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# Derelict fishing nets in Puget Sound and the Northwest Straits: Patterns and threats to marine fauna

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ABSTRACT

Derelict fishing gear remains in the marine environment for years, entangling, and killing marine organisms worldwide. Since 2002, hundreds of derelict nets containing over 32,000 marine animals have been recovered from Washington's inland waters. Analysis of 870 gillnets found many were derelict for years; most were recovered from northern Puget Sound and high-relief rocky habitats and were relatively small, of recent construction, in good condition, stretched open, and in relatively shallow water. Marine organisms documented in recovered gillnets included 31,278 invertebrates (76 species), 1036 fishes (22 species), 514 birds (16 species), and 23 mammals (4 species); 56% of invertebrates, 93% of fish, and 100% of birds and mammals were dead when recovered. For all taxa, mortality was generally associated with gillnet effectiveness (total area, age and condition, and suspension in the water). Mortality from derelict fishing gear is underestimated at recovery and may be important for species of economic and conservation concern.

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## 1. Introduction

Derelict fishing gear is recreational or commercial fishing nets, lines, pots, and traps lost or abandoned in the environment. According to a recent report of the Food and Agriculture Organization of the United Nations (FAO) and the United Nations Environment Program, about 640,000 ton of discarded fishing gear gets added to the oceans yearly, which is approximately 10% of the world total of marine debris (Macfadyen et al., 2009). Derelict fishing gear has been implicated in the deaths of countless marine mammals, seabirds and invertebrates annually, and associated mortality may be having a global impact on the sustainability of already stressed fisheries. Not only is it degrading economic and ecological resources (APEC, 2004), but it is recognized as a significant threat to marine fauna (USCOP, 2004). In response to the latter report, an interagency marine debris coordinating committee was re-established to reduce marine debris from all sources, particularly focusing on derelict fishing gear (USOAP, 2004).

Derelict fishing gear can get caught on rocky and coral reefs or float on the ocean surface and pose a hazard for navigation as well as for commercial and recreational divers. Derelict gear can degrade marine habitats by inhibiting access to habitats via multiple layers of gear, suffocating habitat by trapping fine sediments, and contributing to habitat destruction through scouring (Morton, 2005; UNEP, 2005). In recent decades, this problem has worsened; during the 1950s, most of the world's fishing industries replaced nets and gear made of natural fibers such as cotton, jute and hemp with those made of synthetic materials, such as nylon, polyethylene and polypropylene; unlike natural fiber, synthetic fishing gear is functionally resistant to degradation in the water, and, once discarded or lost, this gear may remain in the marine environment for decades (USOAP, 2004), negatively impacting economies and environments worldwide (UNEP, 2005).

One consequence of derelict fishing gear in the marine environment is the entanglement and killing of target and non-target fishery species long after the gear has been lost or abandoned, a process also known as "ghost-fishing" (Breen, 1990). In some cases, catch rates of derelict gear can approach zero after a relatively short time; in shallow water, nets may lose their effectiveness as they get weighed down by accumulated catch, become more visible due to caught organisms and bio-fouling, and generally break down (Erzini et al., 1997). In other cases, catch rates of commercial species in derelict nets can be substantial over time, particularly in deeper water or if nets are stretched open (Humborstad et al., 2003; Kaiser et al., 1996; Santos et al., 2003; Sancho et al., 2003), where they can catch target and non-target species for an extended period of time. This is particularly likely where ocean circulation intersects with topographically complex habitats (Donohue et al., 2001). Quantifying the loss of marine resources due to derelict gear

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mortality can be difficult, but it may represent a non-trivial portion of target fishery populations.

Derelict fishing gear also poses a threat to a variety of non-target fish (Stewart and Yochem, 1987), turtle (Carr, 1987; White, 2006), seabird (Schrey and Vauk, 1987; Piatt and Nettleship, 1987), whale (Volgenau et al., 1995) and seal species (Hofmeyr et al., 2002; Page et al., 2004; Boland and Donohue, 2003). According to one review, 136 marine species have been reported in entanglement incidents in the wider US area, including six species of sea turtles, 51 species of seabirds, and 32 species of marine mammals (Laist, 1996). In the Northwestern Hawaiian Islands, derelict fishing gear from throughout the North Pacific finds its way to the area's coral reefs. Not only does the gear abrade, enshroud, and break the fragile coral reefs, it injures and kills federally endangered Hawaiian monk seals (*Monachus schauinslandi*), protected sea turtles, and cetaceans. Between 1982 and 2000, over 200 Hawaiian monk seals were found entangled in derelict nets (Boland and Donohue, 2003); entanglement rates are greater in El Niño years, when oceanographic factors deliver more debris to the islands (Donohue and Foley, 2007). Since 1998, NOAA Fisheries and other state and federal organizations have removed hundreds of tons of derelict nets from the Northwestern Hawaiian Islands' coral reefs in an effort to restore fragile habitats and reduce the impact on the local marine fauna.

### 1.1. Derelict gear in Puget Sound

In Puget Sound and the Northwest Straits, bottom trawl surveys by the Washington Department of Fish and Wildlife (WDFW) have estimated that up to 117,000 derelict nets and pots weighing approximately 2.6 million pounds lay beneath the waters of Puget Sound (WDFW, unpublished data). The Northwest Straits Commission estimates that approximately 4000 derelict fishing nets and between 14,000 and 20,000 derelict crab pots remain in Puget Sound (NWSF, 2007). A long legacy of fishing by the Puget Sound gillnet fleet, which primarily targets Pacific salmon (*Oncorhynchus* spp.), and Pacific cod (*Gadus macrocephalus*) and spiny dogfish (*Squalus acanthius*) to a lesser extent, has likely resulted in the loss of thousands of full-size gillnets over the past 30 years (WDFW, unpublished data). Likewise, thousands of commercial and recreational crab pots have become lost or abandoned over many years of fishing in some areas, resulting in considerable mortality of Dungeness crab (*Cancer magister*). In Port Susan bay in central Puget Sound, estimates of annual crab loss to derelict pots were upwards of 23,000 individuals, which is a considerable portion of the area Dungeness crab fishery (NRC, 2003). The legacy of such gear can be devastating to marine populations in Puget Sound; divers reported a single derelict gillnet suspended between rocks off the southwest corner of Lopez Island in the San Juan Islands that had thousands of bones piled 1–3 feet deep and running the length of the 30 m span of the net (NRC, 2004a). The accumulation of reports and potential risks has raised the removal of derelict gear to an immediate priority action for a healthy Puget Sound by 2020 (PSP, 2008).

Since 2002, the Northwest Straits Commission, working with Natural Resources Consultants, Inc., the Washington Department of Fish and Wildlife, and National Oceanic and Atmospheric Administration (NOAA) Fisheries, has documented and removed over 94 tons of derelict nets, pots and traps from the inland marine waters in Washington (NWSC, 2008). The overall objective of the derelict gear removal project is to locate and remove existing derelict gear in the Puget Sound and the Northwest Straits. Some of this derelict gear is in or near marine areas important for foraging and breeding of commercially important crabs and benthic fish, migration of Pacific salmon, and foraging for marine birds and mammals. Clearing these important underwater habitats of this known source of mortality might help conserve and recover imperiled species in the region. While derelict pots represent the majority of derelict gear by number and weight, their potential biological impact is largely confined to crabs. By contrast, derelict nets have a much broader potential for impact, as they are known to entangle and kill a variety of fish, marine bird and mammal species. The goals of the analyses presented here are: (1) to describe patterns in the characteristics of the derelict gillnets recovered, (2) to document the magnitude and taxonomic breadth of damage to marine fauna documented in recovered derelict gear, and (3) to preliminarily identify conditions that appear to be conducive to accumulating derelict fishing gear for future surveys and recovery efforts.

## 2. Methods

We recovered derelict fishing gear at sites throughout Puget Sound and the Northwest Straits (the US portions of the straits of Juan de Fuca and Georgia; Fig. 1). Some sites were targeted by city, county, and tribal entities as known areas of derelict gear accumulation, and some were targeted using reports from a derelict gear database developed from years of reports from the fishing community, sport and research divers, and any vessels that encounter gear; the remainder resulted from previously unreported gear being encountered during the course of derelict gear recovery efforts. To locate derelict gear, we used a 40-foot vessel equipped for dive-support and gear recovery and a laptop computer linking the GPS-referenced derelict gear database to onboard Nobeltec™ navigation software. Exact gear location was marked on the navigation software when divers reported their observations via an underwater-to-surface communication system. To recover derelict nets, a lead weight attached by line to a surface float was deployed at the site, and the dive-support vessel was anchored nearby. Divers followed the buoy line to the seabed, maintaining real-time two-way radio communications with the support vessel at all times. After locating the derelict net, a recovery line was attached and was hauled aboard the recovery vessel by hand or with the aid of a hydraulic winch after freeing the net from the seabed by hand. In most cases, divers attached air-lift bags to the derelict net and floated it all to the surface where it was recovered by the vessel. Additional nets encountered during recovery efforts were under reported nets or were found during diver surveys of a 350-foot circle from the focal net site.

Net-specific characteristics were reported by the diver and subsequently verified once the net was on board, including its location (GPS coordinates), benthic habitat type, gear type (gillnet, purse seine, etc.), net age (older or more recent construction judged on style and estimated vintage), condition (judged good or poor), length and width, maximum and minimum depth, maximum suspension in the water, and any observations on habitat impacts from the net. Marine fauna-specific information included number and identity (where possible) of whole or partial organisms entangled in the net and their status (alive or dead); evidence of cumulative mortality (bone piles) near the net was also relayed by the divers. Approximately 80% of vertebrate specimens were composed partially or entirely of bony elements and were identified to the lowest taxon possible by comparing skull and post-cranial characters to reference skeletal material. Skeletal elements observed below the net and likely attributable to the net were also collected, identified, and enumerated. An estimated minimum number of individuals (MNI) represented by the skeletal material was based on the most frequently occurring skeletal element. The total MNI of vertebrates in derelict gear was calculated for a variety of taxonomic levels (e.g., MNI of family, genus, species) based on the sum of whole carcass counts and the MNI

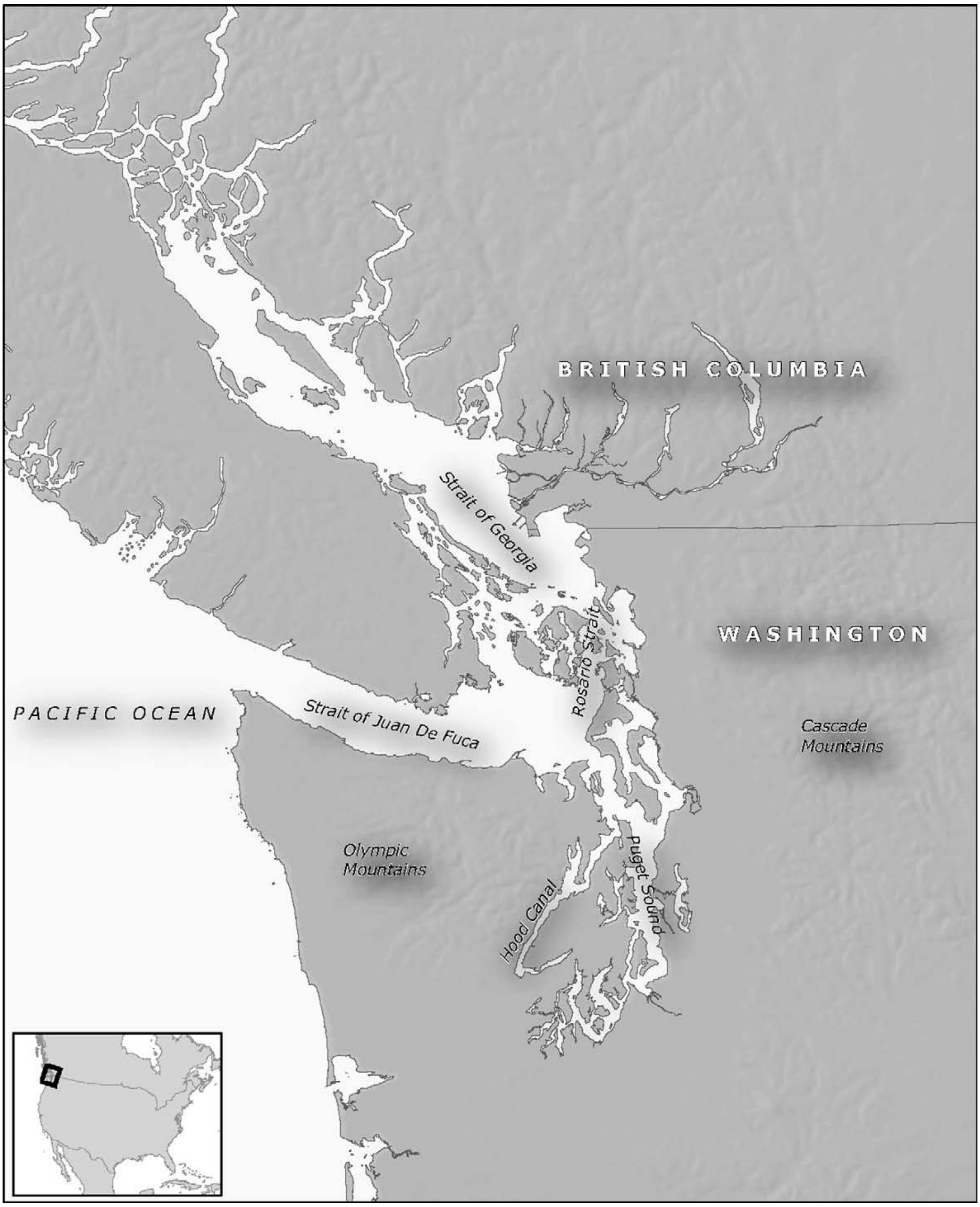


**Fig. 1.** Map showing the study area (Puget Sound and the Northwest Straits).

values obtained from skeletal material. Organisms living on or associated with the derelict gear but not entangled or trapped were noted but not counted, and living organisms were immediately returned to the sea after identification.

### 2.1. Data analyses

To determine the distribution of time gillnets were derelict in the marine environment, we calculated the length of time underwater as the time difference between when a derelict gillnet was reported and when it was recovered. This represents the minimum amount of time spent in the marine environment, since the absolute time is unknown for the vast majority of nets recovered. To explore the spatial distribution of derelict gillnet recoveries, we subdivided Puget Sound and Northwest Straits into six geographic regions roughly corresponding to those used in natural resource planning: the San Juan Islands, Northern Puget Sound, Central Puget Sound, Hood Canal, the Strait of Juan de Fuca, and Southern Puget Sound. Due to small sample sizes in some regions, we combined the San Juan Islands with the Strait of Juan de Fuca and Central Puget Sound with Hood Canal and Southern Puget Sound for analysis of regional effects on mortality patterns. To explore patterns in habitat type, we broadly categorized benthic habitats from which derelict gillnets were recovered: (1) high-relief rocky substrate, (2) low-relief rocky substrate, (3) boulders on sand/mud/gravel, (4) mud/sand/gravel/vegetation, and (5) underwater obstructions (e.g., sunken vessels, pier pilings, and buoy anchors). To explore patterns of age and condition, we categorized derelict gillnets as being of relatively recent or older construction ((old = net tattered, material weak, appearing to have been in place for several years; new = net appeared more recently lost, little or no algal growth, material remained strong), and as being in relatively good or poor condition (good = net still in fishable condition; poor = net in overall poor condition.). To explore patterns of derelict gillnet overall size, we calculated net area from data collected on net height and width and summarized data on gillnet maximum suspension. To explore patterns of derelict gillnet depth, we summarized data collected on gillnet minimum and maximum depth in the water.

We report the minimum number of individuals and species identified during and after gear recovery operations; unknown species may represent heretofore unreported taxa. The small % of fish recorded alive were counted as dead for purposes of assessing fish mortality, as trapped fish would most likely have died in derelict nets if not for gear recovery efforts. Marine mammal mortality was documented in a small number of nets, so these data were combined with marine bird data for analyses. We used two-way Chi-square analyses (SYSTAT, 2007) to explore associations between mortality of marine taxa and gillnet characteristics: minimum amount of time derelict (<1 year, 1–6 year, 6–24 year), region, benthic habitat, net area (<200 $m^2$, 200–1000 $m^2$, 1000–14,000 $m^2$), age, condition, maximum suspension (0 m, 0–1 m, 1–2 m, >2 m), and minimum depth.

## 3. Results

### 3.1. Spatial patterns and characteristics of derelict fishing gear

Of the 902 derelict fishing nets recovered from Puget Sound and the Northwest Straits as of June 2008, 876 were gillnets. The remaining nets were purse seines ($n = 23$), trawl nets ($n = 2$), and aquaculture nets ($n = 1$). Of the 876 gillnets, 870 had datasets complete enough to examine spatial patterns and characteristics of derelict fishing gear and mortality patterns of marine fauna that we documented during gear recovery. One-quarter of the nets ($n = 216$) were recovered on the day they were detected/found and thus derelict for an unknown amount of time; 36% ($n = 308$) were documented to have been derelict for periods of up to a year, while 25% were derelict for somewhere between 5 and 24 years (Fig. 2). Excluding those with an unknown history (recovered on the day they were discovered), the median time gillnets were documented to have been derelict was more than 1 year.

Gillnets were recovered from areas throughout the Puget Sound and Northwest Straits, however, most of them were recovered from the San Juan Islands ($n = 500$) and Northern Puget Sound ($n = 241$), followed by Central Puget Sound ($n = 110$), Hood Canal ($n = 14$), the Strait of Juan de Fuca ($n = 3$), and Southern Puget Sound ($n = 2$; Fig. 3). Most gillnets were recovered from habitats with high-relief rocky substrate ($n = 363$) and boulders on sand/mud/gravel ($n = 297$), with lower numbers recovered from low-relief rocky substrate ($n = 77$), mud/sand/gravel/vegetation ($n = 71$), and underwater obstructions ($n = 62$). Most derelict gillnets recovered (66%) were relatively small in size ($\leqslant$1000 $m^2$); 35% of gillnets recovered were $\leqslant$200 $m^2$ in area, 31% were from 200 $m^2$ to 1000 $m^2$ in area, and a small number ($n = 11$) were >6000 $m^2$ in area (Fig. 4). The majority of gillnets recovered (54%) were of relatively recent construction, while 46% were of older construction. Most gillnets recovered (71%) were in relatively good condition, while only 29% were in poor condition. Most gillnets (81%) recovered were suspended open in the water column to some extent (i.e., maximum suspension > 0 m); the maximum suspension of gillnets ranged from 0 to 36.6 m (Fig. 5), with a median of 0.6 m. Gillnets were primarily recovered from depths of less than 22 m;

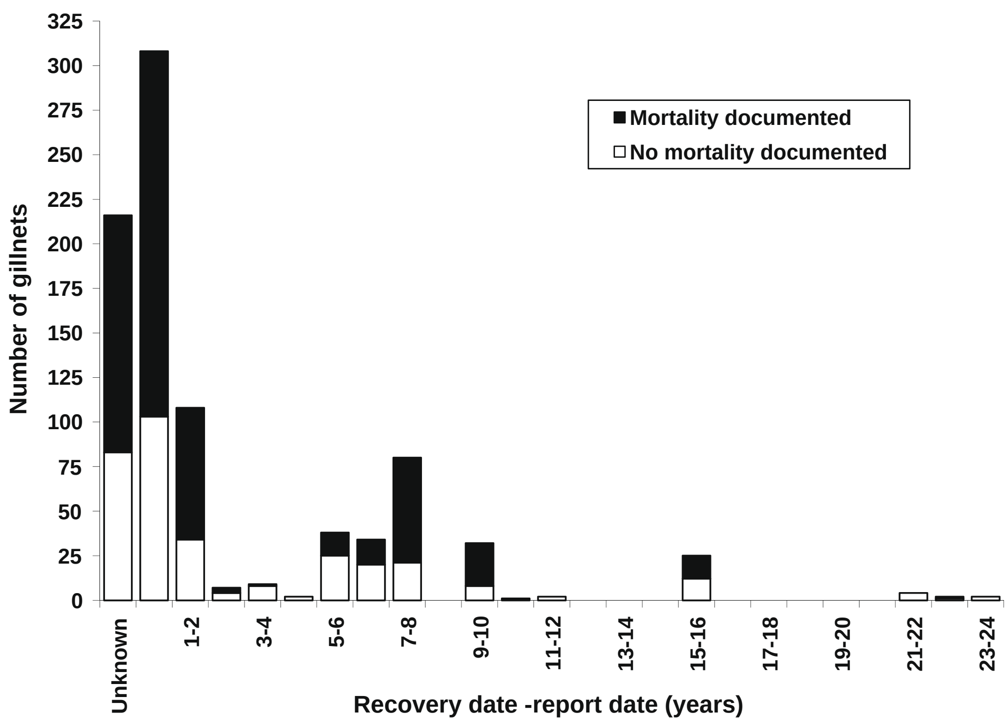


**Fig. 2.** Distribution of the minimum amount of time derelict gillnets ($n = 870$) were documented underwater (date recovered–date reported) in years. "Unknown" represents gillnets recovered on the day they were detected/reported and thus derelict in the water for an unknown period of time. Black bars are nets with mortality documented at recovery; white bars are nets with no mortality documented at recovery.

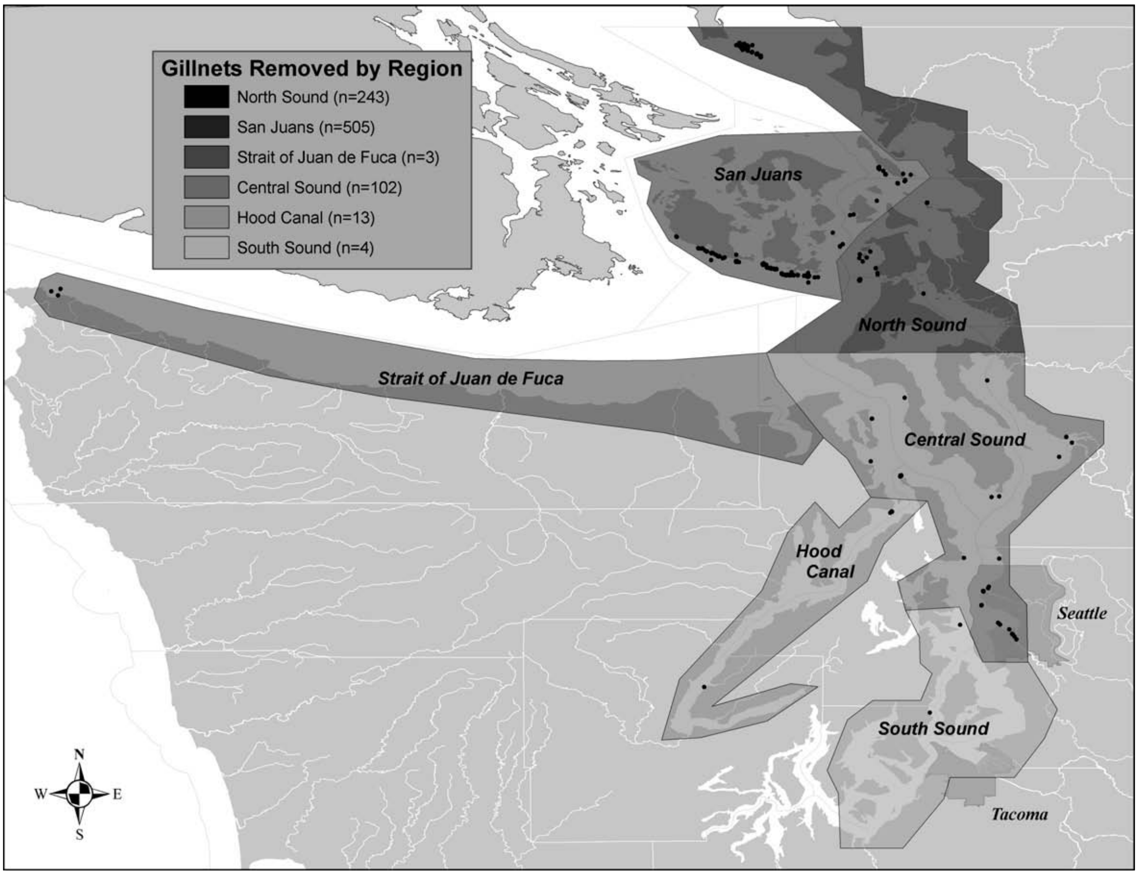


Fig. 3. Map showing the location and number of removed gillnets ($n = 870$).

the minimum depth of recovered gillnets ranged from 0 to 36.6 m (mean = 17.0 m), while the maximum depth ranged from 1.2 to 42.7 m (mean = 19.8 m). The maximum practical diver working survey and removal depth was about 32 m.

## 3.2. Mortality patterns in derelict fishing gear

We documented 32,846 marine organisms in derelict gillnets recovered from Puget Sound and the Northwest Straits. The number

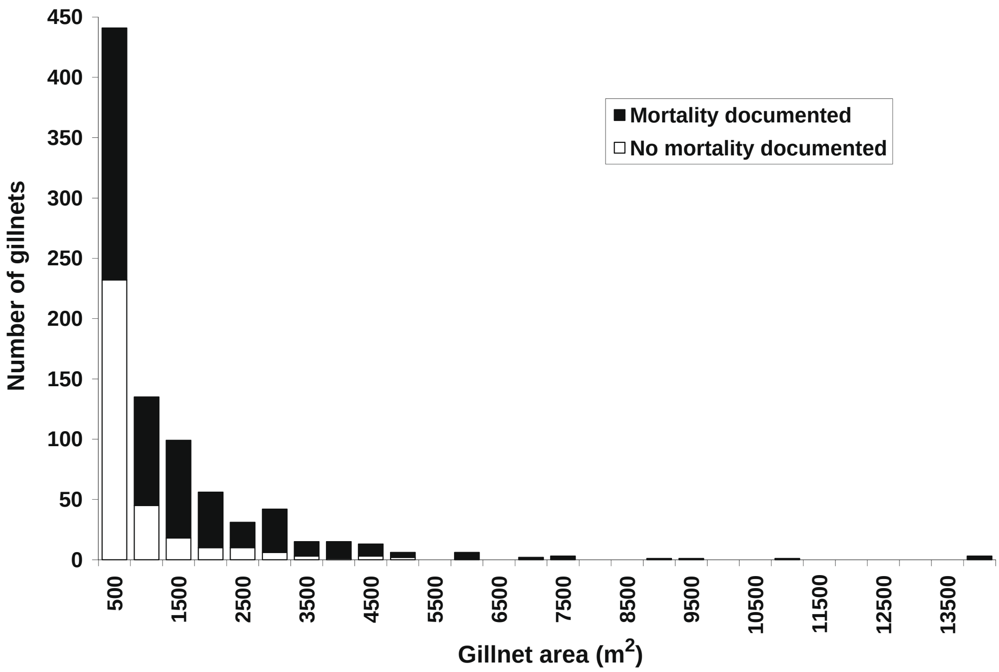


Fig. 4. Distribution of the area ($m^2$) of derelict gillnets ($n = 870$). Black bars are nets with mortality documented at recovery; white bars are nets with no mortality documented at recovery.

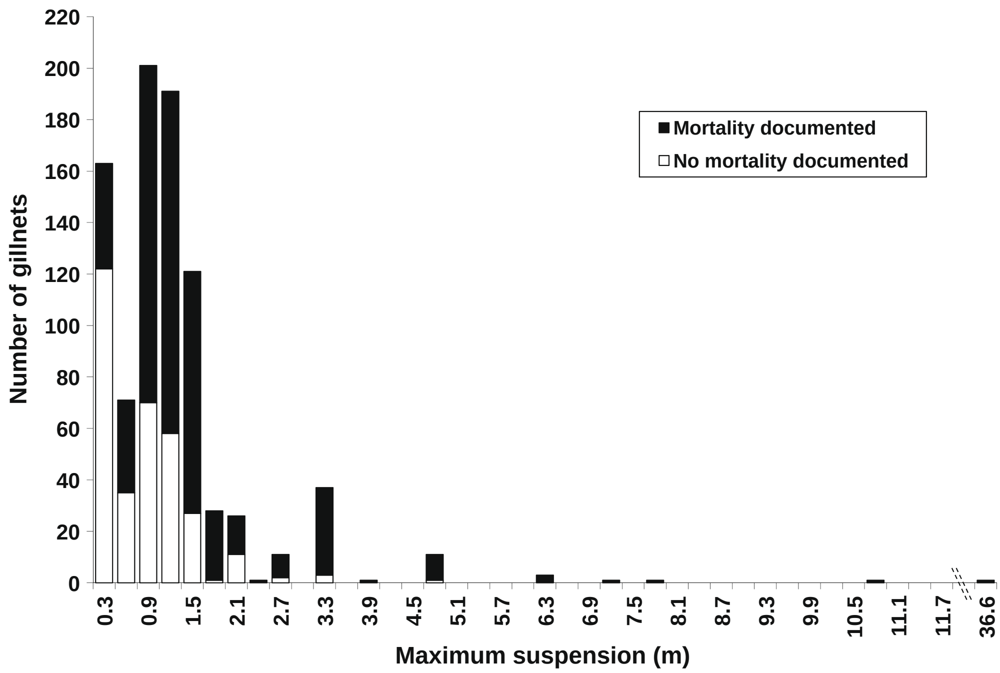


**Fig. 5.** Distribution of the maximum suspension (m) of derelict gillnets ($n$ = 870). Black bars are nets with mortality documented at recovery; white bars are nets with no mortality documented at recovery.

of marine organisms documented dead varied widely among nets. Derelict gillnet contained from 0 to 1025 marine invertebrates (mean = 19.6), from 0 to 360 marine fish (mean = 1.2), from 0 to 142 marine birds (mean = 0.59), and from 0 to 4 marine mammals (mean = 0.03). Of the 31,278 marine invertebrates documented, 55% ($n$ = 17,062) were dead, while 45% ($n$ = 14,216) were alive. Of the 1036 marine fishes documented, 93% ($n$ = 960) were dead, while only 7% ($n$ = 76) were alive. All of the marine birds ($n$ = 509) and mammals ($n$ = 23) documented were dead. Derelict gillnets entangled and/or killed at least 106 species of marine fauna – at least 65 species of marine invertebrates, 22 species of marine fishes, 15 species of marine birds and 4 species of marine mammals (Tables 1–4). Most of the derelict gillnets contained evidence of entanglement and death. We documented mortality (whole or partial dead marine animals) in 62% ($n$ = 541) of derelict gillnets recovered; we documented invertebrate mortality in 51% ($n$ = 448), marine fish mortality in 24% ($n$ = 211), and marine bird and mammal mortality in 16% ($n$ = 139) of derelict gillnets recovered. We documented a broad taxonomic array of entangled taxa, several of which were species of conservation concern (Tables 1–4).

Marine invertebrate mortality was associated with region (most likely in the Central/Southern Puget Sound/Hood Canal), area (more likely in medium and large size classes), inferred age and condition (more likely in gillnets of recent construction and relatively good condition), and maximum suspension (more likely in gillnets suspended open to some extent); marine invertebrate mortality was not associated with gillnet time in the water, habitats where gillnets were found, or any particular minimum depth at recovery (Table 5). Marine fish mortality was associated with gillnet time in the water (less likely in nets derelict between 1 and 6 years), area (more likely in medium and large size classes), inferred age and condition (more likely in gillnets of recent construction and relatively good condition), and suspension (increasingly likely as gillnet suspension increases); marine fish mortality was not associated with region, habitats where gillnets were found, or any particular minimum depth at recovery (Table 6). Marine bird and mammal mortality was associated with gillnet time in the water (most likely in nets derelict less than 1 year), area (most likely in large size classes), inferred age and condition (more likely in gillnets of recent construction and relatively good condition), maximum suspension (increasingly likely as gillnet suspension increases), and depth at recovery (least likely at depths between 10 and 20 m (Table 7).

## 4. Discussion

The recovery of hundreds of derelict nets from throughout Puget Sound and the Northwest Straits is testimony to an unintended legacy created by decades of lost and abandoned commercial fishing gear. The continued presence of additional thousands of derelict gillnets in a variety of habitats in the inland waters of Washington poses a substantial risk to those habitats as well as to the many marine species contained therein. While more than 32,000 marine invertebrates, fish, birds, and mammals have been documented during recovery of just 870 derelict gillnets, the real number of animals that have fallen prey to these nets is much greater, since observed mortality only represent animals that have not decomposed since entanglement.

The majority of derelict nets were gillnets recovered from locations in the San Juan Islands and northern Puget Sound. This is likely driven by the fact that historical and extant salmon fishing has been greatest in the northern parts of Puget Sound (PFMC, 2008). The project database has been dominated by reports of derelict gear in these regions, and gear removal projects conducted there have verified that marine birds and mammals were particularly hard hit in the San Juan Islands and north Puget Sound (NRC, 2003, 2004a,b).

Most derelict gillnets were also recovered from habitats dominated by high-relief rocky ledges and boulders, which, along with man-made obstructions, create a topographically complex ocean bottom in many areas of Puget Sound. These habitats tend to stretch the nets open, often to a meter or more, and this poses a danger to many species of marine animals (Nakashima and Matsuoka, 2005), as nets stretched open by natural or man-made struc-

**Table 1**
Marine invertebrate species identified in derelict fishing gillnets recovered from the inland marine waters of Washington. Seventy-six species from six phyla were documented.

| | | Alive | Dead |
|---|---|---|---|
| *Crustaceans* | | | |
| Giant barnacle | *Balanus nubilis* | 2392 | 4813[c] |
| Dungeness crab | *Cancer magister* | 690 | 1345 |
| Red rock crab | *Cancer productus* | 849 | 1391 |
| Longhorn decorator crab | *Chorilia longipes* | 972 | 59[c] |
| Puget Sound king crab | *Lopholithodes mandtii* | 44 | 52 |
| Northern kelp crab | *Pugettia producta* | 71 | 48[c] |
| Golfball crab | *Rhinolithodes wosnessenskii* | 40 | 17 |
| Cryptic kelp crab | *Pugettia richii* | 80 | 15[b] |
| Heart crab | *Phyllolithodes papillosus* | 11 | 4[b] |
| Red fur crab | *Acantholithodes hispidus* | 5 | 2 |
| Helmet crab | *Telmessus cheiragonus* | 9 | 1[b] |
| Graceful crab | *Cancer gracilis* | 3 | 1[c] |
| Black-eyed hermit crab | *Pagurus armatus* | 0 | 1 |
| Brown box crab | *Lopholithodes foraminatus* | 0 | 1 |
| Granular claw crab | *Oedignathus inermis* | 0 | 1 |
| Tanner crab | *Chionoecetes* spp. | 0 | 1 |
| Hairy lithodid | *Hapalogaster mertensii* | 0 | 1[b] |
| Slender kelp crab | *Pugettia gracilis* | 820 | 0 |
| Porcelain crab | *Petrolisthes* spp. | 20 | 0 |
| Sharpnose crab | *Scyra acutofrons* | 16 | 0 |
| Spot shrimp | *Pandalus platyceros* | 15 | 0 |
| Hermit crab (unid.) | *Pagurus* spp. | 9 | 0 |
| Hairy cancer crab | *Cancer oregonensis* | 5 | 0 |
| Butterfly crab | *Cryptolithodes typicus* | 2 | 0 |
| Purple shore crab | *Hemigrapsus nudus* | 2 | 0 |
| Scaly lithodid | *Placetron wosnessenskii* | 2 | 0 |
| Hairy hermit crab | *Pagurus hirsutiusculus* | 1 | 0 |
| Signal crayfish | *Pacifastacus leniusculus* | 1 | 0 |
| Squat lobster | *Munida quadrispina* | 1 | 0 |
| *Molluscs* | | | |
| Butter clam | *Saxidomus giganteus* | 29 | 4176 |
| Smooth pink scallop | *Chlamys rubida* | 1732 | 2679[c] |
| Pacific littleneck clam | *Protothaca staminea* | 10 | 1175 |
| Nuttall's cockle | *Clinocardium nuttalli* | 0 | 317 |
| Oregon triton | *Fusitriton oregonensis* | 547 | 236[c] |
| Geoduck clam | *Panopea abrupta* | 6 | 166 |
| Green false-jingle | *Pododesmus machrochisma* | 0 | 130 |
| Blue mussel | *Mytilus trossulus* | 312 | 73[b] |
| Leafy hornmouth | *Ceratostoma foliatum* | 357 | 81[c] |
| Blunt gaper | *Mya truncata* | 14 | 65 |
| Rock scallop | *Crassedoma giganteum* | 7 | 40 |
| Common lampshell | *Terebratalia transversa* | 309 | 38[b] |
| Manila clam | *Ruditapes philippinarum* | 4 | 25 |
| Northern abalone[a] | *Haliotis kamtschatkana* | 1 | 7 |
| Bent nose macoma | *Macoma nasuta* | 6 | 2[b] |
| Pacific oyster | *Crassostrea gigas* | 1 | 1 |
| Tellina (unid.) | *Tellina* spp. | 1 | 1 |
| Moon snail | *Polinices lewisii* | 0 | 1 |
| Giant Pacific chiton | *Cryptochiton stelleri* | 93 | 0 |
| Clown dorid | *Triopha catalinae* | 23 | 0 |
| Yellow margin dorid | *Cadlina luteomarginata* | 7 | 0 |
| Hudson's dorid | *Acanthodoris hudsoni* | 1 | 0 |
| Common Pacific octopus | *Octopus dolfleini* | 1 | 0 |
| *Echinoderms* | | | |
| Green sea urchin | *Strongylocentrotus droebachiensis* | 817 | 55[c] |
| Sunflower star | *Pyncnopodia helianthoides* | 163 | 21[b] |
| Blood star | *Henricia leviuscula* | 598 | 14[b] |
| Red sea urchin | *Strongylocentrotus franciscanus* | 290 | 4[c] |
| Fat Henricia | *Henricia sanguinolenta* | 7 | 1[b] |
| California sea cucumber | *Parastichopus californicus* | 503 | 0 |
| Daisy brittle star | *Ophiopholis aculeata* | 100 | 0 |
| Brittle star (unid.) | *Ophiuroidea* spp. | 100 | 0 |
| Painted star | *Orthasterias koehleri* | 90 | 0 |
| Spiny pink star | *Pisaster brevispinus* | 11 | 0 |
| Orange sea cucumber | *Cucumaria miniata* | 10 | 0 |
| Mottled star | *Evasterias troschelii* | 9 | 0 |
| Spiny mud star | *Luidia foliolata* | 3 | 0 |
| Striped sunstar | *Solaster stimpsoni* | 2 | 0 |
| Vermilion sea star | *Mediaster aequialis* | 2 | 0 |
| Purple sea urchin | *Strongylocentrotus purpuratus* | 2 | 0 |
| Long ray star | *Stylasterias forreri* | 1 | 0 |
| Gunpowder star | *Gephyreaster swifti* | 1 | 0 |
| Rose star | *Crossaster papposus* | 1 | 0 |
| *Porifera* | | | |
| Cloud sponge | *Aphrocallistes vastus* | 5 | 0 |
| Hermit crab sponge | *Suberities suberea* | 2 | 0 |
| Tennis ball sponge | *Craneilla villosa* | 9 | 0 |
| *Cnidaria* | | | |
| Hydroid coral | *Abietineria greenei* | 396 | 0 |
| *Chordata* | | | |
| Stalked hairy sea squirt | *Boltenia villosa* | 1591 | 1[b] |
| Total | | 14,239 | 17,062 |

[a] Candidate (WA), species of concern (USA), and threatened (Canada).
[b] Animals living/dying on nets that may become entangled only during removal process.
[c] Animals that may live or move across nets but also are entangled and killed by net.

tures can create a larger killing field over long periods of time. The likelihood of documenting mortality in nets stretched open just two meters or more was greater than for unopened nets for all taxa combined ($\chi^2 = 139.6$, df = 2, $P < 0.001$; see Fig. 5); this was true for marine invertebrates (3×), marine fish (15×), and marine birds and mammals (25×). In general, nets in flat featureless sandy or muddy habitats tend to ball up and pose less risk to target stocks (Matsuoka et al., 2005) as well as a variety of non-target species. However, even in these comparatively benign habitats, natural and man-made obstructions can create hazardous situations. One derelict gillnet in a muddy habitat in the Port Susan area of central Puget Sound entangled some large, heavy commercial crab pots and woody debris, stretching the gillnet open over six meters off the seabed in places. In this one net, we documented 50 fish, 142 marine birds (64 freshly killed), and one marine mammal; the piles of bones beneath it were testimony to the larger numbers it likely killed. Given constant rates of recruitment and degradation over the 23 weeks it was derelict in the environment, it may have killed upwards of 1800 marine birds (J. June, unpublished data).

The extent of historical fishing effort superimposed on the complex bottom topography and oceanography has likely led to "hotspots" of derelict fishing gear accumulation in northern Puget Sound and the San Juan Islands. We are modeling the interrelationship of these factors using geospatial data on bottom topography, hydrodynamic models and historical fishing effort (J. Davies and T. Good, unpublished data), and we will conduct surveys of putative hotspots in Puget Sound and the Northwest Straits to test the model predictions. The interplay between ocean bathymetry and ocean circulation can result in derelict gear hotspots, even where fishing effort resulting in gear loss is external to the area. In the Northwest Hawaiian Islands, derelict trawl nets (86–91% of gear, depending on site) and gillnets (4–7% of gear) get entangled on topographically complex coral reef habitat (Donohue et al., 2001). These nets that pose a risk to Hawaiian coral reef fauna ride oceanographic currents down from the north Pacific (Boland and Donohue, 2003), and their accumulation is especially high in El Niño years (Donohue and Foley, 2007). Here, physical modeling of derelict net accumulation has identified reefs that have been cleaned of derelict gear previously but that require additional efforts to remain free of gear (Dameron et al., 2007).

In our study, derelict gillnets were recovered in condition capable of catching target and non-target taxa, despite the time between reporting and recovery ranging from one week to more

**Table 2**
Marine fish species identified in derelict fishing gillnets recovered from the inland marine waters of Washington. Twenty-two species from 10 families were documented. Status (E – endangered; T – threatened; C – candidate; S – sensitive; RL – red list; BL – blue list; SC – special concern) according to state (WA – Washington), provincial (BC – British Columbia), and federal (USA, Canada) authorities (from Brown and Gaydos (2007)).

| | | Alive | Dead | Status |
|---|---|---|---|---|
| Fish (unidentified) | | 2 | 125 | |
| *Salmonidae* | | | | |
| Salmonid spp. | *Oncorhynchus* spp. | 0 | 165 | |
| Sockeye salmon | *Oncorynchus nerka* | 0 | 25 | E (Canada) |
| Chinook salmon | *Oncorhynchus tshawytscha* | 0 | 5 | T (USA), C (WA) |
| *Chimaeridae* | | | | |
| Spotted ratfish | *Hydrolagus colliei* | 0 | 118 | |
| *Squalidae* | | | | |
| Spiny dogfish shark | *Squalus acanthias* | 3 | 100 | |
| *Hexanchidae* | | | | |
| Sixgill shark | *Hexanchus griseus* | 0 | 1 | |
| *Pleuronectidae* | | | | |
| Flatfish spp. | | 2 | 94 | |
| Starry flounder | *Platichthys stellatus* | 0 | 3 | |
| Slender sole | *Lyopsetta exilis* | 0 | 3 | |
| English sole | *Parophrys vetulus* | 1 | 2 | |
| *Scorpaenidae* | | | | |
| Black rockfish | *Sebastes melanops* | 0 | 50 | C (WA) |
| Rockfish spp. | *Sebastes* spp. | 25 | 49 | |
| Quillback rockfish | *Sebastes maliger* | 2 | 4 | C (WA) |
| Puget Sound rockfish | *Sebastes emphaeus* | 1 | 3 | |
| Copper rockfish | *Sebastes caurinus* | 0 | 3 | C (WA) |
| *Hexagrammidae* | | | | |
| Lingcod | *Ophiodon elongates* | 4 | 94 | |
| Kelp greenling | *Hexagrammos decagrammus* | 6 | 64 | |
| Greenling spp. | *Hexagrammos* spp. | 0 | 1 | |
| *Cottidae* | | | | |
| Cabezon | *Scorpaenichthys marmoratus* | 9 | 21 | |
| Red irish lord | *Hemilepidotus hemilepidotus* | 12 | 11 | |
| Sculpin spp. | | 5 | 9 | |
| Great sculpin | *Myoxocephalus polyacanthocephalus* | 2 | 7 | |
| Sailfin sculpin | *Nautichthys oculofasciatus* | 1 | 1 | |
| Pacific staghorn sculpin | *Leptocottus armatus* | 0 | 1 | |
| Longfin sculpin | *Jordania zonope* | 1 | 0 | |
| Total | | 76 | 959 | |

**Table 3**
Marine bird species identified in derelict fishing nets recovered from the inland marine waters of Washington. Thirteen species from eight families were documented. Status (E – endangered; T – threatened; C – candidate; S – sensitive; RL – red list; BL – blue list; SC – special concern) according to state (WA – Washington), provincial (BC – British Columbia), and federal (USA, Canada) authorities (from Brown and Gaydos (2007)).

| | | Alive | Dead | Status |
|---|---|---|---|---|
| Seabird (unidentified) | | 0 | 148 | |
| *Phalacrocoracidae* | | | | |
| Cormorant (unid.) | *Phalacrocorax* spp. | 0 | 95 | |
| Brandt's cormorant | *Phalacrocorax penicillatus* | 0 | 59 | C (WA), RL (BC) |
| Pelagic cormorant | *Phalacrocorax pelagicus* | 0 | 41 | RL (BC) |
| Double-crested cormorant | *Phalacrocorax auritis* | 0 | 8 | BL (BC) |
| *Anatidae* | | | | |
| Surf scoter | *Melanitta perspicillata* | 0 | 31 | |
| Scoter (unid.) | *Melanitta* spp. | 0 | 27 | BL (BC) |
| White-winged scoter | *Melanitta fusca* | 0 | 15 | |
| Greater scaup | *Aythya marila* | 0 | 1 | |
| Merganser spp. | *Mergus* spp. | 0 | 1 | |
| *Gaviidae* | | | | |
| Loon (unid.) | *Gavia* spp. | 0 | 58 | |
| Common loon | *Gavia immer* | 0 | 9 | S (WA) |
| Pacific loon | *Gavia pacifica* | 0 | 32 | |
| Red-throated loon | *Gavia stellata* | 0 | 27 | |
| *Podicipedidae* | | | | |
| Western/Clark's grebe | *Aechmophorus* spp. | 0 | 15 | C (WA), RL (BC) |
| Grebe (unid.) | *Podiceps* spp. | 0 | 14 | |
| Red-necked grebe | *Podiceps grisegena* | 0 | 2 | |
| *Scolopacidae* | | | | |
| Shorebird (unid.) | | 0 | 1 | |
| *Alcidae* | | | | |
| Common murre | *Uria aalge* | 0 | 1 | C (WA), RL (BC) |
| Pigeon guillemot | *Cepphus columba* | 0 | 1 | |
| *Ardeidae* | | | | |
| Great blue heron (Pacific) | *Ardea herodias fannini* | 0 | 1[a] | BL (BC) |
| Total | | 0 | 516 | |

[a] Bones entangled in net but mortality probably not attributable to gillnet.

than 20 years. The likelihood of documenting mortality in nets was similar in nets with the minimum amount of time as derelict gear of less than 1 year and those with 6–24 years for all taxa combined ($\chi^2 = 5.6$, df = 2, $P = 0.059$; see Fig. 2). Marine invertebrates and fish were nearly as likely to be documented in derelict gillnets recovered 6–24 years from being reported as in gear recovered <1 year from being reported, while marine birds/mammals were more likely to be documented in a derelict gillnet recovered <1 year from being reported (Tables 6–8). It may be that bird and mammal bones fall out of gillnets after long periods of time, which would affect our documenting them in nets; bone piles beneath some nets certainly attest to this possibility.

The true time span over which derelict nets are in the environment is likely much longer than the "minimum amount of time as derelict gear" we calculated here. The Washington Department of Fish and Wildlife established a "no-fault" reporting mechanism for fishermen who lose nets; however, this accounts for a handful of derelict net reports annually. For the vast majority of derelict nets, we have no way of knowing how long they have been derelict before being detected and reported by divers, fisherman, scientists, or the general public, which underscores the minimum estimates of mortality. In the northwestern Hawaiian Islands, efforts to identify invertebrates on derelict nets is informing managers of the risk posed by nets as invasive species vectors; these same techniques may be useful for ageing nets in general.

Almost all derelict gillnets recovered were smaller than the full-size nets generally used in Puget Sound today (16,500 $m^2$). Many nets were recovered with intact leadlines but no float lines, likely resulting from entanglement on the bottom and cutting to salvage a portion of the net. The difference between small (<200 $m^2$) and larger (1000–14,000 $m^2$) recovered derelict gillnets was important for all marine taxa combined ($\chi^2 = 139.8$, df = 2, $P = 0.001$; see Fig. 4); in the larger gillnets, the likelihood of documenting mortality increased for marine invertebrates (2×), marine fish (5×), and marine birds and mammals (4×). This contrasts with derelict nets recovered from reefs in the Northwest Hawaiian Islands, where derelict nets were primarily small pieces of net <10 $m^2$ in size (Donohue et al., 2001).

**Table 4**
Marine mammal species identified in derelict fishing nets recovered from the inland marine waters of Washington. Four species from four families were documented. Status (E – endangered; T – threatened; C – candidate; S – sensitive; RL – red list; BL – blue list; SC – special concern) according to state (WA – Washington), provincial (BC – British Columbia), and federal (USA, Canada) authorities (from Brown and Gaydos (2007)).

| | | Alive | Dead | Status |
|---|---|---|---|---|
| Marine mammal (unid.) | | 0 | 5 | |
| *Phocidae* | | | | |
| Harbor seal | *Phoca vitulina* | 0 | 14 | |
| *Otariidae* | | | | |
| California sea lion | *Zalophus californianus* | 0 | 2 | |
| *Delphinidae* | | | | |
| Harbor porpoise | *Phocoena phocoena* | 0 | 1 | C (WA), BL (BC), SC (Canada) |
| *Mustelidae* | | | | |
| River otter | *Lontra canadensis* | 0 | 1 | |
| Total | | 0 | 23 | |

**Table 5**
Entanglement of marine invertebrates in relation to characteristics of recovered derelict gillnets.

| Net characteristics | Total nets | W/ remains | No remains | $\chi^2$ | df | *P* |
|---|---|---|---|---|---|---|
| *Minimum time derelict* | | | | 4.3 | 2 | 0.1 |
| <1 year | 308 | 184 | 124 | | | |
| 1–6 years | 164 | 82 | 82 | | | |
| 6–24 years | 182 | 99 | 83 | | | |
| *Region* | | | | 10.9 | 2 | 0.004 |
| San Juans/Strait of Juan de Fuca | 503 | 249 | 254 | | | |
| Northern Puget Sound | 241 | 117 | 124 | | | |
| Central/Southern Puget Sound/Hood Canal | 126 | 82 | 44 | | | |
| *Habitat* | | | | 1.3 | 4 | 0.9 |
| High-relief rocky substrate | 363 | 181 | 182 | | | |
| Low-relief rocky substrate | 77 | 42 | 35 | | | |
| Boulders on sand/mud/gravel | 297 | 154 | 143 | | | |
| Mud/sand/gravel/vegetation | 71 | 36 | 35 | | | |
| Underwater obstructions | 62 | 35 | 27 | | | |
| *Size (total area)* | | | | 81.7 | 2 | <0.001 |
| Small (<200 m$^2$) | 303 | 94 | 209 | | | |
| Medium (200–1000 m$^2$) | 273 | 159 | 114 | | | |
| Large (1000–14,000 m$^2$) | 294 | 195 | 99 | | | |
| *Inferred age* | | | | 6.7 | 1 | 0.01 |
| Recent construction | 472 | 262 | 210 | | | |
| Older construction | 398 | 186 | 212 | | | |
| *Condition* | | | | 48.6 | 1 | <0.001 |
| Good | 614 | 363 | 251 | | | |
| Poor | 256 | 85 | 171 | | | |
| *Maximum suspension* | | | | 78.4 | 3 | <0.001 |
| 0 m | 163 | 34 | 129 | | | |
| 0–1 m | 464 | 262 | 202 | | | |
| 1–2 m | 174 | 105 | 69 | | | |
| >2 m | 68 | 46 | 22 | | | |
| *Minimum net depth where recovered* | | | | 1.8 | 2 | 0.4 |
| 0–10 m | 82 | 46 | 36 | | | |
| 10–20 m | 540 | 269 | 271 | | | |
| 20–40 m | 248 | 133 | 115 | | | |

**Table 6**
Entanglement of marine fish in relation to characteristics of recovered derelict gillnets.

| Net characteristics | Total nets | W/ remains | No remains | $\chi^2$ | df | *P* |
|---|---|---|---|---|---|---|
| *Minimum time derelict* | | | | 14.4 | 2 | 0.001 |
| <1 year | 308 | 87 | 221 | | | |
| 1–6 years | 164 | 21 | 143 | | | |
| 6–24 years | 182 | 42 | 140 | | | |
| *Region* | | | | 2.8 | 2 | 0.2 |
| San Juans/Strait of Juan de Fuca | 503 | 130 | 373 | | | |
| Northern Puget Sound | 241 | 49 | 192 | | | |
| Central/Southern Puget Sound/Hood Canal | 126 | 32 | 94 | | | |
| *Habitat* | | | | 3.8 | 4 | 0.4 |
| High-relief rocky substrate | 363 | 83 | 280 | | | |
| Low-relief rocky substrate | 77 | 20 | 57 | | | |
| Boulders on sand/mud/gravel | 297 | 69 | 228 | | | |
| Mud/sand/gravel/vegetation | 71 | 18 | 53 | | | |
| Underwater obstructions | 62 | 21 | 41 | | | |
| *Size (total area)* | | | | 82.6 | 2 | <0.001 |
| Small (<200 m$^2$) | 303 | 26 | 277 | | | |
| Medium (200–1000 m$^2$) | 273 | 66 | 207 | | | |
| Large (1000–14,000 m$^2$) | 294 | 119 | 175 | | | |
| *Inferred age* | | | | 77.7 | 1 | <0.001 |
| Recent construction | 472 | 170 | 302 | | | |
| Older construction | 398 | 41 | 357 | | | |
| *Condition* | | | | 69.7 | 1 | <0.001 |
| Good | 614 | 197 | 417 | | | |
| Poor | 256 | 14 | 242 | | | |
| *Maximum suspension* | | | | 128.6 | 3 | <0.001 |
| 0 m | 163 | 7 | 156 | | | |
| 0–1 m | 464 | 87 | 377 | | | |
| 1–2 m | 174 | 75 | 99 | | | |
| >2 m | 68 | 42 | 26 | | | |
| *Minimum net depth where recovered* | | | | 1.2 | 2 | 0.6 |
| 0–10 m | 82 | 16 | 66 | | | |
| 10–20 m | 540 | 135 | 405 | | | |
| 20–40 m | 248 | 60 | 188 | | | |

Some gillnets recovered appear to be decades old, based on mesh size and construction material; others were nearly new, with little or no algal growth and retaining nearly all of their original breaking strength. Relatively newer nets were more deadly; the likelihood of documenting mortality in newer nets increased for marine invertebrates (3×), marine fish (3.5×) and marine birds and mammals (2.5×). The difference between poor and good condition derelict gillnets was also measurable; the likelihood of documenting mortality in good condition nets increased for marine invertebrates (2×), marine fish (6×) and marine birds and mammals (4×). The growth of epiphytes and epifauna on nets (bio-fouling) has been found to profoundly alter the configuration and catch rates of some nets (Santos et al., 2003), but that may be less of an issue here in Puget Sound. Moreover, nets are likely to continue catching invertebrates (especially crabs) even after vertebrates are no longer caught (Akiyama et al., 2007).

Estimating recruitment rates to the nets and degradation/turnover rates in derelict nets over time is logistically challenging and ethically contentious, due to the risk long-term deployments would pose to a variety of threatened and endangered marine taxa. Short-term experiments have made some progress in estimating these rates for some taxa (NRC, 2008), and observations of derelict

**Table 7**
Entanglement of marine birds and mammals in relation to characteristics of recovered derelict gillnets.

| Net characteristics | Total nets | W/ remains | No remains | $\chi^2$ | df | P |
|---|---|---|---|---|---|---|
| *Minimum time derelict* | | | | 6.3 | 2 | 0.04 |
| <1 year | 308 | 55 | 253 | | | |
| 1–6 years | 164 | 18 | 146 | | | |
| 6–24 years | 182 | 20 | 162 | | | |
| *Region* | | | | 25.8 | 2 | <0.001 |
| San Juans/Strait of Juan de Fuca | 503 | 95 | 408 | | | |
| Northern Puget Sound | 241 | 12 | 229 | | | |
| Central/Southern Puget Sound/Hood Canal | 126 | 22 | 104 | | | |
| *Habitat* | | | | 7.7 | 4 | 0.1 |
| High-relief rocky substrate | 363 | 55 | 308 | | | |
| Low-relief rocky substrate | 77 | 12 | 65 | | | |
| Boulders on sand/mud/gravel | 297 | 34 | 263 | | | |
| Mud/sand/gravel/vegetation | 71 | 13 | 58 | | | |
| Underwater obstructions | 62 | 15 | 47 | | | |
| *Size (total area)* | | | | 47.1 | 2 | <0.001 |
| Small (<200 m$^2$) | 303 | 19 | 284 | | | |
| Medium (200–1000 m$^2$) | 273 | 34 | 239 | | | |
| Large (1000–14,000 m$^2$) | 294 | 76 | 218 | | | |
| *Inferred age* | | | | 28.8 | 1 | <0.001 |
| Recent construction | 472 | 98 | 374 | | | |
| Older construction | 398 | 31 | 367 | | | |
| *Condition* | | | | 29.5 | 1 | <0.001 |
| Good | 614 | 117 | 497 | | | |
| Poor | 256 | 12 | 244 | | | |
| *Maximum suspension* | | | | 127.7 | 3 | <0.001 |
| 0 m | 163 | 3 | 160 | | | |
| 0–1 m | 464 | 43 | 421 | | | |
| 1–2 m | 174 | 48 | 126 | | | |
| >2 m | 68 | 35 | 33 | | | |
| *Minimum net depth where recovered* | | | | 7.7 | 2 | 0.02 |
| 0–10 m | 82 | 15 | 67 | | | |
| 10–20 m | 540 | 66 | 474 | | | |
| 20–40 m | 248 | 48 | 200 | | | |

gillnets draped over a shipwreck in Puget Sound verified the capture of fish, marine birds and invertebrates for over 3 years (High, 1981). Moreover, the tendency of nets in Puget Sound to remain stretched open over long time periods and the piles of bones beneath some nets suggests that rates of entanglement and mortality may not decline to negligible rates. Nets hung up on rocky reefs and underwater obstructions tend to remain stretched open more so than those in open sandy habitats (Akiyama et al., 2007), even during extreme weather events. In the relatively shallow water from which derelict gillnets in our study have been recovered, nets seem not to have lost their effectiveness; rather than being weighed down from accumulated catch, becoming more visible due to caught organisms and bio-fouling, and generally breaking down (Kaiser et al., 1996; Erzini et al., 1997), derelict gillnets in Puget Sound seem to act as magnets to predators and scavengers, maintaining the potential for mortality over time.

Although newer nets appear to have greater diversity and number of species entangled and killed, older nets still have fresh specimens upon recovery. Moreover, visual documentation of nets *in situ* suggests that scouring and/or sedimentation under derelict nets is greater than in adjacent areas; this likely suffocates or eliminates sessile organisms and marine plant growth and prevents access by fish and invertebrates to important habitat features. Finally, derelict gear facilitates the accumulation of additional fishing gear; commercial and sport crab pots and many items associated with sport fishing get entangled in derelict nets, including downrigger balls and wire, lures, hooks, flashers and jigs.

Our results suggest that derelict gillnets may pose a substantial hazard to marine fauna in Puget Sound and the Northwest Straits, as it has been recovered from a variety of benthic habitats, in and around marine protected areas, important marine bird breeding colonies and marine mammal haul-out areas. As with derelict gear elsewhere (Laist, 1996), derelict gillnets captured a diverse assemblage of marine taxa, a number of which are of commercial and conservation concern. Invertebrates are the most numerous victims, no doubt due to their overall abundance in benthic habitats, where most gillnets end up. Sessile invertebrates can settle on nets and be recovered alive; however, those recorded dead have largely been entangled in nets draped directly on them while they are open and feeding.

Many invertebrate scavengers (crabs, sunflower stars) are numerous in recovered gillnets and are likely drawn to the nets as they accumulate dead animals, and some scavengers, in turn, become entangled (Kaiser et al., 1996). Although many species are scavengers drawn to derelict gillnets, more than 40 species of marine invertebrate were recovered dead, and these crustacean and mollusk taxa often dominate derelict gear as time under water increases (Puente et al., 2001). In Puget Sound, sunflower stars (*Pycnopodia helianthoides*) are the most commonly observed scavengers on and under gillnets, but they are rarely entangled, and are often returned alive. Dungeness crabs (*C. magister*) often become entangled in derelict nets, where they can survive long periods without being fully mobile; even given this survival advantage over vertebrates, 50% of Dungeness crabs recovered from gillnets were dead. Derelict nets can entangle crabs even after tearing free of obstructions and balling up on the ocean floor (High, 1981). Mortality of entangled crustaceans and gastropods can be overestimated if escape from nets is possible (Akiyama et al., 2007); however, most Dungeness and red rock crabs are so entangled that they have to be cut from nets (J. June, pers. obs.), and underestimation due to degradation and turnover of specimens prior to documentation in the net (NRC, 2008) likely offsets this. While crab mortality from derelict gillnets is small relative to the tens of thousands of crabs killed annually by derelict crab pots (NRC, 2003), the numbers documented here are not insubstantial.

Gillnets are especially lethal for marine fish, as nets are designed specifically for catching and killing them. Studies of derelict gear in various depths are usually dominated by target and non-target fish taxa (Kaiser et al., 1996; Erzini et al., 1997; Puente et al., 2001; Humborstad et al., 2003; Santos et al., 2003; Sancho et al., 2003), although abundant benthic and scavenging species such as spiny dogfish can be especially vulnerable (Carr et al., 1985). In our study, almost all fish were recovered dead from derelict nets; as degradation can occur over days to weeks and fall-out rates of bones and decomposing animals can be upwards of 40% during recovery (NRC, 2008), the number and species diversity of fishes affected may be much greater than we have estimated. In fact, in the deeper parts of Puget Sound (i.e., >50 m), ghost-fishing gillnets likely degrade more slowly and accumulate fouling organisms more slowly; thus, the capture of target species may continue for long periods (Breen, 1990).

Gillnets are also deadly for marine birds and mammals, which must periodically surface to breathe air. Diving birds and marine mammals appear to fall prey to nets while pursuing fish underwater; some of the forage fish and smaller fish species aggregate in and under the relative safety of the netting, which results in entanglement of their predators. For marine birds, marine debris-related mortality increased substantially at the end of the 20th century

(Tasker et al., 2000). It is difficult to assess the biological impacts of derelict gear, beyond reporting the breadth and extent of documented and identified individuals caught in the net, without detailed distribution and abundance data for all marine bird and mammal taxa. Still, "back-of-the-envelope" estimates of the potential mortality to upper trophic levels in the Puget Sound ecosystem from derelict gear are sobering. Expanding from the absolute minimum mortality documented in this study by monthly turnover of carcasses in nets (NRC, 2008), a 13% rate of carcass drop-out during net recovery (NRC, 2008), and the calculated time gillnets were derelict in the marine environment, upwards of 450,000 marine invertebrates, 12,000 fish, 12,000 marine birds, and 400 marine mammals may have been killed by the 870 nets recovered as part of this study. These estimates do not include the estimated 3000+ nets still out in the marine environment of Puget Sound and the Northwest Straits.

For marine mammals, marine debris-related mortality is likely important but requires closer examination in particular situations. Where that has been done, e.g., with Hawaiian monk seals, there is a greater understanding of how local, regional and ocean basin-wide factors contribute to their entanglement, mortality, and population dynamics (Donohue and Foley, 2007). As we increase the numbers of studies into this issue globally, we will no doubt suggest that the problem may have worsened in many areas.

To our knowledge, no other derelict gear recovery program rivals the extent and scope of marine taxa (at least 32,000 individuals of at least 117 species) that we have documented entangled and killed by derelict fishing nets in Puget Sound. In addition to commercially important Dungeness crab and several salmon and rockfish (*Sebastes* spp.) species that are of conservation concern in the United States and/or Canada, almost half of the identified marine birds documented are the very species (scoters (*Melanitta* spp.), loons (*Gavia* spp.), grebes (*Aechmophorus* spp. and *Podiceps grisegena*)) whose wintering populations have been declining in Puget Sound (Nysewander et al., 2005). In the Pearl and Hermes Atoll reefs in the Hawaiian Islands, by contrast, a small number of marine invertebrate taxa (13 species) and fish (10 species) as well as endangered Hawaiian monk seals have been documented in many tons of recovered trawl nets (Donohue et al., 2001). Our efforts have documented double that number of fish species. In Australia, while animals recorded in derelict nets include juvenile hawksbill turtles (*Eretmochelys imbricata*), catfish (*Arius* sp.), triggerfish (Balistidae) and shark (*Carcharhinus* sp.; White 2006), the breadth of species is a fraction of what we have documented. Gill and trammel net experiments in Portugal documented seven species of invertebrates and 32 species of marine fishes and no seabirds, reptiles or mammals (Erzini et al., 1997). Other studies have documented only handfuls of fish species (Humborstad et al., 2003; Sancho et al., 2003; Santos et al., 2003; Akiyama et al., 2007).

The overall goals of any derelict fishing gear program include assessing the extent of the derelict fishing gear damage to marine organisms and ecosystems and to identify possible remedies. The Northwest Straits Initiative's Derelict Fishing Gear Assessment, Recovery, Training and Outreach Program will continue to quantify and understand the loss and abandonment of fishing gear, recover and dispose of existing derelict fishing gear, and prevent derelict fishing gear through outreach efforts. Commercial net fishing effort has been significantly reduced in recent years due to endangered species protection and reduction in target salmon species abundance. Net fishing communities also have and make use of modern navigation and electronic charting capabilities that help avoid net loss. Combined with the "no-fault" lost gear reporting system, future net loss should be minimal and net recovery almost immediate, which will reduce overall impacts of derelict nets on the marine environment. The largest challenge is finding and removing the legacy gear – lost nets accumulated over the past 50+ years of net fishing in inland Washington waters. These efforts will benefit the Puget Sound marine ecosystem by reducing the level to which marine debris is a threat, and they will benefit society by reducing risks to human health, safety and navigation by facilitating the removal and reduction of derelict gear in nearshore marine environments. Finally, these efforts will highlight the continuing problem of discarded fishing gear and marine debris, which threatens our global oceans.

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## References

Akiyama, S., Saito, E., Watanabe, T., 2007. Relationship between soak time and number of enmeshed animals in experimentally lost gill nets. Fisheries Science 73, 881–888.

APEC (Asia-Pacific Economic Cooperation), 2004. Derelict Fishing Gear and Related Marine Debris: An Educational Outreach Seminar Among APEC Partners. Seminar Report, 13–16 January 2004, Honolulu, HI [APEC#204-FS-04.2].

Boland, R.C., Donohue, M.J., 2003. Marine debris accumulation in the nearshore marine habitat of the endangered Hawaiian monk seal, *Monachus schauinslandi* 1999–2001. Marine Pollution Bulletin 46 (11), 1385–1394.

Breen, P.A., 1990. Report of the working group on ghost fishing. In: Shomura, R.S., Godfrey, M.L. (Eds.), Proceedings of the Second International Conference on Marine Debris, NOAA Technical Memorandum NMFS-TM-NMFS-SWFSC-154, pp. 571–599.

Brown, N.A., Gaydos, J.K., 2007. Species of concern in the Puget Sound – Georgia Basin: changes from 2002 to 2006. In: Proceedings of the 2007 Georgia Basin Puget Sound Research Conference. Vancouver, British Columbia.

Carr, H.A., Amaral, E.A., Hulbert, A.W., Cooper, R., 1985. Underwater survey of simulated lost demersal and lost commercial gill nets off New England. In: Shomura, R.S., Godfrey, M.L. (Eds.), Proceedings of Workshop on the Fate and Impact of Marine Debris, NOAA Technical Memorandum NMFS-TM-NMFS-SWFSC-54, pp. 438–447.

Carr, A., 1987. Impact of non-degradable marine debris on the ecology and survival outlook of sea turtles. Marine Pollution Bulletin 18, 352–357.

Dameron, O.J., Parke, M., Albins, M.A., Brainard, R., 2007. Marine debris accumulation in the Northwestern Hawaiian Islands: an examination of rates and processes. Marine Pollution Bulletin 54 (4), 423–433.

Donohue, M.J., Boland, R.C., Sramek, C.M., Antonelis, G.A., 2001. Derelict fishing gear in the Northwestern Hawaiian Islands: diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. Marine Pollution Bulletin 42 (12), 1301–1312.

Donohue, M.J., Foley, D.G., 2007. Remote sensing reveals links among the endangered Hawaiian Monk Seal, marine debris, and El Niño. Marine Mammal Science 23 (2), 468–473.

Erzini, K., Monteiro, C.C., Ribeiro, J., Santos, M.N., Gaspar, M., Monteiro, P., Borges, T.C., 1997. An experimental study of gill net and trammel net 'ghost-fishing' off the Algarve (southern Portugal). Marine Ecology Progress Series 158, 257–265.

High, W., 1981. Wreck-netters capture more fish than they know. National Fisherman 62 (7), 122.

Hofmeyr, G.J.G., Bester, M.N., De Maine, M., Kirkman, S.P., Pistorius, P.A., Makhado, A.B., 2002. Entanglement of pinnipeds at Marion Island, 1991–2001. Australian Mammalogy 24, 141–146.

Humborstad, O.-B., Løkkeborg, S., Hareide, N.-R., Furevik, D.M., 2003. Catches of Greenland halibut (*Reinhardtius hippoglossoides*) in deepwater ghost fishing gillnets on the Norwegian continental slope. Fisheries Research 64, 163–170.

Kaiser, M.J., Bullimore, B., Newman, P., Lock, K., Gilbert, S., 1996. Catches in 'ghost-fishing' set nets. Marine Ecology Progress Series 145, 11–16.

Laist, D.W., 1996. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement an ingestion records. In: Coe, J.M., Rogers, D.R. (Eds.), Marine Debris Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 99–139.

Macfadyen, G., Huntington, T., Cappell, R., 2009. Abandoned, lost or otherwise discarded fishing gear. UNEP Regional Seas Reports and Studies, No. 185; FAO Fisheries and Aquaculture Technical Paper, No. 523. UNEP/FAO, Rome, 115p.

Matsuoka, T., Nakashima, T., Nagasawa, N., 2005. A review of ghost fishing: scientific approaches to evaluation and solutions. Fisheries Science 71 (4), 691–702.

Morton, B., 2005. Fishing perturbations and beached corals in the Cape d'Aguilar Marine Reserve, Hong Kong (2000–2002) and a summary of data obtained from January 1996 to March 2003. Marine Pollution Bulletin 50, 1273–1286.

Nakashima, T., Matsuoka, T., 2005. Ghost fishing mortality and fish aggregation by lost bottom-gillnet tangled around fish aggregation device. Nippon Suisan Gakkaishi 71, 178–187.

NRC (Natural Resources Consultants), 2003. Derelict fishing gear identification and retrieval project: Port Susan. Prepared for Stillaguamish Tribe by Natural Resources Consultants, Inc., 32p.

NRC (Natural Resources Consultants), 2004a. Derelict fishing gear removal project: NOAA Community Restoration Program/Salmon Recovery Funding Board – Lopez Island. Prepared for Northwest Straits Foundation by Natural Resources Consultants, Inc., 11p.

NRC (Natural Resources Consultants), 2004b. Derelict fishing gear removal project: Greystone Foundation. Prepared for Northwest Straits Foundation by Natural Resources Consultants, Inc., 41p.

NRC (Natural Resources Consultants), 2008. Rates of marine species mortality caused by derelict fishing nets in Puget Sound, Washington. Prepared for the Northwest Straits Initiative by Natural Resources Consultants, Inc. <http://www.derelictgear.org/uploads/Images/Derelict_Gear/DG%20Reports/DG-MortalityRates.pdf>.

NWSC (Northwest Straits Commission), 2008. Derelict Gear Removal – Program Accomplishments. <http://www.derelictgear.org/Progress-/27.aspx>.

NWSF (Northwest Straits Foundation), 2007. Derelict fishing gear priority ranking project. Prepared by the Northwest Straits Foundation, Mt. Vernon, 40p.

Nysewander, D.R., Evenson, J.R., Murphie, B.L., Cyra, T.A., 2005. Report of marine bird and mammal component, Puget Sound Ambient Monitoring Program for July 1992 to December 1999. Prepared for Washington Department of Fish and Wildlife and Puget Sound Action Team. Washington Department of Fish and Wildlife, 194p.

Page, B., McKenzie, J., McIntosh, R., Baylis, A., Morrisey, A., Calvert, N., Haase, T., Berries, M., Dowie, D., Shaughnessy, P.D., Goldsworthy, S.D., 2004. Entanglement of Australian sea lion and New Zealand fur seals in lost fishing gear and other marine debris before and after government and industry attempts to reduce the problem. Marine Pollution Bulletin 49, 33–42.

Piatt, J.F., Nettleship, D.N., 1987. Incidental catch of marine birds and mammals in fishing nets off Newfoundland, Canada. Marine Pollution Bulletin 18, 344–349.

PFMC (Pacific Fisheries Management Council), 2008. Historical Data of Ocean Salmon Fisheries: Escapements to Inland Fisheries and Spawning Areas (Appendix B). <http://www.pcouncil.org/salmon/salbluebook/salbluebook.html>.

PSP (Puget Sound Partnership), 2008. Puget Sound Action Agenda: Protecting and Restoring the Puget Sound Ecosystem by 2020. Puget Sound Partnership, 207p.

Puente, E., Arregi, L., Gomez, E., Sancho, G., 2001. An experimental approach to study the effects of lost static fishing gear on the Bay of Biscay benthic communities: FANTARED-2. ICES CM 2001/R:04.

Sancho, G., Puente, E., Bilbao, A., Gomez, E., Arregi, L., 2003. Catch rates of monkfish (*Lophius* spp.) by lost tangle nets in the Cantabrian Sea (northern Spain). Fisheries Research 64, 129–139.

Santos, M.N., Saldanha, H.J., Gasper, M.B., Monteiro, C.C., 2003. Hake (*Merluccius merluccius* L., 1758) ghost fishing by gill nets off the Algarve (southern Portugal). Fisheries Research 64, 119–128.

Schrey, E., Vauk, G.J.M., 1987. Records of entangled gannets (*Sula bassana*) at Helgoland, German Bight. Marine Pollution Bulletin 18, 350–352.

Stewart, B.S., Yochem, P.K., 1987. Entanglement of pinnipeds in synthetic debris and fishing net and line fragments at San Nicolas and San Miguel Islands, California. Marine Pollution Bulletin 18, 336–339.

SYSTAT, 2007. Statistics I and II. Version 12. SPSS, Inc., Chicago.

Tasker, M.L., Camphuysen, C.J., Cooper, J., Garthe, S., Montevecchi, W.A., Blaber, S.J.M., 2000. The impacts of fishing on marine birds. ICES Journal of Marine Science 57, 531–547.

UNEP (United Nations Environment Program). 2005. UNEP regional seas programme, marine litter and abandoned fishing gear. Report to the Division of Ocean Affairs and the Law of the Sea, Office of Legal Affairs, United Nations Headquarters by the Regional Seas Coordinating Office, United Nations Environment Program, Nairobi, 30p.

USOAP (US Ocean Action Plan), 2004. US Ocean Action Plan: the Bush Administration's Response to the US Commission on Ocean Policy Report, 39p.

USCOP (US Commission on Ocean Policy), 2004. An Ocean Blueprint for the 21st Century. Final Report, Washington, DC, 676p.

Volgenau, L., Kraus, S.D., Lien, J., 1995. The impact of entanglements on two substocks of the western North Atlantic humpback whale, *Megaptera novaeangliae*. Canadian Journal of Zoology 73, 1689–1698.

White, D., 2006. Marine Debris in Northern Territory Waters 2004. World Wildlife Report, WWF-Australia, Sydney, 38p.