ICES Journal of
Marine Science

ICES Journal of Marine Science (2013), 70(1), 114–122. doi:10.1093/icesjms/fss138

A trap with a twist: evaluating a bycatch reduction device to prevent rockfish capture in crustacean traps

Brett Favaro[1,2]*, Stefanie D. Duff[2], and Isabelle M. Côté[1]

[1]*Department of Biological Sciences, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada*
[2]*Department of Fisheries and Aquaculture, Vancouver Island University, Nanaimo, BC, V9R 5S5, Canada*

**Corresponding Author: tel: +1-778-782-3989; fax: +1-778-782-3496; e-mail: bfavaro@sfu.ca*

Favaro, B., Duff, S. D., and Côté, I. M. 2013. A trap with a twist: evaluating a bycatch reduction device to prevent rockfish capture in crustacean traps. – ICES Journal of Marine Science, 70: 114–122.

Received 24 May 2012; accepted 1 July 2012; advance access publication 8 August 2012.

Bycatch, or the incidental capture of non-target species, occurs in fisheries around the world, with often detrimental ecological consequences. Bycatch reduction devices (BRDs) that increase catch specificity have been used successfully in some fisheries, and the development of such devices remains an important component of the global effort to reduce bycatch rates. We tested novel devices designed to exclude juvenile rockfish (*Sebastes* spp.) from traps used to catch spot prawns (*Pandalus platyceros*), a commercially important species in British Columbia, Canada. The devices included reductions in trap opening sizes and novel bent-tunnel openings. Reducing trap opening size did not affect bycatch rates of rockfish or other non-target fish species. In contrast, bent-tunnel BRDs eliminated rockfish bycatch, and two of the bent-tunnel variants also excluded other fish species. However, prawn catch rates were reduced in all modified gear, and large prawns were often excluded more than small prawns. Videos recorded *in situ* revealed that prawn attempts to enter traps took longer and were more likely to fail in BRD-equipped than in unmodified traps. We conclude that bent-tunnel BRDs have the potential to be useful, but improvements are needed to increase prawn catch to levels similar to that of unmodified traps.

Keywords: behaviour, catch comparison, fishing gear, selectivity, underwater filming.

Introduction

Bycatch—or the unintentional catch of non-target species during fishing—represents an ongoing challenge to fisheries managers. Globally, between 8 and 40 percent of fishing mortality is attributed to the capture of non-target species during the fishing process (Kelleher, 2005; Davies *et al.*, 2009), and bycatch has been implicated in population declines of cetaceans (Read, 2008), various species of seabirds (Lewison *et al.*, 2005; Dillingham and Fletcher, 2008; Watkins *et al.*, 2008), turtles (Wallace *et al.*, 2008), and sharks (Ward *et al.*, 2008).

The magnitude of bycatch in a fishery depends in large part on the selectivity of the gear used (Chuenpagdee *et al.*, 2003). Some gears are selective by nature, while others, such as benthic trawls, are notoriously unselective (Alverson *et al.*, 1994). It is increasingly common to develop modifications, or Bycatch Reduction Devices (BRDs), which improve the selectivity of existing gears (FAO, 2002). Some BRDs are highly successful (Isaksen *et al.*, 1992; Shiode and Tadash, 2004), but as a whole the development and testing of BRDs lag behind the number of identified bycatch issues in fisheries around the world (Kennelly and Broadhurst, 2002).

Though some gear types are well known for their high bycatch rates, conservation problems can also arise from the use of traditionally selective gears. Trapping is a common fishing practice that is often assumed to be sustainable due to normally low bycatch rates and minimal habitat destruction. However, as with any fishing gear, trap-based fisheries do capture some non-target species (Carlile *et al.*, 1997). For example, in British Columbia, on the west coast of Canada, a large-scale trap fishery exists to catch spot prawns (*Pandalus platyceros*). From 2002–2008, an average of 3.4 million traps were deployed each year during the eight-week season (Rutherford *et al.*, 2010). Prawns traps are highly selective, but bycatch of juvenile rockfish (*Sebastes* spp.) has been observed, albeit at a low rate per trap (Favaro *et al.*, 2010; Rutherford *et al.*, 2010). Due to the large number of trap-days, even a low per-trap bycatch rate has the potential to produce significant numbers of fish lost in absolute terms. This bycatch is an issue because the majority of the 37 rockfish species occurring in BC waters are vulnerable to overfishing due to their late age at maturity and variable recruitment success (Leaman, 1991; Love *et al.*, 2002), leading to the decline of rockfish populations over the past decades (Love *et al.*, 2002; Yamanaka *et al.*, 2004; Yamanaka *et al.*, 2006). In addition, rockfish caught in traps and discarded do not survive, due in part to the barotrauma-induced rupture of their swim bladders when rapidly brought to the surface in fishing gear (Hannah *et al.*, 2008). The quillback rockfish (*Sebastes maliger*) is the most common rockfish species caught in prawn traps (Favaro *et al.*, 2010; Rutherford *et al.*, 2010), and has been listed as "threatened" by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (COSEWIC, 2009a) – the independent scientific body which recommends species for listing under the Species at Risk Act in Canada (COSEWIC, 2009b).

The motivation to reduce rockfish bycatch in prawn traps is twofold. First, due to the depressed state of rockfish populations, any development that reduces mortality could assist the recovery of these species. Second, prawn trapping is one of the activities permitted within Rockfish Conservation Areas (RCAs), areas where most commercial fishing activities are banned to facilitate rockfish recovery (Fisheries and Oceans Canada, 2007). The bycatch of rockfish by prawn traps in RCAs, even at low rates, could inhibit the recovery of rockfish within these areas, jeopardizing the mandate of RCAs to protect rockfish from "all mortality associated with recreational and commercial fisheries" (Fisheries and Oceans Canada, 2007) and potentially leading to stricter fishing regulations.

The greatest challenge in tackling problematic bycatch is that BRDs must not only reduce or eliminate bycatch, but must also maintain catch rates of the target to have as small an impact as possible on fisher livelihoods. It is therefore important when designing new devices to assess the catch rates of both target and non-target species, as well as the selectivity of the conventional and modified fishing gears across body sizes of organisms (Holst and Revill, 2009).

In this paper, we examine the effectiveness of various BRDs at eliminating rockfish bycatch while maintaining prawn catch at levels close to those of unmodified commercial traps. We test two broad families of BRD designs – simple reductions of the size of the trap openings, and novel opening attachments designed to facilitate prawn entry while excluding rockfish and other fishes from the traps. Using both catch data from a large field study and data collected *in situ* using an underwater camera apparatus purpose-built to record activity around deployed prawn traps (Favaro *et al.*, 2012), we assess the performance of BRDs by comparing the catch of modified traps to the catch of unmodified commercial gear, and examine bycatch rates and size selectivity of each gear design. Our primary goal was therefore to assess these novel BRDs, test how they perform at excluding non-target species while retaining target species, and—based on observations from the video data—determine potential ways to improve the performance of the gear for future use in the commercial fishery.

Material and Methods

Bycatch reduction device designs

Commercial prawn traps have a truncated cone design made up of three stainless steel circular rings, covered by a 3.8 cm soft mesh (Figure 1a). There are three circular entrances, held open by 7.6 cm-diameter stainless steel rings, on the sides of each trap. There is no one-way door or other device which prevents prawns or other organisms from escaping the trap, but based on *in situ* video observation, escape rates from traps are low

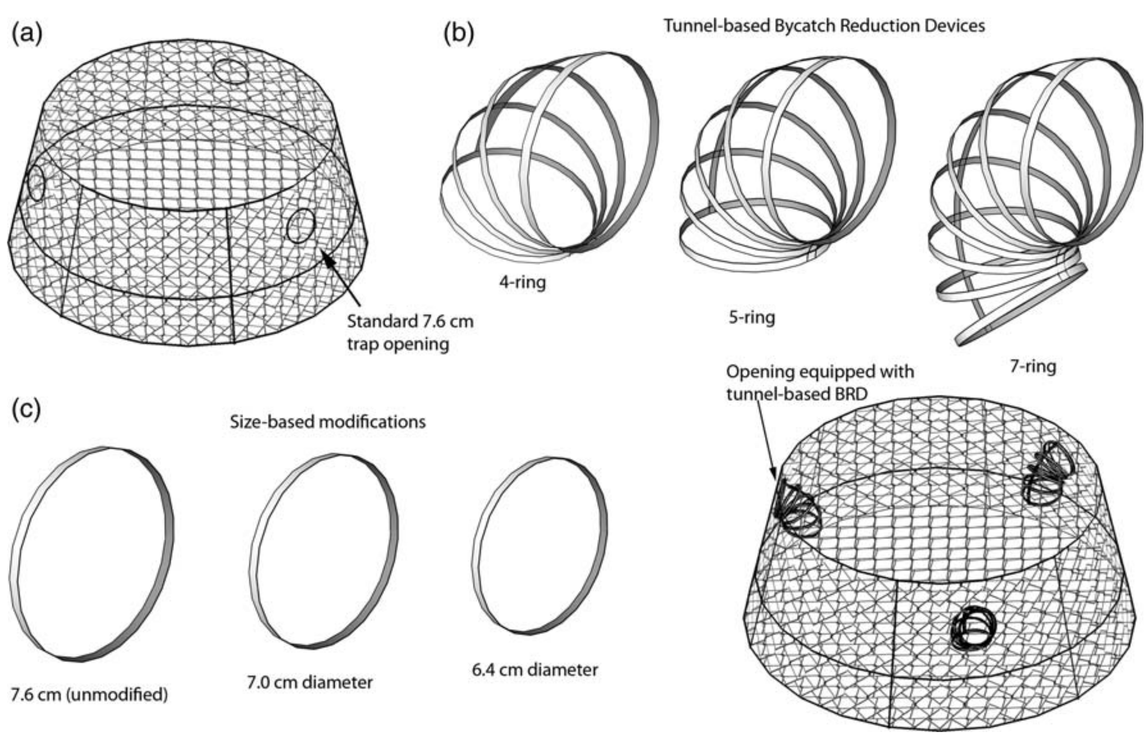

Figure 1. Bycatch reduction devices (BRD) used on spot prawn (*Pandalus platyceros*) traps. (a) Unmodified commercial prawn traps with three 7.6-cm diameter entrances. (b) The three tunnel-based BRDs used in this study, and (bottom right) shown when clipped onto the existing 7.6-cm entrances. (c) Two ring-based BRDs, reduced versions of the standard entrance diameter.

(BF, unpublished data). The selectivity of these traps is determined largely by the diameter of the entrances (preventing large organisms from entering), as well as the size of the mesh on the trap (preventing escape). However, since mature spot prawns and juvenile rockfish are similar in size, it is unlikely that a simple size adjustment of the mesh or entrances will exclude rockfish while maintaining prawn catch rates. We nevertheless tested two entrances of smaller diameters (6.4 cm and 7.0 cm; Figure 1c) than the standard entrance ring (7.6 cm).

We also designed BRDs based on extensive observations of prawns and rockfish interacting with traps. Observations were made of animals in experimental aquaria, in the wild by scuba divers, and through analysis of video collected by a deep-water camera apparatus attached to a prawn trap (Favaro *et al.*, 2012). Prawns move in three ways: by walking on their pereiopods (legs), swimming using their abdominal pleopods, and by eliciting a retrograde escape response where they flick their abdominal tail to escape predators (Bauer, 2004). When prawns approach and enter prawn traps, they predominantly do so by walking along the mesh, up the side of the trap, and through the openings (BF, personal observation, Video S1). By contrast, rockfish swim using a combination of labriform and subcarangiform swimming modalities (Sfakiotakis *et al.*, 1999), in which they use their pectoral fins for slow, precise movement, and their tail fins for fast travel. We therefore designed a series of bent-tunnel BRDs that were built to restrict the ability of rockfish to move within the opening (i.e. by requiring an unnatural bend of the fish's body), while providing a ladder-like structure for prawns to crawl over. These devices attached to the trap entrance rings, and comprised a series of rings that formed a curved tunnel (Figure 1b). We used rings rather than a solid bent tunnel (such as with a PVC elbow) because prawns appeared to have difficulty crawling over smooth plastic surfaces (BF, personal observation). We tested three bent-tunnel BRDs of increasing length, i.e. with four, five, or seven rings (Figure 1b). These BRDs were hand-built by cutting a 7.6 cm stainless steel pipe into small rings, which were spot-welded in place. We tested PVC versions of the openings in a pilot study, but they were not durable and did not retain their shape during normal fishing use.

Field test

Between June and August 2010, we field-tested five BRDs (i.e. two entrance-ring and three bent-tunnel variants) as well as unmodified traps (control) to identify the BRD design that offers the best trade-off between minimizing bycatch while maintaining prawn catch. From a 9.8 m-long research vessel, we deployed gears in "strings" which contained 10 traps connected to a single line weighted with one cinder block at each end. We deployed a total of 154 strings (i.e. 1540 traps). The most common configuration of traps in each string was: two control traps (7.6 cm entrances), one trap with 7.0 cm entrances, one trap with 6.4 cm entrances, and two of each BRD variant (4-ring, 5-ring, and 7-ring), with the order of traps being randomized within each string. Early in the study, we included PVC variants of the BRDs (so that each string had one steel and one PVC variant of each BRD type) but all PVC variants were eventually discarded because they were not durable (total of 155 PVC-BRD traps excluded). In addition, we included the 6.4 cm variant one week into the study, when we became curious about a more extreme reduction in trap opening size. One string of gear was lost during the study, while another was carried several kilometres from its original deployment site, and so its data were discarded. Three traps also became detached from one string line and were lost. Data from 1362 traps were therefore included in the present analysis (322 control traps (i.e. 7.6 cm entrances), 256 traps with 7.0 cm entrances, 145 traps with 6.4 cm entrances, 214 traps with 4-ring tunnels, 214 traps with 5-ring tunnels, and 211 traps with 7-ring tunnels).

We deployed gear in two regions of southern British Columbia (Figure S1): Howe Sound, near Vancouver (49°25′30″N 123°20′00″W), and the southern Gulf Islands, near Sidney (48°39′00″N 123°23′00″W). We selected deployment sites based on personal experience of prawn fishing, input from commercial fishers, and local knowledge. We baited all traps with standard commercial prawn bait, which is made of fishmeal pellets (Rutherford *et al.*, 2004). Deployment depths ranged from 50 to 120 m (mean $\pm$ 1 *SD*: 82 $\pm$ 17 m, determined by depth sounder), and strings were deployed for an average of 26.5 $\pm$ 11.6 h (range: 12.8 to 98 h) before retrieval, thus matching commercial fishing conditions ($\sim$ 24 h, Fisheries and Oceans Canada, 2011).

Traps were retrieved with an electric Anchormax capstain winch, which pulled strings at a steady rate of approximately 0.2 ms^{-1}. We recorded the number of individuals of each species caught, as well as the total weight of each species caught per trap. For fishes we recorded individual fish weight as well as total length, body width, and body depth at the deepest point. In addition, we recorded the carapace length (i.e. the distance from the posterior orbital rim to the median dorsal carapace edge, Butler, 1980) of each captured prawn.

Statistical analysis

To compare rates of fish bycatch and prawn catches across gear designs, we used generalized linear mixed-effects models (GLMMs) and linear mixed-effects models (summary of models; Table S1; Bolker *et al.*, 2009). GLMMs are a powerful tool for data analysis in ecology, and their use has become widespread because they can handle data that violate many assumptions necessary for simple linear models (Zuur *et al.*, 2009). In addition, the nested nature of our experimental design (i.e. catch data nested within strings) can be incorporated in the models as random effects. We displayed most of our data using beanplots, a boxplot-like method of data presentation that shows all values recorded in a given category, while plotting an estimated distribution around the data (Kampstra, 2008). In beanplots, there is no arbitrary exclusion of outliers – rather, all data are displayed along with a mean for easy comparison between groups (Kampstra, 2008).

The first suite of models examined the bycatch of all fishes across fishing gears. There were too few captures of rockfish (see Results) to examine this group separately from other fish families. First, we examined the rate of fish bycatch per trap by testing the fixed effects of trap variant (control, 7.0 cm opening, 6.4 cm opening, 4-ring, 5-ring, and 7-ring tunnels) and fishing region (Howe Sound and Gulf Islands) while incorporating the random effect of string identity. Differences in overall catch rates between regions could make the interpretation of differences among trap variants within region difficult. Therefore, when catch rates varied significantly between regions, we repeated the analysis separately for each region, testing variants against unmodified traps. We assumed a negative binomial distribution of fish catch rates (verified with the Curvefit function in the VCD package in R - Likelihood Ratio: $x^2 = 1.62$, $df = 2$, $p = 0.45$, Meyer *et al.*, 2011), and conducted the analyses using the glmmADMB package in R (Skaug *et al.*, 2011). We also examined the body depth and body mass of fishes caught across trap variants and regions (both fixed effects, with string as a random effect) to determine potential underlying reasons for any exclusion attributed to the BRDs. These two variables were distributed normally, enabling us to construct linear mixed-effects models using the simpler NLME package (Pinheiro *et al.*, 2011). We log-transformed fish body weight to improve the model fit.

While fish bycatch rates are reported mostly by count in the commercial fishery, prawn catch is reported by weight. Therefore, in our analysis of prawn catch, we examined the weight of prawns caught per trap rather than prawn number. We used a linear mixed-effects model to test the effects of trap variant and fishing region on weight of prawns caught per trap, while incorporating string identity as a random effect. Since there was a large difference in prawn catch rates between fishing regions (see Results), we conducted a separate analysis for each region. Finally, we tested the effect of trap variant and fishing region on the body sizes (i.e. carapace length) of prawns caught.

We then performed a catch comparison analysis, following the procedure outlined in Holst and Revill (2009), to test whether body size affected the likelihood of being caught in BRD gear vs. control gear. In this procedure, GLMMs are used to plot the relationship between proportion of catch in traps of each BRD type versus control traps, and the body size of organisms caught in the gear (Holst and Revill, 2009). For prawns, our measure of body size was carapace length, while for fishes it was body depth, as we expected the ability of fish to enter traps to be limited by the length of their dorsoventral axis. This framework is designed to highlight the differences in catch between unmodified and modified traps, and it tests the proportion of catch across the spectrum of observed body sizes which occurred in each trap variant vs. control traps. Variability associated with sampling over multiple deployments of our gear is incorporated in the model as a random effect. We began by fitting polynomial regressions followed by reductions until all terms were significant. We used the glmmPQL function from the MASS package (Venables and Ripley, 2002) in R to conduct this analysis separately for fishes and spot prawns.

Video deployment and analysis

While catch data can provide information on the effectiveness of each BRD, they do not reveal the mechanism of action, i.e why BRDs may be increasing or decreasing bycatch (Sala *et al.*, 2011). We therefore deployed traps equipped with a specially designed underwater camera apparatus (Favaro *et al.*, 2012) to compare the performance of control and BRD-equipped traps. We analyzed video collected from five deployments of our underwater camera apparatus at a location in Howe Sound (Figure S1). Three deployments were conducted with unmodified, 7.6 cm opening traps, and two were equipped with 5-ring BRDs. Video duration ranged from 12.1 to 13 h per deployment (Table S2).

We recorded data from our videos by counting the number of prawns that entered the field of view (termed "approaches"), and the number which attempted to enter ("attempts"). An attempt was recorded every time a prawn climbed onto the mesh immediately surrounding a trap opening. The time between prawn contacting the mesh and entering the trap through an opening ring was recorded as the "time to enter." Alternatively, if the prawn did not enter, and instead crawled or swam away from the trap opening after starting its approach, the attempt was recorded as a "failure to enter". Using these data, we calculated the average proportion of successful entry attempts, as well as the mean time to enter, across video deployments of control and 5-ring BRD-equipped traps, and compared them using t-tests of unequal variances (Ruxton, 2006). In addition, we took qualitative notes about the prawns' entry process, focusing on identifying design issues that could be affecting prawn entry into the traps.

Results

Rockfish bycatch

We caught a total of only six rockfish across all traps. Three were caught in unmodified (control) traps (one greenstriped rockfish, *Sebastes elongatus*, two quillback rockfish, *S. maliger*), two in traps with 7.0-cm entrances (one quillback rockfish, one vermillion rockfish, *S. miniatus*), and one (Puget Sound rockfish, *S. emphaeus*) in traps with 6.4-cm entrances. We caught no rockfish in 639 deployments of tunnel-equipped traps.

Overall fish bycatch

We caught a total of 118 individual fish across the entire study, which comprised the aforementioned four species of rockfish as well as 17 other species or families of fish (Table S3). Fish body weight ranged from <50 g to 900 g (mean $\pm$ 1 *SD* = 187 $\pm$ 184 g), and body depth ranged from 0.8 cm to 7.8 cm (mean $\pm$ 1 *SD* = 4.3 $\pm$ 1.4 cm).

Overall fish bycatch rates were 69% and 68% lower in the traps equipped with 5- and 7-ring BRDs, respectively, than in control traps (GLMM: 5-ring, $\beta = -1.178$, S.E. = 0.417, $z = -2.82$, $p = 0.005$; 7-ring, $\beta = -1.137$, S.E. = 0.419, $z = -2.72$, $p = 0.006$; Figure 2a). Fish catch rates in traps with other BRDs (i.e. both entrance diameter reductions, and 4-ring tunnel) did not differ significantly from those in the control traps. Fish capture rate in Howe Sound region was only 32% of that of the Gulf Island region ($\beta = -1.150$, S.E. = 0.292, $z = -3.94$, $p < 0.001$). Patterns of fish catch were therefore examined separately in each region. Within the Gulf Islands, the 5-ring and 7-ring designs reduced fish capture by 66 and 72%, respectively, relative to unmodified traps (Table S4). In comparison, in Howe Sound, where only 28 fish were caught, all designs except the 6.4 cm-opening trap produced significantly lower fish bycatch rates than unmodified traps (reductions in fish catch: 7.0 cm, 87%; 4-ring, 86%; 5-ring, 78%; 7-ring, 71%; Table S4).

Trap design also had significant influence on both the average body weight (Figure 2b) and body depth (Figure 2c) of trapped fishes. Fishes were, on average, 38% lighter in traps with 5-ring BRDs (LME: $\beta = -0.962$, S.E. = 0.290, $t = -3.317$, $p = 0.002$), and had significantly shallower average body depth in traps with 5-ring and 7-ring entrances than in the control traps (LME: 5-ring, $\beta = -1.656$, S.E. = 0.495, $t = -3.347$, $p = 0.002$; 7-ring, $\beta = -2.316$, S.E. = 0.521, $t = -4.450$, $p < 0.001$). Fish body weight and body depth did not vary across the other trap variants or between regions.

Prawn catch

Every trap variant caught fewer prawns overall than unmodified traps (Table S4). The catch of prawns, in terms of total weight per trap, was greater in Howe Sound than in the Gulf Islands (mean $\pm$ 1 *SD*: Howe Sound = 337 $\pm$ 380 g trap^{-1}, Gulf Islands = 140 $\pm$ 250 g trap^{-1}; LME: $\beta = 241$, S.E. = 36, $t = 6.6$, $p < 0.001$), leading to separate

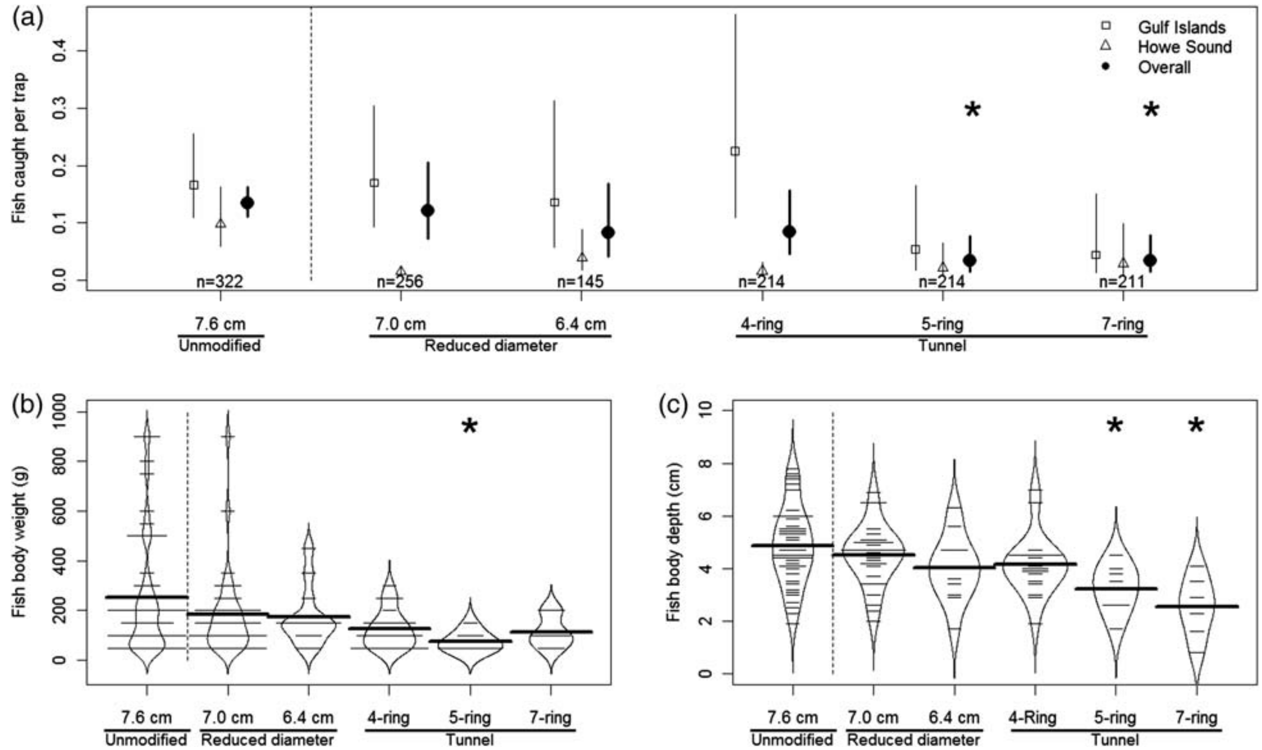

Figure 2. Characteristics of fish catch in unmodified (control) spot prawn traps and traps equipped with either reduced-diameter (7.0 cm or 6.4 cm entrances) or tunnel (4, 5 or 7 ring) bycatch reduction devices. (a) Fish catch rate (all fish combined; numbers caught per trap); means are shown with 95% C.I. (assuming a negative binomial error distribution) for each study region separately and combined. (b) Fish body weight (g) and (c) fish body depth (cm), shown as bean plots of distributions. Each thin black line indicates a data point at a given *y* value, with line width increasing with the number of observations per value. The thick black lines indicate group means. Asterisks indicate statistically significant differences ($p < 0.05$) from unmodified traps, shown to the left of the vertical dashed line.

further analyses for each region. In the Gulf Islands, the low overall catch masked any effect of BRDs because all traps experienced low catches, although the 5- and 7-ring BRDs caught fewer prawns than control traps (Table S4). By contrast, in Howe Sound where overall prawn catch was greater, all BRDs reduced prawn catch significantly compared to the control traps (Figure 3a, Table S4). Overall, prawns caught in Howe Sound were significantly smaller than those caught in the Gulf Islands region (LME: $\beta = -0.117$, S.E. $= 0.031$, $t = -3.751$, $p < 0.001$). In Howe Sound, captured prawns were significantly larger in unmodified traps than in the traps equipped with 7.0 cm entrances (LME: $\beta = -0.072$, S.E. $= 0.030$, $t = -2.385$, $p = 0.017$), 5-ring (LME: $\beta = -0.103$, S.E. $= 0.027$, $t = -3.802$, $p < 0.001$), and 7-ring tunnels (LME: $\beta = -0.138$, S.E. $= 0.029$, $t = -4.793$, $p < 0.001$) (Figure 3b). In the Gulf Islands, only the 7-ring tunnels caught significantly smaller prawns than unmodified traps (LME: $\beta = -0.167$, S.E. $= 0.051$, $t = -3.296$, $p = 0.001$).

Body size selectivity of trap variants

In the traps equipped with 5-ring BRDs, the proportion of total fish catch (expressed by numbers) dropped markedly as fish body depth increased (Figure 4, Table S5). These BRDs were therefore disproportionately selective against increasingly deeper-bodied fishes. For traps equipped with 4-ring and 7-ring tunnels, and 7.0-cm, and 6.4-cm entrances, there was no relationship between fish catch proportion and body depth (Figure 4). For prawns, all BRD designs caught less than 50% of the total catch (by weight), and size-selectivity was evident for all trap designs except for the traps with 6.4-cm entrances (Figure 4). For traps with 5- and 7-ring tunnels, which were best described by a linear GLMM, the relative proportion of observed catch (by weight) in BRD-equipped traps decreased as carapace length of prawns increased (Figure 4, Table S5). The relationships between catch proportion and carapace size for traps with 7.0-cm entrances and 4-ring tunnels were best described by quadratic models, suggesting that they were selective against both small and large prawns, but allowed the entry of mid-sized prawns, though still to a lesser extent than unmodified traps (Figure 4, Table S5).

Mechanisms of action of BRDs: Video evidence

In five deployments of the camera apparatus, we recorded 38 hours of video of control traps, and 25 hours of video of traps equipped with 5-ring BRDs. Across all videos, we observed a total of 2380 spot prawns approach the trap (Table S2). Of those, 777 attempted to enter, and 243 did so successfully (180 in control traps, 63 in 5-ring deployments). The average proportion of successful entries was higher in unmodified traps (mean $\pm$ 1 $SD = 46\% \pm 12\%$) than in traps with 5-ring tunnels ($18\% \pm 12\%$; $t = 3.273$, $df = 2.9$, $p = 0.049$). Furthermore, it took longer for prawns to complete entries in the modified traps (mean $\pm$ 1 $SD =$ 106 ± 9 s) than in control traps (57 ± 19 s; $t = -3.871$, $df = 2.9$, $p = 0.033$).

In control traps, prawns could easily crawl through the openings uninhibited. Prawns attempting to enter modified traps crawled easily over the rings of the BRD, but often caught their

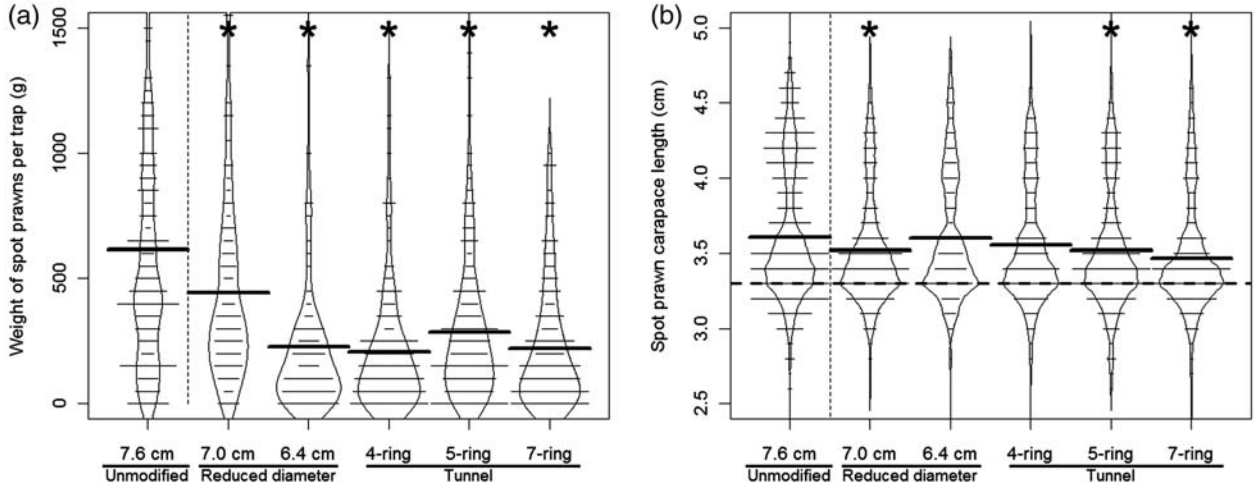

Figure 3. Beanplots comparing the distributions of (a) total catch weight and (b) individual carapace length of prawns caught per trap in Howe Sound, British Columbia, in unmodified (control) spot prawn traps and traps equipped with either reduced-diameter (7.0 cm or 6.4 cm entrances) or tunnel (4, 5 or 7-ring) bycatch reduction devices. The thick black lines indicate group means. The horizontal dashed line in (b) indicates the legal minimum size in the commercial fishery. Asterisks indicate significant differences ($p < 0.05$) relative to unmodified traps, shown to the left of the vertical dashed line. The results for the Gulf Islands region are not shown because prawn catches were generally low.

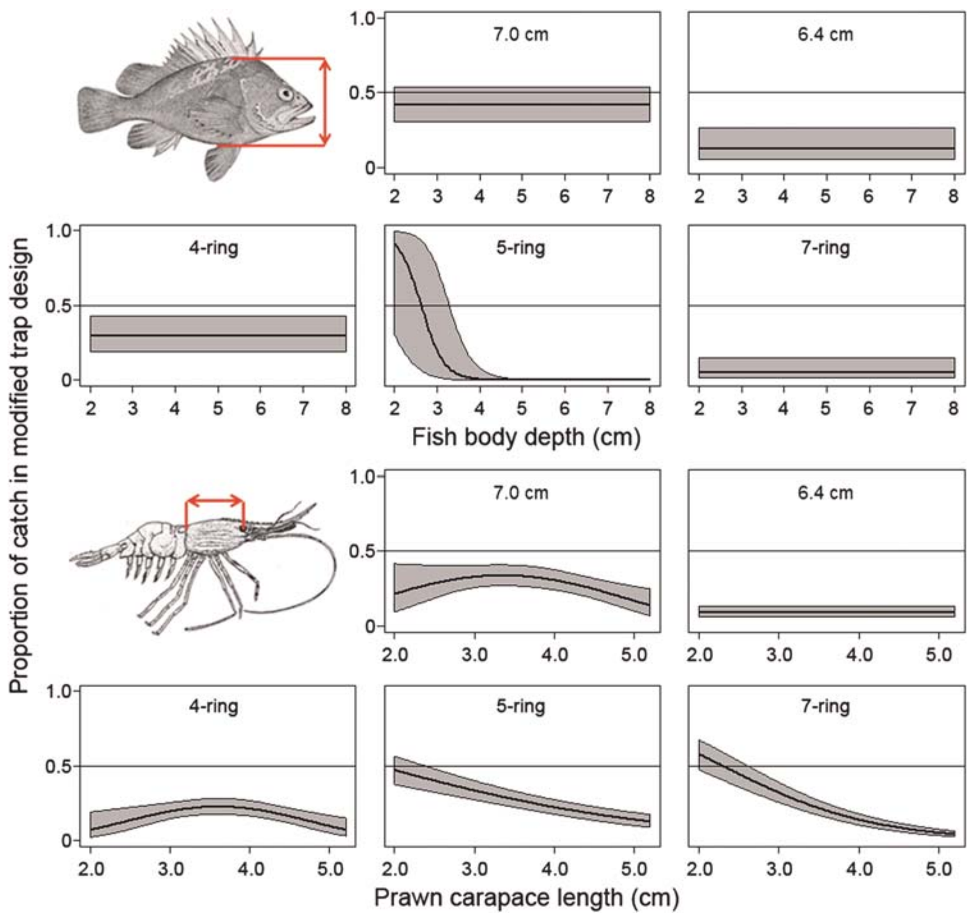

Figure 4. GLMM-modeled proportions of the number of fish and prawns caught in each gear type in relation to fish (top; body depth, the largest distance measured on the dorsoventral axis of the fish) or prawn (bottom; carapace length, the distance from the posterior orbital rim to the median dorsal carapace edge) body size. The horizontal line at $y = 0.5$ indicates that catch was similar between the modified and unmodified traps (i.e. 50% of the catch at any given body size occurred in each trap type). Lower values indicate that fewer organisms at a given length were caught in the BRD-equipped traps than in the unmodified traps. The thick black lines show the modelled means, while the grey shading indicates the 95% C.I. Line drawings of fish and prawn from (Fisheries and Oceans Canada, 2011) and (Whitney, 1911), respectively.

rostrums between the two bottom rings of the tunnel entrance (Video S2). It often took multiple attempts for prawns in modified traps to successfully negotiate the opening.

We observed a single quillback rockfish enter an unmodified trap on video. The rockfish spent 26 min ∼20–30 cm above the trap before attempting (and failing) to consume a Dungeness crab (*Metacarcinus magister)*, which had climbed on top of the trap (Video S2). After this interaction, the rockfish remained above the trap for six more minutes before entering the trap through one of the openings. While inside the trap, the rockfish attempted to consume trapped prawns twice, but both attempts failed. The rockfish was present in the trap for the remainder of the video, but it escaped in the 8 hours between termination of recording and gear retrieval. We observed no attempt by rockfish to enter the 5-ring-equipped traps.

Discussion

In this study, we tested potential technical solutions to a bycatch problem in a trap fishery. To be adopted in a fishery, a BRD should satisfy three main conditions: it should achieve reduction in bycatch, it should maintain a target catch, and it should be practical for use in the fishery (e.g. durable, minimal alteration to fishing process). If these three criteria are met, the BRD will achieve the goal of maintaining a fishery's profitability while achieving conservation outcomes. Our tunnel BRDs appear to meet the first and third criteria: we found that novel bent-tunnel devices, which can be easily attached to standard commercial prawn traps, were effective at excluding rockfish and other species of fish, and that BRDs with 5- and 7-rings were more selective than 4-ring devices. However, none of the BRDs tested here met the second criterion. We found that any modification, including a simple reduction in the size of the trap openings, reduced significantly the capture of prawns. Our *in situ* observations of prawns interacting with traps give us insights into modification needed to develop an optimal BRD that can prevent fish entry into traps while maintaining prawn catches.

Our bent-tunnel entrances, particularly the 5- and 7-ring BRDs, were highly effective at excluding fishes from prawn traps, compared to unmodified traps. They were also better at excluding fishes than simple reductions in opening size, in terms of both the numbers and sizes of fish caught. The 5-ring tunnel BRD was especially selective against larger fishes of the sizes that correspond to the juvenile rockfish most commonly caught in commercial traps (BF, unpublished data). The complete exclusion of rockfish by the bent-tunnel BRDs is especially important because of the precarious state of many rockfish populations (Yamanaka and Lacko, 2001; Love *et al.*, 2002). The catch rates of rockfish in our unmodified traps was low but comparable to rates observed in the commercial fishery: the average rockfish encounter rate in the commercial fishery from 2002–2008 was 0.004 rockfish per trap in Howe Sound, and 0.002 and 0.008 for regions within the Southern Gulf Islands (Rutherford *et al.*, 2010). The lower rate of capture in tunnel-equipped traps also extended to other fish species of commercial interest, such as Pacific cod (*Gadus macrocephalus*), which like rockfish are sensitive to barotrauma-induced mortality (Nichol and Chilton, 2006). Those fish species which were not excluded by BRDs, such as small sculpins and eelpouts, are likely of less concern owing to their lack of a swim bladder and apparent ability to survive the capture and discard process (Berghahn *et al.*, 1992).

From a product design perspective, the tunnel BRDs appeared to be practical to use in a commercial fishery. First, they are easy to attach to existing traps, hence fishers would not have to fully replace their usual complement of 300–500 traps. Second, the devices do not require alteration in fishing behaviour, so there is little risk that improper use will reduce the effectiveness of these devices. Third, they are extremely durable, and we experienced no damage to our devices, which were used daily across two months of field study. Finally, since these devices attach to the inside of the traps only, they present no risk of snags or entanglements during the deployment and retrieval processes.

The reduction in fish bycatch in traps equipped with BRDs came at the expense of reduced prawn catches. The difficulty in maintaining prawn catch with BRDs was highlighted by the results from the BRDs with smaller entrances. Even the traps equipped with 7.0 cm entrances, which is a mere 0.6 cm reduction in opening diameter, yielded a 28% reduction in prawn catch in Howe Sound. The large effect on prawn catch of such a minor trap modification suggests that most physical devices which slightly hamper prawn entry into traps are likely to negatively affect prawn catch to some degree. Our *in situ* video data gave us insights into how such difficulties arise, at least with bent-tunnel BRDs. A high proportion of prawns that attempted to enter traps with tunnel entrances failed to negotiate the bend because their rostrum got stuck between the rings of the BRDs. As a result, it took substantially longer for prawns to complete a successful entry into modified traps than into unmodified traps. It appears that to facilitate prawn entry, we should retain the lattice-like structure that allows prawns to crawl into the trap, but we need to develop a method to prevent rostrum entanglement. One possible solution might be to use a tunnel that is solid and smooth on top (on the outer bend) but ringed on the bottom (on the inner bend).

There may be alternative (non-design) ways for the fishing industry to cope with the use of BRDs that reduce the catch of target organisms. One possibility for the prawn fishery might be to extend the short fishing season to allow fishers to accumulate catches similar to those obtained without BRD-equipped traps. However, increasing overall fishing effort would also increase the absolute amount of bycatch produced by the fishery (Hall and Mainprize, 2005). Simple back-of-the-envelope calculations (see online supplement) suggest that, given the BRD-specific observed reductions in prawn catch and the corresponding BRD-specific increases in fishing effort required to compensate for these reductions, the 5-ring and 7-ring BRDs would still achieve reduced fish bycatch relative to unmodified traps (Table 1). In fact, the 5-ring BRD appears to be the best option, extending the fishing season by ∼60% but still producing only 39% as much fish bycatch as the current fishery (Table 1). By contrast, traps with reduced opening sizes would produce substantially more fish bycatch than unmodified traps during extended fishing seasons (Table 1).

Another possible way to reduce the negative effect of BRDs on prawn catch may be to adopt a flexible, site-dependent use of the devices. This would be highly unusual, since when BRDs are used to improve catch specificity, they are usually mandated for use across the entire fishery (Broadhurst *et al.*, 2012). However, the easily attachable design of our bent-tunnel devices could permit managers to require these devices only in areas where rockfish bycatch is known to be high, or where the tolerance for bycatch is low, such as in Rockfish Conservation Areas. A site-specific adoption rule could represent a compromise which would

Table 1. Adjusted fish bycatch rates for each trap design, accounting for the increased fishing effort which would be required to maintain existing catch rates, assuming full use of each BRD.

Design	Mean number of fish trap^{-1}	Average catch of prawns trap^{-1} (g)	Proportion of prawn catch trap^{-1} relative to unmodified design	Proportion of fishing effort required to maintain existing prawn catch	Fish bycatch relative to unmodified traps (%)
Unmodified	0.134	370	1.000	1.000	100.0
7.0 cm entrance	0.121	246	0.665	1.504	135.8
6.4 cm entrance	0.083	184	0.497	2.011	124.6
4-ring tunnel	0.084	192	0.519	1.927	120.8
5-ring tunnel	0.033	229	0.619	1.616	39.8
7-ring tunnel	0.033	174	0.470	2.126	52.4

enable prawn fishers to access RCAs, where prawn catches are sometimes high (BF, personal observations) while maintaining the purpose of the closed areas as refuges from rockfish extraction (Yamanaka and Logan, 2010).

In summary, we found that, as expected, simple reductions in entrance size did not reduce fish bycatch in the spot prawn fishery. In fact, if the fishery increased effort to compensate for the reduced prawn catches of these modified traps, fish bycatch could actually increase compared to the current fishery. However, tunnel-based BRDs appeared to be effective at excluding fishes, but in their current form also result in lower prawn catches that may be unacceptable to the fishing industry. Our *in situ* observations of deployed traps point to a potential modification to the tunnel BRDs that could mitigate the loss in prawn catch, but a redesigned BRD would need to be tested at a wide scale to verify its effectiveness. Recent studies have investigated gear modifications to reduce bycatch in traps, but these usually focus on enhancing escape rates of non-target species through various forms of escape hatches (Bury, 2011; Johnson, 2010; Boutson *et al.*, 2009) rather than preventing their entry. The much lower volume of work on BRD development for traps, compared to trawl and longline fisheries, may stem from the perceived high selectivity of traps. However, not all traps are highly selective (Alverson *et al.*, 1994), and in some ecosystems and regions, trapping is a major contributor to overall catch and bycatch (Mahon and Hunte, 2001; Shester and Micheli, 2011). Our study demonstrates that BRDs have the potential to reduce bycatch, even for gear with relatively high specificity, but the design of such devices should be underpinned by a thorough understanding of the behaviour, distribution, and physical characteristics of the target and non-target species.

Acknowledgements

Thank you to Corinna Lichota and Vin Fogarty for assistance with fieldwork, Douglas Braun, Sean Anderson, and Andrew Revill for statistical advice, and Rachel Charish, Leslie Hurteau, Kelsey Palis, and Meghan Ray for help with video analysis. Ocean Quest Dive Centre provided dive lights used for the video work. We thank Sewell's Marina and Parks Canada for providing moorage for *CJ Walters*.

Funding

BF was supported by a Natural Science and Engineering Council of Canada (NSERC) scholarship, and research was funded by the Pacific Prawn Fishers Association, the Ocean and Marine Fisheries Branch of the BC Government, the Mitacs Accelerate Program, the Andy Spencer Fellowship to SD, and NSERC operating grants to IMC (RGPIN 327010) and SD (CRDPJ 341335-06).

Supplementary data

Supplementary data are available at *ICES Journal of Marine Science* online.

References

Alverson, D. L., Freeberg, M. H., Pope, J. G., and Murawski, S. A. 1994. A global assessment of fisheries bycatch and discards. FAO, Fisheries Technical Paper 339.

Bauer, R. T. 2004. Remarkable Shrimps: Adaptations and Natural History of the Carideans. University of Oklahoma Press, Oklahoma City.

Berghahn, R., Waltemath, M., and Rijnsdorp, A. D. 1992. Mortality of fish from the by-catch of shrimp vessels in the North Sea. Journal of Applied Ichthyology, 8: 293–306.

Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H. H., and White, J. S. S. 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecology & Evolution, 24: 127–135.

Boutson, A., Mahasawasde, C., Mahasawasde, S., Tunkijjanukij, S., and Arimoto, T. 2009. Use of escape vents to improve size and species selectivity of collapsible pot for blue swimming crab *Portunus pelagicus* in Thailand. Fisheries Science, 75: 25–33.

Broadhurst, M. K., Brand, C. P., and Kennelly, S. J. 2012. Evolving and devolving bycatch reduction devices in an Australian penaeid-trawl fishery. Fisheries Research, 113: 68–75.

Bury, R. B. 2011. Modifications of traps to reduce bycatch of freshwater turtles. Journal of Wildlife Management, 75: 3–5.

Butler, T. H. 1980. Shrimps of the Pacific Coast of Canada, Dept. of Fisheries and Oceans, Ottawa.

Carlile, D. W., Dinnocenzo, T. A., and Watson, L. J. 1997. Evaluation of modified crab pots to increase catch of pacific cod and decrease bycatch of pacific halibut. North American Journal of Fisheries Management, 17: 910–928.

Chuenpagdee, R., Morgan, L. E., Maxwell, S. M., Norse, E. A., and Pauly, D. 2003. Shifting gears: assessing collateral impacts of fishing methods in US waters. Frontiers in Ecology and the Environment, 1: 517–524.

COSEWIC. 2009a. COSEWIC assessment and status report on the Quillback Rockfish Sebastes maliger in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. vii + 71 pp.

COSEWIC. 2009b. About COSEWIC. Committee on the Status of Endangered Wildlife in Canada. http://www.cosepac.gc.ca/eng/sct6/index_e.cfm (last accessed 23 May, 2012).

Davies, R. W. D., Cripps, S. J., Nickson, A., and Porter, G. 2009. Defining and estimating global marine fisheries bycatch. Marine Policy, doi:10.1016/j.marpol.2009.01.003.

Dillingham, P. W., and Fletcher, D. 2008. Estimating the ability of birds to sustain additional human-caused mortalities using a simple decision rule and allometric relationships. Biological Conservation, 141: 1783–1792.

FAO. 2002. Fishing technology equipments. Bycatch Reduction Devices (BRDs). *In* Technology fact sheets. FAO Fisheries and Aquaculture Department, Rome. http://www.fao.org/fishery/equipment/brd/en (last accessed 23 May, 2012).

Favaro, B., Lichota, C., Côté, I. M., and Duff, S. D. 2012. TrapCam: An inexpensive camera system for studying deep-water animals. Methods in Ecology and Evolution, 3: 39–46.

Favaro, B., Rutherford, D. T., Duff, S. D., and Côté, I. M. 2010. Bycatch of rockfish and other species in British Columbia spot prawn traps: Preliminary assessment using research traps. Fisheries Research, 102: 199–206.

Fisheries and Oceans Canada. 2007. Rockfish Conservation Areas – Protecting British Columbia's Rockfish. Fisheries and Oceans Canada, Pacific Region. http://www.pac.dfo-mpo.gc.ca/fm-gp/rec/restricted-restreint/rca-acs-eng.htm (last accessed 23 May, 2012).

Fisheries and Oceans Canada. 2011. Integrated fisheries management plan - Prawn and Shrimp by Trap, May 1 2011 to April 30 2012. http://www.dfo-mpo.gc.ca/Library/343253.pdf (last accessed 23 May, 2012).

Hall, S. J., and Mainprize, B. M. 2005. Managing by-catch and discards: how much progress are we making and how can we do better? Fish and Fisheries, 6: 134–155.

Hannah, R. W., Rankin, P. S., Penny, A. N., and Parker, S. J. 2008. Physical model of the development of external signs of barotrauma in Pacific rockfish. Aquatic biology, 3: 291–296.

Holst, R., and Revill, A. 2009. A simple statistical method for catch comparison studies. Fisheries Research, 95: 254–259.

Isaksen, B., Valdemarsen, J. W., Larsen, R. B., and Karlsen, L. 1992. Reduction of fish by-catch in shrimp trawl using a rigid separator grid in the aft belly. Fisheries Research, 13: 335–352.

Johnson, A. E. 2010. Reducing bycatch in coral reef trap fisheries: escape gaps as a step towards sustainability. Marine Ecology Progress Series, 415: 201–209.

Kampstra, P. 2008. Beanplot: a boxplot alternative for visual comparison of distributions. Journal of Statistical Software, Code Snippets, 28: 1–9. http://www.jstatsoft.org/v28/c01/ (last accessed 23 May, 2012).

Kelleher, K. 2005. Discards in the world's marine fisheries; an update. FAO Fisheries Technical Paper, 470: 131.

Kennelly, S. J., and Broadhurst, M. K. 2002. By-catch begone: changes in the philosophy of fishing technology. Fish and Fisheries, 3: 340–355.

Leaman, B. 1991. Reproductive styles and life history variables relative to exploitation and management of *Sebastes* stocks. Environmental Biology of Fishes, 30: 253–271.

Lewison, R. L., Nel, D. C., Taylor, F., Croxall, J. P., and Rivera, K. S. 2005. Thinking big - Taking a large-scale approach to seabird bycatch. Marine Ornithology, 33: 1–5.

Love, M. S., Yoklavich, M., and Thorsteinson, L. 2002. The Rockfishes of the Northeast Pacific. University of California Press, Berkeley and Los Angeles.

Mahon, R., and Hunte, W. 2001. Trap mesh selectivity and the management of reef fishes. Fish and Fisheries, 2: 356–375.

Meyer, D., Zeileis, A., and Hornik, K. 2011. VCD: Visualizing Categorical Data. R package version 1.2–12.

Nichol, D. G., and Chilton, E. A. 2006. Recuperation and behaviour of Pacific cod after barotrauma. ICES Journal of Marine Science, 63: 83–94.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., and Team, R. D. C. 2011. nlme: Linear and nonlinear mixed effects models. R package version 3.1–101.

Read, A. J. 2008. The looming crisis: Interactions between marine mammals and fisheries. Journal of Mammalogy, 89: 541–548.

Rutherford, D. T., Fong, K., and Nguyen, H. 2010. Rockfish Bycatch in the British Columbia Commercial Prawn Trap Fishery. DFO Canadian Science Advisory Secretariat Research Document 2009/109: 25.

Rutherford, D. T., Nguyen, H., and Boutillier, J. 2004. Assessment and management of spot prawn *Pandalus platyceros* along the British Columbia coast. Journal of Shellfish Research, 23: 658–659.

Ruxton, G. D. 2006. The unequal variance *t*-test is an underused alternative to Student's *t*-test and the Mann-Whitney *U* test. Behavioral Ecology, 17: 688–690.

Sala, A., Lucchetti, A., and Affronte, M. 2011. Effects of turtle excluder devices on bycatch and discard reduction in the demersal fisheries of the Mediterranean Sea. Aquatic Living Resources, 24: 183–192.

Sfakiotakis, M., Lane, D. M., and Davies, J. B. C. 1999. Review of fish swimming modes for aquatic locomotion. IEEE Journal of Oceanic Engineering, 24: 237–252.

Shester, G. G., and Micheli, F. 2011. Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets. Biological Conservation, 144: 1673–1681.

Shiode, D., and Tadash, T. 2004. A review of development, modification and implementation of TED (Turtle Excluder Device) to reduce sea turtle bycatch in trawl fisheries. FAO Fisheries Reports, 738: 171–177.

Skaug, H., Fournier, D., Nielsen, A., Magnusson, A., and Bolker, B. 2011. glmmADMB: Generalized linear mixed models using AD model builder. R package version 0.6.4.

Venables, W. N., and Ripley, B. D. 2002. Modern Applied Statistics with S, 4th edn. Springer, New York.

Wallace, B. P., Heppell, S. S., Lewison, R. L., Kelez, S., and Crowder, L. B. 2008. Impacts of fisheries bycatch on loggerhead turtles worldwide inferred from reproductive value analyses. Journal of Applied Ecology, 45: 1076–1085.

Ward, P., Lawrence, E., Darbyshire, R., and Hindmarsh, S. 2008. Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers. Fisheries Research, 90: 100–108.

Watkins, B. P., Petersen, S. L., and Ryan, P. G. 2008. Interactions between seabirds and deep-water hake trawl gear: an assessment of impacts in South African waters. Animal Conservation, 11: 247–254.

Whitney, W. D. 1911. The Century Dictionary: An Encyclopedic Lexicon of the English Language. The Century Company, New York.

Yamanaka, K. L., and Lacko, L. C. 2001. Inshore rockfish (*Sebastes ruberrimus, S. maliger, S. caurinus, S. melanops, S. nigrocinctus,* and *S. nebulosus*) stock assessment for the west coast of Canada and recommendations for management. Canadian Science Advisory Secretariat Research Document 2001/139: 102.

Yamanaka, K. L., Lacko, L. C., Lochead, J. K., Martin, J., Haigh, R., Grandin, C., and West, K. 2004. Stock assessment framework for inshore rockfish. Canadian Science Advisory Secretariat Research Document: 69.

Yamanaka, K. L., Lacko, L. C., Miller-Saunders, K., Grandin, C. L., Lochead, J. K., Martin, J. C., Olsen, N., and Wallace, S. S. 2006. A review of quillback rockfish *Sebastes maliger* along the Pacific coast of Canada: biology, distribution, and abundance trends. Canadian Science Advisory Secretariat Research Document 2006/077: 58.

Yamanaka, K. L., and Logan, G. 2010. Developing British Columbia's inshore rockfish conservation strategy. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 2: 28–46.

Zuur, A. F., Ieno, E. N., Walker, N., Saveliev, A. A., and Smith, G. M. 2009. Mixed Effects Models and Extensions in Ecology with R. Springer.

Handling editor: David Demer