A REVIEW OF GHOST FISHING BY TRAPS AND GILLNETS

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ABSTRACT

Ghost fishing occurs when lost fishing gear continues to catch and kill animals. This paper reviews what is known about ghost fishing in trap and gillnet fisheries, how the information was obtained and how it has been used, how ghost fishing can be prevented, and what regulatory approaches have been taken to address the problem. Some standard terms are proposed to prevent confusion.

Ghost fishing by traps can occur through several mechanisms. The problem is serious in several fisheries, minor in at least one, and remains unexamined for the majority of trap fisheries. Timed-release devices are simple, inexpensive, and effective at preventing ghost fishing by opening the trap some time after loss. In all Dungeness crab fisheries, such devices are required in crab traps, and other regulations attempt to minimize trap loss. In the American lobster fishery, only Connecticut and Maine address ghost fishing, which is known to be a problem. Ghost fishing by traps is poorly recognized as a problem outside North America.

Ghost fishing by coastal gillnets has been documented in several locations and may persist for several years. For large pelagic gillnets the limited evidence suggests that lost nets form tangled nonfishing masses. More work, both descriptive and experimental, is required to document the nature, extent, and persistence of ghost fishing by gillnets, especially by pelagic gillnets if their use continues.

It is not clear how to prevent ghost fishing by gillnets. Preventive measures suggested to date must be examined for possible side effects.

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INTRODUCTION

Ghost fishing can be defined as "the ability of fishing gear to continue fishing after all control of that gear is lost by the fisherman" (Smolowitz 1978a), i.e., when gear is lost, a common occurrence in many fishing operations. The subject was previously reviewed for trap fisheries by Smolowitz (1978a, 1978b, 1978c) and for several gear types by High (1985).

Fishing gear that requires active control, for example trawls, troll gear, and purse seines, may become virtually inert and probably catches insignificant numbers of animals after loss. By contrast, gear which normally fishes passively, such as traps, tangle nets, and gillnets, may continue to fish at significant rates after loss.

This paper looks at what is known about ghost fishing by traps and gillnets, how this knowledge was obtained and used, and what measures can be taken to reduce ghost fishing by traps and gillnets. Other fishing gear may well ghost fish--High (1980, 1987) reports Pacific halibut, *Hippoglossus stenolepis*, striking and being caught by bare longline hooks--but the literature at this stage adds little to High's (1985) review for other gear types.

Why Ghost Fishing May Be a Problem

An increasing proportion of fishing gear is now constructed from nondegradable materials such as stainless steel, other metals, fiberglass, injection-molded plastics, vinyl-coated wire, monofilament netting, and polypropylene twine. Whereas fishing gear made from natural materials deteriorated quickly in the sea--Pacific salmon, *Oncorhynchus* spp., fishing ports all featured tanks of copper sulfate for dipping nets to preserve them--gear made from modern materials lasts much longer in the sea.

The very large volumes of fishing gear now deployed translate to a large volume of lost gear even if the loss rate is small. Some crustacean trap fisheries are so overcapitalized that jurisdictions try to limit the large number of traps used. Hundreds of thousands of kilometers of pelagic gillnets are in use. If this gear ghost fishes when lost, then there is a serious biological and economic problem.

Terminology

Some standard definitions are proposed. First, I use "lost" to describe lost or discarded fishing gear. Previous authors have used "ghost" or "derelict" to describe such gear. However, using "ghost" to mean "lost" creates confusion--the lost gear may or may not actually be ghost fishing. Sutherland et al. (1983) propose a distinction between intact lost gear, still theoretically capable of fishing, and damaged or "derelict" gear that can no longer fish. "Derelict" should be limited to this sense. Where gear loss is simulated experimentally, I use the term "simulated lost" gear.

Second, two types of special openings in traps need careful differentiation. Traps can be modified by openings designed to allow animals to escape (Wilder 1945). These openings have been termed "savings gear" (Jow 1961), "escape vents" (Pecci et al. 1978; Anthony and Caddy 1980), and "escape gaps" (Brown and Caputi 1986). Traps can also be modified by openings or mechanisms designed to release animals from a lost trap. These have been termed "biodegradable sections" (Anthony and Caddy 1980), "timed-release mechanisms" (Blott 1978), "ghost panels" (Krouse pers. commun.), "escape panels" (draft Maine legislation), and "destruct panels" (Hipkins and Beardsley 1970). I suggest that the first type of special opening be called "sublegal escape gaps" and that the second type be called a "timed-release" opening.

GHOST FISHING BY TRAPS

Mechanisms

There is no single mechanism of ghost fishing by traps because traps vary widely in their design, intended mode of capture, target species, and conditions of deployment. To understand ghost fishing it is first necessary to look briefly at trap operation.

Some traps simply attract fish or crustaceans with bait. Although the animals can apparently escape at will, a number are found inside the traps: there is a temporary balance between catch and escape rates. Examples are reef fish traps (Munro et al. 1971; Munro 1974), Australian snapper traps (Dews et al. 1988), and British Columbia prawn traps (Boutillier pers. commun.). Difficult exits in fish traps reduce escapement rates to increase the number of fish in the trap (see Munro 1983).

Escape can be made more difficult by fitting "nonreturn valves" to traps (e.g., Munro 1974). Dungeness crab, *Cancer magister*, traps are fitted with hinged metal gates called "triggers" (High 1976) that permit entry but effectively block exit. Sablefish, *Anoplopoma fimbria*, traps may have similar devices (Hipkins and Beardsley 1970). Homarid lobster, *Homarus americanus* and *H. gammarus*, traps commonly have inner chambers or "parlors" to hinder escape (Pecci et al. 1978; Lovewell et al. 1988).

In the simplest form of ghost fishing, trapped animals die in lost traps and their bodies act as bait (von Brandt 1984). Hipkins and Beardsley (1970, p. 29) state: "It appears then that blackcod (sablefish) pots. . .will continue to fish with dead fish serving as bait to attract new fish which eventually die to attract more fish and so on ad infinitum until the pot deteriorates. . . ." They present indirect evidence for this mechanism. Pecci et al. (1978) suggest this mechanism may operate in lost American lobster traps. For no species has this "autorebaiting" mechanism been conclusively demonstrated.

Traps may be rebaited by species other than the target species. Alaska king crab *Paralithodes camtschatica* traps are rebaited when Pacific halibut or Pacific cod, *Gadus macrocephalus*, enter and die (High and Worlund 1979). Pecci et al. (1978) report a variety of fishes caught and perhaps acting as bait in simulated lost American lobster traps.

Some species of fish are attracted to live conspecifics in an unbaited trap (Munro 1974); for these, ghost fishing might occur without the auto-rebaiting mechanism.

In the simplest model of ghost fishing, trapped animals starve in the traps. Other forms of mortality might be important, causing death sooner. In crustaceans, cannibalism of newly molted individuals may occur. Pecci et al. (1978) observed this in simulated lost American lobster traps; Demory (1971) and Barry (pers. commun.) observed this for Dungeness crabs. Scarratt (1965) reported predation of captured American lobsters by amphipods. Ritchie (1972) and Gabites (pers. commun.) report predation on trapped New Zealand spiny lobsters, *Jasus edwardsii*, by octopus, *Octopus maorum*; Morgan (1974) describes predation by *Octopus* sp. on the Western Australian spiny lobster *Panulirus cygnus*; High (1985) describes attempts by *O. dofleini dofleini* to capture trapped Dungeness crabs. Pecci et al. (1978) reported mortality of American lobsters in simulated lost traps caused by black sea bass, *Centropristis striata*. Trapped crabs may be smothered when the trap is buried by silt (High 1985).

Even when animals manage to escape from ghost fishing traps, they may die as a result of their confinement--High and Worlund (1979) demonstrated this important effect experimentally for Alaska king crabs.

Fishes and crustaceans may enter unbaited traps. This is reported for Hawaiian spiny lobsters, *P. marginatus*, (Paul 1984) in the laboratory; New Zealand spiny lobsters in the field (Gabites pers. commun.); and American lobsters in the field (Pecci et al. 1978; Smolowitz 1978b; but cf. Karnofsky and Price 1989). Dungeness crabs (Breen 1987) and Alaska king crabs (Meyer unpubl. manuscr.) entered empty traps months after simulated trap loss. Munro (1983) describes fish traps that catch fish unbaited. Juvenile reef fishes in Florida use traps as shelter (Sutherland et al. 1983). High and Ellis (1973) found that unbaited traps caught as many reef fish as baited traps. For such traps an autorebaiting mechanism is not necessary for ghost fishing to take place.

In some cases dead crustaceans repel conspecifics. Hancock (1974) demonstrated this effect experimentally for the spiny lobster *P. cygnus*, and also presented evidence that the crabs, *Cancer pagurus*, are not attracted to traps baited with the crab *Carcinus maeanas*. Miller (1977) demonstrated in experimental trapping that the Newfoundland snow crab, *Chionoecetes opilio*, are repelled by dead conspecifics, and High (pers. commun.) also reports this for the Alaska king crab. However, Pecci et al. (1978) found that *H. americanus* are not repelled by dead conspecifics. For species repelled by dead conspecifics, the autorebaiting mechanism will not cause ghost fishing.

Thus ghost fishing can occur through a variety of mechanisms: auto-rebaiting, rebaiting by other species, attraction by living conspecifics, or attraction by the trap alone. The trap may kill through starvation or by facilitating cannibalism and predation. For some species, conspecific repellency may prevent or reduce ghost fishing. Ghost fishing may be significant on species other than the target species.

Demonstrations That Traps Ghost Fish

Recovered Lost Gear

Recovery, especially after long periods, of lost gear that contains live and dead animals is good evidence that ghost fishing occurs. Hipkins and Beardsley (1970) recovered nine sablefish traps lost for approximately 6 weeks. These contained dead fish and up to 24 live fish per trap, suggesting that the autorebaiting mechanism was operative.

In Oregon, Demory (1971) retrieved 117 Dungeness crab traps which had been abandoned for at least 6 weeks. They contained 3,629 crabs, 91% of which were legal-sized males. Dahlstrom (unpubl. manuscr.) recovered an Oregon Dungeness crab trap, lost for 10 months, containing 20 crabs and 2 empty carapaces. The trap was still in excellent condition. Meyer (unpubl. manuscr.) reports that recovered lost Alaska king crab traps "often contain as many as 100 marketable king crab."

Smolowitz (1978a) recovered 18 intact offshore American lobster traps lost for approximately 9 weeks. They contained 24 lobsters weighing a total of 70.8 kg (156 lb). High and Worlund (1979) recovered a snow crab, *Chionoecetes* spp., trap containing 12 king and 14 snow crabs 3 months after loss. Sutherland et al. (1983), using a submersible, found five undamaged fish traps in Florida, lost for an estimated 4-6 months. These held 14 fish, 14 Caribbean spiny lobsters, *Panulirus argus*, and a fish skull.

When lost traps are empty on recovery, it is often inferred that ghost fishing does not occur. For instance, Boutillier (pers. commun.) observed lost prawn, *Pandalus platyceros*, traps from a submersible in British Columbia; none contained prawns and he concluded that ghost fishing did not occur. However, simulated lost Dungeness crab traps that were empty for considerable parts of the year caught and killed crabs (Breen 1987). If traps ghost fish through other than the autorebaiting mechanism, then an empty trap may subsequently kill. Inferences made from empty traps are suspect unless made over large numbers of traps and over several seasons.

Another inference is often made from the way catch rates fall as soak time increases. Traps left to soak for too long give poor catches; the inference is that most of the catch escapes after the bait ceases to attract. Then by extension ghost fishing is inferred not to be a problem. Examples include the Tasmanian spiny lobster, *J. novaehollandiae* (Kennedy pers. commun.), British crabs and lobsters (Bannister pers. commun.), and Dungeness crabs. However, in Dungeness crab traps the catch rate declines with increased soak time, yet lost traps continue to catch and kill at a slow rate (Breen 1987). So ghost fishing may occur in the long term despite apparent short-term escapement.

Trap Loading Experiments

Ideally, all ideas about ghost fishing should be tested experimentally. Three approaches have been used: experiments in which traps are loaded and escape rates or mortality rates measured, laboratory observations that simulate fishing, and field experiments with simulated lost traps.

Munro (1974) found that 50% of reef fishes escaped from Antillean fish traps after 14 days; this implies a 5% escapement per day and 23% retention after a month. These rates suggest that ghost fishing is likely to occur in such traps. However, Munro (1983) estimated an escapement rate of 12% per day from "Z" fish traps, a rate implying only a 2% retention after 30 days.

Sheldon and Dow (1975) loaded 98 tagged American lobsters into 35 unbaited simulated lost traps and checked the traps by diving and hauling for nearly 2 years. The traps continued to catch lobsters, of which 12-18% died in the traps, demonstrating for the first time ghost fishing for American lobsters.

Newfoundland snow crab traps were loaded and examined at intervals by diving (Miller 1977). After 3 weeks no crabs had escaped. Miller then tested the mechanism of ghost fishing in this species by fishing with four treatments. Unbaited traps and traps baited with dead crabs caught nothing; on average squid-baited traps caught 31 crabs per trap; traps baited with a mixture of dead crabs and squid caught 7 crabs per trap. Miller concluded that dead snow crabs repel conspecifics and that the only loss from ghost fishing would involve those crabs originally attracted by the bait.

High and Worlund (1979) observed a 20% retention rate for legal size Alaska king crabs and 8% for sublegal crabs in experimental traps after 18 days. Mortality in standard traps was 2-7% over this period.

Muir et al. (1984) baited Dungeness crab traps daily and observed that 35% of the captured crabs died in the traps. High (1985) placed Dungeness crabs in traps with and without triggers and sublegal escape gaps. The mortality in traps with functional triggers and sublegal escape gaps was 17% after 12 days, confirming ghost fishing as a problem with these traps.

Laboratory Observations

Paul (1984) observed that Hawaiian spiny lobsters in a large tank normally did not escape from traps. The trap lids "had to be removed to prevent them from becoming permanently trapped inside."

Behavior of reef fishes around traps was observed in a large tank by Harper and McClelland (1983, cited by Heneman and Center for Environmental Education (CEE) 1988). Most species appeared to learn to escape, leading to "an equilibrium state. . .with frequent movements in and out of the trap."

Booth (pers. commun.) used a time-lapse camera in a large tank to record the behavior of *J. edwardsii* around simple cane traps, as used in the New Zealand fishery, and parlor-type traps not used in the fishery. There was a rapid turnover of lobsters in the simple trap, but greatly reduced escapement in the parlor traps. Booth concluded that ghost fishing is probably not a problem for the cane traps, but could be a problem if more complex traps were introduced. Plastic truncated-cone entrances on the top of the trap appear to limit escape in this species in large laboratory tanks (Breen unpubl. data; Gabites pers. commun.).

Field Experiments

Information from trap loading and laboratory studies must be treated with caution: problems with extrapolation from the laboratory to the field and from short to long term must be carefully considered. Possibly the best information comes from underwater observations of simulated lost traps. Tagging of trapped individuals by divers can be used to follow turnover.

Pecci et al. (1978) reported only 30% escapement in American lobsters entering simulated lost traps observed by divers. Mortality rate was 25%. The authors estimated that a ghost fishing trap caught at a rate near 10% that of a surface-hauled trap, confirming ghost fishing as a problem in this fishery.

Breen (1987) simulated 10 lost Dungeness crab traps in a sheltered bay for 1 year, during which approximately 100 crabs died in the traps. At the end of the study, traps were still killing crabs at a steady rate. The results cannot be generalized directly to other Dungeness crab fisheries. For instance, many traps lost off high-energy beaches are destroyed or put ashore by wave action.

Western Australian snapper, *Chrysophrys auratus*, traps were observed in the field with underwater video (Anonymous 1984; Dews et al. 1988; Moran and Jenke 1989) partly to examine possible ghost fishing (Bowen 1961). Fish seemed capable of leaving traps easily and some even swam out "in reverse." Moran and Jenke (1989) simulated lost traps for various periods from 1 to 21 days. Catches were similar to commercial catches after 15 min, indicating that cumulative catching did not occur. These workers concluded that ghost fishing is not a problem with snapper traps. However, three fish were dead in the 21-day trap, suggesting that some ghost fishing may take place.

Hawaiian spiny lobsters appear to move out of simulated lost traps once the bait has deteriorated (Okamoto pers. commun.; Parrish pers. commun.).

Rates of Trap Loss

Traps are lost for many reasons. Simple vessel traffic and towboating may sever buoy lines or drag traps into water deeper than the buoy line. Weak or chafed buoy lines may break. Buoys may become detached from the buoy line, or may be attacked by marine birds (Smolowitz 1978b) or mammals (High 1985). Storms or strong currents may "drown" traps either directly or by rolling them over the bottom, wrapping the buoy line around the trap

(Smolowitz 1978b; Sutherland et al. 1983; von Brandt 1984). Traps set on rocky ground may snag and be unrecoverable (Bowen 1961).

Traps may be carried into deep water, or buoy lines cut, by other fishing activities such as trolling, trawling and gillnetting. When traps are set on ground lines, ground lines may be intentionally cut when lines become fouled. Internecine buoy line cutting or ground line cutting may result from unresolved fishing disputes (Smolowitz 1978b; Breen 1987). In some areas vandals cut buoy lines (Sutherland et al. 1983).

Estimates of trap loss rate must be obtained through surveys or industry interviews. These give the total loss of traps, which might include stolen traps.

American Lobster Traps

For the U.S. American lobster fishery, Smolowitz (1978a) cites anecdotal estimates of the annual loss of traps as 20-30% along the Atlantic seaboard. In the offshore lobster fishery he suggests that 40,000 all-metal traps may have been lost during the period 1971-78. In the inshore fishery Krouse (pers. commun.) suggests an annual loss rate of 5-10%. Based on a 1987 estimate of 1.87 million traps fished, this leads to an annual loss estimate of 93,500-187,000 traps lost annually. An unpublished study (CEE 1987) cited by Heneman and CEE (1988) estimated an annual loss of 500,000 traps annually. In Rhode Island a logbook study led to an estimate of 10-15% annual loss (Fogarty pers. commun.).

In Newfoundland, no estimates have been made of lobster trap loss rate, but divers observe few lost traps on the fishing grounds. Many lost traps are washed ashore (Ennis pers. commun.). Losses have not been estimated in the rest of the Canadian lobster fishery.

Dungeness Crab Traps

In California, 100,000 Dungeness crab traps are estimated lost each year (Kennedy 1986). Some silt into the bottom, but others could fish for an estimated 2 years. In Washington State, Northup (1978, cited in Muir et al. 1984), estimated that 17.6% of the coastal Washington State crab traps were lost in 1975-76, considered a typical year. Barry (pers. commun.) estimated mean annual loss in the same fishery as 11.9%. He considers that ghost fishing traps are <50% of the total loss and may be as low as 10%. In the Puget Sound portion of the fishery, gear loss was estimated from a questionnaire survey to be 15% (Bumgarner pers. commun.). Breen (1987) estimated Fraser River Dungeness crab trap loss as 11%, based on a questionnaire survey. About half those surveyed thought that half the lost traps were ghost fishing.

Thus in several coastal trap fisheries, annual trap loss rates are on the order of 10-20%. American lobster and Dungeness crab fisheries are both cases where more traps than optimum are fished (and thus lost) (Bell and Fullenbaum 1986; Methot 1986). Cumulative trap losses are a cause for concern in fisheries where ghost fishing is known to occur.

The Fate of Lost Traps

Not all lost traps become ghost fishing traps even where ghost fishing is a problem. Smolowitz (1978b) reviews sources of trap destruction. Storms destroy or strand many inshore American lobster and Dungeness crab traps in exposed locales. Burial by storm action or alluvia occurs quickly in some Dungeness crab fishing areas (Hipkins 1972, cited in Smolowitz 1978b; Breen 1987).

Untreated wooden traps are destroyed by borers in a relatively short time, but treated wooden traps may last up to 2 years (Smolowitz 1978b; Fogarty pers. commun.). Twelve percent of the wooden traps used by Sheldon and Dow (1975) were so damaged by lobster chelipeds that escape became possible. Increasingly, however, traps are made from metal (Acheson 1982) or synthetic materials. Averill (pers. commun.) believes that "wooden" American lobster traps last as long as wire traps when lost. Long-term experiments are required to determine the fishing lifespan of various trap types.

High and Worlund (1979) estimate that metal-framed, synthetic mesh-covered Alaska king crab traps could have an effective longevity of 15 years after loss. Breen (1987) found that metal-framed, stainless steel-covered Dungeness crab traps were in excellent condition after a year's submersion. Electrolytic corrosion probably destroys most metal traps eventually. New designs include plastic traps (e.g., Piatt 1988) and vinyl-coated mesh (e.g., Maynard and Branch 1988), which might last for decades. The present Maine trap inventory is 50-60% vinyl-coated wire (Averill pers. commun.).

Note that much of the information just presented is based on short-term studies. The real fate of lost fishing gear has not been well studied.

Impact of Trap Ghost Fishing

How much fishing takes place by ghost-fishing traps? To answer this for a specific fishery requires 1) estimates of the number of traps fished and the loss rate, 2) an assumption about the percentage of lost traps that ghost fish, 3) an estimate of the rate of mortality in ghost-fishing traps, and 4) an estimate of the effective ghost fishing lifespan of a trap. Ideally, for requirement 3 one should also know the natural mortality rate, because some individuals killed by ghost fishing would have died before commercial capture. Many individuals would also have grown before commercial capture. However, the unavoidable imprecision of the other estimates implies that only a crude answer can be obtained in any case.

For the Newfoundland snow crab fishery, Miller (1977) used spot interviews to estimate trap loss at 8%, and combined this with commercial catch rates and experimental observations to obtain an estimate of ghost-fished catch of 10 metric tons (MT) annually. Smolowitz (1978b) estimated the impact of ghost fishing in the U.S. portion of the American lobster fishery. The estimated annual ghost fishing catch was 670 MT, worth an estimated 1978 US$2.5 million. From a 1976 study using different assumptions (CEE 1987, cited by Heneman and CEE 1988), the economic loss of just those lobsters within traps at the time of loss was estimated at 1976 US$2.5 million. Krouse (pers. commun.) assumed a loss rate of 5% in the U.S. American lobster fishery and that traps last for 2 years and take two lobsters per year. This leads to an estimate of 204 MT lost to ghost fishing annually, worth 1989 US$1.2 million. This is a conservative estimate, because it is based on the low end of the range of trap loss estimates.

Breen (1987) estimated the impact of ghost fishing in one part of the British Columbia Dungeness crab fishery, using loss rates and lifespan estimates from an industry survey and experimental ghost fishing data. He estimated the ghost-fished catch to be 7% of reported landings, worth about 1985 Can$80,000.

For the sablefish fishery of British Columbia, Scarsbrooke et al. (1988) used trap loss rate from an industry survey, the commercial catch rate, and simple assumptions about turnover rate, trap lifespan, and timed-release device effectiveness. For traps lost from 1977 to 1983, before timed-release devices were fully employed, the estimate of ghost fishing catch was approximately 300 MT annually, compared with landings of 1,000-4,000 MT.

These cases illustrate that ghost fishing can be substantial. I can find no fishery for which the impact of ghost fishing on stocks has been determined, or where ghost fishing is addressed by stock assessments or management plans. In Oregon, where traps are required to incorporate timed-release mechanisms, biologists consider that ghost fishing, although subtracting from the potential catch, would have no stock-recruitment effect. The size limit is set so that all legal-sized males could theoretically be taken without affecting reproduction (Demory pers. commun.).

Prevention of Trap Ghost Fishing

Remedial measures may either reduce trap loss or prevent lost traps from killing. A simple way to reduce trap loss is to reduce the number of traps fished (Smolowitz 1978b). Effort is excessive in many fisheries, so this approach is often desirable for that reason alone. The extreme solution, vessel trap limits or transferable trap entitlements, is extremely expensive to enforce and therefore was rejected as a management option in the New Zealand *J. edwardsii* fishery (Anonymous 1987).

Trap designs can be improved to reduce storm and current losses caused by traps rolling on the bottom (see Smolowitz 1978b). Losses caused by vessels can be reduced by prohibiting buoyed traps in areas of heavy traffic. In Washington State, trap-free lanes for towboats have been established to minimize trap loss from that source (Bumgarner pers. commun.). The Washington Department of Fisheries also facilitates coordination between trap and net vessels to avoid gear collisions. In the Canadian sablefish fishery, ground lines must be buoyed at each end. In practice, the marking employed far exceeds the minimum standard required (McFarlane pers. commun.). In the Puget Sound recreational trap fisheries of Washington State, regulations require solid buoys (to prevent losses from puncture) and nonfloating buoy lines (to prevent loss from vessel traffic) (Bumgarner pers. commun.).

The large literature on sublegal escape gaps shows that they greatly reduce catches of sublegal crustaceans, presumably through escapement (e.g., Cleaver 1949; Fogarty and Borden 1980; Brown and Caputi 1986; see review in Smolowitz 1978c). Because escape gaps reduce trap saturation effects (Miller 1979), they may lead to increased catches of legal animals.

Ghost fishing mortality was reduced for sublegal American lobsters by sublegal escape gaps in simulated lost traps (Pecci et al. 1978; Smolowitz 1978a). High (1985) found greatly increased sublegal escapement in simulated lost Dungeness crab traps fitted with sublegal escape gaps. Breen (1987) found that as many sublegal as legal Dungeness crabs died in simulated lost traps fitted with appropriate sublegal escape gaps, but the absolute catch rates of legal and sublegal crabs were unknown. Sublegal crabs may have had a high turnover rate in the traps.

Measures to prevent lost traps from ghost fishing usually involve some deliberate failure (timed-release) in a trap component to open the trap or create a new opening for escapement.

Natural fiber twine can be used either to make a timed-release panel or to sew a timed-release panel shut. Panels can also be made from untreated softwood. Blott (1978) tested a variety of materials with potential for use as timed-release elements in traps. Jute and manila twine and steel wire appeared to be realistic, while wool and leather were not.

In Maine, various materials have been tested for use in closing timed-release openings (Averill pers. commun.). Industry was given traps with many openings secured with test materials and asked to fish them during their regular season. Mild steel hog rings appear to last the desired time (ca. 200 days), and are consistent in their total degradation time. Cotton twine and sisal twine are also good candidates for this purpose.

Scarsbrooke et al. (1988) tested failure rates of several binding materials for timed-release openings in sablefish traps. They also fished traps with three types of opening in alternation with control traps to measure the effectiveness of timed-release openings. Triangular or square openings were more than 90% effective in allowing trapped fish to escape; simple "slashes" were less effective. They concluded that appropriately shaped timed-release openings eliminated the problem of ghost fishing in these traps.

Plastic crab and lobster traps in Florida (Piatt 1988) have a rectangular opening which the user fills with a timed-release device such as a plywood panel.

Blott (1978) describes a solid timed-release panel made from galvanized steel and held shut with natural twine or a degradable metal ring. The panel can also incorporate the sublegal escape gap, leading to the name "catch escape panel." Blott tested various materials for suitability as catch escape panels; galvanized sheet steel seemed most appropriate. Pecci et al. (1978) tested such panels in simulated lost American lobster traps and concluded that such panels "are an effective means of releasing entrapped lobsters." Traps with this type of panel are now commercially available from a Maine manufacturer (Lazarus 1988). However, Averill (pers. commun.) considers that the combination of sublegal escape gaps and a timed-release opening leads to confusion of two separate management issues.

In California, magnesium pins are used to hold together the two halves of plastic or fiberglass traps or to attach the lids of plastic and fiberglass traps (Estrella pers. commun.).

Dungeness crab traps are serviced through the "lid," a hinged section of the top secured by a hook attached by a rubber strap from the side of the trap (High 1976). A timed-release hook, or hook attachment, would allow the trap to open. Breen (1987) unhooked 10 simulated lost traps that had ghost fished for a year. Over a week, 22 of 29 trapped crabs escaped and no new captures were observed. Thus a timed-release device that unhooked the lid would probably be effective in this type of trap.

It is possible to make plastics that are degraded by organisms, light, oxidation, other chemical reaction, and dissolution (see review by Andrady 1988). Various degradable plastic compounds designed specifically for the fishing industry are now being tested (Gonsalves et al. 1989, Gonsalves 1990). Japanese chemists are designing "bacterial co-polymers" which degrade slowly into natural chemicals in water (Doi et al. 1988).

Premature failure of timed-release elements reduces industry acceptance of the concept (Smolowitz 1978b). The early failure of a batch of hog rings used to close timed-failure panels in lobster traps resulted in industry resistance to the devices in Maine (Anonymous 1988; Averill pers. commun.). A similar experience in California led to delayed legislation (Estrella pers. commun.). Material failure rates vary widely with local conditions and probably cannot be predicted accurately. Agencies proposing timed-release regulations must conduct widespread materials testing to find a mechanism that will both fail reliably after the desired time and not fail prematurely. Studies conducted by the industry under actual fishing conditions are more likely to be accepted by the industry.

The dollar and time costs of timed-release modifications are important to acceptance by industry (High and Worlund 1979). Breen (1987) calculated the annual economic cost of Dungeness crab trap ghost fishing done in 1985 as Can$1.46 per trap in use, and suggested that annual modifications must therefore cost less than this. This simple study appears to be the only published cost-benefit analysis of the problem. Other managers consider that "off-the-cuff cost-benefit analysis would indicate that [ghost fishing] should be addressed" (Averill pers. commun.).

Finally, Smolowitz (1978b) suggests development of "habipots" that catch animals seeking them as shelter. Such traps would not entrap animals and thus would have only biologically positive effects when lost. Some *Octopus* traps operate on this principle (Mottet 1975).

Regulations to Prevent Trap Ghost Fishing

The American lobster and Dungeness crab fisheries are interesting to examine for regulations designed to minimize ghost fishing. In both fisheries ghost fishing is known to occur, trap losses are high, and the fisheries take place over several jurisdictions in two countries with differing management approaches.

Dungeness Crabs

California requires all traps to incorporate timed-release devices or openings. These may be trap lid hooks made of soft steel <6 mm diameter, lid hooks attached to the strap with single loops of natural fiber twine, any modification of the upper mesh secured with natural fiber to create a 125-mm diameter hole, or magnesium pins as discussed above. Testing of these materials has been carried out, and cotton twine is the preferred option (Estrella pers. commun.). All traps or ground lines of traps must be buoyed and the buoys marked with identification markings.

Oregon requires Dungeness crab traps to contain a timed-release device as in California (Demory pers. commun.). Individual traps must be buoyed and marked.

Since October 1988, Washington also requires timed-release devices as above but not including the mild steel hook; openings must be unimpeded, at least 76 × 127 mm and closed with natural fiber. Washington also has buoy and buoy line standards described earlier.

In British Columbia, Fisheries and Oceans Canada introduced a regulation in 1990 requiring a single loop of specified cotton twine in the lid strap and nonfloating buoy lines. Traps or ground lines must be buoyed with marked floats, but this regulation is often ignored (Breen 1987).

In Alaska, Dungeness crab traps are required to have timed-release devices (Koeneman pers. commun.). At least as early as 1974, Alaska sablefish traps were required to incorporate timed-release panels (Hipkins 1974, cited in High and Worlund 1979).

Alaska also requires that "traps left unattended for over 2 weeks must have bait removed and doors secured open as protection against ghost fishing." This is the only regulation dealing with ghost fishing listed by Miller's (1976) review of crab management regulations in North America, demonstrating the relatively recent recognition of the problem.

Most other major trap fisheries on the Pacific coast have similar regulations. Scarsbrooke et al. (1988) describe the requirement for a timed-release panel in the sablefish fishery. In this case the fishing industry actually included such devices before being regulated. Regulations governing a new trap fishery for hagfish, *Eptatretus* spp., require timed-failure openings in British Columbia and Oregon (Harbo pers. commun.).

American Lobsters

In the United States, Connecticut has been the only jurisdiction to require incorporation of a timed-release panel into the trap. Maine drafted legislation in 1982, which will take effect in 1990 (Krouse 1989), requiring a timed-release panel at least 95 mm square, made of untreated natural material: twine <5 mm diameter, ferrous metal less than about 2.5 mm diameter, or softwood. In the federally controlled part of the fishery, degradable fasteners closing a timed-release opening will be required in 1992 (Fogarty pers. commun.).

In the federally regulated portion of the fishery, lobster traps must be marked with the owner's identification number, and traps set on ground lines must be marked with a buoy or flagpoles and radar reflectors, depending on how many traps are set.

In the Canadian fishery, no regulations are directed at ghost fishing. Anthony and Caddy (1980) recognized the problem and recommended that timed-release panels or "links" be included in all traps and especially deepwater traps.

GHOST FISHING BY GILLNETS

Mechanisms

Gillnets work by trapping animals in the mesh of the net; ghost fishing is a simple continuation of the gillnetting process after the net is lost.

A wide variety of species are targeted with many types of gillnet worldwide (see Uchida 1985 for a comprehensive review). In comparison with the trap fisheries reviewed above, there has been little work on ghost fishing by gillnets. This may reflect failure to recognize a problem: Herrick and Hanan (1988) review problems caused, inter alia, by California gillnets without considering ghost fishing.

Pelagic or drift gillnets are used by Japan and Taiwan in the North Pacific to catch salmon and squid (Uchida 1985), and in the South Pacific by Japan, Korea, and Taiwan to catch albacore and skipjack tuna (Hinds 1984; Murray 1988). Ghost fishing in pelagic gillnets may be overshadowed by their incidental catch performance. They catch a long list of other nontarget species including fishes, birds, turtles, and marine mammals. Even reindeer have been reported caught by gillnets (Beach et al. 1976). Sloan (1984) and McKinnell et al. (1989) give extensive species lists in the incidental catch in Japanese squid gillnetting off British Columbia. In the same fishery Jamieson and Heritage (1987) estimate the catch of birds at one per 18 km of net set, the catch of mammals at one per 140 km. Harwood and Hembree (1987) estimate the incidental catch of cetaceans in pelagic gillnetting off northern Australia, 1981-85, to have been on the order of 14,000 individuals. Incidental catches of cetaceans are also a serious problem in coastal gillnet fisheries. Read and Gaskin (1988) estimated the catch of harbor porpoises, *Phocoena phocoena*, by groundfish gillnets in the Bay of Fundy, concluding that the incidental catches threaten the population. Recreational gillnetting is a major threat to the endangered Hector's dolphin, *Cephalorhynchus hectori*, in New Zealand (Dawson 1990).

Demonstrations of Gillnet Ghost Fishing

Recovered Lost Gear

In Iceland, synthetic cod gillnets were found a "fairly long time" after loss (von Brandt 1984); they appeared to be fishing actively based on the number and appearance of fish.

Way (1977) described catches of live fishes and crabs in lost demersal Newfoundland cod gillnets retrieved with purpose-designed dragging gear. He concluded that lost gillnets continued to fish "at a declining rate."

DeGange and Newby (1980) described finding a drifting 3.5-km pelagic gillnet lost for at least a month. The net contained 99 birds and 78 fishes. Live birds appeared to be attracted to the net, perhaps by the material already caught, and many of the fish were fresh. These authors confirm the fears of Bourne (1977) that lost gillnet fragments continue to catch and kill birds.

High (pers. commun.) found a lost salmon gillnet with fish skeletons, diving ducks, and seals, *Phoca vitulina*, in varying states of decay, indicating the net continued to kill these animals.

Underwater Observations

After discovering lost salmon gillnets in Washington, High (1985) used scuba to observe them for 6 years. The nets continued to catch crabs, fishes, and birds for 3 years. One net 180 m long contained an estimated 1,000 female crabs (High pers. commun.).

In New England, Carr et al. (1985) made observations from a submersible. They describe fishes entangled in nets estimated to have been lost for at least 2 years. Observations were continued for 3 years from a submersible and remotely operated vehicle (Carr and Cooper 1987; Carr 1988). Nets lost for 3-7 years continued to catch a variety of species, including spiny dogfish, *Squalus acanthius*; American lobsters; and bluefish, *Pomatomus saltatrix*. Later observations on one net indicated that gadoid fish successfully avoided the net, but crabs, *Cancer irroratus* and *C. borealis*, continued to be killed. Carr and Cooper (1987) estimated that lost nets were fishing at approximately 15% of the rate of commercial nets.

Dennis Chalmers (pers. commun.) reported finding a British Columbia herring (*Clupea harengus pallasi*) gillnet lost for at least 4 years: "This net was all bunched and tangled up against a rock ledge in 15 ft [4.6 m] of water and, at the time, there were a few rockfish [*Sebastes* spp.] trapped inside it." Another net found in 11-12 m depth had been lost for at least

7 years. It had no cork line, but the net had enough buoyancy to sit in fishing position and contained several fresh herring.

As in crustaceans, decaying fishes of some species may repel conspecifics. It is believed in New Zealand, for instance, that dead rig, *Mustelus lenticulatus*, and rig offal near a net reduce net catches (Bradstock pers. commun.). This effect might reduce ghost fishing for some species, but no formal research appears to have been conducted.

Schrey and Vauk (1987) reported that more than 2.6% of gannets, *Sula bassana*, visiting Helgoland become entangled in lost gillnets, which caused 30% of the total gannet mortality observed.

Field Experiments

Two simulated lost demersal gillnets were observed by divers in New England (Carr et al. 1985). The nets continued to catch fishes and crabs over 2 1/2 months of observation.

Kim Walshe (pers. commun.) observed simulated lost inshore gillnets by diving for a year in New Zealand. The nets were partly disabled by algal growth and wrapping up, but continued to catch and kill some fish at intervals through the year. Rock lobsters, *J. edwardsii*, are attracted to the fish and are themselves caught by lost inshore gillnets (Anonymous 1978).

Rate of Gillnet Loss

Storms can break gillnets or break off the end markers. Vessels and trawls may run over or cut gillnets. Marine mammals and large fishes may break and carry away nets. In northern waters ice causes gillnet loss (Way 1977). Way also suspected that some nets were simply abandoned at the end of the season. Net fragments may simply be discarded (Gerrodette et al. 1987). In inshore gillnet fisheries, nets snag on obstructions and are lost.

In the New England groundfish gillnet fishery, loss of nets was investigated by CEE (1987, cited by Heneman and CEE 1988). The study examined claims for lost gear made under a U.S. Federal act providing for compensation for gear loss caused by foreign fishing activities. For 1985 and 1986, claims were made for 48 and 29 km of net, respectively. It is unknown what proportion of the total net loss this represented.

Fosnaes (1975) estimated that 5,000 Newfoundland cod, *Gadus morhua*, gillnets were lost annually. Way (1977) conducted a program of lost net retrieval on commercial grounds, finding 148 nets in 48.3 h in 1975 and 167 nets in 53.5 h in 1976.

The density of lost demersal gillnets on a commercial ground in New England was estimated from a submersible by Carr et al. (1985). They found 10 lost nets over 40.5 ha of bottom in 37.5 h search time.

For large pelagic gillnets, a major concern is the tremendous quantity of net in the water. Eisenbud (unpubl. manuscr.) estimated that 5,000 km of net were used in the Japanese North Pacific salmon net fishery alone. Uchida (1985) estimated that 170,000 km of pelagic net were used in 1984 in the North Pacific. Coe (1986) estimated that more than 1.6 million km of squid net were used by Japan, Republic of Korea, and Taiwan in 1985. Even a very small loss rate results in a very large estimate of lost net.

Pelagic gillnets are lost from most of the same causes as coastal gillnets. Because of their great length (12-15 km), these nets are vulnerable to vessel traffic. In the Japanese fishery, intact nets are easier to recover than fragments because radio buoys and lights are installed at each end; most nets recovered by Japanese observers were fragments (Morimoto pers. commun.). Additional causes of loss suggested by Eisenbud (unpubl. manuscr.) are desertion of nets in prohibited areas after removal of end markers, and simple discard of old netting. A fisheries observer, Goldblatt (1989), describes a pelagic gillnet vessel entangling her own net in the propeller, then cutting away and discarding a large fragment.

Eisenbud (unpubl. manuscr.) reported an estimate that 0.06% of Japanese salmon pelagic gillnet is lost at each set. Gerrodette et al. (1987) report an estimate of 0.05%. They consider this estimate to be low, but Morimoto (pers. commun.) considers that the loss rate would be lower in the squid gillnet fishery because of calmer sea conditions. Tsunoda (1989) observed a Japanese pelagic squid gillnet vessel for 4 weeks and observed no gear loss. When nets were severed by vessels, Tsunoda reports that the crew quickly recovered the subsections. Eisenbud (unpubl. manuscr.) estimated annual loss from the Japanese North Pacific squid and salmon gillnet fisheries to be approximately 2,500 km of net.

The density of lost gillnet material can be estimated at sea from transect surveys (Baba et al. 1990; Day et al. 1990). However, the absolute density of lost nets is very low, net fragments cannot be seen from a significant distance, and the tendency is for drifting debris to become nonrandomly distributed by winds and currents. Assessing the impact of lost gillnets through direct surveys is therefore difficult.

Fate of Lost Gillnets

Gillnets are usually made from synthetic materials which can last for long periods of time. High (1985) observed that lost salmon gillnets continue to kill birds and fish for 3 years, and estimated that crabs may be killed for at least 6 years. The direct observations of Chalmers (pers. commun., described above) on herring gillnets tend to support these estimates.

In inshore waters, algal growth on sunken nets may stop fishing by making the nets highly visible to fishes and birds (High 1985; Dennis Chalmers pers. commun.), but Kim Walshe (pers. commun.) reports that fish are caught even in overgrown nets. Strong currents cause the net to tangle lead line over cork line (Way 1977) or end over end (High 1985). High suggests that rolled netting stops catching birds and fishes but may continue to catch crabs. Drift macrophytes and the catch of fish and crabs may cause the net to sink and stop fishing efficiently (Way 1977; Carr et al. 1985; Millner 1985, cited in Heneman and CEE 1988). Dogfish caused twisting of the demersal gillnets observed by Carr et al. (1985). These authors found three main types of lost net configuration, and speculated that these related to how the nets were lost.

Gerrodette et al. (1987) attached radio transmitters to four sections of gillnet 50-1,000 m long, then monitored the simulated lost nets. The shortest net "collapsed" very quickly, but the largest net remained in fishing condition for at least 10 days. The authors estimated that a 1-km net would remain in a fishing configuration for several weeks.

In a similar study, Mio et al. (1990) examined five simulated lost pelagic gillnets, each 1,200 km long, for nearly 4 months. At the end of this time all nets had twisted themselves together end for end to form a large mass. One net completed this process in 20 days; the others took longer.

The wrapping up of nets may be accelerated by storms. Sloan (1984) observed that squid gillnets off British Columbia became tangled at wind speeds >65 km/h.

Merrell (1984) estimated that netting at sea survives for <10 years. This estimate is based on "aging" nets found stranded.

Prevention of Gillnet Ghost Fishing

As with traps, the most effective way to prevent ghost fishing is to prevent gear loss. In the Japanese pelagic gillnet fishery, vessels are required to mark nets with a radio buoy at one end and radar reflectors at both ends. Radio communication is used to deflect vessel traffic around the nets. Discarding of netting is prohibited, and old netting is disposed of on land (Morishita pers. commun.).

Gillnets could be hung from the cork line with natural fiber twine (Way 1977; von Brandt 1984). In theory when the net is lost the twine would rot, and the lead line would pull the net into deep water. This idea is being examined experimentally for coastal gillnets in New England (McKenzie pers. commun.). The tendency of nets to become tangled (lead line over cork line) might prevent sinking, but would also reduce ghost fishing potential. There is also a danger that sinking the net simply transfers a surface ghost fishing problem to the bottom, as suggested by the salmon gillnet observations.

In British Columbia, a proposal to require herring gillnets to be hung with cotton twine has been drafted, but is still under discussion with industry (Dennis Chalmers pers. commun.).

I am aware of no research into degradable materials for use in the web itself. The use of natural fiber for gillnets would be a backward step because of the massive effort required to maintain and preserve nets during fishing. Gillnets are commonly made from monofilament nylon (Uchida 1985), whereas the major effort in degradable plastics has been aimed at polyethylene or polyolephanes (Scott 1990) or composites of polyethylene or polypropylene and natural material (Blott pers. commun.). A potential problem is that degradable nets would form many smaller net fragments instead of one large one.

CONCLUSIONS

Ghost fishing has not been well studied. Significant information exists for only two gear types: traps and gillnets. The importance of ghost fishing as a potential problem is underscored by very large volumes of fishing gear in use, high gear loss rates in many fisheries, and the widespread use of nondegradable materials such as plastics and stainless steel for fishing gear construction.

The fishing behavior of lost traps has been examined for only a handful of fisheries, mostly in North America. For most of the world's many trap fisheries, the impact of lost gear has simply not been addressed.

Ghost fishing by traps can operate through several mechanisms depending on trap type and the target species. Where impact has been estimated, ghost fishing sometimes emerges as only a small problem (e.g., Newfoundland snow crab and Western Australian snapper); in other cases (American lobsters, Dungeness crabs), ghost fishing is clearly an important biological and economic waste.

Modifications to stop traps from ghost fishing are simple and effective, and can be inexpensive. Such modifications are quick and easy to service once installed. Management agencies should determine whether ghost fishing is a problem in specific trap fisheries. If it is, they should conduct research into material failure rates and require timed-release devices or panels in all traps. Appropriate and properly designed research is required both to convince the industry of the problem and to develop effective timed-failure devices for specific situations.

For Dungeness crab fisheries, all jurisdictions now recognize the ghost fishing problem and attempt to control it. In the American lobster fishery, where ghost fishing was well documented much earlier, most jurisdictions have still not addressed the problem.

In the American lobster and British Columbia Dungeness crab fisheries, the amount of waste caused by ghost fishing would not have been recognized without appropriate experimentation. In no fishery should ghost fishing be rejected as a serious potential problem until proper research has been conducted.

Ghost fishing has been documented in a variety of coastal gillnet fisheries. Lost nets may kill fishes, crabs, birds, and seals for several years. Loss rates of coastal gillnets have not been estimated, but at least two studies indicate a substantial density of lost demersal gillnets on commercial fishing grounds.

The situation in pelagic gillnets is less clear. Loss rates are poorly estimated. At least one study indicates that ghost fishing and continuing entanglement of birds occurs; other studies suggest that pelagic nets form tangled nonfishing masses in a short time. Further information is needed in two areas: documentation of lost gear encountered at sea, and direct study of the fishing behavior of lost pelagic gillnets.

Short of preventing net loss or prohibiting gillnetting, it is not clear how to prevent ghost fishing in gillnets. Studies of preventive measures such as using degradable hangings are embryonic. Preventive measures may simply change the form of the problem. Side effects of intended preventive measures must therefore be examined carefully.

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