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An ecosystem-based risk assessment for California fisheries co-developed by scientists, managers, and stakeholders

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ABSTRACT

The intensive harvest of wild populations for food can pose a risk to food security and to conservation goals. While ecosystem approaches to management offer a potential means to balance those risks, they require a method of assessment that is commensurate across multiple objectives. A major challenge is conducting these assessments in a way that considers the priorities and knowledge of stakeholders. In this study, we co-developed an ecological risk assessment (ERA) for fisheries in California (USA) with scientists, managers, and stakeholders. This ERA was intended to meet the requirements of existing policy mandates in the state of California and provide a systematic, efficient, and transparent approach to prioritize fisheries for additional management actions, including the development of fisheries management plans fully compliant with California laws. We assessed the relative risk posed to target species, bycatch, and habitats from nine state-managed fisheries and found risk to target species was not necessarily similar to risks to bycatch and habitat groups. In addition, no single fishery consistently presented the greatest risk for all bycatch or habitat groups. However, considered in combination, the greatest risk for target species, bycatch groups, and habitats emerged from two commercial fisheries for California halibut. The participatory process used to generate these results offers the potential to increase stakeholders' trust in the assessment and therefore its application in management. We suggest that adopting similar processes in other management contexts and jurisdictions will advance progress toward ecosystem-based fisheries management that simultaneously satisfies fisheries, conservation, and relationship-building objectives.

1. Introduction

Fishing is the most widespread practice of capturing wild animals for food in the modern world. This activity affects the populations that are harvested, non-targeted species and habitats in the ecosystem, as well as other user groups (e.g., ecotourists) and sectors (e.g., transportation, energy) (White et al., 2012). Yet viable approaches to evaluate the ecosystem-wide effects of fishing are still nascent. Real-world examples of system-scale evaluations of the potential and realized impacts of fishing, developed with stakeholders and used by decision makers, are even less common (Dolan et al., 2016; Fletcher and Bianchi, 2014; Marshall et al., 2017).

The appraisal of the potential ecosystem-wide effects of fishing can be accomplished via a structured process known as risk assessment (Burgman, 2005). Risk assessment identifies the probabilities that factors impeding or preventing the achievement of fisheries and ecosystem management objectives will persist and the consequences if they do (ISO, 2009). A central challenge in traditional fisheries management has been to negotiate a balance between risk to the persistence of exploited populations and benefits to people, including food provisioning, livelihoods, cultural connections, and way of life (Poe et al., 2014). Evolution of more traditional approaches toward ecosystem-based fisheries management (EBFM) has increased recognition that fisheries also pose risk to species that are not targeted directly and to

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the habitats in which fisheries operate (Hobday et al., 2011). Over recent decades, frameworks for ecological risk assessments (ERAs) have emerged alongside EBFM to enable formal assessment of potential unintended consequences from fishing (Brown et al., 2013; Hobday et al., 2011; Micheli et al., 2014; Patrick et al., 2010; Samhouri and Levin, 2012; Stobutzki et al., 2001). In fact, on a global scale, most EBFM approaches call for ERAs (reviewed recently by Levin et al., 2018).

Although ERAs for the biophysical effects of fishing rely on a generally consistent conceptual framework, they vary in the extent to which they evaluate risk to target species alone (Patrick et al., 2010; Stobutzki et al., 2001) or risk to target species in combination with other ecosystem components (Battista et al., 2017; Micheli et al., 2014; O et al., 2012; Samhouri and Levin, 2012; Williams et al., 2011). This latter type of ERA is one of the few readily-available approaches that can integrate within existing US legal-regulatory processes to broaden fisheries perspectives from single-species toward communities and ecosystems (Dolan et al., 2016; Gibbs and Browman, 2015; Hobday et al., 2011; Hunsaker et al., 1990).

Existing ERAs for the effects of fishing also vary in the extent to which they include government and stakeholders at each step of their development to achieve shared support for management priorities (see recent reviews in Holsman et al., 2017; Stelzenmüller et al., 2018). Indeed, evidence is accumulating that EBFM, like other types of environmental management, will be most effective if it embraces risk assessment that fully integrates stakeholder needs and perspectives (Röckmann et al., 2017) and is matched to the timelines of decision makers. Participation can increase the public's perceived legitimacy of ERAs, even with little or no changes to computational methods. Though the need for stakeholder participation and knowledge co-production is increasingly appreciated in a variety of governance venues (Cook et al., 2013), it remains the exception rather than the rule for EBFM initiatives (Francis et al., 2018).

In this study we capitalized on an opportunity to co-develop an ERA for fisheries in the state of California (USA) by participating in an amendment process to the Marine Life Management Act (MLMA) Master Plan[1,2]. This ERA is an ecosystem-based assessment of the relative risk posed to target species, and bycatch and habitat groups, from nine fisheries in California (Fig. 1), based on the collective knowledge of scientists, managers, and stakeholders. The result is a systematic, efficient, collaborative, and transparent approach to prioritize fisheries species for additional management actions as required by the MLMA. The co-developed ERA reflects a substantive advancement toward EBFM in California because it incorporates extensive stakeholder input, reflects a broad focus on multiple aspects of the biophysical system affected by fisheries, and matches the decision timeline for the MLMA Master Plan Amendment.

2. Methods

2.1. Project design

In California, the MLMA calls for the conservation, sustainable use, and where feasible, restoration of California's living marine resources and the habitats on which they depend. It also requires the engagement of fishery participants in developing ocean management actions,[3] and external reviewers have emphasized this need (Harty et al., 2010). Our work was conducted from July 2016–July 2017 as a core component to informing the MLMA Master Plan Amendment process,[4] which was led by CDFW from late 2015 to June 2018.

The MLMA Master Plan Amendment process includes a mandate to prioritize fisheries for the preparation of FMPs. It stipulates that this prioritization should be based on the need for changes in management to comply with the broad objectives of the MLMA, including the "…sustainable use…of California's living marine resources and the habitats on which they depend." ERAs provide an effective and quantitative approach to assess ecosystem components that are most likely to experience a negative impact from human activities and natural stressors (Smith et al., 2014). The core concern of the ERA described here is therefore to evaluate which fisheries are posing the greatest risk to ecosystem components (where ecosystem components are defined by MLMA).

In this study a project team consisting of CDFW staff scientists and managers and the authors of this manuscript developed the ERA framework and analytical approach. It is adapted from Samhouri and Levin (2012), and we chose it after careful consideration of a number of compelling alternatives (Table 1). Like most ERAs developed for fisheries and EBFM, this one relies on two axes of information. The first axis, referred to as exposure E, distinguishes and quantifies factors that modify the probability that a target species or associated ecosystem component (e.g., bycatch species, habitat) is negatively affected by a fishery. The second axis (sensitivity, S) focuses on factors that influence the response of the ecosystem component if it is exposed to the fishery. More exposed and more sensitive ecosystem components (target species, bycatch groups, habitat groups) are considered to be at higher risk. We define a negative impact as an unwanted outcome, here assumed to be the decline in abundance of a species or group, or in the area or quality of a habitat.

In order to be consistent with the MLMA Master Plan Amendment, we designed the ERA with the specific intent of incorporating input from fishery participants and other interested stakeholders via workshops. We define stakeholders as participants in the nine commercial and recreational fisheries assessed (Fig. 1), representatives from environmental NGOs, academics, or scientists from other agencies. The fisheries were often represented by anglers, commercial fishers, sportfishing operators, and fishing community leaders.

We convened two workshops with stakeholders to solicit input about the framework itself, provide details of its implementation, and enable presentation of different options for consideration by CDFW staff and stakeholders. All interested stakeholders who learned about the workshops through various communication channels and expressed interest in participating were invited to attend. After each workshop, we incorporated input from CDFW staff and stakeholders to arrive at the final product presented here. We did not intend to measure the influence of this participatory process, but rather built it into our methodological approach to increase transparency, meet the requirements of the MLMA, and improve the risk assessment.

One consequence of co-developing this ERA is that difficult choices had to be made, and these choices reflected the personal and professional biases and preferences of the project team and workshop participants. Some of these choices included identification of experts to conduct scoring assessments; selection of target species, and bycatch and habitat groups; and, disproportionate weighting of a subset of exposure and sensitivity attributes. Decisions around these issues allowed us to obtain full and meaningful engagement across a diversity of participants at the workshops, and are described in detail below. We defined experts as CDFW staff most familiar with the social and ecological characteristics of the fisheries under study for this analysis (Fig. 1). These individuals were chosen by CDFW.

2.2. Defining units of analysis: Fisheries and ecosystem components

We developed this ERA and applied it as part of a pilot study of several fisheries. Considerations for selection of a fishery included the need for CDFW to understand its potential impact to invertebrate and vertebrate, nearshore and pelagic, upper- and lower-trophic level, and

[1] https://www.dfg.ca.gov/marine/pdfs/binders_nc/b3_79.pdf
[2] https://www.wildlife.ca.gov/Conservation/Marine/MLMA/Master-Plan
[3] Section 7056, https://www.dfg.ca.gov/marine/pdfs/binders_nc/b3_79.pdf
[4] https://www.wildlife.ca.gov/Conservation/Marine/MLMA/Master-Plan

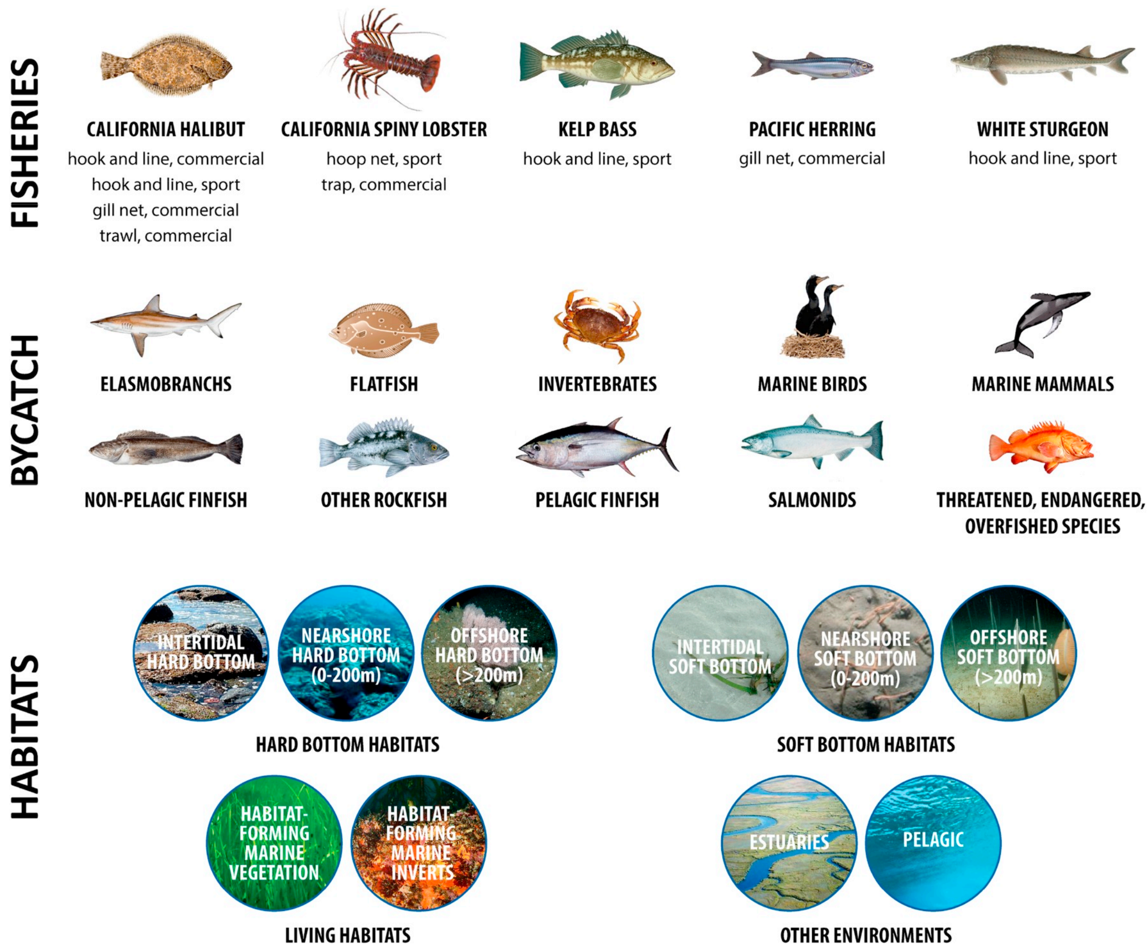

Fig. 1. Fisheries, bycatch groups, and habitats evaluated as part of the ecological risk assessment. Fisheries indicate target species, gear, and sector(s) considered.

data-rich and data-poor species. In addition, we wanted to capture sport and commercial sectors across the state, a range of gear types, varying economic and socio-cultural values, and fisheries with and without existing management plans. Final decisions concerning which species and fisheries to include were made by CDFW staff.

We conducted scoring and analysis for fisheries that focused on five target species, including California halibut (*Paralichthys californicus*), California spiny lobster (*Panulirus interruptus*), kelp bass (*Paralabrax clathratus*), Pacific herring (*Clupea pallasii*), and white sturgeon (*Acipenser transmontanus*). In California, a fishery is defined as the species it targets, the gear used to catch the target species, and the sector (i.e., commercial or sport) in which it occurs. Multiple fisheries were analyzed for two of the target species, resulting in risk assessments for nine fisheries as follows: four California halibut fisheries, two spiny lobster fisheries, and individual fisheries targeting Pacific herring, white sturgeon, and kelp bass (Fig. 1). These fisheries represent a small subset of the many managed by CDFW.

We assessed the risk that each fishery posed to a set of ecosystem components that were specifically highlighted in the MLMA, including target species, bycatch groups, and habitat groups (Fig. 1). Ten bycatch and ten habitat groups were designated by CDFW staff. These groups were chosen to be maximally representative while not overly encumbering CDFW staff with an exhaustive list to score, and could be partitioned in other ways in the future or by others familiar with California fisheries. Risk to a bycatch or habitat group was assessed for a representative species or habitat type chosen by the scorer based on her/his CDFW staff knowledge of the fishery. Definitions of exposure and sensitivity attributes were modified based on feedback received during interactive workshops with stakeholders.[5] Bycatch and habitat groups that did not interact with a particular fishery were not scored by CDFW staff and were not included in the analysis.

For bycatch, we assessed ten groups initially suggested by CDFW, and later these were refined by the project team and stakeholders during workshops (Fig. 1). These groups together represent the full spectrum of taxa considered bycatch in California's marine fisheries. CDFW staff chose to bin many species together into bycatch groups based on protection status, habitat associations, life histories, and other characteristics so that the scoring effort would fit within the project timeline and scoring of other fisheries in the future could be time-efficient as well. This choice also was consistent with CDFW's goal of assessing risk to bycatch overall, rather than to individual bycatch species, for the purpose of prioritizing fisheries for management decisions. Once prioritized, further data collection, analysis, or tools could be employed to look across multiple bycatch species not analyzed here.

The risk to each bycatch group was assessed based on the most frequently caught species within that group. CDFW staff scored a group if any constituent species represented > 1% of the target species catch by weight or number (depending on how landings are recorded for that fishery). Sub- and supra-legals of the target species were considered bycatch, and in many cases bycatch of target species represented the most frequently caught species within a bycatch group. Three bycatch

[5] Specific modifications to the attributes are described in the California Ocean Science Trust report, available online at http://www.oceansciencetrust.org/wp-content/uploads/2017/11/Ecological-Risk-Assessment-report-OST-2017.pdf.

Table 1
Comparison of a range of ecological risk assessment approaches and considerations for their application to California fisheries.

Consideration	Ecological risk assessment framework					
	Ecological Risk Assessment for Fisheries (ERAF) - developed for Canadian fisheries (O et al. 2012)	CARE and CARE lite tool - developed by Environmental Defense Fund (Battista et al., 2017)	Ecological Risk Assessment for the Effects of Fishing (ERAEF) - developed for Australian fisheries (Hobday et al., 2011)	Multiple stressor ecosystem-based risk assessment - (Samhouri and Levin, 2012)	Qualitative consequence risk assessment analysis - developed for Australian fisheries (Fletcher, 2005)	Cumulative impacts assessment - a quantitative assessment for assessing multiple human impacts (Stelzenmüller et al., 2010, Halpern et al., 2009)
Scalable (regional and statewide application)	Yes	Needs to be adapted	Yes	Yes	Yes	Yes
Efficiency of development and application	Longer	Moderate	Less for target, moderate to high for bycatch and habitat	Less for target, moderate for habitat and bycatch	Moderate	Moderate to Longer
Scientifically peer-reviewed	Yes	Yes	Yes	Yes	Yes	Yes
Demonstrated application	Yes	Yes	Yes	Yes	Yes	No
Address fisheries as California defines them	Yes	Needs to be adapted	Needs to be adapted	Yes	Needs to be adapted	Yes
Address habitat, bycatch, and target species in same tool/scale	Yes	Needs to be adapted	Needs to be adapted for habitat	Needs to be adapted	Yes	Needs to be adapted
Incorporate consideration of CA MPA network	Needs to be adapted	Yes	Needs to be adapted	Needs to be adapted	Needs to be adapted	Needs to be adapted
Ability to assess stressors other than fishing (e.g. sea surface temperature, ocean acidification, etc.)	Yes	Yes	Needs to be adapted	Yes	Yes	Yes
Minimal training needed for CDFW	No	Yes	Yes	Yes	No	No
Alignment with federal fisheries management tools	No	No	No	Yes	No	No

groups were scored differently: Marine Mammals, Marine Birds, and Threatened and Endangered Species and/or Overfished Rockfish. For these three bycatch groups, incidental catch of any species in the group, no matter the magnitude, caused CDFW staff to assign a score. This decision was made because these groups include species with legal protections that make even minimal bycatch an issue of management concern.

CDFW staff selected ten habitat groups (Fig. 1) based on their knowledge of California coastal and oceanic ecosystems and characteristics of the nine fisheries under study. Habitat groups were restricted to those defined by CDFW and, like bycatch, limited so that the scoring effort would fit within the project timeline and scoring of other fisheries in the future could be time efficient as well. CDFW staff also estimated the proportion of each fishery's activity that occurs in each habitat for use in subsequent analysis. As with bycatch, the habitat groups were refined by the project team and stakeholders during workshops.

2.3. ERA framework

The risk assessment for each fishery was based on the exposure and sensitivity of each target, bycatch, or habitat group. CDFW staff quantified exposure and sensitivity based on sets of attributes (Tables 2–3). Individual attributes were assigned weightings based on their perceived importance in affecting exposure and sensitivity. Perceived importance emerged from discussions with CDFW staff and via conversations at the stakeholder workshops. A single CDFW staff member scored target, bycatch, and habitat for each fishery, and revised these scores multiple times following discussions with the project team and stakeholders. One CDFW staff member worked with the other CDFW staff members to review scores and ensure that the attributes were interpreted in a consistent manner across all nine fisheries.

2.3.1. Data quality

Accounting for the quality of the data used to score attributes is a key component of any modern ERA (Stelzenmüller et al., 2018). Because ERAs are used to generate scores for data poor and data rich fisheries, the information used for scoring can range from expert opinion to formal quantitative assessments. CDFW staff provided a data quality rationale for each of the attributes they scored. This rationale was based on whether peer-reviewed literature, personal observation, data, model output, or some other source of information was used to determine the score (Table A1). The rationale used in scoring is very important for interpreting results, for ensuring standardization in scoring rationale among CDFW staff, and for transparency with stakeholders. The data quality scores were adapted from Samhouri and Levin (2012). To summarize the assessment of data quality, we averaged data quality scores across exposure or sensitivity attributes for each ecosystem component.

2.4. Stakeholder engagement

We convened two workshops to introduce stakeholders to the ERA tool while it was still under development and solicit feedback and recommendations for improvement. Workshops were held on two different days in Long Beach (June 2017) and Santa Rosa (July 2017), California, between 0830 and 1500, to encourage broad stakeholder participation across the state and improve inclusivity (total number of participants across both workshops: 28).

To ensure success in the project team's efforts to engage with and generate support from stakeholders during the development of the ERA tool (Bednarek et al., 2016), we worked with a local consulting firm that specializes in building and fostering relationships with fishers and other interested stakeholders. Targeted outreach was conducted with fishing leadership within the nine pilot fisheries to increase commercial and recreational fishing representation. Outreach channels to solicit

Table 2
Exposure attributes, definitions, and scoring categories for target (T), bycatch (B), and habitat (H). *indicates that attribute does not vary across fisheries. FMP = Fishery Management Plan, MPA = Marine Protected Area.

Factors/categories	Description	High exposure (4)	3	2	Low exposure (1)
Spatial and temporal factors					
Spatial intensity[T,B]	The overlap between the regional abundance of the species and the relative intensity of the target fishery throughout the region (consider both areal and vertical overlap, but not MPA coverage)	Very High overlap (> 40%) between species and fishery	High overlap (> 20–40%) between species and fishery	Moderate overlap (10–20%) between species and fishery	Low overlap (< 10%) between species and fishery
Spatial overlap[H]	The percent overlap between the area that is fished and the area where the habitat is known to exist	> 40% overlap	21–40% overlap	11–20% overlap	0–10% overlap
Temporal intensity[T,B]	Temporal changes in the target fishery (e.g. temporal or spatial closures that are not year round) that affect the temporal overlap between the species and the normal area the target fishery operates within	No temporal closures and no seasonal migration away from the fishery	Temporal closures or seasonal migrations away from the fishery lasting less than three total months	Temporal closures or seasonal migrations away from the fishery occur between 3 and 6 months	Temporal closures or seasonal migrations away from the fishery occur during more than half of the year
Temporal intensity[H]	The number of months a fishery operates over the course of a year in a particular habitat	9–12 months	7–9 months	4–6 months	0–3 months
Management or other factors					
Current landings trend and management strategy[T]	The current trend of landings data (since stock status is often unknown) taking into account the States largest management measure, an FMP	Stock is formally declared as overfished; no FMP in place	Stock not formally overfished but overfishing may be occurring or annual landings in past 5 years are at or near historic lows or in a continuous decline; no FMP in place	Annual landings during past 5 years increasing, stable, or variable with no trend; no FMP in place	Annual landings during past 5 years increasing, stable, or variable with no trend; FMP in place
Gear selectivity[T]	The ability of the fishing gear to capture fish varies based on their morphological characteristics (e.g., body shape and size, spiny versus soft rayed fins, etc.) and determines the extent to which the gear can avoid sub- and supra-legal individuals.	Gear used may capture a significant number of individuals of the target species which are not of legal size, or which are not of a size desirable for retention, or which are not sexually mature individuals. This number may be greater than the number of legal-sized or otherwise retained individuals.	Gear used may capture a significant number of individuals of the target species which are not of legal size, or which are not of a size desirable for retention, or which are not sexually mature individuals. This number may be as great as the number of legal-sized or otherwise retained individuals.	Gear used PRIMARILY captures individuals of the target species which are of legal size, or are of a size desirable for retention, and are all or primarily sexually mature individuals	Gear used ONLY captures individuals of the target species which are of legal size, or are of a size desirable for retention, and which are all sexually mature individuals
Magnitude[B]	The absolute or relative magnitude of the bycatch. Larger numbers of bycatch mean greater risk to overall population of the bycatch species. Score absolute bycatch if data available, if no data available, score relative bycatch.	Absolute bycatch > 75,000 lbs. or relative bycatch is > 25% of the total catch of the target species	Absolute bycatch is between 40,001–75,000 lbs. or relative bycatch is 11–25% of the total catch of the target species	Absolute bycatch is between 10,001–40,000 lbs. or relative bycatch is 5–10% of the total catch of the target species	Absolute bycatch < 10,000 lbs., relative bycatch is < 5% of the total catch, or, for the target species only, a significant proportion (> 50%) of the total catch which could legally be kept is intentionally released (acknowledges catch-and-release fisheries)
Management effectiveness[B,H]	Track record of management measures (e.g., gear restrictions/ modifications) in place for the target stock reduces impacts to bycatch or habitat	No FMP in place for the target fishery that addresses bycatch or habitat and/ or management measures are not effective; currently considered a stressor on the indicator bycatch species or habitat that is poorly managed	No FMP in place for the target fishery that addresses bycatch or habitat and/or management is considered somewhat effective; currently considered a stressor on the indicator bycatch species or habitat but management measures mitigate some of the impacts, but not all	FMP in place for the target fishery that addresses bycatch or habitat and/or management is known to be effective; currently considered a stressor on the indicator bycatch species or habitat but one that is in control	FMP in place for the target fishery that addresses bycatch or habitat and/or management measures are known to be very effective; or not a direct stressor on the indicator bycatch species or habitat

(*continued on next page*)

Table 2 (*continued*)

Factors/categories	Description	High exposure (4)	3	2	Low exposure (1)
MPA coverage and/or other permanent spatial closures[T,B,*]	The spatial overlap between the regional range of the species and no-take MPAs; MPAs impart a positive benefit or protection to the species	MPAs and/or other spatial closures with appropriate habitat either do not overlap with species regional range, are thought to provide no benefit, or no MPAs were designated specifically to protect this species	MPAs and/or other spatial closures with appropriate habitat comprise < 10% of species regional range and may provide some benefit.	MPAs and/or other spatial closures with appropriate habitat comprise 10–19% of species regional range and may provide some benefit. This recognizes that some MPAs were specifically designated to protect this species from fishing impacts.	MPAs and/or other spatial closures with appropriate habitat comprise 20% or more of species regional range and may provide some benefit. This recognizes that some MPAs were specifically designated to protect this species from fishing impacts.
MPA coverage and/or permanent spatial closures[H]	MPA coverage of habitat and/or significant coverage of active fishing grounds (where effort did not shift to a different portion of the unprotected habitat) imparts some benefit to habitat itself.	MPAs and/or other spatial closures either do not overlap with habitat, are thought to provide no benefit, or no MPAs were designated specifically to protect this habitat.	MPAs and/or other spatial closures comprise < 10% of habitat and may provide some benefit.	MPAs and/or other spatial closures comprise 10–19% of habitat and may provide some benefit.	MPAs and/or other spatial closures comprise 20% or more of habitat's regional range and may provide some benefit. This recognizes that some MPAs were specifically designated to protect this habitat from fishing impacts.
Value of exploited species[T,*]	The ex-vessel value of fished stocks; highly valued stocks are assumed more likely to be affected by stressors because fishing effort is likely to be greater	Stock is highly valued or desired by the fishery (> $5.00/lbs.; > $100,000 K/yr. landed; > 76% retention).	Stock is highly valued or desired by the fishery ($2.25–4.99/lbs.; $10,000 K-$99,000 K/yr. landed; 51–75% retention).	Stock is moderately valued or desired by the fishery ($1–$2.25/lbs.; $500 K–$10,000 K/yr. landed; 26–50% retention).	Stock is not highly valued or desired by the fishery (< $1/lbs.; < $500 K/yr. landed; < 25% retention).

workshop participants focused on reaching community leaders, or "key communicators."

We structured workshops to provide stakeholders with an overview of the MLMA Master Plan Amendment process (described in Section 2.1). We highlighted how this mandate leads to a potential role for ERA in fisheries prioritization, and provided an introduction to ERAs including, Productivity Susceptibility Analysis (PSA; Patrick et al., 2010). An in-depth exploration and discussion of the draft ERA tool occurred during both workshops, including attribute definitions, the approach to scoring and weighting, review of iterations of the ERA tool design, and draft results from the nine pilot fisheries. Between and after the workshops, the ERA tool was modified to reflect the knowledge, expertise, and recommendations of stakeholders. CDFW staff re-assessed the pilot fisheries with the revised ERA tool to yield the final results presented here.[6] The re-assessment followed the same procedure outlined above, but incorporated modifications made in response to stakeholder input.

2.5. Analysis of risk

Given the ERA framework described in Section 2.3 and the stakeholder input received as described in Section 2.4, the relative risk R_i to a target species, or bycatch and habitat group, i was calculated as the Euclidean distance of the species or group from the origin in a space defined by exposure and sensitivity indices, or

$$R_i = \sqrt{(E-1)^2 + (S-1)^2}. \quad (1)$$

Thus, the risk to a species or group increased with distance from the origin and each axis received equivalent weight in estimating risk. Values for each exposure attribute $a_{e,i}$ and sensitivity attribute $a_{s,i}$ were determined by assigning a score ranging from one to four for a standardized set of A_e or A_s attributes (for the exposure and sensitivity axes, respectively; see Tables 2–3). These scores were used to calculate an exposure or sensitivity index with each attribute weighted by a factor w_i (ranging from [0,1] with $\sum_{i=1}^{A} w_i = 1$) related to its importance, as

$$E = \sum_{i=1}^{A_e} w_i a_{e,i} \quad (2)$$

and

$$S = \sum_{i=1}^{A_s} w_i a_{s,i}. \quad (3)$$

2.5.1. Analysis of risk: Target species

For each target species in each fishery, all exposure and sensitivity attributes were assigned an equal weight $w_i = 1/A_e$ or $w_i = 1/A_s$.

2.5.2. Analysis of risk: Bycatch

We assessed risk only to the subset of the ten bycatch groups that interact with each fishery. Attribute scores for each affected bycatch group were averaged by axis (following Eqs. (2)–(3)). Average values for each bycatch group on each axis were summed to provide a cumulative risk score for all bycatch related to each fishery. That is, after using Eqs. (2)–(3) to calculate exposure E_b and sensitivity S_b for each individual bycatch group b, cumulative exposure and sensitivity, $C_{E,B}$ and $C_{S,B}$, to all bycatch groups B that are affected by a fishery were calculated as

$$C_{E,B} = \sum_{i=1}^{B} E_b \quad (4)$$

[6] Proceedings from the workshop are available at http://www.oceansciencetrust.org/wp-content/uploads/2017/09/ERA_KeyThemesSummary_Final.pdf.

Table 3
Sensitivity attributes, definitions, and scoring categories for target (T), bycatch (B), and habitat (H). * indicates that attribute does not vary across fisheries. FMP = Fishery Management Plan, DPS = Distinct Population Segment, EU = Evolutionary Unit.

Factors/categories	Description	High sensitivity (4)	3	2	Low sensitivity (1)
Low resistance factors					
Behavioral response[T,B]	Population-wide behavioral effect of the fishery (or fishing gear) on a species	Behavioral response significantly increases impact (e.g., baited hook/pot/trap, lighted squid boats - attracted into it)	Behavioral response increases impact somewhat (e.g., schooling behavior - herring)	Behavioral response does not change impact (e.g., sedentary species)	Behavioral response reduces impact (e.g., built in inefficiency or ability of a species to get out of a gear)
Current status[H,*]	The regional status of the habitat; increasingly critical status signifies a decrease in the ability of the habitat to recover from the impacts of the pressure	High concern (endangered or threatened status or thought to be imperiled); unrecognizable or substantially degraded compared to historical status	Habitat is highly degraded, but either has no official status or is undergoing significant or successful management efforts to rebuild or restore	Moderate to low concern (e.g., impact studies exist but do not reveal major problems); somewhat degraded compared to historical; efforts underway to rebuild the habitat	No concern; negligible difference from historical
Current status[B,*]	The regional status of the species; increasingly critical status increases the likelihood that effects of a stressor will cause a negative impact	Endangered	Threatened	For marine birds and mammals, fully protected but not T or E; for finfish and invertebrate species, status appears sustainable but no FMP in place	For finfish and invertebrate species; status appears sustainable; FMP in place
Fishing mortality[T]	The proportion of the total population lethally removed from the fish stock on annual basis by fishing activities.	> 0.40	0.31–0.40	0.21–0.30	≤ 0.20
Release mortality[B]	Fish survival after capture and release varies by species, region, and gear type or even market conditions, and thus can affect the susceptibility of the stock.	Probability of survival $< 25\%$	Probability of survival 26–50%	Probability of survival 51–75%	Probability of survival $> 75\%$
Slow recovery factors					
Age at maturity[T,B,*]	Population-wide average age at maturity; greater age at maturity corresponds to longer generation times and lower productivity	> 10 years	6–10 years	2–5 years	< 2 years
Breeding strategy[T,B,*]	The breeding strategy of a stock provides an indication of the level of mortality that may be expected for the offspring in the first stages of life. Additional information in (Winemiller, 1989).	0–1 or External fertilization and no parental care with known low successful reproduction rates	2 or External fertilization and no parental care	3 or Internal fertilization or parental care but not both	≥4 or Internal fertilization and parental care
Fecundity[T,B,*]	The population-wide average number of offspring produced by a female each year	< 10	10^1–10^2	10^2–10^3	$> 10^3$
Population connectivity[H,*]	For biotic habitats, realized exchange with other populations based on spatial patchiness of distribution, degree of isolation, and potential dispersal capability; based on monitoring surveys, and population genetic or direct tracking estimates. Abiotic habitats should be scored as 1.	There is a recognized biogeographical boundary for all or most individuals within the state (e.g. Point Conception); the habitat or some of the organisms that form it are listed species or have protected status.	There is a recognized biogeographical boundary for all of or most individuals within the state (e.g. Point Conception); the habitat or some of the organisms that form it are NOT listed species or have protected status.	There is not a recognized biogeographical boundary for all of or most individuals within the state (e.g. Pt. Conception), and the species has either an egg or larval dispersal period < 1 month or has no egg and larval dispersal period	There is not a recognized biogeographical boundary for all of or most individuals within the state (e.g. Pt. Conception), and the species has an egg or larval dispersal period of 1 month or greater.
Population connectivity[T,B,*]	Realized exchange with other populations based on spatial patchiness of distribution, degree of isolation, and potential dispersal capability; based on monitoring surveys, and population genetic or direct tracking estimates.	There is a recognized biogeographical boundary for all or most individuals within the state (e.g. Point Conception); one or more population(s) is identified as DPS or EU	There is a recognized biogeographical boundary for all of or most individuals within the state (e.g. Point Conception); no populations are identified as DPS or EU.	There is not a recognized biogeographical boundary for all of or most individuals within the state (e.g. Pt. Conception), and the species has either an egg or larval dispersal period < 1 month or has no egg and larval dispersal period	There is not a recognized biogeographical boundary for all of or most individuals within the state (e.g. Pt. Conception), and the species has an egg or larval dispersal period of 1 month or greater.

(*continued on next page*)

Table 3 (*continued*)

Factors/categories	Description	High sensitivity (4)	3	2	Low sensitivity (1)
Potential damage to habitat from fishing gear[H]	Within the footprint of the fishery, the potential modification of habitat when exposed to a fishery (gear, chains, anchors, boats, etc.).	Potential modification to habitat structure is caused by fishing activity using bottom trawl or beam trawl or new gear with unstudied effects	Potential modification to habitat structure is caused by fishing activity using traps on strings with ground lines and weights (e.g. spot prawn, hagfish fisheries), gill nets, or purse seine	Potential modification to habitat structure is caused by trap and hoop nets with individuals lines and floats (e.g. lobster, Dungeness crab), or occasionally by anchor or chain damage from vessels not drifting when fishing with hook-and-line or hand-collection type gear.	No or insignificant potential modifications to habitat structure caused by any of these gears used: hook-and-line, clam fork, abalone iron, urchin rake, hand collection (e.g. sea cucumber fishery), A-frame, midwater trawl
Recovery time[H,*]	For biotic habitats, we refer to recovery time of the habitat as a whole (e.g., a mature kelp forest) rather than recovery time of individuals. For abiotic habitats, shorter recovery times for habitats such as mudflats decrease the sensitivity of exposure to human activities, whereas for habitats made of bedrock, recovery will occur on geological time scales.	Recovery time > 100 years	Recovery time > 10 years	Recovery time 1–10 years	Recovery time < 1 year

and

$$C_{S,B} = \sum_{i=1}^{B} S_b. \tag{5}$$

This cumulative risk method produces higher risk scores for fisheries interacting with many bycatch groups than for fisheries interacting with fewer groups.

Weights w_i for bycatch attributes were assigned to reflect their perceived importance. One exposure attribute (Magnitude) and one sensitivity attribute (Release Mortality) were weighted to represent 50% of the total score for each axis. That is, $w_{\text{magnitude}} = 0.5$ and $w_i = 0.5/(A_e - 1)$ for the other exposure attributes, while $w_{\text{release mortality}} = 0.5$ and $w_i = 0.5/(A_s - 1)$ for the other sensitivity attributes. This decision was made based primarily on the feedback of stakeholders and CDFW staff, the majority of whom felt that these attributes were the main drivers of each category and provided results that matched their understanding of how fisheries create risk to bycatch. All bycatch groups received equal weights—a decision that was expedient because it did not require an additional systematic protocol but also one that reflects a strong position implying equal importance of all bycatch groups (an assumption that can be evaluated directly in future work based on stakeholder preferences, legislative mandates, etc.; Halpern et al., 2013). We highlighted the number of protected groups each fishery affected to demonstrate their presence or absence without changing the score of the fishery.

2.5.3. Analysis of risk: Habitats

As with bycatch, we assessed risk only to the subset of the ten habitat groups that interact with a fishery. Attribute scores for each group were averaged by axis (following Eqs. (2)–(3)).

We weighted risk to habitats instead of using the cumulative risk method (Eqs. (4)–(5)). This decision emerged from stakeholder and CDFW expert feedback. Each fished habitat h was weighted by a factor w_h based on the relative amount of fishing effort occurring within it. That is, exposure and sensitivity of all habitats H affected by a fishery, E_H and S_H, were calculated based on exposure and sensitivity of individual habitats, E_h and S_h, (from Eqs. (2)–(3)) as

$$E_H = \sum_{i=1}^{H} w_h E_h \tag{6}$$

and

$$S_H = \sum_{i=1}^{H} w_h S_h. \tag{7}$$

This weighted average risk method produces highest risk scores for highly exposed and sensitive habitats in which a fishery is primarily concentrated. It is less dependent upon the number of groups affected by the fishery than the cumulative risk method that was used to assess risk to bycatch.

Like bycatch attributes, habitat attributes were additionally weighted to reflect their relative importance. One exposure attribute (gear footprint) and one sensitivity attribute (potential damage to habitat from gear type) were weighted to represent 50% of the total score for all attributes on each axis. That is, $w_{\text{gear footprint}} = 0.5$ and $w_i = 0.5/(A_e - 1)$ for the other exposure attributes, whereas $w_{\text{damage}} = 0.5$ and $w_i = 0.5/(A_s - 1)$ for the other sensitivity attributes. This decision was made based primarily on the feedback of CDFW staff and stakeholders.

2.5.4. Statistical sensitivity analyses

Outside of the stakeholder engagement process, we conducted a sensitivity analysis to evaluate the influence of individual exposure and sensitivity attributes on risk scores for each target species, and of individual bycatch and habitat groups on risk scores for bycatch and habitat related to each fishery (Fig. A1). Following Patrick et al. (2010)

and Samhouri and Levin (2012), we calculated jackknifed estimates of median, 2.5%, and 97.5% values and report these results in the Appendix. Note that for bycatch we calculated jackknifed cumulative exposure and sensitivity scores, rather than jackknifed averages, prior to estimating the median, 2.5%, and 97.5% values, and we considered only equal weightings for the analysis of uncertainty in habitat scores.

2.6. Visualizing risk

Results are represented most simply by ecosystem component-specific figures that display exposure and sensitivity of target species, and bycatch and habitat groups within a fishery. Contour lines in these exposure-sensitivity figures represent equivalent risk. For bycatch results, the size of points in each figure indicates how many groups with protected status (maximum = 3) contributed to the overall score for a fishery. For habitat results, the size of points in each figure indicates how many habitat groups contributed to the overall score for a fishery.

To consider risk across all three ecosystem components for each fishery, we also present standardized risk scores and results of a non-metric multidimensional scaling (nMDS) analysis. The standardized scores are constrained to be > 0 and less than or equal to 1, and are calculated as the target, bycatch, or habitat risk score for each fishery divided by the maximum risk to that ecosystem component observed across the nine fisheries.

The nMDS analysis illustrates the relative similarity among fisheries with respect to the source and magnitude of risk to target species, and bycatch and habitat groups. nMDS arranges objects in a low-dimensional ordination space so that the inter-object distances in the input similarity matrix and in the derived ordination have the same rank order, with the measure of this difference termed stress. Risk scores for target species and all bycatch ($n = 10$) and habitat ($n = 5$) groups that interacted with at least one fishery were included in the analysis. Two–dimensional nMDS was calculated using the Bray–Curtis dissimilarity measure and a maximum of 100 random starts to find a stable solution. A permutation test with 999 iterations was used to determine the stress value. Ordination dissimilarities resulting from nMDS were compared to observed (Bray–Curtis) dissimilarity using correlation results of Shepard plots to assess goodness of fit. All analyses were conducted using R v3.4.3, and the function *envfit* in the package *vegan* was used to calculate and depict variable loadings on the nMDS ordination plot (Oksanen et al., 2008; R Core Team, 2014). A permutation test with 999 iterations was conducted to assess statistical significance of variable loadings.

3. Results

3.1. Risk to target species

Of the nine fisheries assessed, relative risk to target species was greatest for white sturgeon in the sport hook-and-line fishery, followed by California halibut in all four fisheries (Fig. 2a). For all five of these fisheries, relatively high-risk scores resulted from high scores for nearly all exposure attributes.[7] Relative risk to California spiny lobster from trap and sport hoop fisheries and to kelp bass from the hook-and-line fishery were similar to relative risk to California halibut from its four fisheries. However, this outcome resulted from higher sensitivity scores rather than higher exposure scores. For California spiny lobster, high Fishing Mortality, Behavioral Response, and Age at Maturity attribute scores resulted in high sensitivity scores, whereas kelp bass sensitivity scores were relatively high because of Population Connectivity and Breeding Strategy attributes, in addition to their Behavioral Response to the fishery. Pacific herring exhibited the lowest relative risk due to the commercial gill net fishery, with low scores for most exposure and sensitivity attributes. Statistical sensitivity analysis revealed that exposure scores for both lobster fisheries exhibited the greatest variability, but scores on both axes for the remaining fisheries exhibited relatively narrow confidence intervals (Fig. A1).

3.2. Risk to bycatch

Compared with the target species assessment, cumulative risk scores to bycatch were much more variable across the nine fisheries and fell into three main groups (Fig. 2b). The commercial gill net and trawl fisheries for California halibut posed the greatest cumulative risk to all bycatch groups. This result emerged because both fisheries interact with six of the ten bycatch groups, and the magnitude of bycatch and associated mortality is relatively high for some groups. Intermediate cumulative risk scores for bycatch associated with the sport hook-and-line fisheries for white sturgeon and kelp bass resulted from their interactions with five bycatch groups each. Risk scores were lower for California halibut hook-and-line fisheries than for the commercial gill net and trawl fisheries because the score for the Release Mortality attribute is much lower for hook-and-line gear. The remaining three fisheries exhibited notably lower cumulative risk to bycatch groups, largely because those fisheries interacted with only one or two bycatch groups. Statistical sensitivity analysis indicated that median estimates were precise for most fisheries, with halibut fisheries exhibiting the widest spread in jackknifed scores (Fig. A1).

The ten bycatch groups we assessed were at risk from an average of 3.3 (± 1.6 SD) fisheries, with salmon affected by only one fishery and non-pelagic finfishes at risk from six fisheries (Fig. 3). Across the nine fisheries we considered, some bycatch groups were at consistently high or low risk, but risk to other bycatch groups was more variable. For example, several fisheries posed moderate to high risk to flatfishes and invertebrates whereas risk to elasmobranchs and birds from multiple fisheries were all relatively low (Fig. 3). In contrast, threatened and endangered species and/or overfished rockfishes and pelagic finfishes were at high risk from only one of the four fisheries that affected them. Similarly, half of the fisheries affecting non-pelagic finfishes posed high risk whereas half posed low risk (Fig. 3).

3.3. Risk to habitats

Compared with bycatch, the nine fisheries we assessed did not produce as much variability in risk to all of the habitats considered collectively (Fig. 2c). One notable exception was the substantially higher risk to habitats affected by the California halibut commercial trawl fishery (nearshore soft bottom and habitat-forming marine invertebrates; Fig. 3b, Table 4). Importantly, though these two habitats were both highly exposed to the California halibut commercial trawl fishery, neither was expected to be particularly sensitive. Of the remaining eight fisheries, habitats influenced by the commercial gill net fishery for California halibut were at the greatest risk (Fig. 2c). Notably, overall risk to habitats from the two California spiny lobster fisheries was moderate but these fisheries affected the most habitats, including nearshore hard and soft bottom, marine vegetation, and habitat-forming marine invertebrates. The lowest risk to habitats emerged for three hook-and-line fisheries: the sport fishery for kelp bass and both the commercial and sport fisheries for California halibut. The 95% confidence intervals for habitat exposure scores were narrow across all fisheries, with greater uncertainty evident in some sensitivity scores (e.g., halibut sport hook and line, herring commercial gillnet) (Fig. A1).

The ten habitat groups we assessed were at risk from an average of 2.1 (± 2.3 SD) fisheries, ranging from five habitats with no fishery interactions to one habitat (nearshore soft bottom) that was affected by six of the nine fisheries (Fig. 3). A closer inspection of the risk posed by each fishery to individual habitat groups produces two additional

[7] Scores for each fishery-target/bycatch/habitat combination and associated rationale are available online at http://www.oceansciencetrust.org/projects/era/.

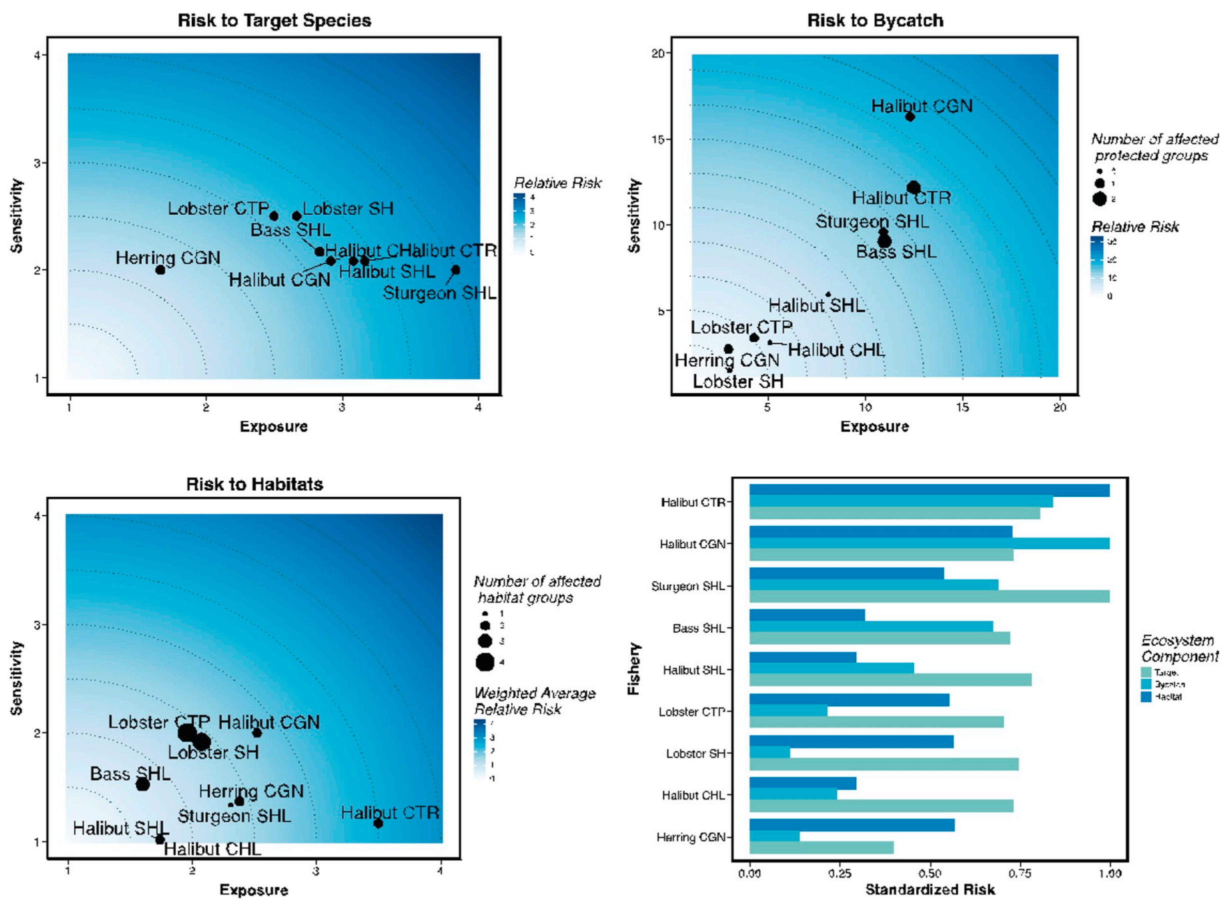

Fig. 2. Risk to (a) target species, (b) bycatch groups, (c) habitats, and (d) all three ecosystem components. Each point represents the risk from an individual fishery; for bycatch and habitat, values reflect risk across all groups (see text for details). CGN = commercial gill net, CHL = commercial hook-and-line, CTP = commercial trap, CTR = commercial trawl, SH = sport hoop, SHL = sport hook-and-line. Contour lines represent combinations of exposure and sensitivity scores that produce equivalent risk.

insights. First, the risk posed by each fishery tended to be relatively consistent and on average moderate across all habitats it affected (Fig. 3, Table 4). Second, and in contrast with risk to individual bycatch groups, risk to each habitat varied more substantially among fisheries. For example, half of the fisheries affecting nearshore soft bottom posed moderate to high risk whereas half posed low risk (Fig. 3).

3.4. Data quality

For the assessment of risk to target species, all of the data quality scores were generally high (greater than or equal to 3; Fig. A2). Data quality of bycatch and habitat risk assessments was more variable than for the target species risk assessment. In some cases, a fishery that had higher data quality for the target species risk assessment had lower data quality for the bycatch or habitat risk assessment (e.g., the California halibut and kelp bass sport hook-and-line fisheries; Fig. A2), or vice versa. In other cases, there were clear differences in data quality used to assess different gears and sectors for a single species. For instance, the data quality for the habitat risk assessment related to the commercial trap fishery for California spiny lobster was much higher than for the sport hoop fishery targeting the same species (Fig. A2c).

3.5. Overall risk to the ecosystem

Three patterns emerge from the comparison of risk scores across all three ecosystem components. First, some fisheries posed consistently high relative risk to target species, and bycatch and habitat groups, whereas others caused consistently low risk. For example, the commercial trawl fishery for California halibut presented high risk across all ecosystem components whereas the commercial gill net fishery for Pacific herring created low risk for all three ecosystem components (Fig. 2d). Second, some fisheries posed high risk to only two of three ecosystem components. The sport hook-and-line fishery for kelp bass provides a case in point, as risk to the target species itself and bycatch were relatively high but risk to habitats was not (Fig. 2d). Third, some fisheries posed low risk to target species and high risk to bycatch and/or habitat groups. For example, risk to target species and bycatch groups from the two fisheries for California spiny lobster were not especially high compared to several other fisheries. However, the sensitivity of habitats due to these fisheries was notably high compared to most of the other fisheries (Fig. 2d).

These conclusions aid in the interpretation of the multivariate nMDS analysis to examine similarity in risk scores across the nine fisheries (Fig. 4). This analysis also indicated that risk to target species was largely similar among fisheries, with differences in risk posed by fisheries largely driven by differential risk to several bycatch and habitat groups. A very strong linear fit was indicated between observed and estimated dissimilarity values ($r^2 = 0.941$). A stress value of 0.09 for the nMDS analysis indicated good interpretive ability but was not significantly different than that expected by chance ($p = 0.158$) due to our

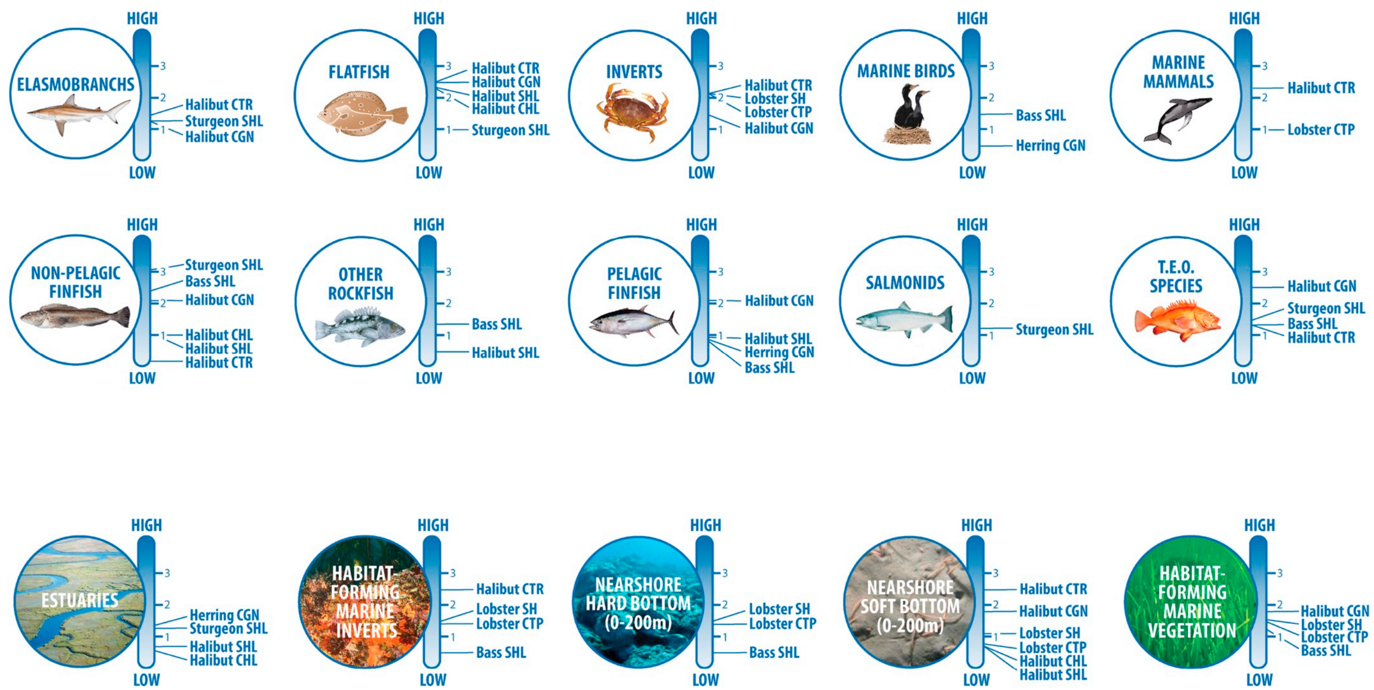

Fig. 3. Risk from each of the nine fisheries to individual bycatch groups and habitats. Actual scores provided in Table 4.

limited sample size and the many bycatch and habitat groups that did not interact with these nine fisheries (zero scores). Three bycatch groups (invertebrates, flatfishes, and non-pelagic finfishes) and one habitat group (habitat-forming marine vegetation) had significant loadings in two-dimensional ordination space (Fig. 4) and together served to separate the fisheries based on the composition and relative magnitude of their risk scores. Habitat-forming marine vegetation exerted the greatest influence on the arrangement of fisheries in the two-dimensional bi-plot ($r^2 = 0.909$, $p = 0.002$). An additional three habitat groups (habitat-forming marine invertebrates, nearshore hard bottom, nearshore soft bottom) and risk to target species had marginally significant loadings ($p < 0.10$) and further contributed to the observed arrangement of the nine fisheries in ordination space.

4. Discussion

Risk assessment is a key step toward the consideration and implementation of environmental management actions (Burgman, 2005). It also provides a formal mechanism to ensure that multiple objectives are met, including those related to conservation. In the case of fisheries, a broad evaluation of how fishing may affect target species and other important components of the ecosystem, including non-target (bycatch) species and habitats, provides important context for determining where management challenges and opportunities are most and least likely to arise. In places like California and in U.S. federal waters, the emergence of initiatives such as the California MLMA Master Plan Amendment process and the National Marine Fisheries Service ecosystem-based fisheries management policy make risk assessments a core part of agency directives.

Our pilot study of an ERA for a subset of California fisheries clearly indicates the potential for discordance between risk to target species and risk to incidentally captured species and to habitats. It also highlights how risk from individual fisheries that each affect other species (bycatch groups) and habitats may accumulate to amplify risks from fishing for a variety of ecosystem components. Because our insights reflect the outcome of a participatory process with stakeholders and the agency mandated to implement such assessments, there is an increased likelihood that the process and outcomes will be trusted and used in future decision making (though we note that public participation per se is necessary but insufficient for trust and use; National Research Council, 2008).

In this way, this ERA provides a model that is at once generalizable and customizable for advancing the implementation of EBFM. It is generalizable because it follows a simple mapping from policy mandate to project team formation to framework application and stakeholder engagement. It is customizable because the particulars of the ERA framework used here can be adapted to best inform the process under consideration in other settings. This approach is thus potentially useful in the context of Integrated Ecosystem Assessments at a variety of jurisdictional levels (state, federal, etc.) in the US and beyond (Foley et al., 2013).

The risk posed to the persistence of species that are targeted by fisheries is a well-known and actively-managed issue, particularly in the Northeast Pacific (Costello et al., 2016). Risks to non-targeted species affected by these fisheries, as well as the habitats in which the target species occur, are lesser known. Such information is critical as more agencies in the U.S. and around the world move toward EBFM (Dolan et al., 2016; Fletcher and Bianchi, 2014; Marshall et al., 2017). Because it evaluates risk to bycatch and habitat groups, this assessment presents an alternative perspective of ecological risks associated with nine fisheries compared to that gained from an assessment of risk to target species alone.

4.1. Integrative and cumulative perspectives on risk

CDFW indicated during the co-development of this ERA tool that the

Table 4
Risk to individual bycatch and habitat groups due to each fishery. Risk scores calculated based on Eq. (1).

	California halibut commercial hook & line	California halibut sport hook & line	California halibut commercial trawl	California halibut commercial gillnet	White sturgeon sport hook & line	Spiny lobster sport hoop net	Spiny lobster commercial trap	Kelp bass sport hook & line	Pacific herring commercial gillnet
Bycatch									
Elasmobranchs			1.53	1.31	1.33				
Flatfish	2.31	2.32	2.53	2.50	0.98				
Marine birds								1.45	0.45
Marine invertebrates			2.16	1.53		2.12	2.00		
Marine mammals			2.30				0.99		
Non-pelagic finfish	1.05	1.05	0.25	2.13	3.08			2.47	
Other rockfish		0.44						1.37	
Pelagic finfish		0.94		2.16				0.78	0.80
Salmonids					1.21				
Threatened/endangered species, overfished rockfish			1.32	2.67	1.41			1.37	
Habitat									
Estuaries	0.67	0.75			1.35				1.41
Habitat-forming marine invertebrates			2.51			1.51	1.41	0.56	
Habitat-forming marine vegetation						1.62	1.54	1.31	1.80
Hard bottom intertidal									
Nearshore hard bottom						1.51	1.41	0.56	
Nearshore soft bottom	0.75	0.75	2.51	1.80		1.06	0.80		
Offshore hard bottom									
Offshore soft bottom									
Pelagic									
Soft bottom intertidal									

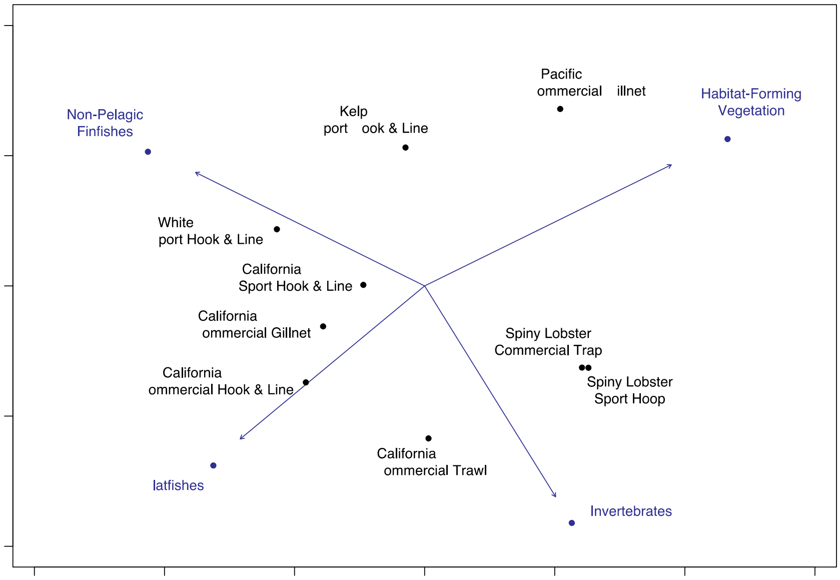

Fig. 4. Non-Metric Multidimensional Scaling (nMDS) 2D ordination plot indicating relative similarity among the nine fisheries with respect to risk scores for target species and each bycatch group and habitat group that was affected by at least one fishery. Significant variable loadings ($p < 0.05$) are depicted.

ability to distinguish different fisheries based on the risk they pose to disparate parts of the ecosystem would help to achieve MLMA objectives. Our analysis produced much less variability in risk to target species compared to risk to bycatch or habitat groups. A PSA (cf. Patrick et al., 2010) conducted in parallel with the effort described here (but focused on a great number of fisheries) showed similar rank order risk to target species for these nine fisheries, and had very little variability in risk scores for target species across the larger group of fisheries assessed (Swasey et al., 2016). In an assessment of global fisheries, Costello et al. (2016) suggested that the consistency in status of target species in the US reflects the success of existing management efforts and achievement of sustainable fisheries. We contend that a broader definition of sustainability that accounts for risks to a greater range of ecosystem components may in certain cases lead to different conclusions. The larger range of scores for bycatch and habitat groups in our analysis bolsters this claim and is also indicative of the extensive customization of this ERA for management needs in California.

This pilot ERA provides a window into risk for target species, and bycatch and habitats groups considered collectively, while also identifying fisheries that pose higher relative risk to bycatch groups and habitats and lower relative risk to target species. Collective risk was greatest for the commercial trawl and gill net fisheries for California halibut. These fisheries not only effectively capture California halibut, but also affect seven of the ten bycatch groups (including some protected species) and cause nearshore soft bottom habitats to be highly exposed. These risks were acknowledged previously by CDFW (Frimodig et al., 2008) but are not considered qualitatively or quantitatively in the most recent stock assessment (Maunder et al., 2011).

Perhaps more surprising was the relatively high risk to habitats posed by the two California spiny lobster fisheries, which pose intermediate or low risk to the target species. A new FMP was released by CDFW in 2016,[8] but it did not consider risks to habitats posed by lobster fishing activities. Our assessment indicates that these issues may warrant further investigation for habitat-forming and nearshore habitats in future reviews of the lobster fishery.

In addition to this fishery-by-fishery perspective, our assessment provides a lens through which to consider the potential for cumulative impacts on bycatch and habitat groups (Halpern et al., 2009; Micheli et al., 2014; Stelzenmüller et al., 2018). For example, while some habitats—like intertidal and offshore areas—are unaffected by these nine fisheries, others like nearshore soft bottom are affected by most of them. This type of result provides a high-level perspective for CDFW, which can be used to determine whether additional assessment or management action is necessary. In other contexts, consideration of the cumulative risks posed by multiple co-occurring fisheries in an ecosystem has provided essential information for conservation and management of coastal resources (Halpern et al., 2009; Micheli et al., 2014; Stelzenmüller et al., 2015, 2018).

The other important perspective provided by considering bycatch and habitat groups individually is that in several cases low and moderate risk to all groups masked much higher risk to a single group affected by a fishery (e.g., spiny lobster fisheries posed high risk to the marine invertebrate bycatch group, primarily because of bycatch of sub-legal lobster). This type of insight can potentially be used to guide future assessments, technological changes in these fisheries (e.g., gear design), or management actions. In short, it is possible to obtain a high-level ecosystem-based understanding of fisheries-induced risk without losing sight of risk to individual components.

4.2. Key considerations and limitations

Although this ERA identified potentially important issues for CDFW to investigate further, it also failed to highlight at least one at-risk fishery. Our assessment concluded that risk to Pacific herring and associated bycatch groups and habitats was low relative to the other eight fisheries. While low risk to other ecosystem components from fishing for herring is not surprising, the low risk assessed for the target species itself is puzzling. It contrasts with observations that herring populations in California have been below-average in size for three consecutive years, though this situation is not thought to be a result of fishing (CDFW, 2018). By design and based on CDFW needs, this ERA did not attempt to capture changes in target population status driven by climate variability or other factors. In the case of a forage fish like Pacific herring, this omission is especially important because population declines likely have impacts throughout the food web (Koehn et al., 2017), an issue also not addressed by the ERA.

[8] https://www.wildlife.ca.gov/Conservation/Marine/Lobster-FMP

However, future adaptations of the ERA tool presented here (i.e., Samhouri and Levin, 2012) could be used to close this gap by considering other stressors such as climate variability and change alongside fishing pressure. CDFW is currently developing an FMP for Pacific herring,[9] and this shortcoming of the ERA, along with potential solutions, are worth noting there. Other regions in the US are engaged in similar efforts to incorporate ecosystem-based risk assessment in fisheries management (e.g., Gaichas et al., 2016).

Several other important considerations for this ERA affect its interpretation and application. First, for the sake of expediency and in consideration of CDFW staff capacity, we chose to lump species caught as bycatch and multiple habitat types into groups. However, it is likely that some bycatch or habitat groups have many subgroups that are at higher risk, but only contribute a single score to the bycatch and habitat risk scores (Burgess et al., 2013; Fletcher, 2005; Hobday et al., 2011; Williams et al., 2011; Zhou et al., 2016; Zhou and Griffiths, 2008). Conversely, because each expert scorer selected the taxon that they considered at highest risk in a bycatch group, this ERA could be considered excessively precautionary at the group level. In addition, it is important to keep in mind that this is a relative risk assessment, implying that the ranked risk of fisheries will change as additional fisheries are evaluated. This feature suggests that future work to validate relative risk scores against more quantitative, absolute measures of risk (e.g., via formal stock assessment or population viability analysis) will be needed. Finally, the risks posed by fishing in this assessment are not contextualized relative to other challenges facing these ecosystem components or relative to their potential socio-economic and socio-cultural costs and benefits (Poe et al., 2014). These types of analyses could enrich our assessment and provide even greater insight into appropriate management actions, though they would vastly increase the staff capacity, time, and resources needed to complete such an evaluation.

4.3. Evolution of ecosystem approaches via participatory processes

No static framework can be directly applied to address every environmental policy need (Table 1). In the case of fisheries, if the goal is long-term agreement and acceptance of the outcomes and process from fishers and other stakeholders, each fishery, ecosystem, management structure, and policy context will have particular nuances that need to be considered from the outset (Weichselgartner and Kasperson, 2010). Further, almost any tool used to support environmental decision making will have limitations, and the ERA described here is no exception. However, as in other arenas of environmental management, processes that incorporate active participation, information exchange, transparency, fair decision-making, and positive participant interactions are more likely to be supported by stakeholders, meet management objectives, and fulfill conservation goals (Clark et al., 2016; National Research Council, 2008; Sayce et al., 2013; Wall et al., 2017).

Participatory processes for improving trust in marine fisheries management are particularly important in California. CDFW is mandated to provide analyses of the State's fisheries and guidance on the development and prioritization of fishery management plans. The ERA process described here is the outcome of a participatory process that included a deep partnership between CDFW staff and external scientists, along with active involvement and input by fishers, representatives from environmental non-governmental organizations, and interested members of the public. One goal of employing this approach was to ensure that our research questions and scientific outputs were matched to (a) expected decision timelines related to the California MLMA Master Plan Amendment process, and (b) available technical capacity (Cash et al., 2003; Clark et al., 2016). In contrast, ERA tools are often developed by academic scientists or government managers with little to no stakeholder input (the "loading dock" model; Francis et al., 2018). The final tools may be shared with stakeholders so the implications of the tools' application are known, but in many cases these results are not shared publicly. Stakeholders rarely have the opportunity to learn about, engage with, and shape the tool during the development phase (but see Arkema et al., 2015), as we facilitated with this ERA tool.

The decision to not engage stakeholders during development comes at the expense of a less comprehensive and accurate tool that does not incorporate stakeholders' intimate knowledge of the operation of a fishery or on-the-water observations and understanding of data (Plagányi et al., 2013). Furthermore, this decision can decrease stakeholders' trust in the tool and challenge future implementation efforts (Jarvis et al., 2015; Weichselgartner and Kasperson, 2010). This is especially true in California and other states that have a legislative mandate to engage in a deep public process associated with the management of their fisheries. California has very few organized fishing associations, and – as is true of small social networks generally (Barnes et al., 2017)—working knowledge and trusted relationships with key communicators in the fishing industry were critically important to facilitating the co-development of the ERA tool. Indeed, these key communicators acted on behalf of many other fishers to negotiate a shared agreement about what a new ecological risk assessment tool should look like. Knowledge co-production is a core component of actionable science, though barriers of applying the resulting outputs to actions still exist (National Research Council, 2008; Weichselgartner and Kasperson, 2010).

5. Conclusions

The ERA approach described here has been adopted into the 2018 Master Plan[10] and we understand that this outcome occurred in part because of the process we used to develop it. Absent our efforts, any risk assessment adopted into the MLMA Amendment would likely have been less integrative (across target species, bycatch, and habitats) and more qualitative. If MLMA stipulations are implemented in good faith, partnerships among scientists, managers, and stakeholders will form the foundation for future engagement in fisheries and ecosystem management issues in California and perhaps beyond. Such engagements could facilitate risk assessment for a greater number of fisheries and other types of analyses. For example, one potential extension of this work—and a recommendation heard by stakeholders during workshops— includes downscaling this ERA from a California-wide assessment to one that is regional (e.g., southern, central, northern California) and reflective of issues prioritized at a local level. Indeed, a regional representation of the ERA would be more accurate for certain fisheries, like California halibut, that occur over a broad area of the state. It is our hope that this ERA will inspire an approach to fisheries prioritization that is more transparent and inclusive of diverse sources of knowledge, and can lead to a more effective, comprehensive, and trustworthy package of information to guide management decisions.

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[9] https://www.wildlife.ca.gov/Fishing/Commercial/Herring/FMP

[10] https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=159222&inline

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Appendix A. Attributes of risk

A.1. Attributes for target species, bycatch groups, and habitats

A.1.1. Target species

CDFW staff assessed exposure of each target species to each fishery based on two attributes that did not vary among fisheries (hereafter, baseline attributes), the value of the exploited species and MPA coverage (and/or other permanent spatial closure) in place to protect the species (Table 2). In addition, CDFW staff determined exposure of each target species based on four attributes that varied among fisheries, including: spatial intensity, temporal intensity, gear selectivity, and current landings trend and management strategy.

Sensitivity of each target species to each fishery was scored by CDFW staff based on four baseline attributes and two attributes that varied among fisheries (Table 3). Baseline attributes included: age at maturity, breeding strategy, fecundity, and population connectivity. Behavioral response and fishing mortality were non-baseline attributes.

A.1.2. Bycatch groups

Two baseline attributes and four additional attributes were scored to assess exposure of bycatch groups (Table 2). Current status and MPA coverage were considered baseline attributes. Non-baseline attributes included: magnitude, management effectiveness, spatial intensity, and temporal intensity.

Four baseline attributes and two additional attributes were scored to assess sensitivity of bycatch groups (Table 3). Age at maturity, breeding strategy, fecundity, and population connectivity were baseline attributes. Behavioral response and release mortality were considered non-baseline attributes.

A.1.3. Habitat groups

One baseline attribute (MPA coverage) and three additional attributes were scored to assess exposure of habitat groups (Table 2). Non- baseline attributes included: management effectiveness, spatial overlap, and temporal closures.

Two baseline attributes and two non-baseline attributes were scored to assess sensitivity of habitat groups (Table 3). Population connectivity and current status were the baseline attributes whereas non-baseline attributes included recovery time and potential damage to habitat from fishing gear.

Appendix B. Statistical sensitivity analyses

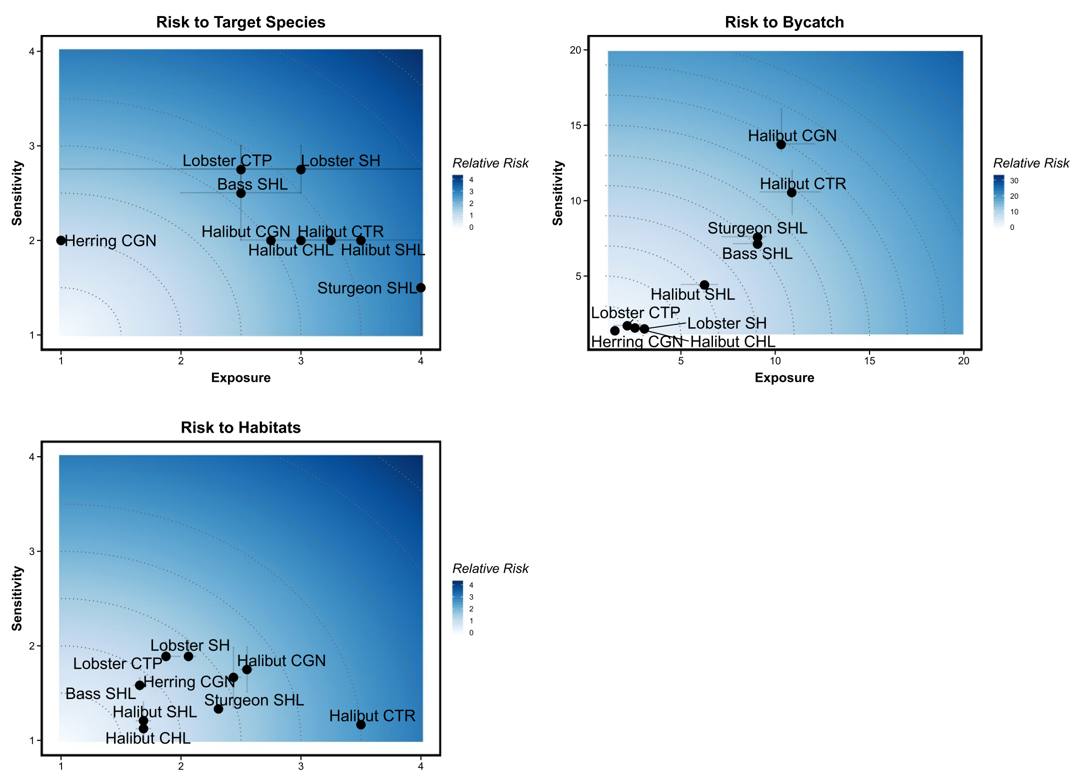

Fig. A1. Risk to (a) target species, (b) bycatch groups, and (c) habitats. Each point represents the median risk from an individual fishery; for bycatch and habitat, values reflect risk across all groups (see text for details). Error bars indicate 95% confidence intervals based on jackknife analyses (see Section 2.5.4 for details). CGN = commercial gill net, CHL = commercial hook-and-line, CTP = commercial trap, CTR = commercial trawl, SH = sport hoop, SHL = sport hook-and-line. Contour lines represent combinations of exposure and sensitivity scores that produce equivalent risk.

Appendix C. Data quality

Table A1
Descriptions and examples associated with each data quality score.

Score	Description	Example
1	Very limited data. Information based on expert opinion surveys or on general literature reviews from a wide range of habitats or taxa.	No empirical literature exists to justify scoring for a habitat or taxa in relation to a particular activity/ pressure but reasonable inference can be made by the person conducting the risk assessment.
2	Limited data. Estimates with high variation and limited confidence, or based on studies of similar habitats/taxa or of the focal habitat/taxa in other regions.	Scoring based on a study of a similar habitat or taxa outside of the study region.
3	Adequate data. Information is based on limited spatial or temporal coverage, moderately strong or indirect statistical relationships, or for some other reason is deemed not sufficiently reliable to be designated as "best data."	Use of presence-absence data from ad hoc sampling efforts; use of relatively old information; etc.
4	Best data. Substantial information exists to support the score and is based on data collected for the habitat or taxa in the study region.	Data-rich assessment of habitat or taxa status, with reference to historical extent and current trends.

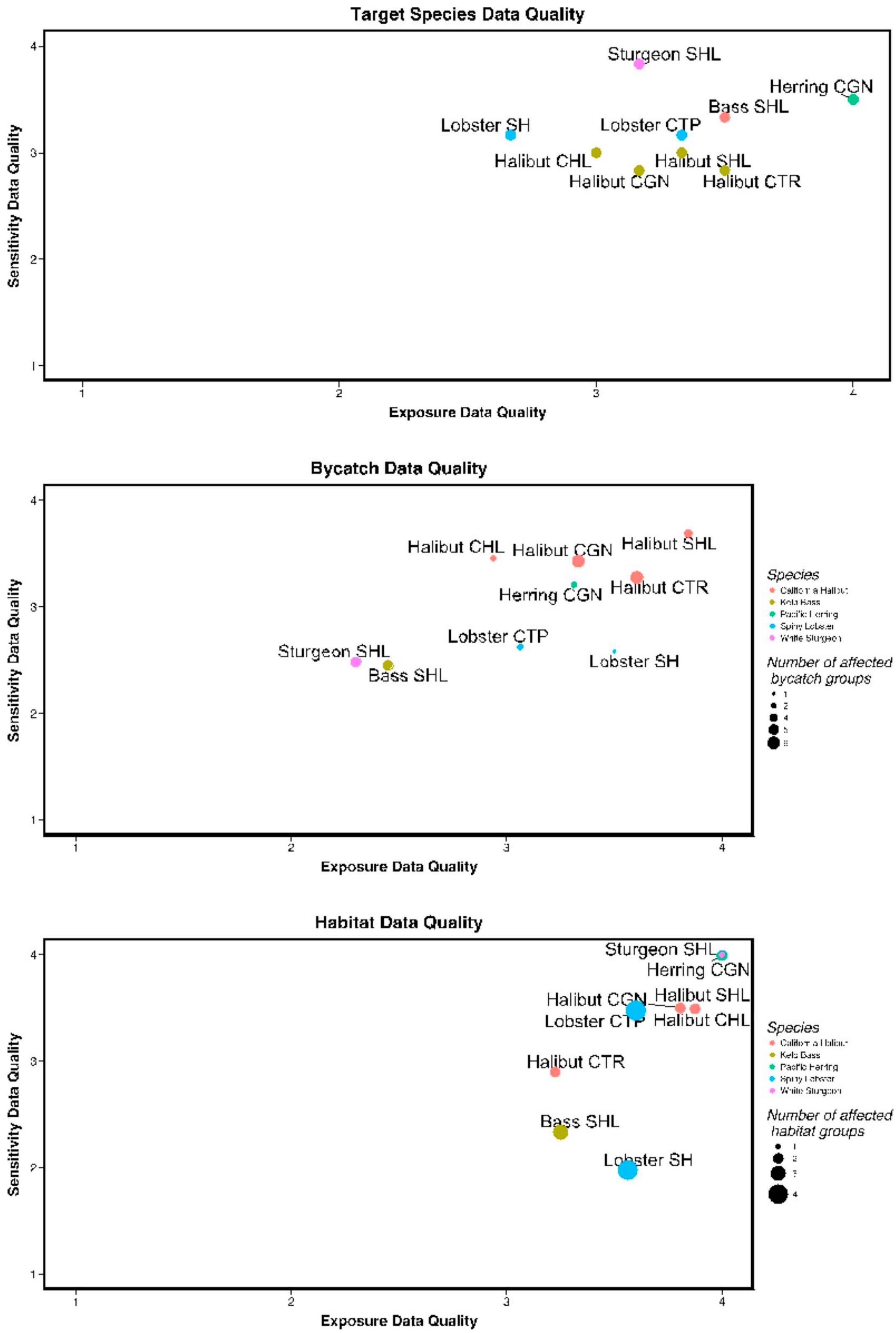

Fig. A2. Data quality for assessment of risk to (a) target species, (b) bycatch, and (c) habitats. Points represent the average of data quality scores for all exposure and sensitivity attributes. For the bycatch and habitat assessments, these scores are also averaged across all bycatch or habitat groups affected by each fishery.

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