence of bait may have interrupted swimming and made fish more aware of the net. In their experiment, Kallayil et al. (2003) noticed that relatively more cod were tangled than gilled or wedged in baited gillnets compared with nonbaited gillnets, indicating that most of fish were not directly swimming into the baited gillnets.

8.5 MEASURES TO REDUCE BYCATCH AND DISCARDS IN GILLNETS

Gillnets can catch a variety of species, with many of them being considered as bycatch and subsequently

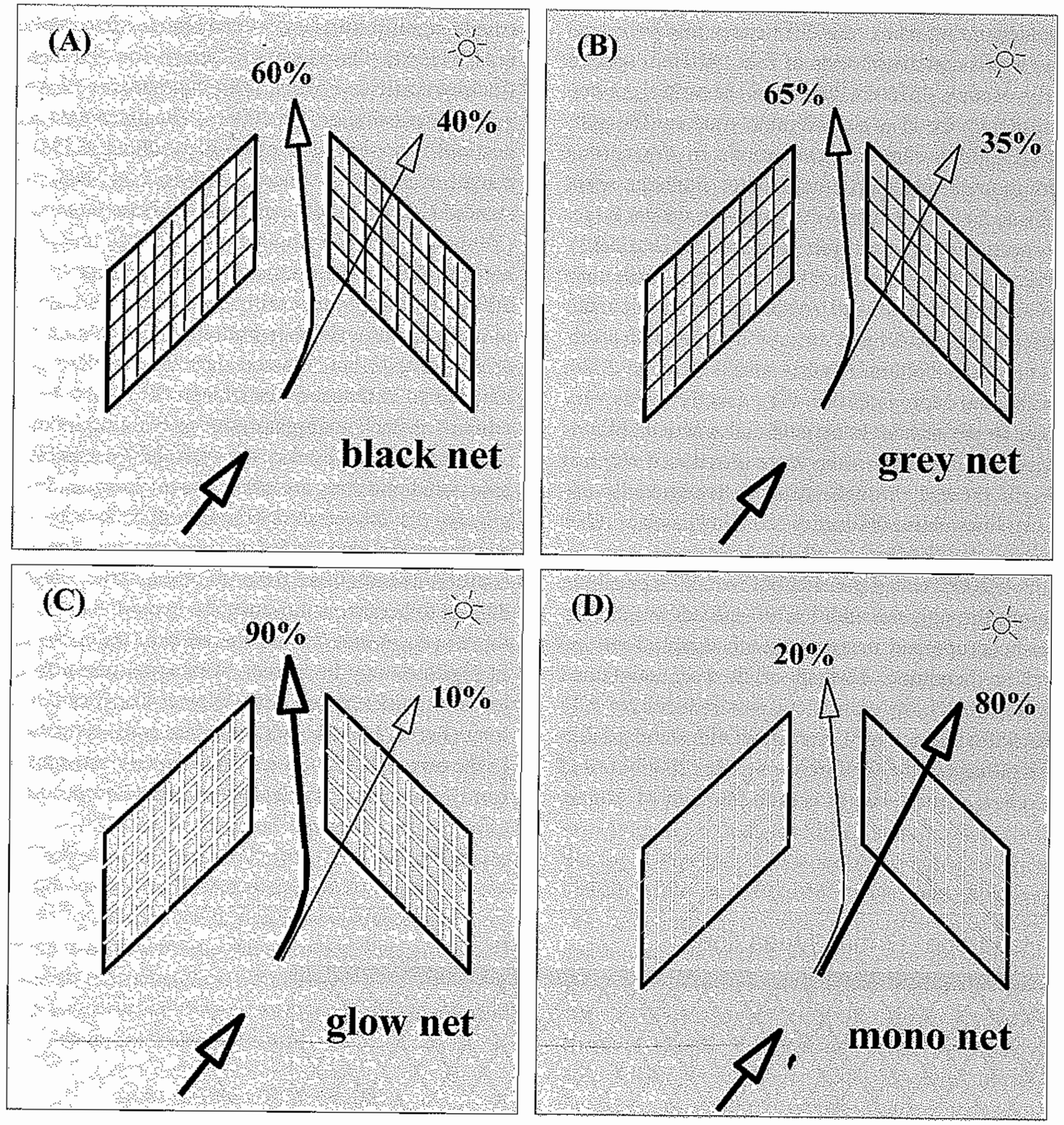


Figure 8.8. Avoidance of Atlantic mackerel (*Scomber scombrus*) to nets of different colors. (Redrawn from data in SOAFD 1992.)

discarded. While the rate of discard from gillnet fisheries was considered low on a global scale (0.5% by weight), discard in some specific gillnet fisheries is quite high (Kelleher 2005). Morizur et al. (1996, cited in Kelleher 2005) reported that up to 100% of fish caught in offshore gillnets soaked for more than 6 days may be discarded due to poor quality. Murawski (1993) reported that 44% of fish by weight were discarded from Gulf of Maine groundfish gillnets in 1991. In this case, the majority of discards from gillnets were due to a lack of market for the bycatch species (Alverson et al. 1994).

Bycatch of nontarget species may be reduced by understanding and using differences in the vertical and horizontal distribution of fish. Different species may occupy different levels of the water column and some spend a considerable time on the substrate. Video camera observations in the natural environment indicated that winter flounder spent 33% to 68% of time on the substrate with a larger proportion of time at lower temperatures (He 2003). The fish were never observed to rise to more than 0.6 m from the seabed. Although some flounder species take prolonged excursions to higher levels in the water column (Cadrin and Westwood 2004; Walsh and Morgan 2004), they usually reside very close to the seabed. In commercial practice, gillnets targeting flounders often have a reduced vertical height created through reduced floatation or tie-down lines, thus avoiding or reducing catch of other species that live higher off the bottom.

Pol (2006) tested the effect of reduction of gillnet height through the addition of spaced weights on the headrope and using nets with double footrope and no headrope. Flatfish catch was maintained while bycatch of Atlantic cod was reduced by 49% and 58%, respectively, compared with standard flatfish gillnets in the Gulf of Maine. He (2006b) tested two low vertical height nets in the Gulf of Maine. The 8 meshes deep (MD) experimental gillnets caught significantly less cod than the regular 25 MD net, whereas the catch efficiency for flounders (mainly American plaice [*Hippoglossoides platessoides*]) was similar (He 2006b). The extended gillnets with an extra 10 meshes of webbing (35 MD) caught significantly more Atlantic cod than the standard 25 MD nets in tests in Newfoundland (Yetman 1989). Norwegians use much higher gillnets (60 MD) when targeting cod (Engas et al. 2000). Similarly, nets with tie-down lines caught more flounder and other bottom-dwelling animals (e.g., lobsters) but less cod than the standard cod net due to a reduced vertical profile and a large amount of slack netting near the seabed (He 2006b).

Crabs and lobsters are strongly substrate-associated and thus are often caught in groundfish gillnets (Godøy et al. 2003; He 2005, 2006b). In some jurisdictions, retention of crustacean species is prohibited in gillnet fisheries or they are so abundant as to become a nuisance. To avoid the catch of these species that live on the seabed, the footrope of a gillnet may be raised. Norwegian researchers tested a gillnet rigged with "Norsel lines" of 0.5 m long (Fig. 8.9). Although there was some reduction in the targeted Atlantic cod, the Norsel nets significantly reduced the catch of king crabs (*Paralithodes camtschaticus*) (Godøy et al. 2003). Similar experiments were carried out in Newfoundland to reduce snow crab bycatch in Greenland halibut fishery (Brothers 2002). Preliminary experiments in the Gulf of Maine to reduce cod catch when targeting haddock (*Melanogrammus aeglefinus*) and pollock (*Pollachius virens*) with Norsel nets provided encouraging but limited results (Eayrs and Salerno 2008).

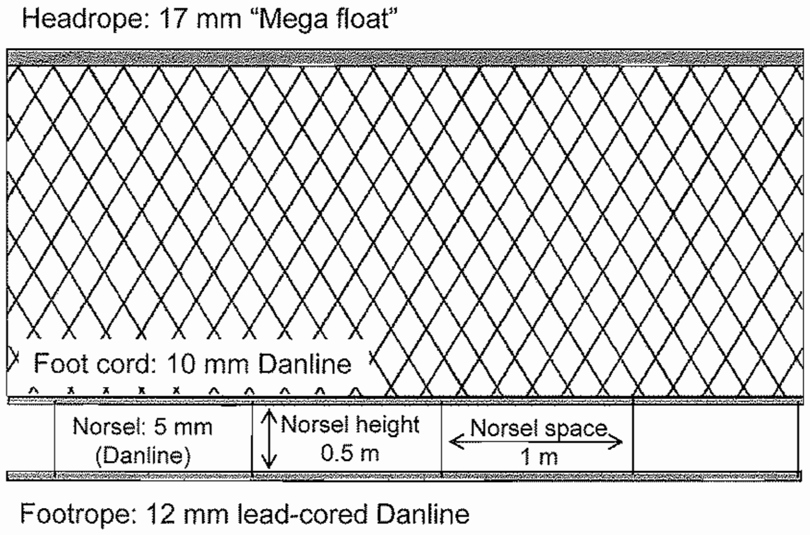


Figure 8.9. Design of the Norsel net to avoid bycatch of king crabs (*Paralithodes camtschaticus*) in northern Norway. (Redrawn based on Godøy et al. 2003.)

Bycatch species escaped, released, or discarded from gillnets may experience physiological and physical impact, and eventual mortality, related to capture and discard processes (Suuronen 2005; also see Chapter 11). Buchanan et al. (2002) estimated that traditional gillnets targeting other species caused 35% to 70% of total mortality on coho salmon (*Oncorhynchus kisutch*) in the Pacific coast. Shorter soak durations together with an onboard recovery procedure reduced mortality rates significantly. The mortality rate from 40-min set was 6.7% and those from 140-min set was 52% to 72% after being held in net pens for 48 h (Buchanan et al. 2002). Vander Haegen et al. (2004) found an immediate survival rate of greater than 95% for spring chinook salmon (*Oncorhynchus tshawytscha*) caught by several tangle nets and gillnets using tagging and recapture methods, but fish released from tangle nets recovered better than those from gillnets. The recovery rate from 114-mm mesh size tangle nets was 1.9 times that of 203-mm gillnets. They found that fish in small-mesh tangle nets were often snagged by the snout rather than gilled and argued that snagging would have reduced injury compared with gilling or wedging and also allowed the fish to continue to respire.

8.6 INTERACTION OF MARINE MAMMALS, SEABIRDS, AND SEA TURTLES WITH GILLNETS

Bycatch and related mortality of charismatic animals, including marine mammals, seabirds, sea turtles, and others, has created negative images for gillnets. As a result, gillnets and driftnets are banned in some areas. While the interaction of megafauna species with fishing gears and mitigation measures are discussed in detail in Chapter 13, a brief account of issues related to gillnet fishing is provided here.

Seabird bycatch occurs in almost all gillnet types, especially those nets set near the surface, adjacent to bird colonies, and in shallow waters (DeGange and Day 1991; Forney et al. 2001; Lewison et al. 2004; Lien et al., 1989; Melvin et al. 1999). During the capelin spawning season in Newfoundland, intense inshore feeding by birds and peak commercial fishing activities with both bottom and surface gillnets coincided, resulting in significant seabird mortality (Lien et al. 1989). The greatest bycatch of birds by gillnets was near bird breeding colonies, with diminishing bycatch as distance from the colony was increased (Lien et al., 1989). Common murres (*Uria aalge*) were most often caught in monofilament groundfish gillnets, whereas Atlantic puffins (*Fratercula arctica*) were more often caught in surface gillnets for salmon.

Descriptions of mitigation measures to reduce seabird mortality are limited (Manville 2005). Hayase and Yatsu (1993) submerged high-sea driftnets 2 m below the surface and significantly reduced seabird entanglement. However, there was a substantial reduction in targeted species. Faulkner (1994) theorized that a "window-pane" gillnet containing a thicker twine and larger mesh top panel and regular gillnets underneath it might reduce seabird bycatch. Melvin et al. (1999) used a similar principle and tested a modified salmon gillnet with the top 20 meshes of the webbing made of highly visible white multifilament twine, and they were able to significantly reduce bycatch of common murre and rhinoceros auklet (*Cerorhinca monocerata*) (Fig. 8.10). Melvin et al. (1999) also found that acoustic pingers (1.5-kHz frequency in 4-s bursts at 120 dB re 1 µPa) attached to the headrope of a gillnet were able to reduce seabird bycatch. Because most seabird bycatch occurred at dawn and dusk and during certain times of the year, a combined measure of gear modification, time restriction, and area closure may reduce seabird bycatch by 70% to 75% without significant reduction in target species (Melvin et al. 1999).

Interactions between marine mammals and gillnets can result in animal mortality and severe damage to the fish and the fishing gear (Lewison et al. 2004; Lien 1995; Lien et al. 1989; Northridge 1991). Globally, more than 80,000 small cetaceans have been reported killed annually in coastal waters,

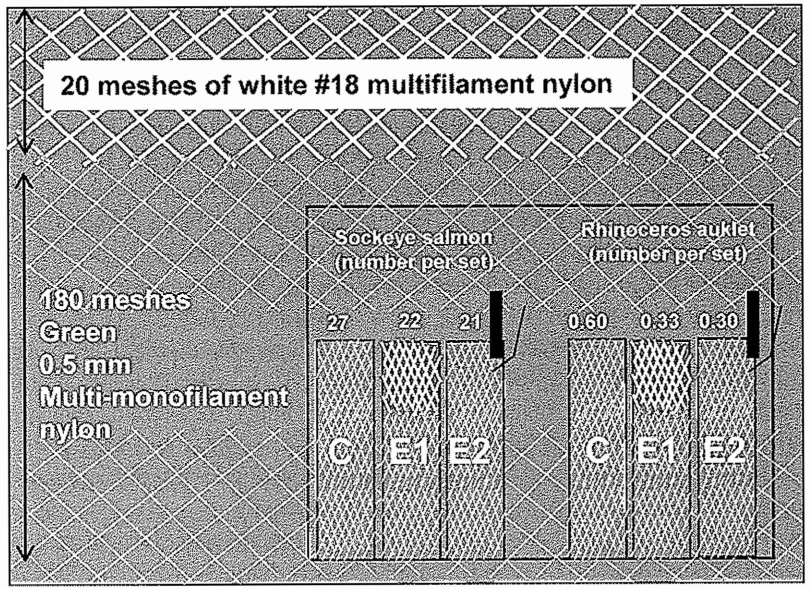


Figure 8.10. Design of a gillnet with high contrast white netting on the top to reduce seabird bycatch in Puget Sound sockeye salmon driftnet fishery. C, control net; E1, experimental net with 20 mesh white netting on the top; E2, experimental net with 1.5-kHz pingers. (Redrawn from data in Melvin et al. 1999.)

with many of them killed as a result of fishing activities (Jefferson and Curry 1994). According to Lien et al. (1989), an annual average of 24 humpback whales (*Megaptera novaeangliae*) were entrapped in Newfoundland groundfish gillnets between 1978 and 1987. Belden et al. (2006) reported that 2292 marine mammals were caught in the U.S. Northeast groundfish gillnets in 2004, with another 231 animals in the Mid-Atlantic coastal gillnets. Carretta et al. (2005) reported marine mammal, sea turtle, and bird mortality in the California driftnet fishery for swordfishes and sharks between 1996 and 2002 with a variety of mortality rates for different species. Bycatch of marine mammals by large-scale drift nets resulted in a ban of driftnet fishing in the high seas.

Harbor porpoises (*Phocoena phocoena*) are incidentally caught in gillnets throughout their distribution range in northern waters (Perrin et al. 1994). Acoustic pingers tested in groundfish gillnets in the Gulf of Maine and Bay of Fundy reduced mortality of harbor porpoises, and the use of the devices has become mandatory in the fishery (Kraus et al. 1997; Trippel et al. 1999). Kraus et al. (1997) demonstrated that 10-kHz pingers were able to reduce porpoise catch while maintaining target species catch of cod and pollock. However, the mechanism by which acoustic pingers were able to reduce porpoise bycatch was not clear (Dawson et al. 1998; Kraus et al. 1997). Harbor porpoise feed on herring, and it was argued that herring can hear high-frequency sound and might have avoided gillnets with pingers. Less herring near gillnets with pingers may have resulted in less porpoise bycatch (Kraus et al. 1997; Trippel et al. 1999). Additionally, Cox et al. (2004) monitored bottlenose dolphin (*Tursiop truncatus*) in an inshore gillnet site and found that dolphins stayed farther away from gillnets with active pingers. Borodino et al. (2002) reduced Franciscana dolphin (*Pontoporia blainvillei*) bycatch in gillnets using pingers but found increased pinniped depredation on target species. Mixing of barium sulfate ($BaSO_4$) within monofilament nylon increases reflectivity of the net (Cox and Read 2004; Mooney et al. 2004) and has been reported to reduce harbor porpoise bycatch without a reduction in target species (cod, haddock, and pollock) (Trippel et al. 2003).

Trippel et al. (1996) found that the majority (96%) of porpoise bycatch was on the upper two-thirds of the gillnet that had a standup height of approximately 4 to 5 m. A reduced height gillnet

may have a positive effect on reducing porpoise bycatch in the gillnet fishery. For some bottom-dwelling species such as flounder, the height of the net may be reduced without affecting the catch of the target species (He, 2006b). Other measures to reduce bycatch of harbor porpoises focus on prevention of entanglement through the use of stiff, neutrally buoyant or sinking ropes or on escape once entanglement occurs, through weak ropes or weak links. These measures are required in New England gillnet and pot fisheries (NOAA 2008).

8.7 DERELICT GILLNETS: GHOST FISHING PROBLEMS AND SOLUTIONS

Gillnets and other fishing gears can become lost due to adverse weather or sea conditions or by conflict with other fishing gears or vessel traffic (Matsuoka et al. 2005). Gillnets, whether lost unintentionally, abandoned, or otherwise discarded at sea, have a similar effect on animals and the environment. The derelict gillnets may continue to fish for an extended period of time, causing additional mortality to fish and other organisms. This phenomenon is called "ghost fishing." Gear designs and modification to eliminate ghost fishing or to reduce the fishing capacity of ghost gears are called "de-ghosting" technologies. With the introduction of synthetic materials in gear construction, these derelict gillnets may continue to fish for several years before they become inactive.

In the Northeast Atlantic, including the Mediterranean, as many as 25,000 gillnets were reported lost each year, with loss rates as great as 3.2% (Macfadyen et al. 2009). Canadian Fishery Consultant Ltd (CFCL 1994) estimated that around 5000 gillnets were lost annually in Atlantic Canadian waters. Gear loss in this region may be aggravated by increased use in deep waters for species and in more hostile sea conditions such as in the Greenland halibut fishery. Cooper et al. (1988) conducted video camera surveys by a remotely controlled underwater vehicle in the Gulf of Maine and estimated that there might be 2497 nets (91 m each) on a 64-nm^2 area of traditional gillnet grounds on Stellwagen Bank and Jeffries Ledge, equivalent to 39 derelict nets per square nautical mile.

Direct observations of derelict gillnets or simulated lost gillnets confirm that these nets continue to fish (Carr et al. 1985; Cooper et al. 1988). Gillnets deliberately set over wrecks in U.K. coastal waters continued to catch and kill fish for at least 2 years (Revill and Dunlin 2003). It was estimated that lost salmon nets might fish for 2 years for fish and 6 years for crabs (High 1985). In shallower waters, derelict gillnets may become overgrown by algae, or "biofouled." Because these algae-laden nets are more visible, their fishing capacity is correspondingly reduced. Takagi et al. (2007) estimated that the height of bottom gillnets declined rapidly after 15 days and to zero after 25 days of deployment. Fishing capacity decreased to about 15% to 20% of a typical net in the first few weeks (Carr and Cooper 1988; Revill and Dunlin 2003). However, shallow water is usually rich in marine life, so catch rates can still be considerable. Erzini et al. (1997) set "damaged" gillnets in 15 and 18 m off southern Portugal. They estimated that the lifetime of a ghost gillnet was between 15 and 20 weeks. Observations after 8 to 11 months indicated complete destruction or heavy colonization by algae resulting in incorporation into a reef. They estimated that a lost 100-m length of gillnet will catch 314 fish over a 17-week period (Erzini et al. 1997) but thought that this number was likely an underestimate due to predation and scavenging.

Prevention of ghost fishing may include prevention of gear loss, derelict gear retrieval, and de-ghosting technologies. Inshore gillnets use floats on the headrope and leadline on the footrope to spread the net vertically. Therefore, use of degradable material that causes the lost gillnet to lose floatation could reduce the vertical profile and hence fishing capacity. Carr et al. (1992) tested degradable plastic plates for attaching floats to the headrope of gillnets (Fig. 8.11). The gear was set to simulate ghost fishing for a period of 220 days. Two types of degradable plastic plates were used. Divers made underwater observations to check net profiles and catch. Only 2 of the 20 degradable attachment panels partially degraded after 220 days—apparently the panel can be modified to increase degrading process. No significant differences in catch were observed between sections of the net rigged with degradable float attachments and those with

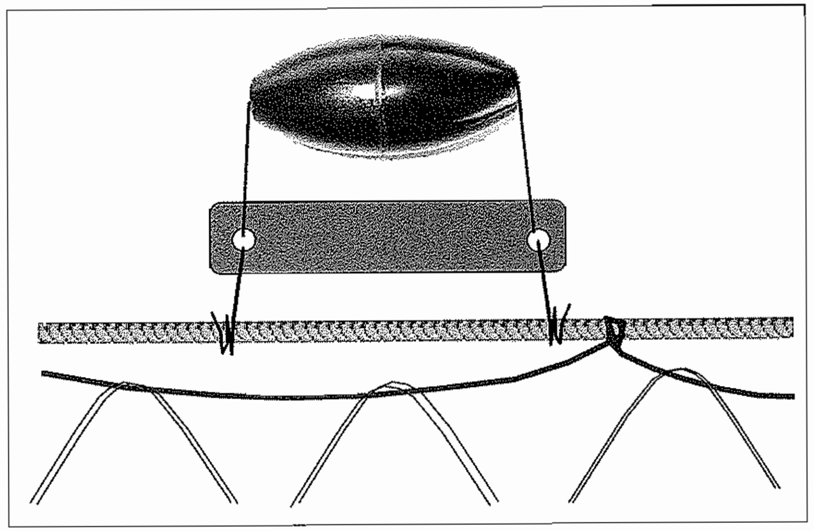


Figure 8.11. Degradable plastic panel for attaching floats to the headrope of a gillnet. (He 2006a.)

regular rigging. Although there was a report of degradable fishing nets being developed in Japan (Anon. 1993), the commercial application of degradable nets has not been implemented.

The final attempt to reduce ghost fishing is to retrieve the derelict gillnets and "clean up" the fishing grounds. Several countries conduct gear retrieval operations regularly (see Macfadyen et al. 2009; Matsuoka et al. 2005). Mandatory reporting of gear loss and the use of acoustic transponders can facilitate retrieval of nets if they become lost.

8.8 CONCLUDING REMARKS

Gillnets are very size selective, landing only a narrow range of fish size. Size selectivity of gillnets is closely related to mesh size and changes in type of webbing material, twine size, and hanging ratio. Although gillnets are simple in design and operation, the behavior of fish near gillnets and their capture processes are not well understood. Research is needed to better understand the influence of tide and other factors on net height and on vertical distribution of target species. There are two major conservation challenges facing gillnet fisheries. Gillnets have poor species selectivity, resulting in bycatch and discards and causing mortalities to marine mammals, sea birds, and turtles. Research on mitigation measures has shown progress, including successful implementation of pinger use in some fisheries, but more work is needed. Ghost fishing of derelict gillnets remains a challenge, except in the countries that conduct active retrieval of derelict net.

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SPECIES MENTIONED IN THE TEXT

American plaice, *Hippoglossoides platessoides*
Atlantic cod, *Gadus morhua*
Atlantic mackerel, *Scomber scombrus*
Atlantic puffin, *Fratercula arctica*
Atlantic salmon, *Salmo salar*
Baltic cod, *Gadus morhua*
bottlenose dolphin, *Tursiop truncatus*
chinook salmon, *Oncorhynchus tshawytscha*
coho salmon, *Oncorhynchus kisutch*
common murre, *Uria aalge*
European dab, *Limanda limanda*
Franciscana dolphin, *Pontoporia blainvillei*
Greenland halibut, *Reinhardtius hippoglossoides*
haddock, *Melanogrammus aeglefinus*
hake, *Merluccius merluccius*
harbor porpoise, *Phocoena phocoena*
herring, *Clupea harengus*
humpback whale, *Megaptera novaeangliae*
king crab, *Paralithodes camtschaticus*
ling, *Molva molva*
paddlefish, *Polyodon spathula*
pikeperch, *Stizostedion lucioperca*
pollock, *Pollachius virens*
rainbow trout, *Oncorhynchus mykiss*
rhinoceros auklet, *Cerorhinca monocerata*
saithe, *Pollachius virens*
shearwater, *Puffinus* spp.
skipjack tuna, *Katsuwonus pelamis*
winter flounder, *Pseudopleuronectes americanus*
walleye, *Sander vitreus*
yellowfin tuna, *Thunnus albacares*