



Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets

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ARTICLE INFO

Article history:

Received 11 August 2010
Received in revised form 31 January 2011
Accepted 21 February 2011
Available online 22 March 2011

Keywords:

Bycatch
Baja California
Coral
Kelp
Gillnet
Trap
Artisanal
Fishery

ABSTRACT

Small-scale fisheries provide over half the world's wild-caught seafood, employ over 99% of its fishers, and are frequently promoted as a sustainable alternative to large-scale industrial fisheries. However, few studies have quantitatively examined how possible habitat impacts and non-target species composition vary across gears used in small-scale fisheries, as data are sparse and conservation efforts are largely focused on more iconic species. Here, we quantify and compare the ecosystem impacts of four fishing gears (lobster traps, fish traps, set gillnets, drift gillnets) used in small-scale fisheries of Baja California, Mexico, using at-sea observations and field experiments. Set gillnets had the highest overall impact on both non-target species and habitat, with discard rates higher than most industrial fisheries (34.3% by weight), and an estimated 19.2% of *Eisenia arborea* kelp and 16.8% of gorgonian corals damaged or removed within 1 m of the net path. Fish traps had the lowest discard rates (0.1%) while lobster traps and drift gillnets had intermediate discard rates (15.1% and 18.5% respectively). In contrast with gillnets, traps caused minimal immediate damage to gorgonian corals and rarely interacted with kelp. Results indicate that ecological impacts depend more on fishing gear type and habitat characteristics than the size of fishing vessels, calling into question broad generalizations that small-scale fisheries are inherently more sustainable than industrial fisheries. Our findings highlight the ecological impacts of artisanal gillnet fisheries as priorities for research, management, and conservation efforts in Baja California and other coastal areas.

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1. Introduction

Most of what we know about the ecological impacts of specific fishing gears has come from studies of large-scale fishing operations from industrialized countries. Primary direct impacts include overexploitation of target species, incidentally caught bycatch, and impacts to benthic habitats (Dayton et al., 1995; Dulvy et al., 2003; Kappel, 2005). While there have been several studies worldwide on the impacts of artisanal fisheries particularly on marine turtles (e.g., Koch et al., 2006), seabirds (e.g., Moreno et al., 2006), and mammals (e.g., Amir et al., 2002; Lopez et al., 2003), studies remain sparse that compare bycatch compositions and habitat impacts of small-scale fishing gears used in the same habitat type. Small-scale fisheries (defined by vessels under 15 m long, mechanized or manual fishing gears, low relative catch per vessel, and dispersed, local ownership), provide over half of total global fisheries production and employ over 99% of the world's 51 million fishers (Berkes et al., 2001; Chuenpagdee et al., 2006). These fisheries often suffer

from competition with large-scale fisheries and lack of resources and infrastructure to monitoring and manage of exploited populations and ecosystems. Despite these shortcomings, some of the characteristics of small-scale fisheries, including the relatively low technology used for extraction, limited aerial extent of fishing, and capability for effective local governance (e.g., Jacquet and Pauly, 2008) are expected to lead to low ecological impacts, making small-scale fisheries 'our best hope for sustainable utilization of coastal marine resources' (Pauly, 2006).

A major documented ecological impact of fisheries occurs through bycatch. Bycatch, or the incidental catch and discarding of undesired organisms in a fishery, occurs when fishing gear catches unwanted species whose retention is either not economical or prohibited by law (Dayton et al., 1995). Bycatch in commercial fisheries can cause severe impacts to marine populations including sea turtles (Spotila et al., 2000; Lewison et al., 2004; Peckham et al., 2007), marine mammals (Mangel, 1993), seabirds (Zydelis et al., 2009), skates (Brander, 1981; Casey and Myers, 1998), corals (Anderson and Clark, 2003), and entire marine ecosystems (Dayton et al., 1995; ICES, 1995). For fisheries where discard reporting exists, discard rate estimates vary widely by gear type (Kelleher, 2005). While some fisheries have negligible levels of discards, other fisheries discard more than they retain

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(e.g. Mexican Pacific shrimp trawl fishery discards 76.4%, (Bojorquez, 1998).

In addition to discards, some fishing gears can remove or damage benthic structures that form habitat for marine life. The impacts of bottom trawling on seafloor habitats are well studied (Johnson, 2002) and found to reduce the complexity, diversity, and productivity of benthic habitats (Watling and Norse, 1998; NRC, 2002). Biogenic structures in the marine environment, including algae, seagrass, corals, and sponges, are among the most sensitive habitats to fishing gear impacts. Cold-water corals in particular have come to the attention of policymakers because of their sensitivity to human impacts, long lifespan, and ecological importance (Krieger and Wing, 2002; Freiwald et al., 2004; Roberts and Hirshfield, 2004; Love et al., 2007). Impacts to gorgonian corals are a focus of this study because they are found throughout the world's oceans from the tropics to the poles, and their three-dimensional structure makes them widely indicative of fisheries impacts across a broad range of habitat types.

Small-scale fisheries are generally assumed to have a low or negligible discard rate (3.7% of total catch in aggregate) (Kelleher, 2005), but recent studies suggest that wide variation in bycatch rates may exist, with some small-scale fisheries having levels of discards that have the potential to extirpate some populations of megafauna (D'agrosa et al., 2000; Voges, 2005; Peckham et al., 2007). Similarly, studies on the habitat effects of artisanal fishing gears, particularly traps and gillnets, have been sparse and results have been mixed (Breen, 1989; ICES, 1995; Erzini et al., 1997; Quandt, 1999; Appeldoorn et al., 2000; Stephan et al., 2000; Eno et al., 2001) creating uncertainty regarding how to manage these activities.

Small-scale fisheries employ a wide variety of gear types, including traps, set gillnets, and drift gillnets, which vary in the way they interact with marine ecosystems (e.g., Morgan and Chuenpagdee, 2003). Comparing the impacts across different fishing gears used by the same fishing community is important because it can help communities make decisions about the “portfolio” of activities they choose to engage in. In addition, such comparisons may highlight potential negative interactions among fisheries, either directly through bycatch of commercial species targeted in another fishery or indirectly through damage to habitats used by species targeted in another fishery.

In this study, we quantify and compare for the first time the potential impacts of four artisanal fishing gear types (lobster traps, fish traps, set gillnets, and drift gillnets) in terms of their bycatch and impacts to benthic habitats. The lobster fisheries of this region use only traps and are managed through effort control, size limits, area-based concessions, and seasonal closures. These fisheries were the first small-scale fisheries from a developing country to be certified as sustainable by the Marine Stewardship Council, which assess the stock status of target species, ecosystem effects, and management regime of commercial fisheries (Lopuch, 2008; Phillips et al., 2008). As a condition of certification, the fisheries were required to collect data on the bycatch and habitat impacts of the lobster traps. In contrast, no management plan or concession exists for the finfish fisheries. We conducted fisheries observations and field experiments in two fishing cooperatives located within the Vizcaino Desert Biosphere Reserve in the Pacific region of Baja California Sur, Mexico, characterized by a temperate to sub-tropical kelp forests and rocky reefs. We asked: (1) if bycatch and habitat impacts of lobster fishing are negligible, as assumed in the spiny lobster fishery certification assessment (SCS, 2004); (2) whether finfish fisheries have significant ecological impacts, how these might vary depending on the gear used, and how they compare with possible impacts of the certified lobster fisheries; and (3) if interactions among these fisheries occur through bycatch or impacts on benthic habitat used by the target species.

2. Methods

2.1. Bycatch quantification

To quantify the amount and composition of bycatch in each fishery we observed 106 distinct fishing trips between January and November 2006 allocated across the four fisheries (Table 1; see Appendix A). We adopt the definition of bycatch of the US National Marine Fisheries Service (MSA, 1996) to include all organisms that are caught in fishing gear, but not kept for sale or personal consumption. With the exception of some lobster fishing trips observed in Bahía Tortugas, all observations took place in the Punta Abreojos Fishing Cooperative.

On each fishing trip, we recorded the size, species, and fate of all organisms caught, then estimated their biomass from known size-weight conversions based on the equation: $Biomass = a \cdot Length^b$. For fish, we used total length-weight conversions (a and b constants) from Froese and Pauly (2008) to convert length to biomass, and used available estimates from the literature for invertebrates, rocks, and algae (see Appendix B).

We quantified discard rates for each gear type in three different ways: (1) as the percent discarded by number of individuals; (2) as the percent of total biomass caught; and (3) as bycatch biomass per unit revenue from the sale of market species. For bycatch per unit revenue, we used our observed discards and all reported landings to the cooperative on each trip, which we received from the cooperative production manager. To calculate revenue, we used prices the cooperative received for each species in July 2006 and the exchange rate at the time of 11.13 pesos/USD. Discarded species were not counted toward revenue.

For trap fisheries, we analyzed discard rates excluding sub-legal target species as these are discarded live as mandated by fishing regulations (Kelleher, 2005). We divided discards into seven categories: finfish, elasmobranchs, bait species, habitat-formers, other invertebrates, seabirds, and marine mammals (Table 2). Estimates of bycatch were compared among gear types using one-way ANOVAs, with gear type as the fixed factor and fishing trips as replicate observations. To assess the potential vulnerability of different finfish and elasmobranch populations to mortality associated with bycatch, we used the relative vulnerability estimates provided by Cheung et al. (2005). Cheung et al. (2005) combined several life history and ecological characteristics of species (i.e. fecundity, lifespan, and geographic range) into a relative index (on an arbitrary scale of 1–100) of intrinsic extinction vulnerability to fishing that correlates well with observed declines of some species. We quantified the composition of the fish catch in each of four vulnerability categories: low, medium, high, and very high as assigned by Cheung et al. (2005) and report bycatch by biomass and number of individuals per unit revenue in each of these categories.

2.2. Habitat impact assessment: field experiments

To examine the possible impacts of lobster traps and set gillnets on benthic habitat, we conducted field experiments in two rocky

Table 1

Total fishing effort observed by onboard researchers in this study to obtain bycatch rates, broken down by the four gear types in terms of quantity of gear use and number of fishing trips.

Gear type	Gear use observed	Trips observed
Lobster traps	4940 Traps set ~24 h each	56
Fish traps	502 Traps set ~30 min each	16
Set	83 Daily net deployments and retrievals (total 13,600 m of net)	30
gillnets	4 Overnight net deployments and retrievals (1400 m each)	4

Table 2

Total discard biomass (kg) per \$1000 of fishery revenue generated by each gear type on observed trips.

Species name	Common name	Lobster traps	Fish traps	Set gillnets	Drift gillnets
Finfish		–	–	–	–
<i>Anisotremus davidsoni</i>	Xantic sargo	0.010	–	1.007	0.070
<i>Anisotremus interruptus</i>	Burrito grunt	–	–	8.110	–
<i>Antennarius avalonis</i>	Roughjaw frogfish	0.004	–	–	–
<i>Atractoscion nobilis</i>	White sea bass	–	–	0.294	–
<i>Balistes polylepis</i>	Finescale triggerfish	0.012	–	–	–
<i>Brotula clarkae</i>	Brotula	–	–	0.101	–
<i>Calamus brachysomus</i>	Pacific porgy	0.054	–	1.472	1.188
<i>Caulolatilus princeps</i>	Ocean whitefish	–	*	0.299	–
<i>Cheilotrema saturnum</i>	Black croaker	–	–	0.041	–
<i>Chromis punctipinnis</i>	Blacksmith	–	0.026	0.065	–
Cottidae	Sculpin	–	–	0.130	0.133
<i>Embiotoca jacksoni</i>	Black surfperch	–	0.098	1.499	–
<i>Epinephelus</i> spp., <i>Mycteroperca</i> sp.	Grouper	0.020	–	0.129	–
<i>Girella nigricans</i>	Opaleye	–	–	3.282	–
<i>Gymnothorax mordax</i>	California moray	0.045	0.485	–	–
<i>Halichoeres semicinctus</i>	Rock wrasse	0.001	–	–	–
<i>Hypsypops rubicundus</i>	Garibaldi	0.006	–	6.746	–
<i>Kathetostoma averruncus</i>	Smooth stargazer	–	–	1.275	0.332
<i>Lepophidium prorates</i>	Cusk eel	–	–	0.033	–
<i>Medialuna californiensis</i>	Half-moon	–	–	0.731	–
<i>Microlepidotus inornatus</i>	Wavyline grunt	–	–	0.023	0.058
<i>Ophioscion strabo</i>	Squint-eyed croaker	0.005	–	0.152	–
<i>Paralabrax clathratus</i>	Kelp bass, calico bass	0.008	–	0.008	–
<i>Paralabrax nebulifer</i>	Barred sand bass	0.016	*	0.235	0.820
<i>Paralichthys californicus</i>	Halibut	0.019	–	2.632	0.050
<i>Pepilus</i> sp.	Harvestfish	–	–	–	0.021
<i>Pleuronectiformes</i>	Other flatfish	–	–	0.147	–
<i>Porichthys notatus</i>	Plainfin midshipman	–	–	0.669	0.030
<i>Pristigenys serrula</i>	Popeye catalufa	–	–	32.233	–
<i>Cynoscion parvipinnis</i>	Weakfish	–	–	0.140	–
<i>Scorpaena guttata</i>	California scorpionfish	0.144	0.460	0.415	–
<i>Scorpaenichthys marmoratus</i>	Cabezon	0.025	–	–	–
<i>Sebastes</i> sp.	Rockfish	–	–	8.092	0.023
<i>Sebastes umbrosus</i>	Honeycomb rockfish	–	0.032	0.038	–
<i>Semicossyphus pulcher</i>	California sheephead	0.517	0.083	0.467	–
<i>Seriola lalandi</i>	Yellowtail amberjack	0.130	–	–	–
<i>Sphaeroides annulatus</i>	Bullseye puffer	–	–	0.182	–
<i>Sphyræna argentea</i>	Pacific barracuda	–	–	0.856	4.225
<i>Stereolepis gigas</i>	Giant sea bass	–	–	0.443	–
<i>Synodus lucioceps</i>	California lizardfish	–	–	16.501	–
Subtotal		1.016	1.185	88.448	6.949
Bait fish					
<i>Sarda chiliensis chiliensis</i>	Eastern Pacific bonito	–	–	–	–
<i>Sardinops sagax</i>	Pacific sardine	–	–	0.038	0.517
<i>Scomber japonicus</i>	Pacific mackerel	–	–	0.030	0.879
Subtotal		0.000	0.000	0.068	1.397
Elasmobranchs					
<i>Cephaloscyllium ventriosum</i>	Swell shark	0.025	–	1.049	–
<i>Gymnura marmorata</i>	California butterfly ray	–	–	0.199	–
<i>Heterodontus francisci</i>	Horn shark	0.358	–	18.560	3.377
<i>Mustelus</i> sp.	Smoothhound	–	–	2.240	0.079
<i>Myliobatis californica</i>	Bat eagle ray	0.020	–	12.770	2.998
<i>Platyrhinoidis triseriata</i>	Thornback guitarfish	–	–	1.296	–
<i>Pteroplatytrygon violacea</i>	Pelagic sting ray	–	–	0.048	–
<i>Raja rhina</i>	Longnose skate	–	–	18.413	–
<i>Rhinobatos productus</i>	Shovelnose guitarfish	–	–	0.018	–
<i>Sphyrna</i> sp.	Hammerhead shark	–	–	–	0.918
<i>Squalus acanthias</i>	Spiny dogfish	–	–	2.852	–
<i>Torpedo californica</i>	Pacific electric ray	–	–	0.672	–
<i>Urolophus halleri</i>	Haller's round ray	–	–	0.023	–
<i>Zapteryx exasperate</i>	Banded guitarfish	–	–	20.997	–
Subtotal		0.402	0.000	79.137	7.372
Invertebrates					
Anomura	Hermit crab	0.008	–	0.008	–
Bivalvia	Clam	0.000	–	0.042	–
<i>Callinectes sapidus</i>	Blue crab	0.242	–	–	–
<i>Cancer anthonyi</i>	Yellow crab	1.708	–	0.664	–
Sea cucumber	Cucumber unid.	–	–	0.001	–
<i>Eucidaris thourasii</i>	Pencil urchin	–	–	0.087	–
Gastropoda	Other snail	0.032	–	–	–
<i>Kelletia kelletia</i>	Kellet's whelk	0.012	–	–	–
<i>Lopholithodes</i> sp.	Box crab	1.004	–	–	–

(continued on next page)

Table 2 (continued)

Species name	Common name	Loxosteira traps	Fish traps	Set gillnets	Drift gillnets
<i>Loxorhynchus crispatus</i>	Moss crab	0.478	–	–	–
<i>Megastraea undosa</i>	Turban snail	0.015	–	0.048	–
<i>Octopus</i> sp.	Octopus	0.021	–	0.278	0.014
<i>Panulirus argus</i>	Caribbean lobster	0.005	–	0.278	–
<i>Panulirus interuptus</i>	Red spiny lobster	*	–	11.910	–
<i>Pugettia producta</i>	Northern kelp crab	0.118	–	–	–
<i>Taliepus nuttallii</i>	Southern kelp crab	0.005	–	–	–
Unidentified crab	Mariachi crab	0.005	–	–	–
Subtotal		3.654	0.000	13.316	0.014
Habitat-formers					
<i>Cystoceira osmundacea</i>	Cystoceira kelp	–	–	2.324	–
<i>Eisenia arborea</i>	Southern sea palm	0.038	–	32.642	–
Gorgonacea	Gorgonian coral	0.001	–	0.124	–
Other algae	Other algae	–	–	0.415	–
<i>Phyllospadix</i> sp.	Sea grass	0.010	–	1.568	–
Porifera	Sponge	–	–	0.369	–
Rocks/substrate	Rock	–	–	82.524	–
Subtotal		0.049	0.000	119.966	0.000
Seabirds-marine mammals					
<i>Phalacrocorax pelagicus</i>	Cormorant	0.369	–	0.648	–
<i>Tursiops truncatus</i>	Bottlenose dolphin	–	–	–	36.018
<i>Zalophus californianus</i>	California sea lion	–	–	17.140	–
Subtotal		0.369	0.000	17.788	36.018
Total		5.490	1.185	318.723	51.751

* Regulatory discards of sub-legal target species in trap fisheries omitted.

reefs, Piedra de Layo (N26.72° W113.53°) and Piedra Zúñiga (N26.69° W113.57°), in the Punta Abreojos Cooperative concession area. In all reefs in this area, abundant large (>30 cm in height) gorgonian corals (*Muricea californica*, *Eugorgia daniana*, *Eugorgia ampla*, *Leptogorgia diffusa*, and *Pacificogorgia* sp.; O. Breedy, University of Costa Rica, personal communication), and the Southern sea palm kelp, *Eisenia arborea* (1–2 m in height) form complex three-dimensional habitat hosting a diversity of commercial and non-commercial species. To characterize these habitats, on four randomly placed 10 m transects across the study site, substrate type, vertical relief, and benthic organisms were recorded every 50 cm through Universal Point Counts, and all *Eisenia*, gorgonians, and sponges were counted along a width of 2 m (Table 3).

Initial trials placing traps on *Eisenia* led us to conclude that this species appears to withstand the force of a dropped trap and therefore, we focused on gorgonian corals to examine ‘worst-case’ scenario effects on the habitat features most sensitive to contact. While diving, we observed traps deployed from a boat at the surface, floating slowly to the seabed. To simulate crushing of gorgonians by traps deployed from boats in a worst-case scenario, a diver lifted and forcefully dropped traps on top of gorgonian corals to ensure the traps were at a greater velocity and force than traps deployed by boat. The other diver recorded the trial with in situ video for a total of 37 distinct replicates. During preliminary observations of the lobster fishery, we found that fishermen occasionally drag traps intentionally once deployed to achieve more precise placement. After observing the speed and angle which traps were dragged from a boat while diving, the divers conducted treatments to replicated the speed and angle which we observed from a boat. In five additional trials, the divers pulled a trap at a similar angle by

the line over the corals, to simulate dragging of traps on the bottom by boats. After each treatment, we examined all the gorgonian corals in the area for immediate signs of skeletal damage or tissue loss. Damage was classified into categories of less than 10%, between 10% and 50%, and greater than 50% of tissue damaged, for each colony.

To assess possible habitat impacts of gillnets, we conducted in situ observations of eight set gillnets being lifted at the two field sites, using scuba. Seven gillnets were 100 m long and one was 300 m long. The nets were composed of monofilament plastic with a 17.8-cm (7-in) mesh, which are the most commonly used net type in this cooperative. Set locations ranged from 5 to 22 m depth and bottom type ranged from sandy bottom to bedrock. Divers followed and video-recorded the net as it was pulled off the seafloor. Researchers on the boat hauling the net identified, counted, and measured the longest linear distance across each organism.

In the laboratory, we analyzed videos to describe the environmental context for each net set and the interactions of nets with the seafloor and associated species. First, we determined the size and abundance of the *Eisenia* and gorgonians within one m of the net. A one m distance was selected to account for some net movement resulting from currents. Within the 889 m² area observed, mean densities were 0.75 *Eisenia* plants/m² (SE = 0.18) and 0.37 gorgonian colonies/m² (SE = 0.15). *Eisenia* kelp plants averaged 90.4 cm (SE = 1.0 cm) in height and gorgonian corals averaged 20.9 cm (SE = 0.8 cm) in height.

Second, we estimated the percentage of substrate type (sand, pebbles <10 cm, boulders 10–100 cm, and rock >100 cm) along the length of the net, for each set. Visual distance estimates were made by calibrating known spacing of weights on the net. Because

Table 3

Habitat characteristics of study site for trap experiments based on swath, UPC, and percent cover transects. Mean values shown with standard deviation.

Habitat-forming organisms (#/m ²)	Vertical relief within 1 m	Benthic cover (quadrats)	Substrate type
<i>Eisenia</i> kelp	0.14 ± 0.05	0–10 cm 93 ± 6%	Red coralline algae 23 ± 9% Sand 65 ± 16%
Gorgonian corals	0.18 ± 0.12	10–100 cm 7 ± 6%	Articulated coralline algae 55 ± 16% Cobble 30 ± 21%
Sponges	0.00 ± 0.00	>100 cm 0 ± 0%	Fleshy red algae 3 ± 6% Boulder 5 ± 6%
–	–	–	Bare 20 ± 12% Rock 0 ± 0%

we did not video-record the entire length of net, we kept track of the actual length of net documented and area observed for density calculations. These data showed that substrate composition was generally similar among experimental trials.

Third, we estimated the percent of the observed net that lay directly on the sea floor, was suspended within 2 m of the seafloor, and was suspended over 2 m from the seafloor (out of interaction range with *Eisenia*). In some cases, the *Eisenia* canopy obscured the underlying seabed, so the total area where *Eisenia* was counted was greater than the seafloor area observed for other species.

Finally, we recorded each time the net interacted with an organism by pushing against it or entangling it. Cases where organisms were touched but not tangled or pushed were not counted as interactions. In cases where the entire outcome of an interaction after the net was lifted was captured on video, the immediate damage resulting of each interaction was classified in categories of no damage, partial damage (less than 10% of organism removed, between 10% and 50% of organism removed, over 50% of organism removed), and entire removal.

3. Results

3.1. Bycatch variation among gear types

We found significant differences in the magnitude of bycatch across gear types both in terms of biomass (ANOVA, $F_{3,98} = 15.0$, $p < 0.001$) and abundance of organisms ($F_{3,98} = 36.6$, $p < 0.001$) (Fig. 1A). Set gillnets had the highest mean bycatch rates per trip. Drift gillnets and lobster traps overall have intermediate bycatch rates compared to the other gears (Fig. 1A). In post hoc pairwise comparisons, using a Bonferroni adjustment for multiple testing, all pairs were significantly different in terms of number of individuals ($p < 0.05$) except for drift gillnets and set gillnets. In contrast, fish traps have the lowest bycatch rates as very few individuals other than the two target species, ocean whitefish (*Caulolatilus princeps*) and barred sand bass (*Paralabrax nebulifer*), were caught in the trips we observed (Fig. 1A and Table 2).

Differences in bycatch rates among the gear types are even more pronounced when bycatch is quantified relative to revenue (ANOVA: $F_{3,98} = 13.06$, $p < 0.001$) (Fig. 1B). Set gillnet discards per unit revenue are significantly higher than for lobster traps or fish traps, but not significantly different from drift gillnets ($p < 0.05$).

The taxonomic composition of bycatch differed greatly among gear types (Fig. 2). Fish trap discards were composed exclusively of finfish species. Lobster traps, on the other hand were primarily crabs and other invertebrates (e.g., *Octopus* sp. and the snails *Megastraea undosa* and *Kelletia kelletii*), along with some cormorants (36 individuals caught in the 4940 traps observed), elasmobranchs and finfish (Table 2). While we did not quantify mortality rates, we anecdotally observed that the vast majority of discarded crabs were alive. Two bottlenose dolphins (*Tursiops truncatus*) were caught in drift gillnets. These large marine mammals vastly outweighed the other bycatch species. If these two large specimens are eliminated, drift gillnet bycatch rates are 19.9 kg/\$1000 revenue (SE = 10.4 kg/\$1000), 35.1% (SE = 5.0%) by number of individuals, and 4.02% (SE = 1.79%) by biomass. Other species caught as bycatch included finfish and elasmobranchs (Table 2). Set gillnet fishers discarded a wide diversity of species, including habitat-formers (e.g., *Eisenia* kelp and gorgonians), elasmobranchs, invertebrates (including spiny lobster, *Panulirus interruptus*), finfish, and California sea lions (*Zalophus californianus*) (Table 2).

In terms of highly vulnerable fish species, set gillnet fishers discarded 86.2 kg or 126.6 individuals per \$1000 revenue representing 29 species, while drift gillnet fishers discarded 13.7 kg or

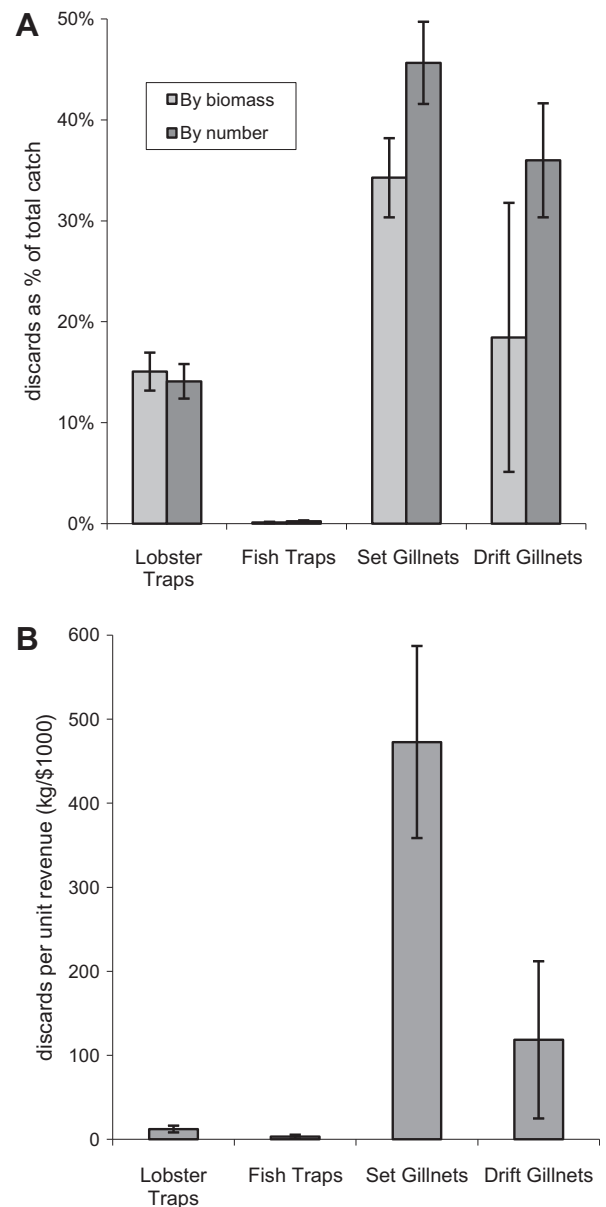


Fig. 1. Mean discard rate of observed trips with each gear type as a percentage of total catch, in terms of biomass and number of individuals (A). Mean discard rates in terms of biomass per unit revenue (B). Error bars show standard error of the mean.



Fig. 2. Discard composition by species group for each observed fishery quantified by biomass.

16.4 individuals representing nine species (Fig. 3). The rates of highly vulnerable fish bycatch in both of the trap fisheries were an order of magnitude lower than drift gillnets and two orders of magnitude lower than set gillnets (Fig. 3).

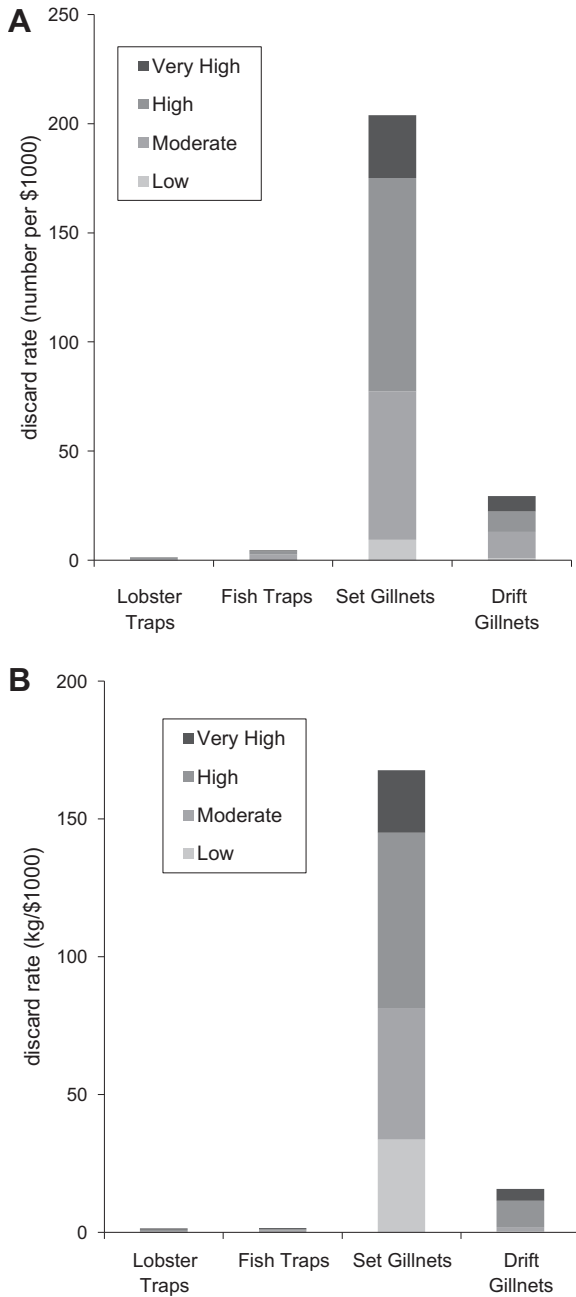


Fig. 3. Discard rates of fish and elasmobranch species grouped by their vulnerability category as defined by Cheung et al. (2005), by number of individuals (A) and biomass (B) per unit revenue.

3.2. Impacts of traps and gillnets on benthic habitat

Treatments of lobster traps dropped onto gorgonian corals appeared to have minimal impacts. In only one of 37 trials, some damage (less than 1% of the colony) was observed to the yellow gorgonian coral *Eugorgia ampla* (Fig. 4A). Dragging of traps on the seafloor caused damage to the corals significantly more frequently than crushing (Chi square = 9.238, df = 1, $p < .01$), though the damage was never over 5% of the skeleton (Fig. 4A). No corals were detached from the seafloor in any of the trials.

In contrast with traps, we observed set gillnets tangle and remove *Eisenia* kelp plants and gorgonian corals. During our in situ observations of the interaction of set gillnets with the seafloor, the net was in contact with the seafloor 43% of the time, suspended within 2 m of the seafloor 53% of the time, and above

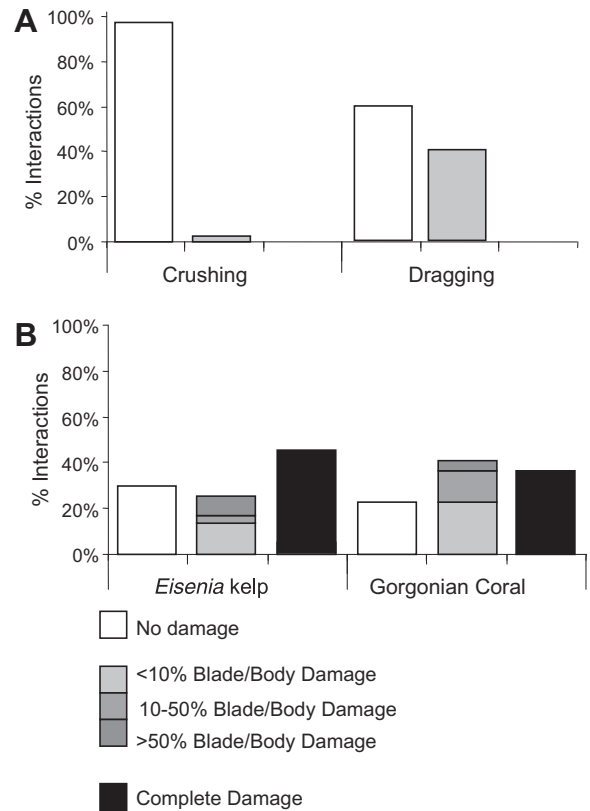


Fig. 4. (A) Outcomes of in situ experimental crushing and dragging treatments of lobster traps. (B) Outcomes of diver-observed interactions of set gillnets on *Eisenia* kelp and gorgonian corals.

2 m from the seafloor 4% of the time. In the eight nets we observed, set gillnets interacted with a mean of 27.4% (SE = 11.0%) of *Eisenia* and 21.7% (SE = 8.8%) of gorgonians within one meter of the net path.

A majority of interactions between nets and habitat-forming species resulted in organisms removal or partial damage. Of 60 observed interactions of set gillnets with *Eisenia*, 45.0% resulted in full removal, 25.0% in partial damage, and 30.0% in no visible damage (Fig. 4B). Of 22 coral interactions, 36.4% resulted in full removal, 40.9% in partial damage, and 22.7% in no damage (Fig. 4B). Set gillnets damaged or removed gorgonians significantly more often than traps (Chi square = 33.05, df = 1, $p < 0.001$) and the damage per interaction was more severe (Fig. 4). Set gillnets damaged or removed, on average, 19.2% of all *Eisenia* and 16.8% of all gorgonians within 1 m of the net path.

Our in situ observations indicate that, of the organisms that were completely removed by the net, 14.8% *Eisenia* plants and 1.7% fish and other invertebrates fell out as the net was being lifted. Moreover, for every total removal of *Eisenia*, there were 0.6 partial damages, and for every total removal of gorgonian coral, there were 1.1 partial damages. These ratios can be used to adjust observer data to extrapolate the total and partial damage. In particular, such adjustment increases our bycatch estimates for habitat-forming species from 37.6% to 40.8% of set gillnet total catch, though such extrapolations should be interpreted with caution.

4. Discussion

Our initial comparison of the ecosystem impacts of fishing gears commonly used in small-scale fisheries supports earlier generalizations that traps are generally more benign in terms of their impacts than gillnets, and confirms that set gillnets are a major

conservation concern. We conducted this study in a temperate kelp forest habitat with relatively flexible biogenic structures and found traps appeared to have negligible effects on benthic invertebrates and algae. Relative to traps, set and drift gillnets have significantly more bycatch and set gillnets cause significantly more damage and removals of corals and kelp plants.

In particular, we found that the mean discard rate we quantified for set gillnets (34.3% by weight) is higher than the global average discard rates for all industrial fishing gears in the FAO discard database except shrimp trawls (Kelleher, 2005). The findings that gillnets have higher discard rates than traps is likely to be widely applicable to systems with a diverse assemblage of fish species, since gillnet selectivity is based on fish size while traps select both on size and feeding preferences. However, use of gillnets in areas of high relative concentrations of target species (e.g., spawning herring, salmon returning to natal rivers) typically has lower bycatch rates of non-target species (e.g., Vander Haegen et al., 2002). Our results on the rate of kelp and gorgonian impacts by set gillnets within the contacted area are on par with published removal rate estimates of living structures (20% median estimate in NMFS, 2005) and hard corals (27% estimate in Krieger, 2001) resulting from a single pass of a bottom trawl. The branched nature of the kelps and corals damaged by gillnets in this study suggests that gillnets would have similar impacts in other habitats where tangling might occur. For example, we would expect gillnets to damage and remove other branched biogenic structures including kelps, sponges, and corals, though significant damage or removal to seagrasses would be less plausible.

Our estimates and previous studies thus indicate that the ecological impacts of small-scale fisheries can be severe (e.g., D'agrosa et al., 2000; Peckham et al., 2007), and even comparable to those of large-scale industrial fisheries on a per unit of catch basis. The type and severity of impacts appear to depend more on the technology of fishing gear and the nature of its interactions with marine species and habitats than the size of fishing vessels. However, while gillnets may have impacts per unit surface area comparable to trawlers, the size of small-scale fishing vessels may likely limit the overall area and depth range affected and hence the cumulative ecosystem impacts.

Lobster traps and fish traps had the lowest impacts, particularly when considered relative to the economic value of the target species. The post-release mortality of discarded organisms was not quantified in this study and likely varies among species and gear types. However, lobster traps have relatively low bycatch rates and minimal impacts on the most vulnerable biogenic habitats, supporting earlier conclusions that habitat and bycatch impacts of traps are expected to be non-significant in the Baja California spiny lobster fishery (SCS, 2004). Yet, while we observed no interactions between traps and marine mammals in this study, we did observe interactions between seabirds and lobster traps, resulting in 100% mortality rates of trapped cormorants. Such interactions had not been highlighted in the certification assessment (SCS, 2004), as the recognized impacts on seabirds elsewhere are primarily from longlines, trawls, and gillnets. Future studies should investigate the possibility of trap interactions with seabirds when set in waters in proximity to seabird concentrations and within the depth range at which birds can dive.

Drift gillnet contact with the seafloor is likely to be infrequent as they are designed to drift through the upper water column, but may have significant impacts through bycatch. Our estimates for drift gillnets should be taken cautiously as we only observed four trips. Despite the few trips observed we found drift gillnet discard rates of high vulnerability fish were an order of magnitude higher than the trap fisheries (Fig. 3) and we observed mortality to marine mammals (Table 2), highlighting drift nets as a priority for further study and management measures.

Based on total catch and effort estimates for 2006, we speculate that set gillnets potentially contacted 236,500 m² of the seabed within this cooperative, representing up to 10% of the total rocky reef in these concessions (C. Abshire, Unpublished results). This worst-case estimate sets an upper bound of two percent damage to the total estimated populations of kelp and corals within each of the Vizcaino region concessions per year, depending on the extent of reef area and fishing effort. However, if set gillnets are preferentially placed in areas with disproportionately higher abundances of biogenic habitats or in areas of high biological importance (i.e. spawning grounds) the relative impacts to species abundance or ecosystem functions could be larger.

Further efforts to assess the population-level impacts of our reported habitat damage rates should consider the total effort in each fishery and compare natural mortality rates with the impacts of anthropogenic disturbance. Dayton et al. (1998) found highly variable winter mortality rates ranging from 4% to 100% for the giant kelp *Macrocystis pyrifera*, caused by storm events, grazing, and the El Niño Southern Oscillation. Damage and removal of *Eisenia* by set gillnets may be well below those associated with natural disturbance and unlikely to result in major deforestation at current levels of fishing effort, especially when compared to other threats such as predation and climate change (Steneck et al., 2002).

In contrast, studies of cold-water gorgonian corals have found high longevity from decades to centuries suggesting extremely low recovery rates (Andrews et al., 2005; Roark et al., 2007; Tracey et al., 2007). Such low recovery rates suggest that long-term impacts of fishing can be significant even at low levels of effort (NMFS, 2005). In addition, partial damage to gorgonians caused by fishing gears have been shown to facilitate harmful algal growth on the tissue scars (Van der Knapp, 1993). The possibility of negative impacts on gorgonians remains and should be investigated further, in this and other coastal ecosystems, with long term studies following the fate of individual colonies affected, and the rates at which colonies removed by nets are replaced by new recruits.

5. Conclusions

While previous studies of artisanal fisheries impacts focus largely on impacts to marine megafauna (mammals, seabirds, and turtles), this study broadens our understanding to other key ecosystem components, particularly non-target fish, invertebrates, and biogenic habitat structures. These ecosystem components are important in shaping community structure and fishery productivity, yet with few exceptions are typically not afforded the attention or legal protections (e.g., endangered species listings) given to more iconic or valuable species. The observer data and habitat impact experiments conducted for the nearshore Mexican fishing gears identified several potentially important interactions among fisheries co-occurring in the same area. Since fishing cooperatives in this region tend to organize and provide local management over the suite of fisheries that occur in the same coastal habitats, an awareness of such interactions among fisheries can help inform decisions regarding how to allocate fishing effort across fishing gears. This study highlighted one key benefit of independent sustainability certification in an artisanal fishery, which provided the impetus for a collaborative research effort that provided valuable data allowing relative comparison of the ecosystem impacts of gear choices. For every \$1000 in revenue, set gillnet fisheries discarded an estimated 11.9 kg of lobsters, worth \$256. Set gillnets also potentially affected habitats on which other target species depend. For example, *Eisenia* kelp is a primary food source for abalone, which is among the most valuable fisheries in the region (Guzmán del Proó, 1992). While the actual impacts of gillnets on non-target populations and whole ecosystems remains to be assessed, this study identifies set gillnets in particular as a priority

conservation concern because they have the potential to affect a wide variety of species through bycatch and are the only gear type used in this region to damage and remove habitat-forming species. At the same time, set gillnets also appear to be less profitable than other gears as the mean ex-vessel revenues per observed trip were \$1388 for drift gillnets, \$338 for fish traps, and \$279 for set gillnets. Therefore, reducing the impacts of set gillnets would likely be the most cost-effective way to improve the sustainability of these cooperatives' cumulative fishing operations. Since many set gillnet fishers also participate in lobster and/or abalone fisheries in this region, there already exist incentives in place to reduce the impacts of gillnets to the extent they perceive a negative impact on these other more valuable fisheries. This study also highlights the broader value of sustainability certifications for providing incentives for artisanal resource users to participate in research that takes a closer look at the ecosystem impacts of alternative practices.

Changes to the way gillnets are set could help reduce the bycatch of some groups of discarded species. For example, Melvin et al. (1999) showed that a combination of gear modifications, abundance-based fishery openings, and time-of-day restrictions could reduce seabird bycatch up to 75% without a significant reduction in target fishing efficiency in a coastal drift gillnet fishery in Puget Sound, Washington. Moreover, California halibut, the major target species in the set gillnet fishery, can also be caught with hook and line techniques, which are likely to be more selective but perhaps not as profitable as set gillnets (Haseltine and Thornton, 1990). However, the lack of area-based concessions for finfish fisheries may prevent the cooperatives from being able to implement such solutions, as the incentives are likely eroded by the incursion of outside fishers (McCay and Acheson, 1987).

Overall, our results suggest that the collateral impacts of fisheries are influenced by the nature of the fishing gears used and the susceptibility of the species and habitats where they are used. The methods used in this study provide a way to compare some of the more common ecological impacts of fisheries across fishing gears in a manner in which fishers can actively participate. Determining the most appropriate gear types to use to target the suite of available commercial species in a particular area should consider the various gears' selectivity for target species, the nature of the gear interactions with habitat features, the inherent vulnerability of various non-target species, and ultimately the trade-offs between minimizing unintended ecological impacts and reducing profits. Answering these questions for the multitude of data poor, small-scale fisheries and developing appropriate incentives to manage fishing practices accordingly, will ultimately provide a pathway to sustainability in over half of the world's wild-caught seafood.

Acknowledgments

This work was supported by a grant from NSF-Biocomplexity in the Environment Grant (OCE-0410439), a National Science Foundation Graduate Research Fellowship, and the Interdisciplinary Program in Environment and Resources at Stanford University. This work was conducted under CONAPESCA permits DGOPA/16991/050186 and DGOPA.01826.200307.-0740. We thank M. Valenzuela, A. Villa, M. Ramade, M. Mendiola, C. Mulholland-Olson, L. Gonzalez, C. Abshire, T. Pena, M. Arce, A. Rettinger, and R. Beas for their input and support with logistics and fieldwork. We thank FEDECOOP and its many fishers who contributed to the data collection effort and participated in the study.

Appendix A. The fisheries

Lobster traps weigh approximately 10 kg depending on the material and weights placed inside them by fishermen and include

escape vents and mesh sizes so fish and small lobsters can escape. Fish traps are slightly larger than lobster traps and have a cone-shaped opening and smaller mesh so larger fish cannot escape. The traps used in this study area are designed to target ocean whitefish (*Caulolatilus princeps*) and barred sand bass (*Paralabrax nebulifer*). Set gillnets are vertically oriented nets 100–300 m long with weights on the bottom line and floats at the top in place, held in place at each end by anchors. Fishers in this region use set gillnets to target over 20 marketable species, primarily halibut (*Paralichthys californicus*), sheephead (*Semicossyphus pulcher*), and scorpionfish (*Scorpaena guttata*). Drift gillnets are similar to set gillnets, but they are designed to fish the upper part of the water column, hence a more pelagic species assemblage. They are much longer (1400 m) and are not anchored. The major targets in this fishery are white sea bass (*Atractoscion nobilis*) and yellowtail (*Seriola lalandi*), though several elasmobranch species are also landed.

Appendix B. Supplemental information on biomass estimates

Southern sea palms (*Eisenia arborea*) were counted only if they included their entire stipe. *Eisenia* biomass was calculated using average weights for size classes of 0–50 cm, 50–100 cm, and greater than 100 cm from Guzmán del Proó and Serviere (unpubl. data, 2007). We used average biomass of yellow crab individuals (*Cancer antennarius*) for all crabs based on our measured carapace lengths and a carapace length–weight conversion in (Carroll, 1982). For bivalves, we used a length–weight relationship for intertidal clams from (Bradbury et al., 2005). For cormorants (*Phalacrocorax pelagicus*), we used a mean weight of 1.5 kg, based on (Hustler, 1991). For California sea lions (*Zalophus californianus*), we used and estimate of 50 kg per individual, which is approximately half the maximum weight for mature females (AFSC, 2008). For gastropods, we used a size–weight conversion for the wavy turban snail, *Megastrea undosa*, from (Martone, unpubl. data, 2006). For lobsters, we used average sizes of legal and sub-legal lobsters (based on measurement of 496 lobsters) caught and measured in 37 randomly selected traps during the September–October 2006 observations and converted to biomass using length–weight conversions from (Guzmán del Proó and Pineda-Barrera, 1992).

We also included rocks and hard substrates in our estimates of bycatch that were pulled up either through entanglement or attachment to kelps and corals, as these indicate damage to physical habitat. We estimated their weight using a diameter–weight conversion in (Stone and Hilborn, 1990). For bycatch in the lobster fishery, we did not take size measurements of individuals, so we used the mean biomass for each species from our set gillnet observations to convert the number of individuals to biomass. For species unique to the lobster fishery, we estimated biomass using (Froese and Pauly, 2008) length–weight conversions and an estimated average size of 40 cm in total length for cabezon (*Scorpaenichthys marmoratus*), frogfish (*Antennarius avalonis*), and yellowtail (*Seriola lalandi*) and 20 cm for rock wrasse (*Halichoeres semicinctus*).

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