Marine Pollution Bulletin 60 (2010) 376–382

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Marine species mortality in derelict fishing nets in Puget Sound, WA and the cost/benefits of derelict net removal

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ARTICLE INFO

Keywords:
Puget Sound
Ghost fishing
Net
Mortality
Cost/benefit

ABSTRACT

Derelict fishing gear persists for decades and impacts marine species and underwater habitats. Agencies and organizations are removing significant amounts of derelict gear from marine waters in the United States. Using data collected from repeated survey dives on derelict gillnets in Puget Sound, Washington, we estimated the daily catch rate of a given derelict gillnet, and developed a model to predict expected total mortality caused by a given net based on entanglement data collected upon its removal. We also generated a cost:benefit ratio for derelict gear removal utilizing known true costs compared to known market values of the resources benefiting from derelict gear removal. For one study net, we calculated 4368 crab entangled during the impact lifetime of the net, at a loss of $19,656 of Dungeness crab to the commercial fishery, compared to $1358 in costs to remove a given gillnet, yielding a cost:benefit ratio of 1:14.5.

1. Introduction

Derelict fishing gear is accidentally lost or intentionally discarded or abandoned fishing lines, nets, pots, traps, or other gear associated with commercial or recreational fishing. Much of this equipment is made of synthetic materials that do not degrade in the ocean environment and has been found to persist for decades. Derelict gear damages the marine ecosystem in different ways, directly and indirectly (Dayton et al., 1995). It also causes damage to vessels and vessel equipment. Derelict nets artificially modify seafloor and rocky reefs, altering the natural rugosity and/or hardness of a reef, obstructing crevices, enshrouding ledges, causing abnormal scouring of the seabed, and entrapping fine sediment that suffocates plants and animals thereby affecting the complexity of microhabitats available for the diversity of animal, plant and algal communities living on the seafloor. Boat propellers catch ropes attached to lost traps and pots or discarded monofilament line, and abandoned gear clutters fishing grounds, impeding fishermen's ability to safely and efficiently deploy their own gear and in some cases causing more gear loss.

Hundreds of marine species have been reported to be affected by fishing gear entanglement and ingestion (Laist, 1996), which has been identified as a major cause of morbidity and mortality in some populations (Fowler, 1987; Stewart and Yochem, 1987; Nakajima, 1990; Page et al., 2004). Fishing line and hooks, ropes, or net fragments entangle and wound animals, restricting movement or foraging ability (Laist, 1987; Arnould and Croxall, 1995; Goldstein et al., 1999; Hanni and Pyle, 2000; Tasker et al., 2000; Zabka et al., 2006). In the Northwest Hawaiian Islands, an estimated 52 tons of derelict fishing gear accumulate annually (Dameron et al., 2007) and derelict gear is thought to be the largest anthropogenic threat to the endangered Hawaiian monk seal (Boland and Donohue, 2003): indeed, annual rates of entanglement in fishing gear ranged from 4% to 78% of the total estimated population of 1300 in recent surveys (Donohue and Foley, 2007). In California, nearly 10% of brown pelicans and gull species treated at marine wildlife rehabilitation centers are admitted due to fishing gear entanglement or ingestion injuries (Dau et al., 2009). Reports of derelict fishing gear impacts on marine resources are not limited to mammals and birds: Tanner crabs (Stevens et al., 2000), corals in the Northwestern Hawaiian Islands (Donohue et al., 2001), sponges, corals and other colonial sessile organisms in the Florida keys (Chiappone et al., 2002), and octopus in Japan (Matsuoka et al., 2005) have been shown to suffer significant mortality due

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doi:10.1016/j.marpolbul.2009.10.016

to entrapment or entanglement in derelict fishing gear. Several studies have been conducted to quantify the impact of derelict fishing gear on marine resources around the world, and models have been developed for predicting total impacts of derelict gear on select resources (Matsuoka et al., 2005).

In order to reduce the threat that derelict fishing gear poses to marine life and underwater habitats, federal and state agencies and organizations are removing significant amounts of derelict fishing gear from marine waters in the United States. In the Northwestern Hawaiian Islands), 579 metric tons of derelict gear have been removed since 1998 through the combined efforts of state and federal agencies. In California, more than 14 tons of fishing gear have been removed since May 2006, including over 1 million feet of fishing line recovered from public fishing piers. And in Washington State over 85 tons of derelict gear, primarily crab pots and gill nets, have been removed from Puget Sound since 2002.

A significant outlay of funds is required for surveys, removal operations, disposal, and reporting of derelict gear. Costs are justified by the direct fiscal benefits of derelict fishing gear removal, which can be conservatively estimated by measuring the value of commercially valuable resources that would otherwise be lost to the fishery due to entanglement or entrapment in derelict fishing gear. Such estimates must take into account the rate of loss of such species in derelict gear, the effective impact lifespan of the gear, and the market value of the species impacted by the gear. Other benefits that are more difficult to measure directly include reducing hazards to non-commercial species, such as protected species, which can be grossly estimated by assigning a contingent valuation based on the comparative cost of benefitting that species via another mitigation method for ameliorating damage to marine wildlife (e.g., oiled wildlife rehabilitation).

To date, a quantitative assessment of the direct impact of derelict fishing gear on marine resources has not been conducted in Puget Sound, WA. Such data, as well as a predictive model that would allow for estimating total mortality of marine life due to derelict gear in Puget Sound, is critical for continuing to garner industry, governmental and public support for derelict fishing gear removal. As well, an assessment of the costs of gear removal relative to the direct fiscal benefits resulting from the removal of hazards to harvestable resources could strengthen the basis for selection of derelict fishing gear removal as a mitigation strategy from among other available mitigation measures.

The objectives of this study were to use data collected from repeated survey dives on derelict nets slated for removal to estimate the daily catch rate of a given derelict gillnet in Puget Sound, and then to develop a model that enables prediction of expected total mortality caused by a given derelict net based on entanglement data collected from the net upon its removal. We also aimed to generate a cost:benefit ratio for derelict gear removal utilizing known true costs compared to known market values of the resources benefiting from removal of the hazard.

2. Methods

2.1. Data collection

Four nets were selected non-randomly from the Washington Department of Fish and Wildlife's derelict fishing gear database (Table 1). Each net had been previously located by sidescan sonar at a depth accessible by standard surface supplied air diving but had not yet been surveyed by divers, and was located in the Northwest Straits region of Puget Sound, for ease of access from our port of embarkation in Anacortes, WA. All four nets were caught on rocky reef or sand/boulder seafloor habitat. To take advantage of optimal ocean conditions for diving, all nets were surveyed in late spring through late summer. One net (#3969) was surveyed five times at 3–14 day intervals over the course of 4 weeks in May–June 2007; two nets (#3957 and 3971) were surveyed three times at 3–4 day intervals over a 1-week period in August 2007; and a fourth net (#4564) was surveyed three times at 3–5 day intervals over a 1-week period in September 2007.

On each survey, two surface supplied air divers, equipped with underwater two-way radios that allowed for communications with project personnel on deck, surveyed each net for 20–45 min, depending upon the size of the net. The same two divers conducted all dive surveys. On the initial dive, divers attached a stainless-steel clip with an individually-numbered plastic tag (13.5 cm disk™, Floy Tag & Mfg Inc., Seattle, WA) to the net next to each entangled animal observed. The diver reported via radio to deck-based personnel the tag number, common name of the entangled animal, and a description of its condition as either FL (fresh live), FD (fresh dead), rotten/partially decomposed (R/PD), bones or shell parts (B/SP) or completely gone (CG) (the latter descriptor used on dives subsequent to the initial). To determine entanglements and decomposition rates for each net, on each subsequent dive the divers followed these same procedures, recording the condition of any previously observed entanglements and marking and describing any new entanglements that had occurred since the previous dive. The presence of predators at or near the entangled animal (e.g., sunflower stars (*Pycnopodia helianthoides*)) was noted. All nets were removed immediately after the final surveys by the divers, who detached the net from the substrate using hand-held cutting instruments, sectioned the net into manageable bundles, and attached lift bags to the bundled sections to raise them to the surface. Removed nets were surveyed again on deck by project personnel, who recorded all entangled species and carcass conditions, noting each identifier number according to the clipped tag.

2.2. Data analysis

Entanglement rates (# of entangled animals/day/net) were calculated by taxa (invertebrates, fish, or birds) by counting the number of animals newly entangled between surveys and dividing by the number of days between observations. Entangled animals

Table 1
Study nets. Locations in Puget Sound, type and dimensions of nets, survey dates, and survey intervals (days since previous dive), SI.

Net identifier	Net #3969	Net #3957	Net #3971	Net #4564
Location (lat/long)	Lopez Island 48°25.00 N 122°50.54 W	San Juan Island 48°27.45 N 123°02.16 W	San Juan Island 48°26.97 N 123°00.28 W	Point Roberts 48°57.53 N 122°58.75 W
Habitat type	Rocky reef	Rocky reef	Boulders/sand	Boulders/sand
Dimension: $L \times W$ (ft)	1000×60	300×50	1000×80	150×3
Minimum depth (ft)	52	57	41	33
Initial survey (date)	5/24/07	8/15/07	8/15/07	9/5/07
2nd survey date (SI)	6/8/07 (15.0)	8/18/07 (3)	8/18/07 (3)	9/7/07 (2.2)
3rd survey date (SI)	6/11/07 (3.2)	8/23/07 (5.0)	8/23/07 (5)	9/12/07 (4.8)
4th survey date (SI)	6/15/07 (3.8)	n/a	n/a	n/a
5th survey date (SI)	6/21/07 (6.0)	n/a	n/a	n/a

marked on initial surveys were included in calculations of total numbers of entangled animals observed during the study, but not included in calculating entanglement rates. Time to decomposition was defined as the time until an individual animal was classified as ''completely gone'' on any subsequent survey dive after the initial observation. Data from animals initially observed on the last survey dive were excluded from decomposition time analysis, as were animals with missing data due to tag loss. ''Drop out'' rates, or the rate of loss of entanglements during the net removal process, were calculated by subtracting the total number of entanglements observed in a removed net on deck from the total number of entanglements observed in the net on the final survey just prior to net removal.

2.3. Model development

A Poisson regression model was developed to estimate daily catch rates (λ) for each taxonomic group separately. The model was extended to include a cluster effect term to account for the possibility that a particular net might catch more of one type of organism than another (intranet correlation), i.e., if a fish was caught in a given net, it is possible that the net was more likely to catch another fish than a bird. Model fit was determined using the Wald chi-square statistic, based on log pseudo-likelihoods for robust standard errors.

$$\ln \lambda_j = \beta_0 + \beta_{\text{bird}} X_{\text{bird}} + \beta_{\text{fish}} X_{\text{fish}} + A_j$$

for j = invertebrates, seabirds or fish, i = cluster or net, and where β_o is the contribution of the reference group, invertebrates, β_{bird} is the contribution of seabirds, β_{fish} is the contribution of fishes and A_i is the cluster effect error term. A_i is assumed to have a mean of zero and therefore does not directly contribute to the estimate of catch rate, only to the variance. Catches within the same net may be statistically correlated and therefore standard methods without this cluster error term would underestimate error terms for estimated catch rates. The decomposition data was fitted to an exponential distribution without additional covariates, producing one model with only an intercept term. The intercept term of an exponential distribution is also called the hazard function and the hazard rate (number of events per time period) is calculated by exponentiating the intercept term. For an exponential distribution, the mean value for the distribution can be found by taking the inverse of the hazard rate, and we used this property of the exponential distribution to find the mean decomposition time for animals caught in a net:

$$h(t|\mathbf{x}_j = \exp(\beta_0) = \varphi \text{ (hazard rate)}$$

$$\mu(\text{mean decomposition time}) = \varphi^{-1}$$

Decomposition time followed an exponential distribution only when data for all three taxonomic groups were combined; therefore a single estimate of decomposition time was calculated. Our estimates for daily catch rate and mean decomposition time were then used to calculate the number of animals one would expect to observe in a given net at a single point in time, based on the number and types of observed entanglements. For a given time interval, the probability that an animal would be observed in the net was the probability that it arrived in that interval ($\lambda\Delta t$) multiplied by the probability that it remained to the end of that interval ($P[S > k\Delta t]$), where k is the interval, λ is the incident catch rate and Δt is the time span of the interval:

$$P = \sum (\lambda\Delta t) \times P[S > k\Delta t] \quad \text{for } k = 1 \text{ to } k = \infty$$

In the limiting case, as the interval k approached ∞, the expected number of animals in a net converges to the incident catch rate (λ) multiplied by the mean decomposition time (μ). Similarly, the expected number of animals in derelict gear was treated as prevalence of animals caught in a net and calculated using the epidemiological equation:

$$\text{Prevalence} = \text{Incidence} \times \text{Duration}$$

where incidence was the incident catch rate for that taxonomic group (λ_j from the Poisson regression) and duration the average length of time the animal spent in the net (μ from the exponential distribution), so that:

$$\text{Expected } \#_j = \lambda_j \times \mu$$

for j = invertebrate, seabird or fish. The same equation was used as a predictive model to estimate the daily catch rate (Λ_j) of a net using the number of animals observed in the net and the mean decomposition time.

$$\Lambda_j = \text{Observed } \#_j/\mu = \text{daily catch rate, where}$$
$$j = \text{invertebrates, seabirds or fish}$$

Therefore, to determine total number of animals caught (total mortality) over the number of days the net was derelict (time):

$$\Lambda_j \times \text{time} = \text{total mortality}$$

Standard errors for the expected number of animals in a net were calculated using log transformation {log(expected#) = log(λ) + - log(μ)} and addition of variances for λ and μ. Covariance terms were not included in the standard error calculations for expected number of animals because the incident catch rate and mean decomposition time were determined to be independent using Spearman's rank correlation coefficient (P = 0.2012). All statistical analyses were performed in STATA 10.0 (STATA, College Station, TX).

2.4. Cost/benefit analysis

For all cost and benefit analyses, we used 2007 dollars as the baseline for comparison, adjusting for inflation using the Bureau of Economic Analysis Gross Domestic Product Implicit Price Deflator (http://research.stlouisfed.org/fred2/data/GDPDEF.txt).

We calculated actual costs incurred in locating and removing derelict nets over a 4-year period between 2004 and 2007. Costs were calculated per derelict net, per operational day. An operational day included costs for: surveys (sidescan sonar, diver); vessel platform; dive removal operations, unloading and disposal of derelict fishing gear; and estimates for field operations planning, notification of jurisdictional agencies, onboard data collection, storage and repatriation of derelict gear to owners, disposal fees, and final report preparation. Benefits of derelict fishing gear removal for commercially harvested species were calculated according to the average ex-vessel value of Dungeness crab (*Cancer magister*) over a 4-year period spanning four seasons, 2004–2007. Benefit estimates were based on the value of adult animals (males and females) without adjusting for reproductive potential to populations or natural mortality rates. In order to simplify our analysis, we assumed that all Dungeness crab not caught in derelict fishing gear would be caught by the commercial fishery. This was a reasonable assumption, given that the Washington state Dungeness crab fishery is regulated by size, sex, and season, with quotas set for fisherman based on expected Dungeness crab population levels (Howard, 2008): crab not caught in derelict gear would be available to catch in the same or next seasons, and/or contribute to population grown and therefore higher quotas. There are clearly additional benefits of derelict net removal beyond Dungeness crab value, such as reduced mortality of fish, mammals, birds and other invertebrates and improved habitat quality. However, it is currently difficult to monetarily calculate those benefits, so they are not included as part of the analysis.

3. Results

3.1. Net mortality

A total of 215 animals were observed entangled in the four gillnets during the study period: 158 invertebrates, 24 fish and 33 birds (Table 2). No entangled marine mammals were observed.

Entanglement rates were calculated by taxa (Table 3). Average rates of entanglement throughout the survey period for each net varied among nets and across taxa, from zero fish observed entangled in net #3957 over a 1-week period, to a high of 7.5 invertebrates/day entangled in #4564 over a 1-week period. The average number of invertebrates entangled per day in all four nets combined was 3.06 (SD = 4.57, 95% CI: 2.97–3.15); the average number of fish entangled per day in all four nets combined was 0.42 (SD = 0.76, 95% CI: 0.41–0.43); and the average number of birds entangled per day in all four nets combined was 0.21 (SD = 0.26, 95% CI: 0.19–0.21). Mean time to complete decomposition for all animals caught in derelict fishing nets was 16.8 days (95% CI: 13.2–21.4 days).

Twenty-four of 139 animals (17.3%) were lost during net recovery following the final survey dive. Drop-out percentages varied by taxonomic group: 13.3% (14/100) of invertebrates, 31.6% of fish (6/19), and 21.1% (4/19) of seabirds were lost in the process of raising the derelict net from the seafloor to the sea surface.

3.2. Predictive model

A total of 132 incident animal observations were used in the Poisson regression model (total entanglements observed, $n = 215$, less the number observed on initial dives on all four nets, $n = 83$). Mean incident catch rates (95% CI) for invertebrates, seabirds and fish with robust standard errors adjusted for correlation within net were 2.119 (0.5734, 7.8328), 0.196 (0.0524, 0.7347) and 0.275 (0.0599, 1.2608), respectively (Table 4). The Poisson regression analysis produced adequate fit (Wald χ^2 (2) = 9.97, $P = 0.0092$). Expected number of animals observed in a net was then calculated for each group using the previous estimates (Table 5).

Table 2
Entanglements in study nets. Species, total # observed in all surveys in all nets.

Invertebrates	
Dungeness crab (*Cancer magister*)	30
Golfball crab (*Rhinolithodes wosnessenski*)	8
Green sea urchin (*Strongylocentrus droebachiensis*)	1
Hermit crab (*Paguridae* spp.)	1
Longhorn decorator crab (*Eualus avinus*)	1
Northern abalone (*Haliotis kamtschatkana*)	1
Northern kelp crab (*Pugettia producta*)	2
Puget Sound king crab (*Lopholithodes mandtii*)	5
Red rock crab (*Cancer productus*)	108
Red sea urchin (*Strongylocentrotus franciscanus*)	1
Fish	
Kelp greenling (*Hexagrammos decagrammus*)	3
Lingcod (*Ophiodon elongatus*)	3
Spiny dogfish shark (*Squalus acanthias*)	7
Spotted ratfish (*Hydrolagus colliei*)	3
Unidentified species	8
Birds	
Common loon (*Gavia immer*)	2
Unidentified grebe species (*Podicipedidae* sp.)	2
Unidentified cormorant species (*Phalacrocoriacidae* sp.)	29

3.3. Cost/benefit analysis

Between 2004 and 2007, we conducted 39 days of diver surveys and located 178 derelict nets, at a total approximate cost of $98,763; average costs for conducting surveys was $2532/day, or $555/net located (Table 6). Over this same time period, we conducted 132.5 days of derelict net *removal*, recovering 604 nets, at a total approximate cost of $484,714; average costs for conducting removal was $3658/day, or $803/net. Therefore, the average cost of finding and recovering a derelict net in the inland waters of Washington State was $1358/net.

In order to determine the economic benefit of derelict fishing gear removal as a marine ecosystem restoration tool, we compared the US $ value of commercially harvested Dungeness crab that would otherwise be lost due to entanglement or entrapment in derelict nets, to the $1358/net it cost to conduct derelict net surveys and removal during this 4-year time period.

To do so, we needed to estimate total mortality of a given net, which requires an assessment of the lifespan of that net as derelict. In most cases, it is very difficult to estimate the age of derelict nets in Puget Sound: many of the nets are believed to have been lost during the peak of the gillnet fishery in the 1970s and 1980s. For the purposes of our analysis, we conservatively estimated an average effective age of 10 years for derelict nets encountered.

One of the nets assessed in this study (#4564) was observed on the final survey with 20 entangled Dungeness crab. Based on our predictive model, the daily catch rate for net #4564 was:

$$\text{Daily catch rate} = \Lambda = 20/16.8 = 1.2\,\text{crabs/day}$$

$$\begin{aligned}\text{Total mortality} &= \Lambda \times \text{time} \\ &= 1.2\,\textit{crabs/day} \times 3640\,\textit{days} = 4368\,\textit{crab}\end{aligned}$$

In our experience, the average weight of Dungeness crab recovered from derelict gear can be conservatively estimated at 2 lbs. Therefore, net #4564 may have consumed 8736 lbs of Dungeness crab in its lifespan as a derelict net. The average ex-vessel value of Dungeness crab in Washington in 2004–2007, adjusted for inflation to 2007 as a base year for comparison, was $2.25/lb (Washington State Department of Fish and Wildlife). Therefore derelict net #4564 may have resulted in the loss of up to $19,656 worth of Dungeness crab to the commercial fishery. The cost–benefit ratio for recovery of net #4564 recovery was $1358:$19,656 or 1:14.5.

4. Discussion

In this study, we estimated for the first time the daily catch rates of derelict fishing nets in Washington, and developed a predictive model to estimate catch rates of nets recovered in the future, based on the number of animals observed in the net on recovery, the mean decomposition time of animals caught in a derelict net, and an estimate of the age of the net. The novel methods developed here eliminate the need for surveys conducted by divers at the time of net removal.

To illustrate the application of this model to a hypothetical situation: imagine that resource managers receive a report from a commercial fisherman that a gillnet was lost at a particular location in Puget Sound. Four months (120 days) later, divers are deployed to remove that net, and once the net is on deck, 17 Dungeness crab are documented as entangled. First, the true number of animals caught in the net at the time of removal can be estimated using the dropout rate for invertebrates. The estimated dropout rate for invertebrates in our study was 13.3%; therefore, the animals observed on deck represent 86.7% of the animals present in the net prior to removal. The actual number of crabs in the net before it was recovered to the surface can then be calculated:

Table 3
Entanglements in study nets. Number of entanglements per dive survey by taxa, average #/day (# per dive/survey interval, SI), average #/day/net by taxa.

	Net #3969			Net #3957			Net #3971			Net #4564		
# of entanglements	#/dive	SI	#/day	#/dive	SI	#/day	Per dive	SI	#/day	#/dive	SI	#/day
Invertebrates												
2nd dive	9	15	0.6	1	3	0.33	6	3	2	23	2.2	10.4
3rd dive	2	3	0.67									
4th dive	1	3.8	0.26									
Final dive	7	6	1.17	1	5	0.20	7	5	1.4	24	4.8	5
Average/day			0.67			0.27			1.7			7.5
Fish												
2nd dive	1	15	0.07	0	3	0	3	3	1	1	2.2	0.45
3rd dive	0	3	0									
4th dive	0	3.8	0									
Final dive	2	6	0.33	0	5	0	5	5	1	0	4.8	0
Average/day			0.1			0			1			0.23
Birds												
2nd dive	0	15	0	1	3	0.33	2	3	0.67	0	2.2	0
3rd dive	0	3	0									
4th dive	0	3.8	0									
Final dive	2	6	0.33	1	5	0.2	3	5	0.6	0	4.8	0
Average/day			0.08			0.27			0.64			0

Table 4
Estimated incident catch rates for invertebrates, seabirds and fish.

Group	*N*	Coefficient (SE)	*P*	Incident catch (per day)	95% CI for incident catch (per day)	
Invertebrates	108	0.751 (0.6670)	0.260	2.119	0.5734	7.8328
Seabirds	10	−2.380 (0.7924)	0.003	0.196	0.0524	0.7347
Fish	14	−2.043 (0.7830)	0.003	0.275	0.0599	1.2608

Table 5
Predicted number of animals observed in a derelict fishing during a single dive survey, based on incident catch rates and estimated decomposition rate. Incident catch rate (λ) and mean decomposition time (μ) were estimated from Poisson regression and exponential models, respectively.

Taxa	λ	μ (days)	Expected #	95% CI	
				Lower	Upper
Invertebrates	2.119	16.8	35.670	9.4369	134.8235
Seabirds	0.196	16.8	3.303	0.8628	12.6430
Fish	0.275	16.8	4.624	0.9983	21.6331

Table 6
Costs of derelict net and pot survey and removal, 2004–2007. We used 2007 $ values as the baseline, adjusting for inflation using the Bureau of Economic Analysis Gross Domestic Product Implicit Price Deflator* and averaging values across all four quarters of each calendar year; 2006 costs were adjusted by a factor of 1.027, 2005 costs by 1.060, and 2004 costs by 1.095.

Year	Surveys		Removals	
	Days	Costs ($)	Days	Costs ($)
Derelict nets: 178 nets located; 604 nets removed				
2004	0	0	37.5	143,719
2005	1.0	2677	26.5	98,315
2006	2.0	5186	31.0	111,430
2007	36.0	90,900	37.5	131,250
Totals	39.0	98,763	132.5	484,714
Derelict pots: 4411 pots located; 1248 pots removed				
2004	25.0	69,122	21.0	80,483
2005	6.0	16,059	25.0	87,500
2006	14.5	37,602	11.0	39,540
2007	3.0	7575	21.5	75,250
Totals	48.5	130,358	78.5	282,773

* <http://research.stlouisfed.org/fred2/data/GDPDEF.txt>.

$$\text{Actual number in net} = 17/0.867 = 19.078 \text{ crabs}$$

Our predictive model could then be used to calculate an estimated daily catch rate for that net, given the observed number of crabs in the net and our estimated decomposition time:

$$\Lambda_{\text{crab}} = \text{Observed } \#_{\text{crab}}/\mu = 19.078/16.8 = 1.135 \text{ crabs/day}$$

Utilizing our model, resource managers could estimate that the net had entangled 136.2 crabs over the 3-month (120-day) period of time that it was in the water.

Our models and the precision of our estimates were limited by small sample size in this study. Specifically, the data were heavily weighted with observations from invertebrates compared to seabirds and fish. This could be a true reflection of the distribution of animals caught in all derelict nets, or it may be biased by factors related to the nets, such as size or composition, or the marine environment at the net's location. As well, we could not take size of the net into account in developing the model because of our small sample size. Moreover, the location of the four nets used in this study were not necessarily representative of the diversity of environmental conditions surrounding derelict fishing nets in all oceans, and therefore our models cannot capture variability due to these settings. The precision of the predicted catch rates could be improved with a more frequent survey scheme as resources allow: time intervals between survey dives ranged from 2.21 to 14.98 days, and data from only six dive intervals were available for modeling. The small sample size and range in time intervals also led to large standard error terms.

A baseline decomposition rate was determined using all animal group data combined in order to fit appropriate model assumptions. This gave us a crude estimate of mean decomposition time of animals caught in derelict fishing nets. More accurate and precise estimates may be obtained with the addition of important covariates in the exponential model, such as the state of decomposition on first observation, and the presence or absence of predators/scavengers such as sunflower stars and octopus; indeed, we have since observed octopus scavenging dead Dungeness crab in derelict nets. Our current model likely underestimates total catch without including scavenger presence as a co-variate; these factors are known to significantly affect median time to decomposition based on Kaplan Meier analyses (data not shown). Additionally, our method of estimating decomposition time did not account for left censoring, or the unobserved interval between the time of initial entanglement in the net and the time when survey dives occurred. We therefore did not observe the entire time at risk for each observation, and underestimated the true mean time of animals remaining in the net. Again, we would gain precision in our estimates with more data collected from more frequent dive surveys to reduce bias from interval truncation.

The estimates of derelict fishing net surveys and removal costs are based on actual costs incurred; estimates of directly measurable benefits in the form of saving commercially valuable Dungeness crab through the removal of derelict nets were based on total mortality as predicted by our model and our assumption of the age of the derelict net. The cost–benefit ratios provided only considers the directly measurable benefits in terms of the commercial ex-vessel value of species likely to be saved by the removal of the net.

The fiscal benefit of derelict fishing net removal was corroborated by our estimates of the cost–benefit ratios for removal of derelict crab pots (Table 6). From 2004 to 2007, it cost $30/pot to find a derelict crab pot and $231 to remove it, for a total of $261/pot. During this time period, we recovered 1248 derelict crab pots, 37% of which contained Dungeness crab, and on average, these actively fishing pots contained 6.2 crab. Based on anecdotal information provided by local commercial crab companies that hold live crab, most crab die within 3–4 weeks of holding. Therefore, we assumed that the live crab we observed in an actively fishing derelict pot represented the catch for 1 month, yielding an annual catch estimate of $12 \times 6.2 = 74.4$ crab/year. Again, if each crab weighed 2 lbs, then a given derelict pot could have consumed $74.4 \times 2 = 148.8$ lbs of Dungeness crab in a year, representing an ex-vessel value of $148.8 \times \$2.25 = \$334.80$ in losses to the fishery. The cost–benefit ratio of derelict pot removal was therefore calculated at $261:$334, or 1:1.3.

The benefits do not reflect the indirect value of the restoration of habitat and the resulting assumed increase in productivity of commercial and non-commercial species and other species important to the integrity of a healthy ecosystem. However, the cost effectiveness of derelict fishing gear removal can be compared with another marine species conservation program, such as oil spill response, or species reintroduction. For example, Jessup (1998) estimated that seabird rehabilitation costs on average $600–$750 per bird and marine mammal rehabilitation costs an average of $4000/animal. In the 604 derelict nets recovered from Puget Sound between 2004 and 2007, we observed 17 dead marine mammals and 208 dead seabirds (mainly cormorants *Phalocrocoracidae* spp. and grebes *Podicipedidae* spp.). However, numerous seabird and marine mammal bones are found under and around the derelict nets recovered, indicating that many more animals than actually recovered are entangled in derelict gear. If, based on these data, we conservatively estimate that a given derelict net has a daily marine mammal catch rate of $(17/604)/16.8 = 0.0017$ mammals/day/net, and that a net had likely been in the water for at least 10 years, then the total marine mammal mortality caused by a given net could have been $0.0017 \times 3650 = 6.2$ mammals. The cost to rehabilitate 6.2 mammals after an oil spill is estimated to be $6.2 \times \$4000$, or $24,820, whereas, as stated earlier, the cost to remove a net that might otherwise have consumed 6.2 mammals averaged $1358/net.

The precision of the comparative values of cost–benefit and cost effectiveness presented herein will increase with further refinement of our mortality model. At present, with cost–benefit ratios of about 1:14.5 with regard to derelict nets posing a hazard to Dungeness crab, derelict fishing gear removal can be justified solely based on the savings in ex-vessel value of commercial species impacted. The additional benefits of reduced mortality of fish, mammals, birds and invertebrates as well as reduced threats to human safety, vessel navigation, habitat quality, and ecosystem health make derelict fishing gear removal even more compelling.

Acknowledgements

Laurel Becket, Biostatistics Unit, Department of Public Health Sciences, University of California, Davis, provided valuable assistance with model development. Brynie Kaplan-Dau, School of Veterinary Medicine, UC Davis, assisted with literature review. Special thanks to Doug Monk, Jack Iotte and Ken Woodside, the divers who collected all underwater data on the nets analyzed in this study. Lucas Bair, Department of Agricultural and Resource Economics, UC Davis, provided invaluable advice on drafts of this manuscript.

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