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Elasmobranch bycatch in US West Coast groundfish fisheries

Jason E. Jannot[1,*], Rhema Bjorkland[1,2], Kayleigh A. Somers[1], Toby Mitchell[1], Vanessa J. Tuttle[1], Jon McVeigh[1]

[1]Fisheries Resource Analysis and Monitoring Division, Northwest Fisheries Science Center,
National Marine Fisheries Service, NOAA, Seattle, WA 98112, USA
[2]George Mason University, Department of Environmental Science and Policy, Fairfax, VA 22030, USA

ABSTRACT: Effective management of multispecies fisheries in large marine ecosystems is challenging. To deal with these challenges, fisheries managers are moving toward ecosystem-based fishery management (EBFM). Despite this shift, many species remain outside protective legislation or fishery management plans. How do species that fall outside of formal management structures respond to changes in fisheries management strategies? In 2011, the US West Coast Groundfish Fishery (WCGF) shifted management to an Individual Fishing Quota (IFQ) program. We used data collected by fisheries observers to examine the impact of this shift on elasmobranch catch (sharks, skates, rays). Historically, not all elasmobranchs were included in the WCGF Management Plan, making them vulnerable to fishing mortality. We grouped elasmobranchs into 8 groups based on 14 ecomorphotypes to examine relative catch within groundfish fishing sectors during the period 2002–2014. Of the 22 sharks and 18 skates and rays that these fisheries capture, 9 are listed as Near Threatened or greater on the IUCN Red List and 10 species are listed as Data Deficient by IUCN. The bycatch of 4 non-managed elasmobranch species was reduced under the IFQ program; IFQ management had no significant impact on the remaining 27 species caught by the IFQ fleet. Overall, catch of non-managed elasmobranchs was relatively low. We show that groups of ecomorphotypes co-occur within fisheries, suggesting natural management units for use in EBFM. This work helps identify gaps in monitoring and assessing the impact of management and policy on elasmobranch populations.

KEY WORDS: Fishing mortality · Individual fishing quota · Sharks · Fisheries management · Ecomorphotype · Discards

1. INTRODUCTION

In the last 20 yr, fisheries science has moved away from single-species approaches to management toward ecosystem-based fisheries management (EBFM), which incorporates ecological processes and components that have historically been left out of fisheries management (Link 2002, 2010, Latour et al. 2003). EBFM fosters a greater consideration of all components of marine ecosystems affected by fishing activity, including non-target species and associated habitats.

An on-going challenge of sustainable EBFM is the incidental catch of non-target species, or bycatch. Over-exploitation via fisheries bycatch has caused declines in several groups of marine organisms, including marine mammals, fishes, sea turtles, and invertebrates (Alverson et al. 1994, Dayton et al. 1995, Kelleher 2005, Dulvy et al. 2014). Evidence collected in recent years indicates that elasmobranchs (sharks, skates, rays) might be particularly susceptible to over-harvesting and bycatch in marine fisheries (Dulvy et al. 2014, Oliver et al. 2015, James

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*Corresponding author: jason.jannot@noaa.gov

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et al. 2016). Elasmobranchs are relatively long-lived vertebrates, with low biological productivity, a product of life history characteristics (e.g. slow growth, late age maturity, extended longevity; Stevens et al. 2000, Cortés 2002) that make them vulnerable to declines and extinctions when fishing-induced mortality rises in the absence of management (Dulvy et al. 2014, Oliver et al. 2015, James et al. 2016). Loss of species from marine systems, including elasmobranchs, can have serious consequences. For example, there is evidence that depletion of top predators such as sharks can have cascading effects throughout the marine ecosystem (Stevens et al. 2000, Baum & Worm 2009, Block et al. 2011). Recent estimates indicate that global shark removals may be in the tens of millions of individuals annually (Clarke et al. 2006, Crowder et al. 2008, Oliver et al. 2015, James et al. 2016). Stevens et al. (2000) estimated that almost 50% of global chondrichthyan catch (elasmobranchs and chimaeras) was non-targeted bycatch.

Retention of incidentally caught elasmobranchs is on the rise for a variety of reasons, with little management oversight (Oliver et al. 2015, James et al. 2016). New markets and demand can drive the retention of incidental elasmobranch catches (Walker 1998, Fong & Anderson 2002) as traditional target species decline (Ward-Paige et al. 2012, Dulvy et al. 2014), resulting in unregulated removals of elasmobranchs (Davies et al. 2009, James et al. 2016). Non-targeted and unmanaged catch can negatively affect elasmobranch populations if mortality for these species goes undocumented and is above maximum sustainable yield (Oliver et al. 2015). Changes in fisheries management provide an opportunity to examine the impact of management on unregulated species such as elasmobranchs.

In 2011, one of the largest segments (a.k.a. sector) of the US West Coast Groundfish Fishery (WCGF) underwent a shift in fisheries management. The WCGF operates along the US Pacific Coast from the Washington–Canada border to the California–Mexico border. Until 2011, the WCGF Limited Entry Bottom Trawl sector fished for groundfish species under a fishery-wide annual catch limit. Fishers could fish and retain up to a limited amount, but were not penalized for discards above the limit. In 2011, management of this sector changed to an Individual Fishing Quota (IFQ) system. IFQ management requires fishers to hold quota for every pound of fish caught, for approximately 70 of the 94 species managed by the Pacific Fishery Management Council (PFMC) West Coast Groundfish Fishery Management Plan (WCGFMP). To ensure compliance, the IFQ program requires discard monitoring of 100% of the fishing trips because both retained and discarded catch are debited against individual's quota. The WCGFMP includes 4 species of elasmobranchs that are actively managed (i.e. defined catch limits): leopard *Triakis semifasciata* and spiny dogfish *Squalus suckleyi* sharks, and longnose *Raja rhina* and big *R. binoculata* skates (see Tables 3–1 in PFMC 2019). The PFMC also monitors, but does not actively manage, a number of skates designated as Ecosystem Component Species (ECS) in the WCGFMP, including Aleutian *Bathyraja aleutica*, Bering *B. interrupta*, sandpaper *B. kincaidii*, roughtail/black *B. trachura*, and all other endemic skates. California skate *R. inornata*, soupfin shark *Galeorhinus galeus*, and spotted ratfish *Hydrolagus colliei* are also currently monitored as ECS; however, during the time period covered in the present study (2002–2014), these 3 species were managed within the WCGFMP, thus we excluded them from our analysis. All other species of sharks, skates, and rays along the US West Coast were outside the umbrella of active management in the WCGFMP during this time period. It should be noted that the PFMC's Highly Migratory Species (HMS) FMP does monitor a number of elasmobranch species not covered by the WCGFMP and that other management agencies and voluntary measures have been adopted by state and tribal agencies to protect some of these elasmobranchs. Our focus here was to assess the impacts of management changes to the WCGFMP on incidental catch of elasmobranchs in fisheries managed by the WCGFMP.

In this study, we tested the hypothesis that the implementation of the IFQ program has reduced the catch of elasmobranchs not actively managed by the WCGFMP (PFMC 2019). IFQ programs incentivize fishers to use resources prudently and fish more efficiently (Branch 2009, Melnychuck et al. 2012). If true, IFQ programs could indirectly reduce the catch of non-quota elasmobranchs in at least 2 ways. First, as fishers approach and eventually attain individual species quotas, fishing effort likely declines, resulting in a reduction in per vessel catch of all species, including non-target elasmobranchs. Second, efficient fishers will be more selective, which might reduce bycatch of unmanaged species. Fishers must carry enough quota to cover their total catch (at-sea discards and dockside landings) for each species within the IFQ program. Fishers should maximize efficient fishing by avoiding species that will cause them to exceed their individual quota for that species (a.k.a. constraining species). Once an individual fisher's quota for a constraining species has been attained, any further catch of that species can incur economic costs of finding more quota on the open market or forgo fishing for the remainder of the season. Thus, constraining species changes fisher behavior by either inducing more selective fishing or reducing effort.

To place our results in the context of global elasmobranch bycatch, we also describe the diversity of elasmobranchs that interact with the WCGF and identify species of concern, estimate incidental catch on those elasmobranch species not actively managed by the current WCGFMP (PFMC 2019), and examine trends in non-managed elasmobranch catch across time and fishery sectors. Even though most elasmobranchs are not part of the IFQ program, these species could exhibit reduced catch under the IFQ program as an indirect effect of more efficient fishing in the IFQ program. Alternatively, non-managed elasmobranch catch could increase under the IFQ program because there are no incentives (i.e. no quota) to reduce non-managed elasmobranch catch per se. Therefore, these species could be discarded at sea or retained and sold to exploit or develop new markets, without penalty. A third possibility is that overall elasmobranch catch does not change, but the proportion of at-sea discards and landings changes for individual species. We would expect this result if, for example, fishers found or developed new markets for unregulated elasmobranchs. We highlight elasmobranch species that are of regional or global conservation concern and which fall outside active management in the WCGFMP. We use these species as an example of the effect of fisheries management on unmanaged species. In addition, our results provide recommendations for improving elasmobranch management in the WCGF as well as around the globe.

2. METHODS

2.1. Federally managed fisheries

The PFMC regulates federally managed fisheries in the WCGF, based on access privileges and gear types. The PFMC, in consultation with state agencies (Washington, Oregon, and California), also sets some fishing regulations for state-managed fisheries that interact with groundfish species listed in the WCGFMP. Access privileges in US federally managed fisheries are either Limited Entry (LE), Open Access (OA), IFQs, or cooperatives that pool and share quota in the IFQ program. A federal groundfish permit is required to participate in the LE fisheries, but not required in the OA fisheries, with LE fishers having access to greater amounts of fishery resources than OA fishers. The permits, gear types, target species, vessel lengths, fishing depths, and management for each sector of the WCGF during the study period (2002–2014) are described in Texts S1 & S2 and Table S1 in the Supplement at www.int-res.com/articles/suppl/n045p109_supp.pdf.

Historically, there were 3 main federal sectors, defined by gear type and target species: LE Bottom Trawl, At-sea and Shoreside Hake (pelagic trawl), and Non-Nearshore Fixed Gear (hook-and-line or pot gears; Table S1). From 2002–2010, management of the LE Bottom Trawl sector included a number of measures designed to maintain catches below prescribed TACs (total allowable catches), including the establishment of conservation areas closed to bottom trawling as well as trip and bi-monthly caps on landings of several species (Table S1). However, fishers could continue to fish until they had reached the maximum landing allowance for each species, discarding at will. In January 2011, management of the LE Bottom Trawl fishery changed to an IFQ system. Individual permit holders can fish, lease, or sell their individual quota. Under IFQ, the scope of allowable gear types was broadened (Table S1). IFQ fishers hold quota for both target (intended catch) and non-target (unintended catch) species and species groups, and both discarded and retained catch debits against individual quota accounts. When a fisher fills their individual quota for a particular species, they cannot catch any additional individuals of that species/group without potentially negative consequences, regardless if they are discarded or landed (NMFS 2010). Since 2011, the PFMC manages non-IFQ species contained in the WCGFMP under trip limits for landings, but at-will discarding is allowed. No management limits were set for species outside the WCGFMP, including non-managed elasmobranchs, during the study period (2002–2014). For the purposes of clarity, in this paper we refer to the 2002–2010 fishery period as the LE Bottom Trawl sector and the 2011–2014 fishery period as the Non-Hake IFQ sector. The LE Trawl–IFQ sector is the focus of this paper, though we compared this fishery to other fishery sectors off the US west coast. These other federal and state fisheries are described in detail in Texts S1 & S2 and Table S1.

2.2. Data

We assessed the impact of US West Coast fisheries that target groundfish or incidentally catch groundfish on elasmobranchs by estimating total catch —

both discards at sea and catch landed at the dock — of each non-managed elasmobranch species for the time period 2002–2014. For simplicity, we refer to the collection of fisheries as the WCGF, even though some of these fisheries only catch groundfish incidentally. We used 3 data sources for this study: at-sea discard data from the Northwest Fisheries Science Center Groundfish Observer Program (NWGOP), federal logbook data, and landed data, both from the Pacific Fisheries Information Network (PacFIN). At-sea discard data (e.g. individuals caught but not landed/retained) from each sector was collected by independent scientific observers placed on commercial fishing vessels by the NWGOP during fishing operations. Collection of discard data has been required on every IFQ Non-Hake and Shoreside Hake fishery trip since 2011 to ensure IFQ program compliance such that 100% of trips have been monitored. Similarly, At-sea Hake Catcher Processors and At-sea Hake Motherships had 100% observer coverage for the 2002–2014 period. All other fishery sectors had less than 100% observer coverage (Somers et al. 2018a). In those sectors with less than 100% observer coverage (see Table S1), observed elasmobranch catch must be expanded to the unobserved portion of the fleet. NWGOP observers collect the following information for each fishing event (a.k.a. a set or a haul): latitude, longitude, date, and time and geolocation of gear placement and retrieval; average fishing depth; the intended target group or species (as indicated by the captain or other crew member); and at-sea catch including at-sea discards. Details of NWGOP observer duties, priorities, and sampling protocols can be found in the NWGOP Manuals (NWFSC 2016a,b,c).

Vessel logbook data, only available for the LE Bottom Trawl sector, were obtained from PacFIN (see Fig. 1 in Bellman et al. 2011). Trawl logbook tows lacking a recorded depth (0.18%) were removed to ensure that all spatial and depth information was complete. Landed catch for all fishing sectors was obtained from fish tickets — trip-aggregated sales receipts issued to vessels by fish-buyers in each port for each delivery of fish and electronically reported by each state to PacFIN. Details of NWGOP data quality control, processing, and matching of discards, logbook, and landings can be found on the NWGOP website (NWFSC 2020a,b).

2.3. Discard and catch estimates

Observer estimates of at-sea discards from sampling each haul were expanded to the haul level (for details see NWFSC 2020a). Haul-level at-sea discard estimates were then expanded to the sector-level for sectors with less than 100% observer coverage (LE Bottom Trawl 2002–2010, LE Sablefish, LE Fixed Gear Daily Trip Limits [DTL], OA Fixed Gear, OA California Halibut, Nearshore, Pink Shrimp). Sector expansion was not required in the Non-Hake IFQ (2011–2014), Shoreside Hake, At-sea Catcher Processor, and At-sea Mothership Catcher Vessel sectors because 100% observer coverage is mandatory in these sectors. A small number of IFQ hauls go unsampled each year (typically <1%; Somers et al. 2018a).

For sectors with less than 100% observer coverage, discard ratios were computed from the observer data as the ratio of observed discard of a single species to the observed retained of target species in that sector (see Somers et al. 2015 for full description). Discard ratios were then used to expand discarded weight of each species from the sampled to the unsampled portion of the catch to give $\hat{D}$, the discard estimate:

$$\hat{D}_{sx} = \frac{\sum_t d_{sxt}}{\sum_t r_{xt}} \times \sum_t R_{xt} \tag{1}$$

where s is the species or species group, x is the sector, t is tows, d is the observed discard weight of species s, r is the observed retained weight of target species in sector x, and R is the total weight of retained target species in sector x. Retained catch in sectors were obtained from fish tickets. Fish tickets contain weight estimates of species or species groups brought back to the dock and are required for fish sales in the WCGF. However, fish tickets do not record measures of effort such as the number of hauls, gear deployments, or fishing durations. Thus, fish ticket weights represent our only measure of fleet-wide effort. Data on fish tickets is often reported as a market category, encompassing multiple species, e.g. 'skate unidentified'. Furthermore, non-managed elasmobranch species are not required to be sorted at the dock and identified to species, and in many instances might be discarded at the dock without ever being recorded on the fish ticket (i.e. unmarketable species; PFMC 2019). Therefore, estimates of landed elasmobranchs in this study likely underrepresent the true amount of non-managed elasmobranchs actually brought back to the docks. The non-managed elasmobranchs in this study are not the target of any of these fisheries. We use the term 'landed' to indicate non-elasmobranch catch brought back to the dock, as opposed to discarded at sea. We reserve the term 'retained' for catch of managed species that are subsequently sold to a fish buyer at the dock.

In the At-sea Hake sectors, each vessel carries 2 observers, therefore nearly 100% of the hauls are sampled for species composition. The expansion factors for unsampled hauls in the At-sea Hake sectors are very small. At the species level, At-sea Hake observers estimate a percent retained for each haul, based on what they observe. This estimate is applied to the total catch weight of the species. At the haul level, observers also calculate a total discard weight for the haul by using the bycatch totals and the percent retained estimates to get the total discard for the haul (all species).

Total catch for each elasmobranch species was calculated by summing the discard (estimated from observer data and fish tickets, see above) and landed estimates (from fish tickets) across all tows and trips for each year–sector–species. We used the landings weight on fish tickets as a proxy for effort. The weight of total landings represents our best measure of the effort for a particular sector in a given year. We calculated total landings across sectors by summing the weight of all species on the fish tickets (landed and retained; including elasmobranchs). To make comparisons among sectors and gear types, we scaled total elasmobranch catch by total landings, our proxy for effort, resulting in relative catch of elasmobranch species for a given year (mt/mt). Relative catch was calculated as the total catch of an elasmobranch species within a sector (see above) divided by the total landings across all sectors (above). Relative catch weight can be thought of as 'catch-per-unit-effort' and provides a standardized metric that can be compared across sectors that have very different target species and gear types. A similar approach was taken by Oliver et al. (2015) in their estimates of global elasmobranch bycatch in commercial longline, trawl, purse seine and gillnet fisheries. For the elasmobranch species in this study, we assume 100% mortality of all individuals from all fisheries because fishing-induced mortality rates for these species have not been determined. Thus, our estimates are conservative and should be considered near the upper bound of mortality in these fisheries since some individuals of some species are likely to survive capture after being discarded at sea.

We classified elasmobranchs into groups based on ecomorphotypes (Table 1) that reflect broad habitat preferences, bathymetric distribution, and feeding ecology. Shark ecomorphotype categories were based on Compagno (1990) and Martin (2010). The data summed at the ecomorphotype level was too sparse (many zeros) for modeling purposes. Therefore, we further combined ecomorphotypes into more general habitat categories (Table 1). The shark ecomorphotypes were grouped into coastal sharks, slope sharks, deep slope sharks, and oceanic sharks. Skate and ray ecomorphotypes were grouped into nearshore, shelf/slope, deep water, and pelagic (Fowler et al. 2005, IUCN 2020). Relative catch was then calculated (see above) for both sharks and skates within each of their respective groupings (Table 1).

2.4. Modeling and analyses

To examine the impact of the IFQ program on elasmobranchs, we used a generalized linear model (GLM) to examine the effect of fishery sector (12 sectors; Table S1), time periods (2002–2006, 2007–2010, 2011–2014), and grouping (8 groups; Table 1) on relative catch. To test for an effect of IFQ implementation on elasmobranch relative catch, the data were grouped into 3 time periods: 2002–2006, 2007–2010, and 2011–2014. These periods were chosen because the 2011–2014 period represents the period when the IFQ program was active. The other periods were chosen to have roughly the equivalent number of years while still using all available data. A significant decline in mean predicted relative catch from the 2007–2010 to the 2011–2014 period would lend support to the idea that the IFQ program reduced the catch of elasmobranchs.

To examine the effects of fishery sector on IUCN-listed species (Table 2), we used GLMs to test the impact of sector on relative catch of the subset of IUCN-listed species. We modeled the effect of sector on IUCN species for 3 habitats: oceanic, which included the oceanic sharks; slope, which included deep slope sharks, slope sharks, and slope skates; and nearshore, which included coastal sharks and nearshore skates and rays. For each habitat, we examined the effect of sector on the IUCN species found in that habitat. We limited each of the 3 analyses to only those sectors that had some catch of at least one IUCN species. The oceanic habitat analysis included all sectors, the slope habitat analysis excluded the Nearshore and Shoreside Hake sectors and the nearshore habitat analysis excluded At-sea Catcher Processors, LE Fixed Gear DTL, LE Sablefish, Pink Shrimp, and Shoreside Hake.

To examine the impact of the IFQ program on elasmobranchs within the LE Trawl–IFQ sector, we used a GLM to examine the effect of species (excluding any groups not identified to species), time period, and catch disposition (at-sea discard vs. landed at dock) on total catch of elasmobranchs (by weight, mt) within the LE Trawl–IFQ sector. Including catch dis-

Table 1. Shark, ray, and skate species observed in the US West Coast groundfish fishery, grouped by ecomorphotype. Shark ecomorphotypes based on Martin's (2010) revision of Compagno (1990). Compagno (1990) ecomorphotypes are given in brackets if different from Martin (2010). Skates and ray ecomorphotypes based on the biology and habitat of individual species. B: benthic/epibenthic; CI: coastal and insular; H: continental shelf and upper slope; L: littoral; O: open ocean; p: pelagic; S: continental slope; SI: continental and insular slope; CA: California

Grouping	Ecomorphotype	Species	Scientific name	Family	Habitat
Coastal sharks	Cancritrophic	Brown smoothhound	*Mustelus henlei*	Triakidae	L, CI
		Gray smoothhound	*Mustelus californicus*	Triakidae	L
	Cancritrophic (probenthic)	Swell	*Cephaloscyllium ventriosum*	Scyliorhindae	L, CI
	Durotrophic (probenthic)	Horn	*Heterodontus francisci*	Heterodontidae	CI
	Eurytrophic	Broadnose sevengill	*Notorynchus cepedianus*	Notorynchidae	L; CI
	Mesotrophic (littoral)	Pacific sharpnose	*Rhizoprionodon longurio*	Carcharhinidae	L
	Platybenthic (squatinobenthic)	Pacific angel shark	*Squatina californica*	Squatinidae	L; CI
Deep sea skates	Deep water skates	Black skate	*Bathyraja trachura*	Arhynchobatidae	S
		Bering skate	*Bathyraja interrupta*	Arhynchobatidae	S
		Deepsea skate	*Bathyraja abyssicola*	Arhynchobatidae	S
		White skate	*Bathyraja spinosissima*	Arhynchobatidae	S
		Broad skate	*Amblyraja badia*	Rajidae	S
Deep slope sharks	Mesobathic (bathic)	Pacific black dogfish	*Centroscyllium nigrum*	Etmopteridae	SI
		Prickly shark	*Echinorhinus cookei*	Echinorhinidae	SI
	Mesobathic (eurytrophic)	Pacific sleeper shark	*Somniosus pacificus*	Somniosidae	SI
		Bluntnose sixgill shark	*Hexanchus griseus*	Hexanchidae	SI
Nearshore skates and rays	Nearshore rays	Banded guitarfish	*Zapteryx exasperata*	Rhinobatidae	B
		Bat ray	*Myliobatis californica*	Myliobatidae	B
		Ca butterfly ray	*Gymnura marmorata*	Gymnuridae	B
		Diamond stingray	*Dasyatis dipterura*	Dasyatidae	B
		Pacific electric ray	*Tetronarce californica*	Torpedinidae	B
		Round stingray	*Urobatis halleri*	Urolophidae	B
		Starry skate	*Raja stellulata*	Rajidae	B
		Shovelnose guitarfish	*Rhinobatos productus*	Rhinobatidae	B
		Thornback guitarfish	*Platyrhinoidis triseriata*	Platyrhinidae	B
Oceanic sharks	Macropelagic (macroceanic)	Bigeye thresher	*Alopias superciliosus*	Alopiidae	O
		Blue shark	*Prionace glauca*	Carcharhinidae	O
		Common thresher	*Alopias vulpinus*	Alopiidae	O
		Pelagic thresher	*Alopias pelagicus*	Alopiidae	O
	Tachypelagic	Shortfin mako	*Isurus oxyrinchus*	Lamnidae	O
		Salmon shark	*Lamna ditropis*	Lamnidae	O
Pelagic ray	Pelagic rays	Pelagic stingray	*Pteroplatytrygon violacea*	Dasyatidae	P
Slope sharks	Anoxybathic	Filetail cat shark	*Parmaturus xaniurus*	Scyliorhinidae	SI
	Cyranobathic (rhynchobatic)	Brown cat shark	*Apristurus brunneus*	Scyliorhinidae	SI
	Cyranobathic	Longnose cat shark	*Apristurus kampae*	Scyliorhinidae	SI
Slope skates	Shelf/slope skates	Aleutian skate	*Bathyraja aleutica*	Arhynchobatidae	H; deeper than 200 m
		Sandpaper skate	*Bathyraja kincaidii*	Arhynchobatidae	H; deeper than 200 m
		Starry skate	*Raja stellulata*	Rajidae	H; shallower than 200 m

position and species in these models allowed us to assess the potential for species-specific shifting uses of bycatch. For example, if new markets were being exploited or developed for certain non-quota elasmobranchs, we would expect landings to rise even as discards at-sea fell. Because a large portion of sharks, skates, and rays were unidentified, we also fit a separate GLM to the unidentified sharks, skates, and rays to examine the effect of group (unidentified shark vs. skates and rays), catch disposition (at-sea discard vs. landed at dock), and time period on total catch (weight, mt) of these unidentified groups. Any group not identified to species was included in the 'unidentified' analysis (see Tables 3 & 4).

Table 2. Shark, skate and ray species observed in the US West Coast groundfish fishery with an IUCN Red List status greater than Least Concern or listed as Data Deficient (IUCN 2020)

Common name	Scientific name	Population trend	IUCN status	Ecomorphotype
Pelagic thresher shark	*Alopias pelagicus*	Declining	Endangered	Oceanic shark
Shortfin mako shark	*Isurus oxyrinchus*	Declining	Endangered	Oceanic shark
Bigeye thresher shark	*Alopias superciliosus*	Declining	Vulnerable	Oceanic shark
Common thresher shark	*Alopias vulpinus*	Declining	Vulnerable	Oceanic shark
Blue shark	*Prionace glauca*	Declining	Near Threatened	Oceanic shark
Bluntnose sixgill shark	*Hexanchus griseus*	Unknown	Near Threatened	Deep slope shark
Broadnose sevengill shark[a]	*Notorynchus cepedianus*	Unknown	Near Threatened	Coastal shark
Pacific angel shark	*Squatina californica*	Declining	Near Threatened	Coastal shark
Horn shark	*Heterodontus francisci*	Unknown	Data Deficient	Coastal shark
Longnose cat shark	*Apristurus kampae*	Unknown	Data Deficient	Slope shark
Pacific black dogfish	*Centroscyllium nigrum*	Unknown	Data Deficient	Deep slope shark
Pacific sharpnose shark	*Rhizoprionodon longurio*	Unknown	Data Deficient	Coastal shark
Pacific sleeper shark	*Somniosus pacificus*	Unknown	Data Deficient	Deep slope shark
Prickly shark	*Echinorhinus cookei*	Unknown	Data Deficient	Deep slope shark
Shovelnose guitarfish	*Rhinobatos productus*	Unknown	Near Threatened	Nearshore
Banded guitarfish	*Zapteryx exasperata*	Unknown	Data Deficient	Nearshore
Deepsea skate	*Bathyraja abyssicola*	Unknown	Data Deficient	Deep sea skate
Diamond stingray	*Dasyatis dipterurus*	Unknown	Data Deficient	Nearshore
Sandpaper skate	*Bathyraja kincaidii*	Unknown	Data Deficient	Slope skate

[a] East Pacific subpopulation

For all models, all possible interactions were added to the model to examine how factors interact (e.g. sector × period) to influence relative or total catch. Non-significant interactions were removed systematically starting with the highest order non-significant interactions. All interactions and main effects of lower order than the order being examined were kept in subsequent model runs. We used Akaike's information criterion (AIC) to assess the relative quality of alternative models (Tables S2 & S4). For the sector by ecomorphotype by time period comparison, we present the model metrics and plot the predicted mean relative catch (±95% CI) from the final model by ecomorphotype for each sector as well as by the 3 time periods by sector. For the comparison of IUCN species by sector, we plot the predicted mean relative catch (±95% CI) for each species by sector for each of the 3 habitats. Finally, for the LE Trawl–IFQ analysis, we present the predicted mean weight of catch (±95% CI, in mt) of at-sea discards and landed at the dock with sharks and skates and rays plotted separately. We used a normal error distribution for all models. Q–Q plots indicated approximately normal distribution with slightly heavy tails for all models. Residual plots indicated either homoscedasticity or only slight heteroscedasticity, depending on the model. We explored time-series analyses (autoregressive integrated moving averages; ARIMAs) to examine the specific effect of year, but they added little to the results, interpretation, or conclusions; given the added complexity, we opted for the simpler models with fixed time periods. Modeling was conducted using R v.3.6.0 (R Core Team 2019), predicted values were obtained using the default settings of the 'effect' function of the R package 'effects', which averages over levels of each (non-focal) factor in the model and weighs levels of the factor in proportion to sample size (Fox 2003, Fox & Weisberg 2018, 2019).

3. RESULTS

3.1. Composition and species of conservation concern

WCGF non-managed elasmobranch bycatch belonged to 14 ecomorphotypes and 8 broad groups (Table 1). Non-managed elasmobranch discards in WCGF fisheries included 20 species of sharks and 3 shark categories not identified to the species level (unidentified cat [Scyliorhinidae] and smoothhound [*Mustelus*] sharks; unidentified shark [of any type; Selachimorpha]; Table 3). In addition, there were 18 species of skates, rays, and guitarfish and 2 categories not identified to species (unidentified skates [Rajidae and Arhynchobatidae]; unidentified rays [Batoidea]; Table 4). Boxplots of total catch by species are shown in Fig. 1. The assemblage includes 9 species of concern: 3 Endangered (EN) species of shark, 4 shark and 1 guitarfish Near Threatened

Table 3. Estimated weight of at-sea discards, landed at the dock, and total catch of sharks in the US West Coast groundfish fishery from 2002–2014. Ecomorphotypes are described in Table 1. Based on IUCN (2020): EN: Endangered, NT: Near Threatened; VU: Vulnerable; DD: Data Deficient; unid.: unidentified. Rounding might produce values that appear to equal zero

Species	Ecomorphotype grouping	At-sea discards (mt)	Landed at dock (mt)	Total catch (mt)
Blue — NT	Oceanic	452.55	4.18	456.73
Salmon	Oceanic	30.90	0.45	31.35
Common thresher — VU	Oceanic	7.91	10.59	18.51
Shortfin Mako — EN	Oceanic	1.21	11.01	12.22
Pelagic thresher — EN	Oceanic	11.10	0.04	11.14
Bigeye thresher — EN	Oceanic	0.00	0.06	0.06
Pacific sleeper — DD	Deep slope	212.46	1.59	214.06
Pacific black dogfish — DD	Deep slope	6.27	0.00	6.27
Bluntnose sixgill — NT	Deep slope	5.61	0.01	5.62
Prickly — DD	Deep slope	0.02	0.00	0.02
Brown cat	Slope	896.08	129.57	1025.65
Filetail cat	Slope	114.25	0.00	114.25
Longnose cat — DD	Slope	31.48	0.00	31.48
Cat unid.	Slope	19.71	0.00	19.71
Brown smoothhound	Coastal	98.03	0.00	98.03
Pacific angel — NT	Coastal	17.93	9.72	27.65
Swell	Coastal	21.48	0.00	21.48
Broadnose sevengill — NT	Coastal	1.58	0.00	1.58
Smoothhound unid.	Coastal	0.95	0.00	0.95
Horn — DD	Coastal	0.20	0.00	0.20
Gray smoothhound	Coastal	0.03	0.00	0.03
Pacific sharpnose — DD	Coastal	0.03	0.00	0.03
Shark unid.	Unknown	1157.39	50.72	1208.11

Table 4. Estimated weight of at-sea discards, landed at the dock, and total catch of skates and rays in the US West Coast groundfish fishery from 2002–2014. Ecomorphotypes are described in Table 1. Based on IUCN (2020): NT: Near Threatened; DD: Data Deficient; unid.: unidentified. Rounding might produce values that appear to equal zero

Species	Ecomorphotype grouping	At-sea discards (mt)	Landed at dock (mt)	Total catch (mt)
Black skate	Deep sea	433.52	0.31	433.83
Deepsea skate — DD	Deep sea	9.96	0.00	9.96
White skate	Deep sea	1.02	0.00	1.02
Roughshoulder/broad skate	Deep sea	0.04	0.00	0.04
Bering skate	Deep sea	0.04	0.00	0.04
Sandpaper skate — DD	Slope	761.09	0.91	762.00
Aleutian skate	Slope	23.12	0.00	23.12
Starry skate	Slope	18.66	0.00	18.66
Alaska skate	Slope	0.06	0.00	0.06
Bat ray	Nearshore	381.70	0.65	382.36
Pacific electric ray	Nearshore	96.64	0.04	96.68
Shovelnose guitarfish — NT	Nearshore	20.07	0.00	20.07
Thornback guitarfish	Nearshore	11.79	0.00	11.79
Pelagic stingray	Nearshore	0.69	0.00	0.69
Round stingray	Nearshore	0.39	0.00	0.39
Diamond stingray — DD	Nearshore	0.25	0.00	0.25
California butterfly ray	Nearshore	0.00	0.00	0.00
Banded guitarfish — DD	Nearshore	0.00	0.00	0.00
Skate unid.	Unknown	2511.36	8195.5	10 706.855
Ray unid.	Unknown	3.00	0.00	3.00

(NT), and 1 shark species in the Vulnerable (VU) category (Tables 3 & 4; IUCN 2020). In addition, 6 shark, 2 skate, 1 ray, and 1 guitarfish species are considered Data Deficient (DD; Tables 3 & 4; IUCN 2020). Some catch retention occurred in 12 species or species groups, most noticeably for all the oceanic sharks (3 EN), but also brown cat shark, the Pacific angel shark (NT), Pacific sleeper shark (DD), sandpaper skate

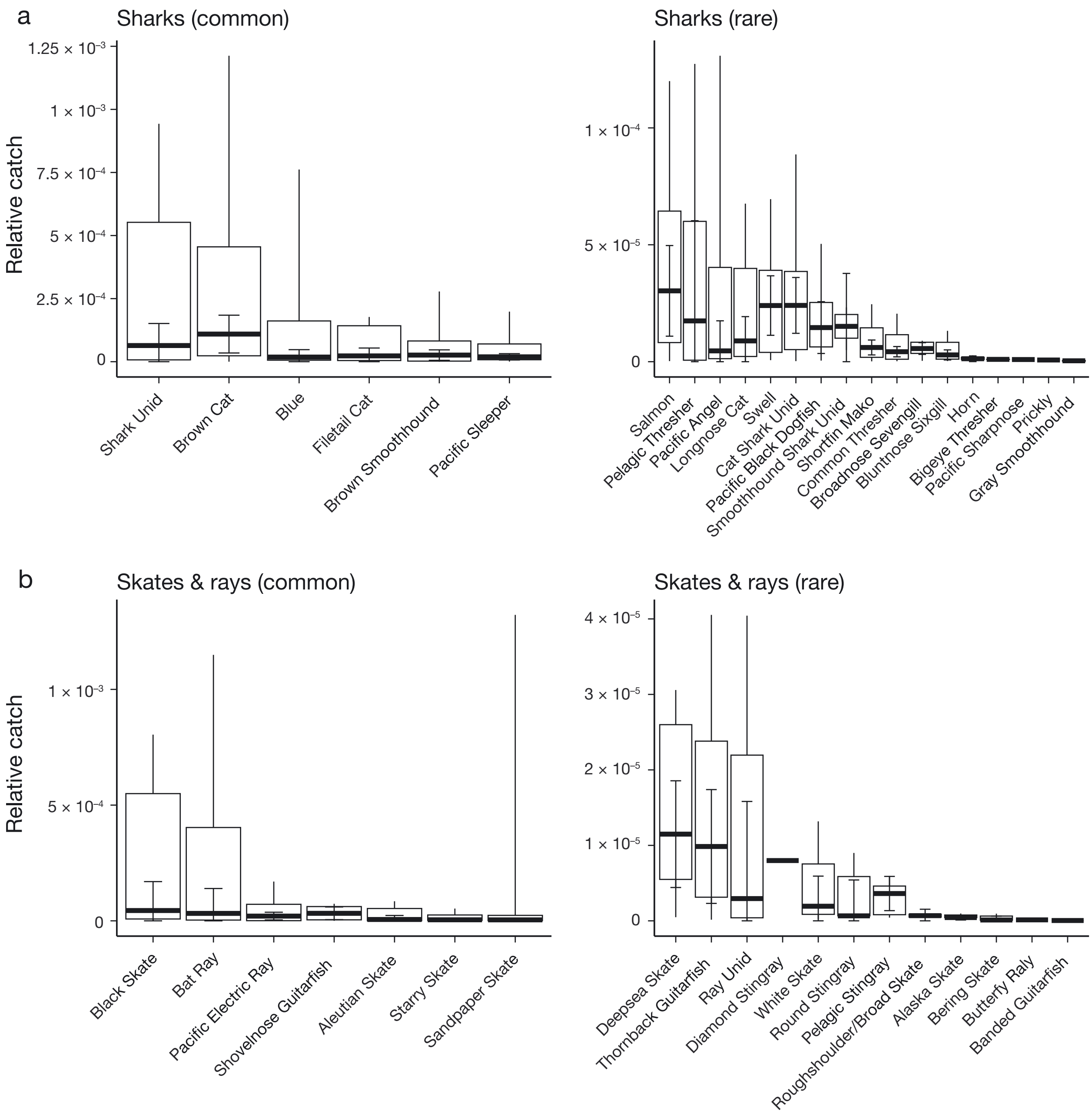

Fig. 1. Relative catch (bar: median; box: ±25%; top whisker: 90%; error bar: 95% CI of median) of (a) sharks and (b) skates, rays, and guitarfish in US West Coast groundfish fisheries. Relative catch was calculated as the total catch of the elasmobranchs divided by the total landed catch. For clarity, elasmobranchs are divided into sharks and skates, and within each group, commonly caught species are plotted separately from rarely caught species. Unidentified skates are not shown

(DD), black skate, bat ray, and unidentified sharks and skates (Tables 3 & 4). Landed catch exceeded discards for bigeye thresher, common thresher, and shortfin mako sharks and unidentified skates. Indeed, the landed portion of the catch of unidentified skates was more than 3 times the at-sea discarded quantity by weight (Table 4), which was likely a reflection of different sorting requirements between the state-managed dock sampling programs and the NWGOP which strives for species-specific identification when possible. Fisheries targeting Pacific hake using pelagic midwater trawl nets (At-sea Catcher Processor, At-sea Mothership Catcher Vessels, and Shoreside Hake) normally dump the entire net contents directly into the hold and deliver without much at-sea sorting (except protected and prohibited species), which could account for retention of pelagic shark species. Overall, the total catch weight of VU or NT species was relatively low compared to other elasmobranch species (Tables 3 & 4). Excluding the 10 species or groups which had ≥50% of their total catch landed, 97% of the remaining total elasmobranch catch was discarded at sea during the study period (Tables 3 & 4).

3.2. Bycatch among sectors, ecomorphotypes, and time periods

WCGF relative catch varied among sectors by ecomorphotype grouping (Tables 5, S2 & S3, Fig. 2). The LE Trawl–IFQ sector, which primarily uses bottom trawl nets near the continental shelf–slope break, had significantly larger catches of deep slope and slope sharks and deep sea and slope skates than all other sectors (Fig. 2, Table S3). The CA Halibut Trawl fishery, which primarily uses bottom trawl nets outside the mouth of San Francisco Bay, had significantly higher catches of nearshore skates and rays compared to other sectors and slightly higher catches of coastal sharks than other sectors (Fig. 2, Table S3). The LE Sablefish fleet, using fixed gear, had high catches of ocean sharks (exclusively on longline gear) relative to other sectors (Fig. 2, Table S3).

WCGF relative catch varied among sectors by period (Tables 5, S4 & S5, Fig. 3). Among fishing sec-

Table 5. Generalized linear modeling results examining the effect of fishery sector (Table 1), ecomorphotype grouping (Table 1), and time period (2002–2006, 2007–2010, 2011–2014) on relative catch of elasmobranchs. Comparison of Akaike's information criterion among models and coefficients can be found in Tables S2 & S3, respectively

	df	Deviance	Residual df	Residual deviance	*F*	p
Null			209	5.09×10^{-7}		
Sector	9	1.41×10^{-7}	200	3.69×10^{-7}	44.28	<0.0001
Grouping	6	2.38×10^{-8}	194	3.45×10^{-7}	11.23	<0.0001
Time period	2	1.84×10^{-9}	192	3.43×10^{-6}	2.61	0.08
Sector × grouping	54	2.87×10^{-7}	138	5.56×10^{-8}	15.06	<0.0001
Sector × time period	18	1.32×10^{-8}	120	4.24×10^{-8}	2.08	0.01

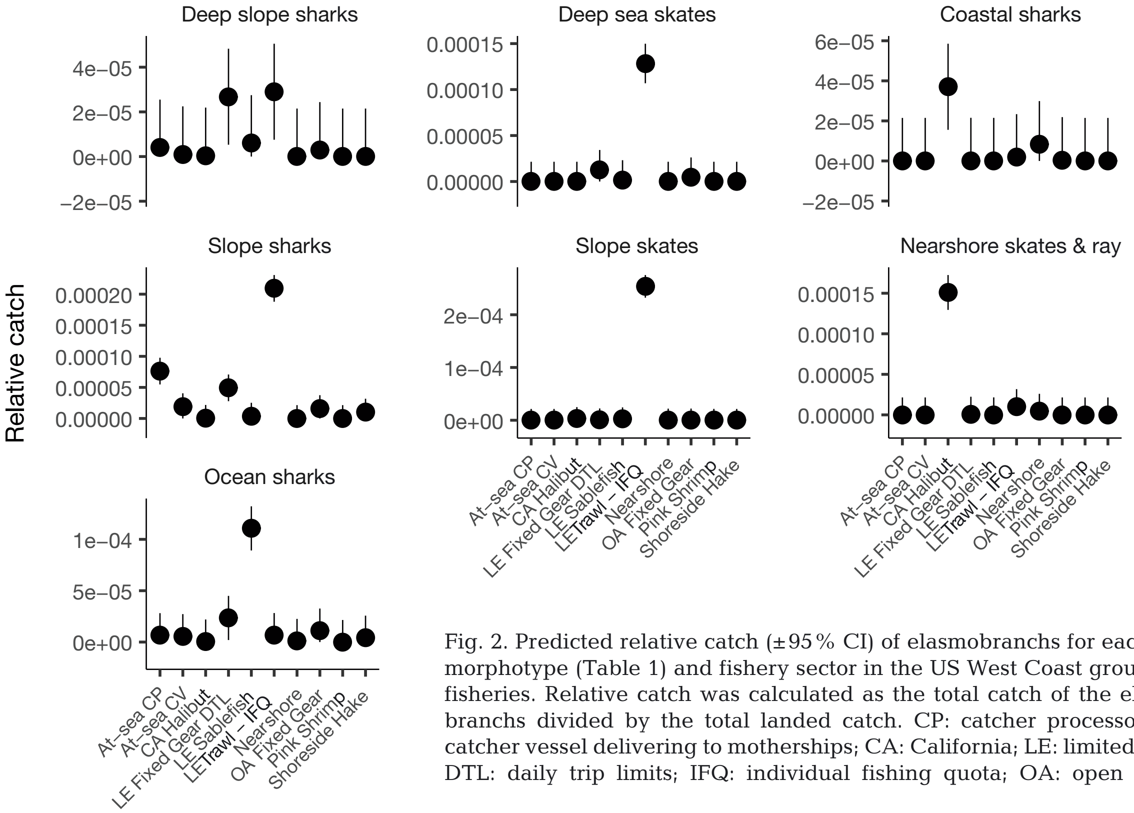

Fig. 2. Predicted relative catch (±95% CI) of elasmobranchs for each ecomorphotype (Table 1) and fishery sector in the US West Coast groundfish fisheries. Relative catch was calculated as the total catch of the elasmobranchs divided by the total landed catch. CP: catcher processor; CV: catcher vessel delivering to motherships; CA: California; LE: limited entry; DTL: daily trip limits; IFQ: individual fishing quota; OA: open access

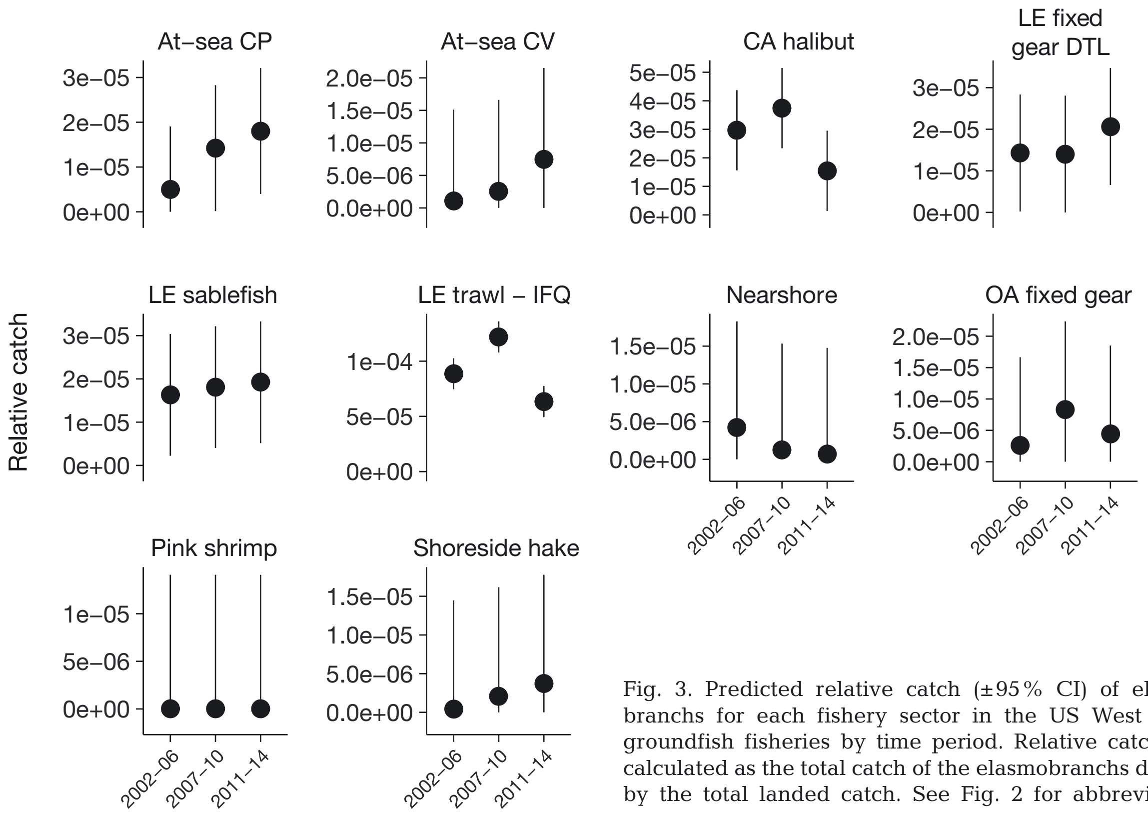

Fig. 3. Predicted relative catch (±95% CI) of elasmobranchs for each fishery sector in the US West Coast groundfish fisheries by time period. Relative catch was calculated as the total catch of the elasmobranchs divided by the total landed catch. See Fig. 2 for abbreviations

tors, the LE Trawl–IFQ sector exhibited an increase from 2002–2006 to 2007–2010 and then a significant drop in relative elasmobranch catch during the 2011–2014 period, coinciding with the implementation of the IFQ program (Fig. 3, Tables 5 & S3). The CA Halibut sector showed a similar, but non-significant trend as the LE Trawl–IFQ sector. The hake sectors (At-sea Catcher-Processor, At-sea Catcher-Vessel, Shoreside Hake) and LE Fixed Gear DTL sector showed slight, but not significant, increases in elasmobranch catch during the 2011–2014 period (Fig. 3). Other sectors did not exhibit significant patterns of elasmobranch catch over the 3 time periods (Fig. 3).

3.3. Bycatch of IUCN species by fishing sector

For IUCN-listed species within all 3 habitats, there were significant species by sector interactions (Tables 6 & S4). In terms of oceanic sharks, the inter-

Table 6. Generalized linear modeling results examining the effect of species and sector on relative catch of IUCN-listed elasmobranchs (Table 4), which were grouped by habitat type and each habitat modeled separately. Comparison of Akaike's information criterion among models and coefficients can be found in Tables S4–S7

Habitat		df	Deviance	Residual df	Residual deviance	*F*	p
Oceanic	Null			149	3.67×10^{-4}		
	Species	9	6.25×10^{-5}	140	3.05×10^{-4}	83.43	<0.0001
	Sector	4	4.99×10^{-5}	136	2.55×10^{-4}	149.83	<0.0001
	Species × sector	36	2.47×10^{-4}	100	8.32×10^{-6}	82.35	<0.0001
Slope	Null			167	2.01×10^{-3}		
	Species	7	2.89×10^{-4}	160	1.72×10^{-3}	19.77	<0.0001
	Sector	6	1.90×10^{-4}	154	1.53×10^{-3}	15.14	<0.0001
	Species × sector	42	1.30×10^{-3}	112	2.34×10^{-4}	14.78	<0.0001
Nearshore	Null			104	6.27×10^{-6}		
	Species	4	8.85×10^{-7}	100	5.39×10^{-6}	5.84	0.0004
	Sector	6	5.86×10^{-7}	94	4.80×10^{-6}	2.58	0.03
	Species × sector	24	2.15×10^{-6}	70	2.65×10^{-6}	2.37	0.003

action was driven by the fixed gear fleets (LE Sablefish, LE Fixed Gear DTL, OA Fixed Gear), which caught significantly more blue sharks than other sectors (Fig. 4 Table S5). These sectors fish with various hook-and-line or pot/trap gear in federally managed waters (5.6 km offshore). Blue sharks were exclusively caught on hook-and-line gear. For slope species, the interaction was driven by significantly higher catches of sandpaper skates in the LE Trawl–IFQ sector and slightly higher, but not significant, catches of Pacific sleeper shark in both the LE Trawl–IFQ and LE Fixed Gear DTL relative to other sectors (Fig. 5, Table S6). Nearshore species interactions were driven by significantly higher catches of Pacific angel sharks and shovelnose guitarfish in the CA Halibut fishery (Fig. 6, Table S7).

3.4. Elasmobranch catch and IFQ implementation

Within the LE bottom trawl–IFQ sector, for taxa identified to species level, there was a significant 3-way interaction between species, catch disposition, and time period (Table 7), suggesting that at-sea discards and landed at the dock differed among species and time periods in different ways. Brown cat and Pacific sleeper sharks as well as black and sandpaper skates appeared to have significantly more at-sea discards than landed at the dock (Fig. 7). At-sea discards for brown cat shark, black skate, and sandpaper skate appeared to be significantly lower during the 2002–2006 and 2011–2014 (IFQ) periods, peaking in 2007–2010 (Fig. 7, Table S8). Pacific sleeper shark at-sea discards increased from 2002–2006 to 2007–2010, peaking during the IFQ period (2011–2014) (Fig. 7, Table S8). Brown cat shark landings at the dock appeared to be up slightly in the 2011–2014 period compared to 2002–2006 and 2007–2010, whereas landings of the 2 skate species followed the pattern for at-sea discards: lower landings in 2002–2006, a peak in 2007–2010, and a drop in landings in 2011–2014 (Fig. 7, Table S8).

4. DISCUSSION

We present the first analysis of non-managed elasmobranch bycatch in the US WCGF. The North Pacific region is identified as an area with substantial gaps in elasmobranch catch and discard estimates (Oliver et al. 2015), and this study helps fill this gap. Our work highlights several important points for management consideration. First, there are species of conservation concern that appear in the catch of

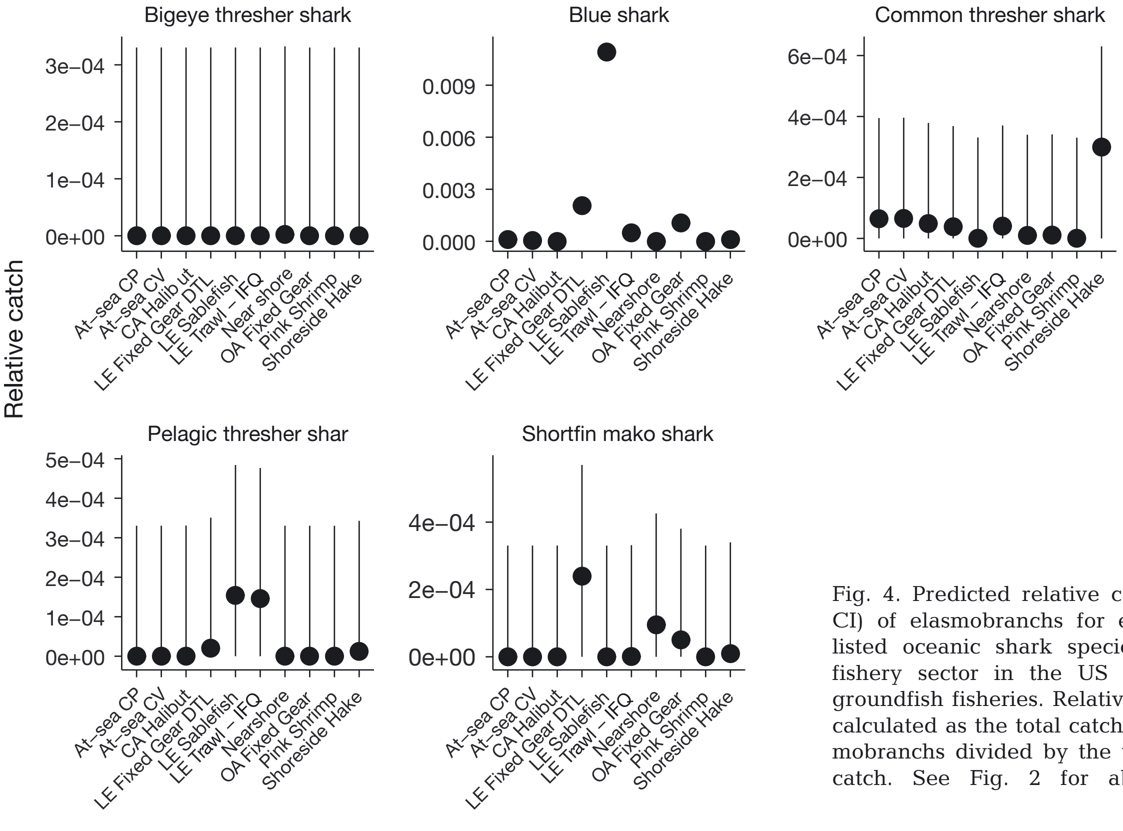

Fig. 4. Predicted relative catch (±95% CI) of elasmobranchs for each IUCN-listed oceanic shark species for each fishery sector in the US West Coast groundfish fisheries. Relative catch was calculated as the total catch of the elasmobranchs divided by the total landed catch. See Fig. 2 for abbreviations

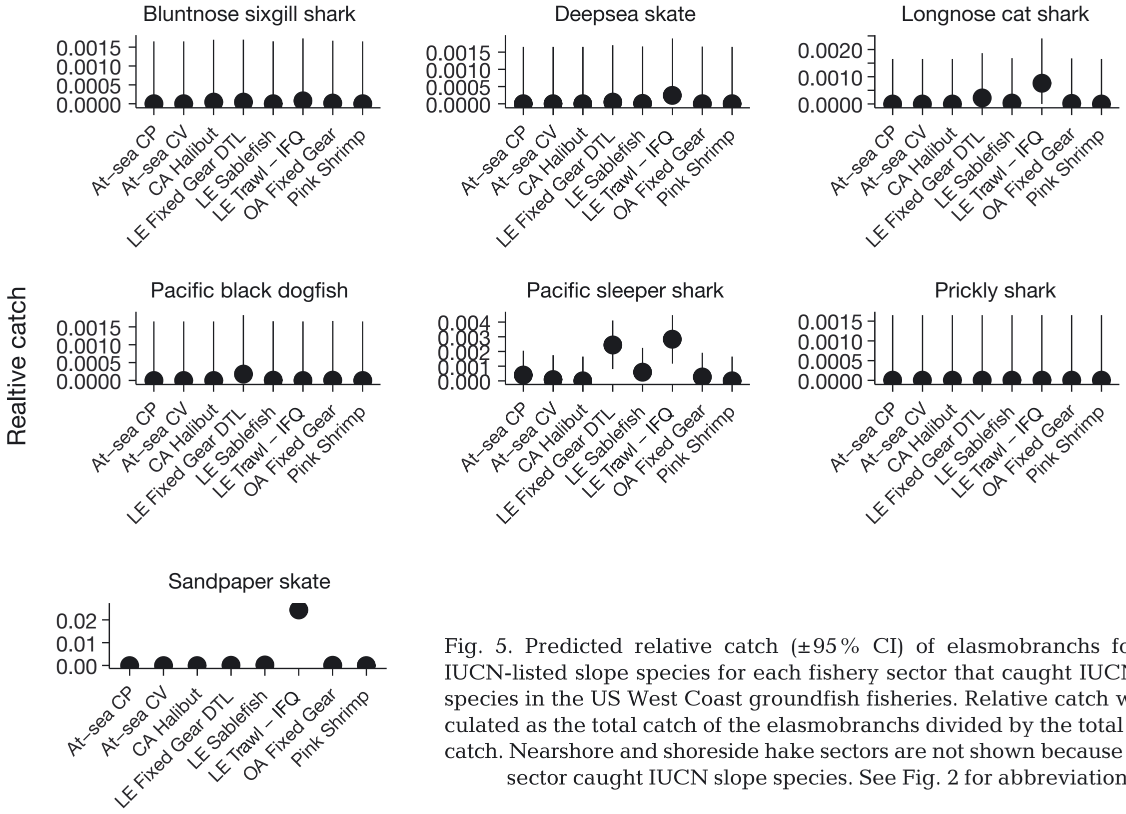

Fig. 5. Predicted relative catch (±95% CI) of elasmobranchs for each IUCN-listed slope species for each fishery sector that caught IUCN slope species in the US West Coast groundfish fisheries. Relative catch was calculated as the total catch of the elasmobranchs divided by the total landed catch. Nearshore and shoreside hake sectors are not shown because neither sector caught IUCN slope species. See Fig. 2 for abbreviations

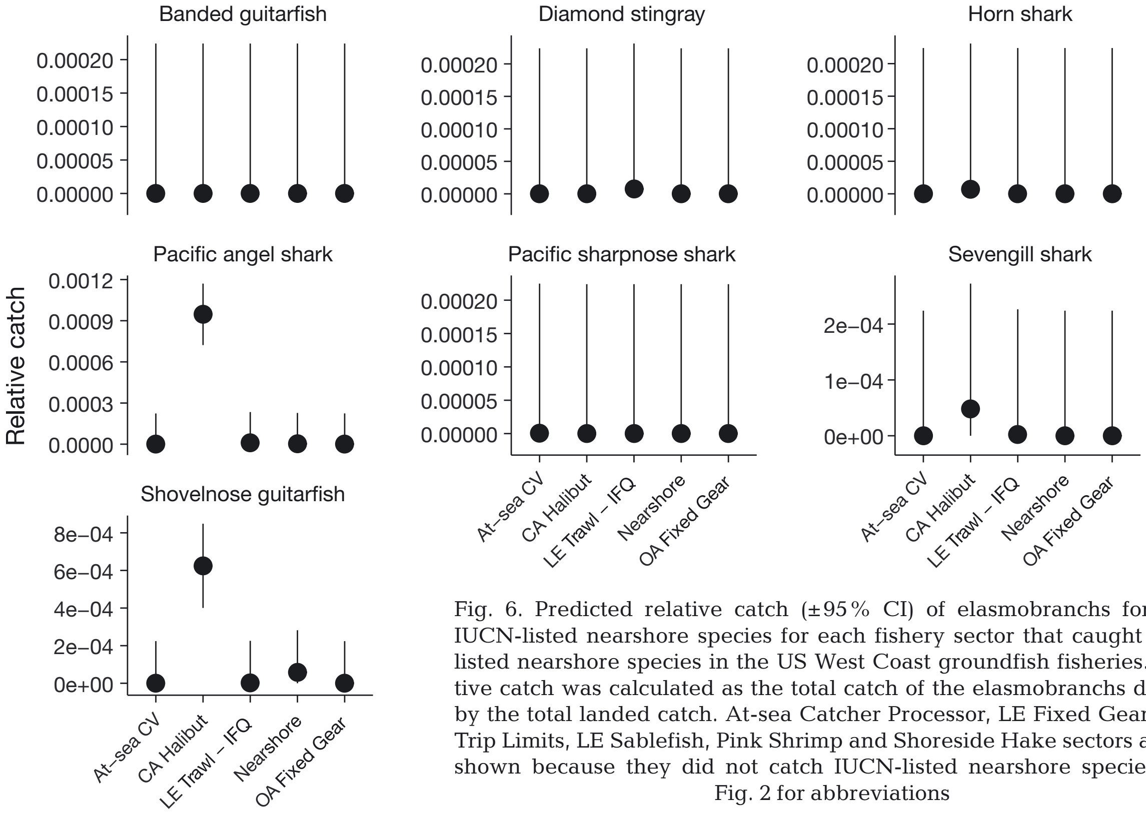

Fig. 6. Predicted relative catch (±95% CI) of elasmobranchs for each IUCN-listed nearshore species for each fishery sector that caught IUCN listed nearshore species in the US West Coast groundfish fisheries. Relative catch was calculated as the total catch of the elasmobranchs divided by the total landed catch. At-sea Catcher Processor, LE Fixed Gear Daily Trip Limits, LE Sablefish, Pink Shrimp and Shoreside Hake sectors are not shown because they did not catch IUCN-listed nearshore species. See Fig. 2 for abbreviations

Table 7. Generalized linear modeling results examining the effect of species, catch disposition (at-sea discard, landed at dock), and time period (2002–2006, 2007–2010, 2011–2014) on catch weight (mt) in the Limited Entry Trawl–Individual Fishing Quota (LE Trawl–IFQ) sector. Coefficients from these models are presented in Table S8

	df	Deviance	Residual df	Residual deviance	*F*	p
Null			779	87 204		
Species	29	35 228	750	51 976	111.82	<0.0001
Catch disposition	1	4844	749	47 132	445.88	<0.0001
Time period	2	167	747	46 964	7.70	<0.0001
Species × catch disposition	29	35 101	718	11 863	111.42	<0.0001
Species × time period	58	2595	660	9269	4.12	<0.0001
Catch disposition × time period	2	166	658	9103	7.62	<0.0001
Species × catch disposition × time period	58	2585	600	6518	4.10	<0.0001

groundfish fisheries on the US West Coast. However, most of these species of concern rarely appear in the catch, and when they are present, they appear in relatively small amounts compared to other fisheries along the US West Coast (e.g. pelagic drift gillnet fishery). Relative catch of non-managed elasmobranchs in WCGF trawl fisheries are closer to the lower end of global averages (Oliver et al. 2015). Second, a large proportion of both shark and skate catches is unidentified, in particular landed catch, limiting the ability of managers to understand the risks to specific species. Third, our work indicates that suites of elasmobranch species with similar ecological requirements might be able to be managed en masse. Ecomorphotypes are area- and depth-specific and appear to be strongly associated with specific fishing grounds and gear types, potentially simplifying management for large groups of non-target species under an ecosystem-based management approach. Fourth, our work suggests that even when species are excluded from explicit fisheries management programs, implementing or changing management strategies could have impacts on unmanaged species. Below, we discuss each of these ideas in-depth and conclude with suggestions for improving elasmobranch bycatch management.

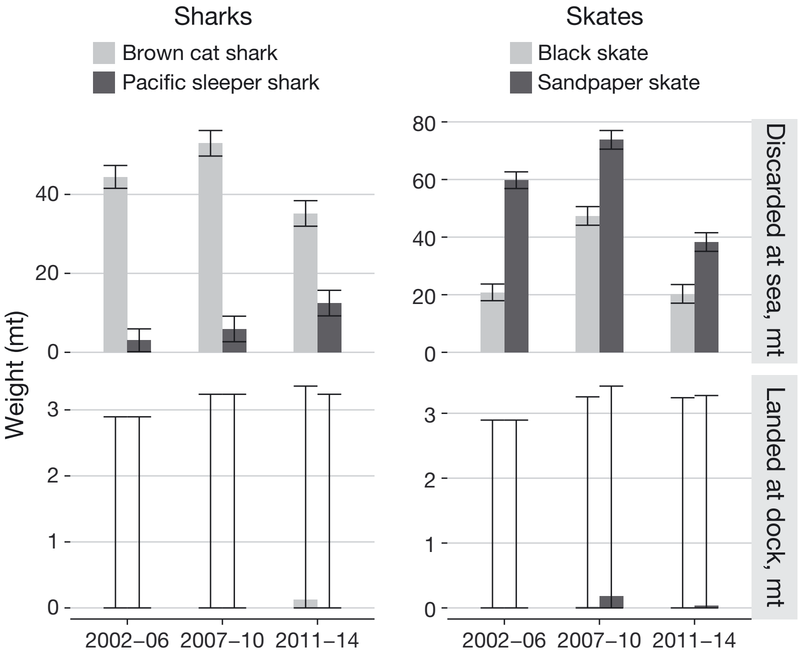

Fig. 7. Predicted weight (±95% CI) of brown cat and Pacific sleeper sharks, black and sandpaper skates in the LE Trawl–IFQ fishery by catch disposition (at-sea discard [upper], landed at dock [lower]) and time period (2002–2006, 2007–2010, 2011–2014)

4.1. Managing species of concern

We identified a suite of elasmobranchs that are of global concern and are caught by these fisheries in relatively low amounts. Nine species found in groundfish catches are currently listed as EN, VU or NT with declining or unknown population trends and 10 species are considered DD (IUCN 2020). Seven of the EN, VU or NT shark species are being landed in small amounts in these fisheries, mainly shortfin mako, common thresher, and Pacific angel shark. A recent stock assessment of shortfin mako sharks over a 42 yr period concluded that it is not likely overfished in the North Pacific (ISC Shark Working Group 2018). However, Rigby et al. (2019b) extended this analysis over 72 yr (3 generations). Under this scenario, rates of decline of the North Pacific shortfin mako population could be as much as

30–49% (Rigby et al. 2019b). Common thresher shark in the Eastern North Pacific also do not appear to be overfished (Teo et al. 2018), but some caution is warranted as this assessment is based largely on data from fishery catches. Other common thresher shark populations do appear to be in decline (Rigby et al. 2019a). Even though the amount of landed catch of these species in the WCGF is relatively low compared to unlisted species, our work fills gaps in reporting (Oliver et al. 2015, Rigby et al. 2019 a,b) and provides baseline data for management of these species on the US West Coast. For example, there is evidence that the commercial fishery for Pacific angel shark in California has been increasing landings in recent years (CDFW 2020). In addition, a number of elasmobranch species, while not yet meriting categorization as Threatened or Endangered, do have restricted ranges and low reproductive potential (e.g. several batoids, coastal shark species), making them vulnerable to overfishing. Closer scrutiny of these species by fisheries managers that could reap ecosystem benefits (Crowder et al. 2008, Ritchie & Johnson 2009, Polovina & Woodworth-Jefcoats 2013).

Closer scrutiny requires better identification requirements for landed non-managed elasmobranchs. Approximately 25% of sharks and 99% of skates in the landed catch were grouped into broad unidentified categories (e.g. sharks unidentified, etc.) because there is no dockside sorting and identification requirements for unmanaged elasmobranch species (PFMC 2019). At-sea observers are required to sort and identify all discarded species to the lowest taxonomic unit possible, including elasmobranchs. Unidentified elasmobranch landings limit our capacity to (1) understand the risks to sensitive elasmobranch species and (2) manage or mitigate those risks. Dockside sorting and identification requirements for landed elasmobranchs would improve our understanding of fishing impacts on these species.

4.2. Ecomorphotypes as a management unit

Our work on ecomorphotype groupings suggests that even regulations targeted at single elasmobranch species could yield benefits for other species of the same ecomorphotype and thereby potentially amplify the benefits of single-species management across multiple species. Ecomorphotypes encompass a number of species that share general habitat characteristics (e.g. depth, area; Table 1). There is a strong relationship between the ecomorphotypes caught by a fishery sector and the general geographic area where that sector typically fishes as exemplified in Fig. 2, which shows slope fisheries (e.g. LE Trawl–IFQ) tend to catch slope species, oceanic hook-and-line fisheries (e.g. LE Sablefish) tend to catch ocean sharks, and coastal fisheries (e.g. CA Halibut) catch nearshore species. This opens an opportunity for managers — managing a gear type, even if for the purposes of a single elasmobranch species, could in effect lead to an EBFM approach with maximum effect because multiple sectors with similar gear types (e.g. hook-and-line) have a similar impact on all the species within an ecomorphotype grouping. For example, the California Halibut Bottom Trawl sector fishes relatively close to shore (<5.6 km offshore) in relatively shallow waters (generally <200 m) and consequently catches a higher proportion of coastal sharks and nearshore skates and rays than other US West Coast fisheries (Fig. 2), suggesting that management of this sector could benefit nearshore ecomorphotypes. Furthermore, there are other fishery sectors that fish in the nearshore (Pink Shrimp, Nearshore Fixed Gear), and thus management of these ecomorphotypes could reap benefits across fisheries. Similar cross-sector impacts could be achieved by managing oceanic sharks in fixed gear fisheries and slope elasmobranchs in off-shore trawl fisheries. The relationship between ecomorphotypes and sectors or gear means that simple single-species management is likely to have impacts on the wider group of ecomorphotypes and therefore bringing management goals in closer alignment with EBFM. Future work should be directed toward a more objective characterization of ecomorphotypes, especially for skates and rays.

4.3. Management impacts on unmanaged species

Our data suggest that at least some unmanaged elasmobranchs might have benefited from the implementation of the IFQ program. The shift was encouraging across all species: elasmobranch catch was initially on the rise from the 2002–2006 to the 2007–2010 period and then at-sea discard dropped by about 36% and landings at the dock dropped by about 44% from the pre-IFQ period (2007–2010) to the IFQ period (2011–2014), similar to levels seen in the 2002–2006 period. Three elasmobranch species (1 shark and 2 skates) showed a significant drop in both at-sea discards and landings at the dock during the 2011–2014 period compared to the past. Furthermore, we detected little change in catch of the remaining 27 elasmobranch species caught by the LE–IFQ bottom trawl fleet. Thus, our study finds some support for the idea that an IFQ program can have indirect positive effects — or at minimum, no negative effects — on non-managed species. There is no *a priori* reason to believe that all unmanaged species will respond positively to an IFQ program (but see Somers et al. 2018b), or any change in management. For example, it is completely plausible that in some cases, a limited IFQ program like the one implemented in the WCGF might incentivize landings of species that are outside the IFQ requirements. In such cases we might expect negative impacts of an IFQ program on unmanaged species, for example, if fishers try to capitalize on unexplored or under-utilized markets with unmanaged species. However, exploiting new or under-utilized species would require investment in market research and testing, which could be expensive and risky. We found no evidence for the idea that fishers began retaining non-managed elasmobranchs. The IFQ program appears to incentivize fishing effort to maximize catch of the valuable IFQ species while avoiding unwanted species. However, it should be noted that there are other explanations for the patterns we observed; most notably, changes in species distribution and/or abundance, which might also contribute to the drop in catch during the 2011–2014 period.

This work is an example of how fisheries management for a subset of the ecosystem has implications for species outside the formal management framework. Initiating new or significant changes to management has the potential to tip the balance between discards at sea and landings of non-managed species as fishers seek new markets with less regulatory oversight. The accuracy of elasmobranch stock assessments, IUCN classifications, fishery management plans, and other reporting forums would benefit from ensuring that WCGF elasmobranch bycatch are included in these management platforms and help reduce the risk of overexploitation of these species (Worm et al. 2013).

4.4. Conclusions and future work

This study emphasized how fisheries management changes might affect unmanaged elasmobranchs and provided some simple solutions for more formal management of these species. One area in need of collaborative work are species of concern that appear in both US West Coast groundfish and HMS fisheries; for example, oceanic sharks. The PFMC manages both the WCGFMP and the HMS FMP. Assessing the total fishing effects on these species and developing an appropriate management strategy will require synthesis and analyses across groundfish and HMS management plans, as is discussed in the WCGFMP (PFMC 2019). In addition, improved management to avoid overexploitation of elasmobranchs is going to require better taxonomic resolution. Dockside sorting requirements for landed elasmobranch species, at the finest taxonomic resolution possible, is one simple step toward better management of these species. Furthermore, the use of ecomorphotypes, which encompass a suite of species that are area- and depth-specific, has the potential to streamline management in an EBFM approach. More precise and objective definitions of elasmobranch ecomorphotypes, especially for skates and rays, will provide a useful tool for managers. Finally, close monitoring of shifting target groups and markets after implementing or changing management strategies will help managers stay ahead of any potential unintended consequences for non-managed species.

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