Productivity and Susceptibility Analysis for Selected California Fisheries

Report to

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and
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1 Introduction

1.1 Background

In California, the Marine Life Management Act (MLMA) is the primary statute for management of marine fisheries. The Act, codified in 1999, provides guidelines for progressing toward ecosystem-based fisheries management which is comprehensive and proactive in order to achieve common objectives and meet identified standards. Since adoption of the MLMA, fisheries management has focused on targeted rulemakings and on the preparation of fishery management plans (FMPs) for select fisheries, sometimes in response to legislative action. FMPs can take a long time to prepare and can require extensive use of staff resources and funding; as a result, most of the state's fisheries have not yet benefited from this component of the MLMA but are nevertheless managed sustainably through the best efforts of the California Department of Fish and Wildlife (CDFW).

CDFW identified three needs to address the requirements of the MLMA for a large number of fisheries, given the resource limitations in terms of funds and staff:

1. A process for prioritizing future management actions both among and within fisheries;
2. A process for scaling those management actions to reflect the needs, risks, and values of each fishery together with the Department's capacity; and
3. A means of conveying up-to-date fisheries information in a way that's easy for stakeholders, researchers, and the public to navigate and digest.

To address the first need identified, the California Ocean Science Trust contracted MRAG Americas, Inc. to conduct a Productivity Susceptibility Analysis (PSA) on the state's most significant fisheries in terms of commercial value and recreational participation.[1] PSA is a method for assessing the vulnerability of a fishery species or stock, using a set of predetermined measureable attributes and scoring rankings. The approach assumes the level of vulnerability depends on two characteristics: the productivity of a species, which determines the rate at which it can sustain or recover from fishery-related impacts, and the susceptibility of the species or stock to fishing activities. As a result, fisheries management among various stocks can be prioritized in a transparent and consistent manner, based on their need for management action.

The PSA methodology is a powerful tool that allows stakeholders and regulators to gain perspective on the inherent risk of a fishery stock to fishing activities. It also allows scientists to clarify specifically where information is lacking and where to focus resources to collect more information, since attributes weigh differently on risk. This report focuses on the PSA analysis conducted by MRAG Americas, Inc. PSAs can be conducted alone or as part of a series of data analyses on vulnerability. PSAs do not consider stock status against approved biological reference points (although they do account for current biomass and fishing mortality levels), risk to the marine ecosystem, harvest guidelines for a stock, or effects of climate change. Using the information gained from a PSA, a potential secondary component

[1] The list fisheries for analysis was provided by CDFW and represent a diversity of stocks that span commercial and sport sectors, gear types, and coastal areas, and include finfish and invertebrates.

of the vulnerability analysis includes an Ecological Risk Assessment (ERA). An ERA assesses the risk a fishery poses to the ecosystem, and is a potential subsequent and separate phase of work.

The analysis provided here follows an established methodology in accordance with uses by NOAA Fisheries. PSAs provide a repeatable, expedient, and scientifically justifiable means to evaluate the relative vulnerability to fishery stocks for use in prioritizing fisheries for management action. They are primarily used for fishery stocks with moderate to strong long-term databases and knowledge of life history parameters, but this does not preclude stocks where less information is known from receiving management review. PSAs can provide managers with information needed to allocate resources appropriately in the short, medium, and long term. They are a first step in a tool kit of available approaches to assess and sustainably manage fisheries. They inform the users as to primary susceptibilities of the fishery stock and uncertainties in data gaps and quality of data used in the analysis. Built from expert opinion and best available scientific information, this type of risk-based approach allows managers the opportunity to decide the appropriate use of uncertainty and vulnerability in developing management strategies.

1.2 Productivity Susceptibility Analysis

Productivity Susceptibility Analysis (PSA) was originally developed to evaluate bycatch sustainability in the Australian prawn fishery by assessing productivity of bycatch stocks and their susceptibility to the fishery (Milton 2001, Stobutzki et al. 2001). In 2004, Australian Ecological Risk Assessment (AERA) team adapted the tool for a broader use in assessing vulnerability of an ecosystem (Hobday et al. 2004). Since then, it has been adapted for various assessments to evaluate vulnerability of ecosystems or stocks (Hobday et al. 2007; Rosenberg et al. 2007; Simpfendorfer et al. 2008; Patrick et al. 2009, 2010; Cope et al. 2011).

The outputs of a PSA vary, depending on the quality of data inputs and the methodologies applied. PSAs are useful for a baseline comparison among many species with varying levels of available information. For some stocks in California, stock assessments are available, some of which have been updated on a regular basis. For other stocks, little is known other than distribution or estimated life history characteristics, in addition to estimates of catch and fishing effort.

Using the PSA approach, productivity and susceptibility attributes of each stock (or assemblage) are examined and scored. The scores are then used in an equation to calculate overall vulnerability and are graphed to produce a PSA plot; the overall vulnerability scores and plot allow comparison of relative vulnerabilities with other units of analysis (target species, gear type, and fishing sector). Using this information, managers can prioritize stocks in high, medium, or low need of management attention and to identify areas where changes in management can most effectively reduce susceptibility. The PSA analysis also highlights gaps in understanding about a species' biology; improved information can allow for a better understanding of a stock's vulnerability.

2 Methodology

2.1 PSA Selection

Four versions of PSA methodologies were considered for use in this analysis; each was adapted from an approach developed by a joint Australian CSIRO/Australian Fisheries Management Authority project for Ecological Risk Assessment for the Effects of Fishing (ERAEF) (Hobday et al. 2007), and provide a good basis for a precautionary evaluation of vulnerability of fishery resources, including those modified by the National Oceanic and Atmospheric Administration (NOAA),[2] MRAG Americas,[3] Marine Stewardship Council,[4] and Monterey Bay Aquarium.[5] Each method has slightly varying attributes and rankings.

In consultation with MRAG Americas and Ocean Science Trust, CDFW selected the NOAA's National Marine Fishery Service (NMFS) PSA approach for the analysis. The approach was developed as a means to evaluate the vulnerability of a stock in response to NMFS' revision of National Standard 1 (NS1) guidelines.

The NMFS approach was based on and developed from the attributes developed by Hobday et al. (2007). Several attributes that NFMS scientists perceived as redundant were removed. Retained attributes were those that were considered to be: (1) scientifically valid for calculating productivity or susceptibility of a stock, (2) useful at different scales (i.e., stocks of various sizes and spatial distributions), and (3) capable of being calculated for most fisheries (i.e., data availability). Attributes that were considered to have some but not all of these characteristics were retained, and four new attributes were added, including (1) recruitment pattern, (2) management strategy, (3) fishing rate relative to natural mortality, and (4) desirability/value of the fishery. The final NMFS PSA approach utilized 22 attributes (10 productivity, 12 susceptibility). Table 1 and Table 2 identify the final list of attributes, brief definitions and scoring criteria (the process of scoring is further detailed below). Additional details on each attribute are available in Patrick et al. (2009, 2010).

The NMFS PSA has been customized to specifically assess the vulnerability of U.S. fish stocks, based on definitions of becoming overfished or undergoing overfishing. An emphasis is placed on assessing data-poor stocks. The NMFS PSA was selected for this evaluation based on its inclusion of attributes that evaluate the management strategy and the value of a stock, and since it considers uncertainty in data sources. Missing data in the PSA are considered an endpoint in a continuum of data quality; therefore, it is suggested that managers account for data deficiencies and employ a precautionary approach when evaluating PSA results with limited or poor data.

[2] Patrick, W. S., P. Spencer, O. Ormseth, J. Cope, J. Field, D. Kobayashi, T. Gedamke, E. Cortés, K. Bigelow, W. Overholtz, J. Link, and P. Lawson. 2009. Use of productivity and susceptibly indices to determine stock vulnerability, with example applications to six U.S. fisheries. NOAA Tech. Memo. NMFSF/SPO-101. 90 pp. http://www.nmfs.noaa.gov/sfa/laws_policies/national_standards/documents/patrick_2009_noaa_tech_memo_spo_101.pdf

[3] MRAG Americas. 2009. Use of Productivity-Susceptibility Analysis (PSA) in Setting Annual Catch Limits for US Fisheries: An Overview. March 2009. http://www.mragamericas.com/wpcontent/uploads/2010/04/PSA_methodology.4.09.pdf

[4] Marine Stewardship Council. 2014. MSC Fisheries Certification Requirements and Guidance V 2.0. http://www.msc.org

[5] Monterey Bay Aquarium Seafood Watch Criteria for Fisheries (version March 31, 2014), PSA modified from MSC (2009).

Table 1. Productivity attributes and rankings used in this PSA analysis, derived from the NMFS PSA approach (adapted from Patrick et al. 2010).

Productivity Attribute	Definition	Ranking		
		High (3)	Moderate (2)	Low (1)
r	r is the intrinsic rate of population growth or maximum population growth that would occur in the absence of fishing at the lowest population size.	>0.5	0.5-0.16 (mid-pint 0.10)	<0.16
Maximum Age	Maximum age is a direct indication of the natural mortality rate (M), where low levels of M are negatively correlated with high maximum ages.	< 10 years	10 - 30 years (mid-point 20)	> 30 years
Maximum Size	Maximum size is correlated with productivity, with large fish tending to have lower levels of productivity, although this relationship tends to degrade at higher taxonomic levels.	< 60 cm	60-150 cm (mid-point 105)	> 150 cm
von Bertalanffy Growth Coefficient (k)	The von Bertalanffy growth coefficient measures how rapidly a fish reaches its maximum size, where long-lived, low productivity stocks tend to have low values of k.	> 0.25	0.15-0.25 (mid-point 0.20)	< 0.15
Estimated Natural Mortality	Natural mortality rate directly reflects population productivity; stocks with high rates of natural mortality will require high levels of production in order to maintain population levels.	> 0.40	0.20-0.40 (mid-point 0.30)	< 0.20
Measured Fecundity	Fecundity (i.e., the number of eggs produced by a female for a given spawning event or period) is measured here at the age of first maturity.	> 10e4	10e2-10e3	< 10e2
Breeding Strategy	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	between 1 and 3	≥4
Recruitment Pattern	Stocks with sporadic and infrequent recruitment success often are long lived and thus may be expected to have lower levels of productivity.	highly frequent recruitment success (> 75% of year classes are successful)	moderately frequent recruitment success (between 10% and 75% of year classes are successful)	infrequent recruitment success (< 10% of year classes are successful)
Age at Maturity	Age at maturity tends to be positively related with maximum age (tmax); long-lived, lower productivity stocks will have higher ages at maturity than short-lived stocks.	< 2 years	2-4 years (mid-point 3.0)	> 4 years
Mean Trophic Level	The position of a stock within the larger fish community can be used to infer stock productivity; lower-trophic-level stocks generally are more productive than higher-trophic-level stocks.	<2.5	2.5-3.5 (mid-point 3)	>3.5

Table 2. Susceptibility attributes and rankings used in this PSA analysis, derived from the NMFS PSA approach (adapted from Patrick et al. 2010).

Susceptibility Attribute	Definition	Ranking		
		Low (1)	Moderate (2)	High (3)
Areal overlap	Areal overlap is the extent of geographic overlap between the known distribution of a stock and the distribution of the fishery.	< 25% of stock occurs in the area fished	Between 25% and 50% of the stock occurs in the area fished	> 50% of stock occurs in the area fished
Geographic concentration	Geographic concentration is the extent to which the stock is concentrated into small areas.	stock is distributed in > 50% of its total range	stock is distributed in 25% to 50% of its total range	stock is distributed in < 25% of its total range
Vertical overlap	Vertical overlap is the position of the stock within the water column (i.e., whether is demersal or pelagic) in relation to the fishing gear.	< 25% of stock occurs in the depths fished	Between 25% and 50% of the stock occurs in the depths fished	> 50% of stock occurs in the depths fished
Seasonal migrations	Seasonal migrations (i.e. spawning or feeding migrations) either to or from the fishery area could affect the overlap between the stock and the fishery.	Seasonal migrations decrease overlap with the fishery	Seasonal migrations do not substantially affect the overlap with the fishery	Seasonal migrations increase overlap with the fishery
Schooling, aggregation, and other behavioral responses	Behavioral responses of both individual fish and the stock respond to fishing activity.	Behavioral responses decrease the catchability of the gear	Behavioral responses do not substantially affect the catchability of the gear	Behavioral responses increase the catchability of the gear [i.e., hyperstability of CPUE with schooling behavior]
Morphological characteristics affecting capture	The ability of the fishing gear to capture fish varies based on their morphological characteristics (e.g., body shape, spiny versus soft rayed fins, etc.).	Species shows low selectivity to the fishing gear.	Species shows moderate selectivity to the fishing gear.	Species shows high selectivity to the fishing gear.
Desirability or value of the fishery	Highly valued fish stocks are assumed to be more susceptible to overfishing or to becoming overfished by recreational or commercial fishermen owing to increased effort.	Stock is not highly valued or desired by the fishery (<$1/lb; <$500K/yr landed; <33% retention).	Stock is moderately valued or desired by the fishery ($1–$2.25/lb; $500K–$10,000K/yr landed; 33–66% retention).	Stock is highly valued or desired by the fishery (>$2.25/lb; >$10,000K/yr landed; >66% retention).
Management strategy	The susceptibility of a stock to overfishing may largely depend on the effectiveness of fishery management procedures used to control catch.	Proactive management; sort requirements; individual specification; discard monitoring; biological data; representative fishery independent indices. Targeted stocks have catch limits and proactive accountability measures; Non-target stocks are closely monitored.	Reactive management; decent catch records; some assessment data; weak spatial knowledge; weakly informed indices. Targeted stocks have catch limits and reactive accountability measures	High catch uncertainty; low assessment data; no sorting; inadequate discard monitoring; low confidence in control rule. Targeted stocks do not have catch limits or accountability measures; Non-target stocks are not closely monitored.

Susceptibility Attribute	Definition	Ranking		
		Low (1)	**Moderate (2)**	**High (3)**
Fishing rate relative to M	As a conservative rule of thumb, it is recommended that M should be the upper limit of F so as to conserve the reproductive potential of a stock. (not avail without stock assessment)	<0.5	0.5 - 1.0	>1
Biomass of spawners (SSB) or other proxies	The extent to which fishing has depleted the biomass of a stock in relation to expected unfished levels offers information on realized susceptibility. This information is not available without a stock assessment.	B is > 40% of B0 (or maximum observed from time series of biomass estimates)	B is between 25% and 40% of B0 (or maximum observed from time series of biomass estimates)	B is < 25% of B0 (or maximum observed from time series of biomass estimates)
Survival after capture and release	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 > 67%	33% < probability of survival < 67%	Probability of survival < 33%
Impact of fisheries on EFH or habitat in general for non-targeted fish	A fishery may have an indirect effect on a species by adverse impacts on habitat.	Adverse effects absent, minimal, or temporary	Adverse effects more than minimal or temporary but are mitigated	Adverse effects more than minimal or temporary and are not mitigated

2.2 Approach

The PSA allows for the flexibility to define the unit of analysis. For this evaluation, the unit of analysis was defined as a combination of target species, gear, and fishing sector (commercial or sport). Some species were included in more than one unit of analysis since the gear type and/or sector differed enough to warrant additional analyses. CDFW provided the final list of species and sectors for evaluation, which included many of the state's most significant managed fisheries in terms of commercial value and recreational participation; the project scope required limiting to 45 units of analysis, which includes 21 finfish and 15 invertebrate species (Table 3).

PSA can be applied to single units of analysis or can consider cumulative impacts on a fishery, including the impacts of multiple gear types or sectors, bycatch, and takes throughout a species' range. This analysis evaluates only the susceptibility for fisheries in California and does not consider other fishing that may occur on a stock (e.g. for Survival After Capture and Release we assess the target species probability of survival once captured with the primary gear and not secondary sources of capture as bycatch in other fisheries). Users of this information should consider the possibility that fisheries in California may contribute a small amount of fishing pressure to a stock or species that is heavily fished in another state or country; this analysis would miss that cumulative pressure, thereby indicating a low risk for a high risk stock and potentially underestimating the overall vulnerability of the stock. Conversely, fishing activity in California may heavily exploit a small part of a non-overfished stock that has a wide range; the PSA would indicate a high risk for a low risk stock. Use of PSA results must consider the limitations of the selected approach for certain species.

Information and scores were initially generated by MRAG staff from readily available information. CDFW experts then reviewed available information and scoring to provide updated sources, results from Department research, expert opinion, and to either add scores not done by MRAG or change those that were based on preliminary or incomplete data by updating the attribute inputs and providing references. Experts involved in day-to-day management and data analysis for California fisheries possess knowledge that may not be contained in published literature. The information for the analyses and the corresponding scores were updated based on this expert evaluation. Once scores for productivity and susceptibility were determined, the overall vulnerability scores were calculated, using the following equation and only included attributes that could be scored: $v = \sqrt{(p-3)^2 + (s-1)^2}$.

Table 3. A unit of analysis is defined by the combination of target species, gear type, and fishing sector (commercial or sport). There are 45 units of analysis, which include 21 finfish and 15 invertebrate species. Some species are included in more than one unit of analysis. Hook and Line gear abbreviated as H&L.

Target Species	Gear Type	Fishery Sector	Target Species	Gear Type	Fishery Sector
Finfish			**Invertebrates**		
Barred sand bass	H&L	Sport	Bay shrimp	Beam trawl	Commercial
Barred surfperch	H&L	Sport	Brown rock crab	Trap	Commercial
Brown smoothhound shark	H&L	Sport	California spiny lobster	Hoop net	Sport
California barracuda	H&L	Sport	California spiny lobster	Trap	Commercial
California barracuda	H&L	Commercial	Dungeness crab	Trap	Sport
California corbina	H&L	Sport	Dungeness crab	Trap	Commercial
California halibut	H&L	Sport	Geoduck clam	Clam fork	Sport
California halibut	Trawl	Commercial	Giant red sea cucumber	Trawl	Commercial
California halibut	Gill net	Commercial	Kellet's whelk	Trap	Commercial
California halibut	H&L	Commercial	Market squid	Purse seine	Commercial
California sheephead	H&L	Sport	Ocean (pink) shrimp	Trawl	Commercial
California sheephead	Trap	Commercial	Pismo clam	Clam fork	Sport
Jackselt	H&L	Commercial	Red abalone	Abalone iron	Sport
Kelp bass	H&L	Sport	Red sea urchin	Hand rake (divers)	Commercial
Night smelt	A-frame	Commercial	Ridgeback prawn	Trawl	Commercial
Ocean whitefish	H&L	Sport	Spot prawn	Trap	Commercial
Pacific angel shark	Gill net	Commercial	Warty sea cucumber	Hand (divers)	Commercial
Pacific bonito	H&L	Sport			
Pacific bonito	H&L	Commercial			
Pacific hagfish	Trap	Commercial			
Pacific herring	Gill net	Commercial			
Redtail surfperch	H&L	Commercial			
Shiner seaperch	Trap	Commercial			
Spotted sand bass	H&L	Sport			
White croaker	H&L	Sport			
White seabass	H&L	Sport			
White seabass	Gill net	Commercial			
White sturgeon	H&L	Sport			

2.3 Scoring

Defining Scores

Productivity and susceptibility attributes are each scored based on predefined scoring bins, as provided in Patrick et al. (2009, 2010). Briefly, collected information and expert opinion provide the data that are compared with the scoring bins to identify a productivity or susceptibility score. All scores range from 1-3, but there is an inverse risk relationship between productivity and susceptibility (Figure 1). A fishery with low productivity and high susceptibility is more vulnerable to fishing activities than a fishery stock that is highly productive and/or has low susceptibility; a highly productive fishery may be able to recover from depletion or other impacts more quickly and is more likely to have a lower susceptibility. Productivity is based on life history information. Susceptibility, however, evaluates the vulnerability of a stock to a given fishery; examining the susceptibility of a stock may present opportunity to reduce the risk. While scores range from 1-3, the NMFS PSA allows the flexibility to input intermediate scores (e.g. 1.5, 2.5) if deemed appropriate. The productivity (P) and susceptibility (S) attribute scores are averaged to yield separate, overall P and S scores.

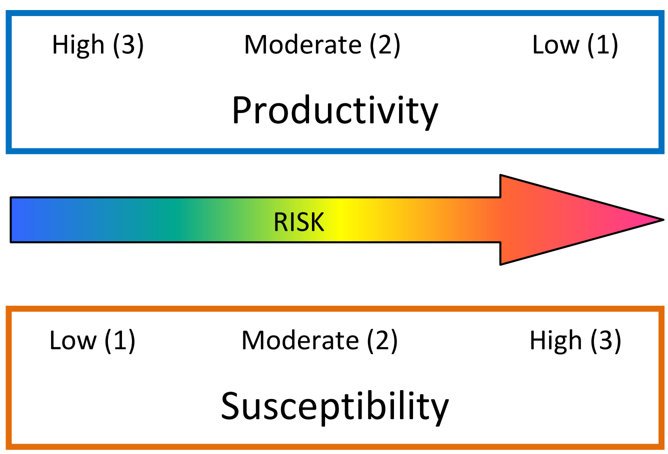


Figure 1. Inverse relationship between productivity and susceptibility in measuring risk.

Treatment of Missing Data

Data were not available for every attribute for every unit of analysis. In some cases, expert opinion could be used to determine an appropriate score based on type of species or similar species where information was available, or based on the expert's best estimate. Where data were absent and expert opinion uncertain, select attributes not scored were left blank. As a precautionary measure, some ecological risk assessment approaches provide higher-level risk scores when data are missing in an attempt to avoid incorrectly identifying a high-risk stock as a low-risk. While precautionary, it may also confound the issue with data quality, where a data-poor stock could receive a high-rick result either from an abundance of missing data or from the analysis with available data. The approach utilized here isolates the treatment of uncertainty from the relative vulnerability and within the larger context of the quality of data used. In doing so, the approach chooses to decouple vulnerability and data quality by not scoring attributes for which we had no information and report the overall quality of data separate from relative vulnerability.

Data Quality Index

Missing attribute scores were not factored into the overall scores but are reflected in the data quality score. Ranging from best data to no data, each attribute is assigned a data quality index to provide an estimate of information uncertainty. Scoring the quality of the data provides an additional lens through which the results should be considered. A data quality score of 1-5 was assigned to each attribute score, based on the reviewer’s confidence in the data used where '1' reflects best available data and '5' indicates the absence of data and no attribute score (Table 4). Aggregate data quality scores for productivity and susceptibility data inputs are averaged from the individual attribute data quality scores; we can derive an overall data quality score from the average of the susceptibility and productivity data quality scores . The data quality score can be improved as more information becomes available on a fishery stock. The addition of information will reduce the uncertainty in the analysis but may not necessarily reduce the relative vulnerability. For invertebrates in particular, there were gaps in knowledge for certain attributes. However, certain attributes could be scored as high productivity, based on general species knowledge.

Incorporating data quality into the analysis allows poorly scored stocks to be flagged as either needing review of the scoring or indicating information is generally lacking for that stock. Therefore, the relative vulnerability scores that result from the analysis can be considered our best estimates based on best available scientific information, while the data quality index measures the information content in that best estimate (Patrick et al. 2009; Cope et al. 2011).

Table 4. The five tiers of data quality used when evaluating the productivity and susceptibility of an individual stock (adapted from Patrick et al. 2010).

Data Quality Tier	Description	Example
1	**Best data.** Information is based on collected data for the stock and area of interest and is established and substantial.	Data-rich stock assessment; published literature documenting methods used
2	**Adequate data.** Information is based on limited coverage and corroboration, or for some other reason is deemed not as reliable as tier-1 data.	Limited temporal or spatial data; relatively old information
3	**Limited data.** Estimates have high variation and limited confidence and may be based on studies of similar taxa or life history strategies.	Similar genus or family, etc.
4	**Very limited data.** Information is based on expert opinion or on general literature reviews from a wide range of species, or outside of region.	General data not referenced
5	**No data.** When there are no data on which to make even an expert opinion, the person using the PSA should give this attribute a "data quality" score of 5 and not provide a "productivity" or "susceptibility" score so as not to bias those index scores. When plotted, the susceptibility or productivity index score will be based on one less attribute, and will be highlighted as such by its related quality score.	

Information Review

For some species, model-generated data in Fishbase[6] were the only information that was available for productivity attributes. In lieu of better data, these data were utilized if cases where other information for a particular species was also missing. In these cases, a low confidence data quality score was also given. The attributes with data gaps highlight uncertainty in scores to aid in interpreting overall vulnerability analyses, and where better data would provide a better evaluation of a stock's vulnerability.

Nineteen different experts were consulted to review and aid in information review and scoring of the productivity and susceptibility attributes. Guidelines detailing the approach and explicit score rankings were provided to each expert for their review (see Table 1 and Table 2). Where scores based on the same or similar information varied considerably, a secondary review and decision was made prior to being finalized.

The NMFS PSA approach recognizes that not all of the productivity and susceptibility attributes will be equally useful for determining vulnerability. Previous versions of the PSA utilized an attribute weighting scheme in which higher weights were applied to the more important attributes as reflected through equations in vulnerability determinations (Stobutzki et al. 2001, Hobday et al. 2004, Rosenberg et al. 2007). The NMFS approach permits attribute weighting to customize the analysis. Attribute weighting is intended to reflect the relevance of the attributes in describing the productivity and susceptibility rather

[6] An online global database of fish species (http://www.fishbase.org/).

than availability of data. No weights were applied to any attributes for any species analysis; given that our units of analysis include duplicative species from different fishery sectors we followed the NMFS recommendation by not assigning different weights among stocks within any given fishery.

3 Results

PSAs were conducted on the 45 units of analysis (Table 3), which included both commercial and sport sectors using a variety of gear types targeting finfish and invertebrate species. Where data or expert judgment provided, attributes were assigned a score; as described in Section 2.3, an accompanying data quality index was assigned to each score based on the information inputs, with the poorest data quality score assigned where an attribute score was missing. Overall data quality scores for productivity and susceptibility criteria (Figure 2) offer a snapshot of the general certainty in the data inputs. The majority of fisheries have good to moderate data quality; this should be considered in concert with the number of missing attribute scores. Further, certain attributes were scored more frequently than others. The frequency of productivity and susceptibility attributes scored and not scored is provided in Figure 3. A complete summary of the PSA results is provided in Table 5, this includes units of analysis, number of attributes scored, productivity (P), susceptibility (S), data quality (DQ) and vulnerability (*V*) scores. All data inputs and resources available were reviewed by CDFW staff to reduce uncertainty where expert opinion would apply and provide a transparent and consistent approach throughout.

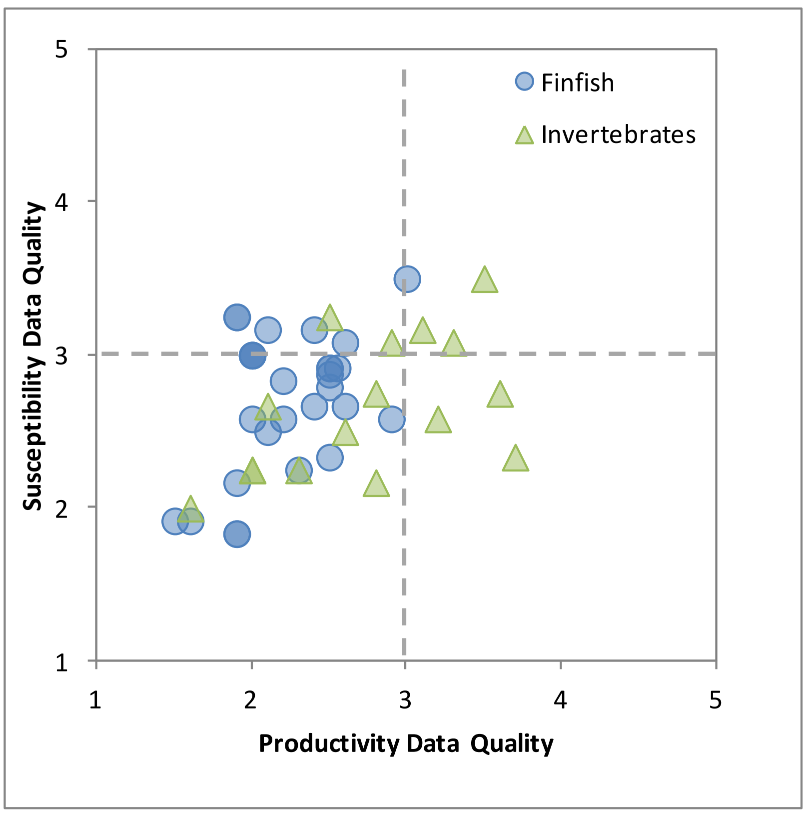


Figure 2. Data quality plots for the productivity and susceptibility scores for all finfish and invertebrate fishery stocks analyzed demonstrates the distribution of data quality used across the analyses. Higher scores indicate poorer data quality (e.g., a score of 5 on either axis means the overall data quality is poorest and information is absent). Scores at the upper right corner therefore indicate the least-informed stocks. Scores closest to the origin are the most informed stocks. The vertical and horizontal lines provide a general guide to relative data quality, with values above 3 on either axis considered poorly informed scores.

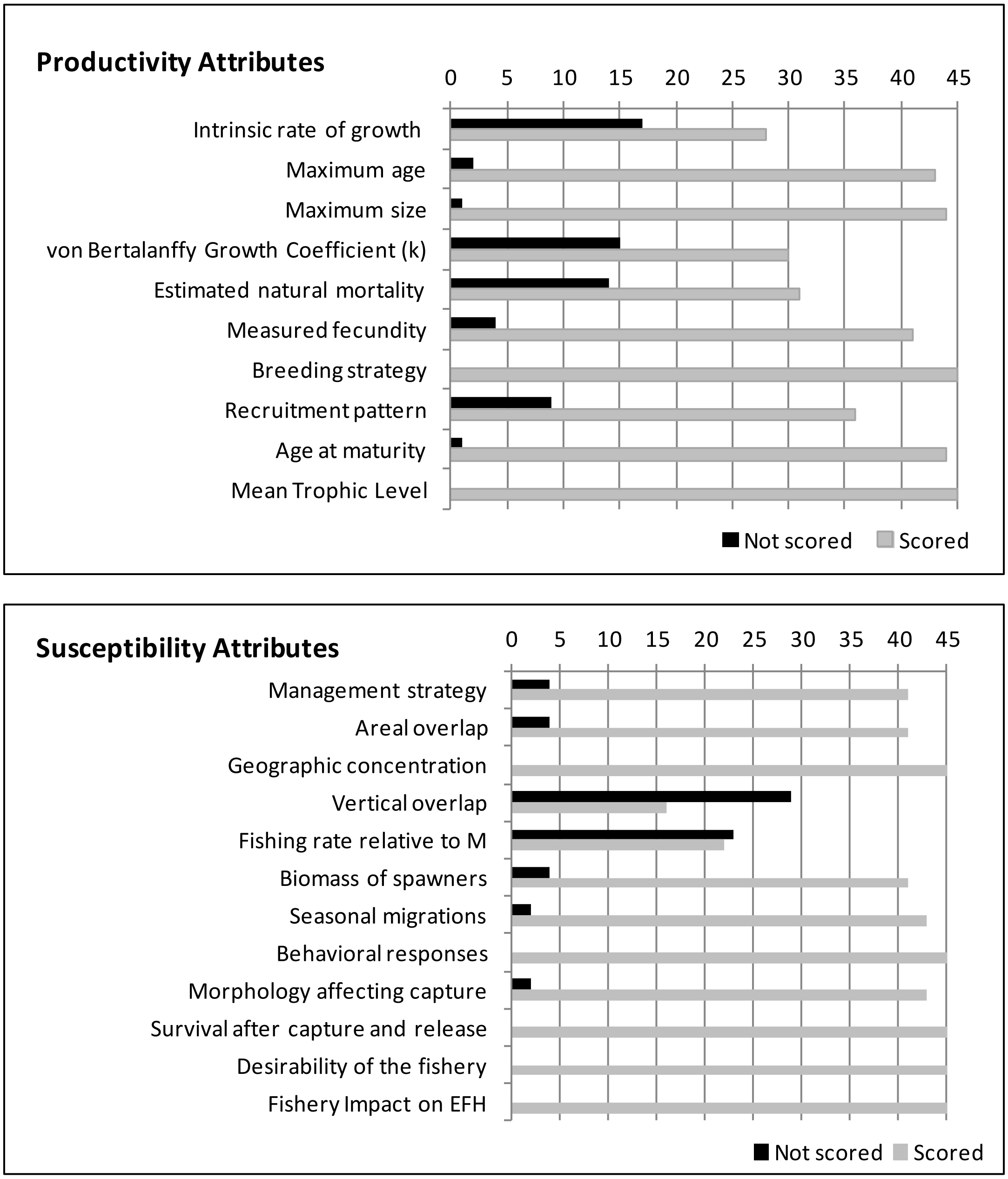


Figure 3. The frequency of productivity attributes (top) and susceptibility attributes (bottom) scored for each of the forty-five units of analysis. Information derived from stock assessments were most frequently absent.

Table 5. Overall scores and results of the productivity–susceptibility analysis (PSA) for the 45 units of analysis. Abbreviations include: Commercial fishery (C), Sport fishery (S), Hook & Line gear (H&L), Productivity (P), Susceptibility (S), and Vulnerability (*V*). The number of attributes scored out of a possible 10 productivity and 12 susceptibility attributes. An * denotes indicator species that were selected by CDFW for multispecies fisheries. The scores are arranged first by increasing vulnerability and secondly grouped by species to allow sector comparisons. Degrees of vulnerability, as follows: lowest, V < 1.8; medium, 1.8 < V < 2.0; high, 2.0 < V < 2.2; and highest, V > 2.2.

Fishery	Species	Gear	No. of attributes scored		P Score	P Data Quality	S Score	S Data Quality	*V*
			P	S					
Jacksmelt (Silversides) (C)	*Atherinopsis californiensis*	H&L	7	9	2.43	2.60	1.67	2.67	0.88
Shiner seaperch (C) *	*Cymatogaster aggregata*	Trap	8	10	2.25	2.20	1.50	2.83	0.90
Dungeness Crab (S)	*Metacarcinus magister*	Trap	8	10	2.75	2.30	1.90	2.25	0.93
Dungeness Crab (C)	*Metacarcinus magister*	Trap	8	10	2.75	2.30	2.10	2.25	1.13
Night smelt (C) *	*Spirinchus starksi*	A-frame	8	10	2.56	2.50	1.85	2.33	0.96
Brown Rock Crab (C) *	*Cancer antennarius*	Trap	6	10	2.83	2.90	1.95	3.08	0.96
Pismo Clam (S)	*Tivela stultorum*	Clam Fork	7	10	2.43	2.60	1.80	2.50	0.98
White Croaker (S) *	*Genyonemus lineatus*	H&L	8	9	2.38	2.60	1.78	3.08	1.00
Bonito (C)	*Sarda chiliensis lineolata*	H&L	10	12	2.40	2.50	1.83	2.92	1.03
Bonito (S)	*Sarda chiliensis lineolata*	H&L	10	12	2.40	2.50	2.00	2.92	1.17
Pacific Hagfish (C)	*Eptatretus stoutii*	Trap	8	10	2.00	2.90	1.30	2.58	1.04
CA Corbina (S)	*Menticirrhus undulatus*	H&L	10	11	2.40	2.20	1.86	2.58	1.05
Ridgeback Prawn (C)	*Sicyonia ingentis*	Trawl	6	12	2.67	3.10	2.04	3.17	1.09
Redtail Surfperch (C) *	*Amphistichus rhodoterus*	H&L	10	10	2.25	2.40	1.80	3.17	1.10
Kellet's Whelk (C)	*Kelletia kelletii*	Trap	6	8	2.33	3.60	1.94	2.75	1.15
Red Sea Urchin (C) *	*Strongylocentrotus franciscanus*	Hand rake	7	11	2.64	2.80	2.14	2.17	1.19
Spot Prawn (C)	*Pandalus platyceros*	Trap	6	10	2.50	3.20	2.10	2.58	1.21
Warty Sea Cucumber (C)	*Parastichopus parvimensis*	Diver	5	9	2.20	3.70	1.94	2.33	1.24
Barred surfperch (S) *	*Amphistichus argenteus*	H&L	10	11	2.00	2.40	1.77	2.67	1.26
White Seabass (S)	*Atractoscion nobilis*	H&L	9	11	2.11	1.90	1.91	1.83	1.27
CA Bay Shrimp (C)	*Crangon franciscorum*	Beam Trawl	6	9	2.33	3.30	2.11	3.08	1.30
Market Squid (C)	*Loligo (Doryteuthis) opalescens*	Purse Seine	9	11	2.50	2.50	2.23	3.25	1.33
CA Halibut (S)	*Paralichthys californicus*	H&L	10	12	1.90	2.00	1.75	3.00	1.33
CA Halibut (C)	*Paralichthys californicus*	H&L	10	12	1.90	2.00	1.75	3.00	1.33

Fishery	Species	Gear	No. of attributes scored		P Score	P Data Quality	S Score	S Data Quality	*V*
			P	S					
CA Halibut (C)	*Paralichthys californicus*	Trawl	10	12	1.90	2.00	2.08	3.00	1.54
CA Halibut (C)	*Paralichthys californicus*	Gillnet	10	12	1.90	2.00	2.13	3.00	1.57
Geoduck Clam (S)	*Panopea generosa*	Clam fork	10	11	1.90	2.10	1.77	2.67	1.34
CA Barracuda (C)	*Sphyraena argentea*	H&L	10	12	1.95	1.90	1.92	3.25	1.39
CA Barracuda (S)	*Sphyraena argentea*	H&L	10	12	1.95	1.90	2.00	3.25	1.45
Pink Shrimp (C)	*Pandalus borealis*	Trawl	7	9	2.57	2.80	2.33	2.75	1.40
Red Abalone (S)	*Haliotis rufescens*	Abalone Iron	9	12	1.89	1.60	1.88	2.00	1.41
White Seabass (C)	*Atractoscion nobilis*	Gillnet	9	11	2.11	1.90	2.14	1.83	1.44
Pacific Herring (C)	*Clupea pallasii*	Gillnet	10	11	2.35	2.10	2.32	2.50	1.47
Spotted Sand Bass (S)	*Paralabrax maculatofasciatus*	H&L	10	10	1.90	2.00	2.00	2.58	1.49
Barred Sand Bass (S)	*Paralabrax nebulifer*	H&L	10	11	2.05	1.60	2.18	1.92	1.52
CA Sheephead (S)	*Semicossyphus pulcher*	H&L	10	10	1.95	2.50	2.10	2.88	1.52
Kelp Bass (S)	*Paralabrax clathratus*	H&L	10	11	1.70	1.50	1.91	1.92	1.59
CA Sheephead (C)	*Semicossyphus pulcher*	Trap	10	10	1.95	2.50	2.30	2.79	1.67
CA Spiny Lobster (S)	*Panulirus interruptus*	Hoop Net	9	12	1.89	2.00	2.08	2.25	1.55
CA Spiny Lobster (C)	*Panulirus interruptus*	Trap	9	12	1.89	2.00	2.25	2.25	1.67
White Sturgeon (S)	*Acipenser transmontanus*	H&L	9	11	1.56	1.90	1.82	2.17	1.66
Giant Red Sea Cucumber (C)	*Parastichopus californicus*	Trawl	6	7	2.00	3.50	2.36	3.50	1.69
Ocean Whitefish (S)	*Caulolatilus princeps*	H&L	9	9	1.67	2.10	2.06	3.17	1.70
Brown Smoothhound Shark (S) *	*Mustelus henlei*	H&L	9	10	1.50	2.55	1.94	2.92	1.77
Pacific Angel Shark (C) *	*Squatina californica*	Gillnet	8	9	1.25	3.00	2.00	3.50	2.02

In compiling results across a variety of species and fisheries, it is meaningful to view the range of overall scores along with how scores relatively compare between species and fisheries. Figure 4 and Figure 5 depict productivity and susceptibility scores, respectively, for finfish and invertebrate species. It is important to note that PSA binning for scores is discrete, not continuous as the colors may reflect. Attribute cut-off scores are as follows: high productivity =1, moderate = 2, and low = 3; low susceptibility =1, moderate = 2, and high = 3. The average of all productivity or susceptibility attributes scored provides the final scores, respectively.

Of the 21 finfish species evaluated, productivities ranged from near high to near low, with the majority around moderate. Of the fifteen invertebrate species, seven were assessed to have high productivity and the remaining eight spanned the range of moderate productivity. Measures of susceptibility are specific to the fishing activity; therefore in the following visualizations we provide the fishery and sector (and for CA halibut we indicate gear type since there are three commercial gear types evaluated). The majority of invertebrate fisheries measured within a fairly narrow band of moderate susceptibility.

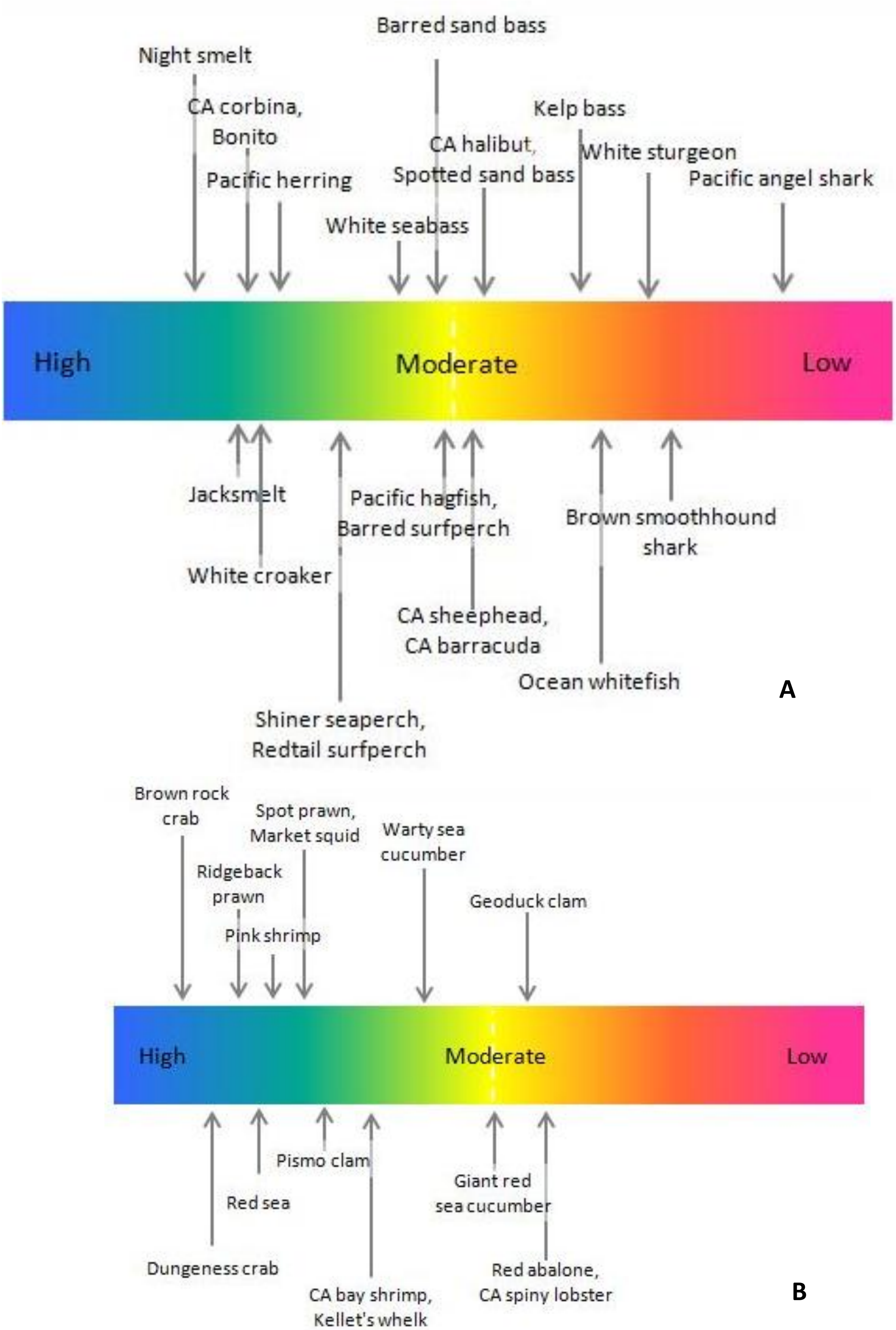


Figure 4. Summarized productivity scores across finfish (A) and invertebrate species (B). While productivity scores are discretely measured as high productivity =1, moderate = 2, and low = 3; we provide a comparative visualization to demonstrate the range of scores.

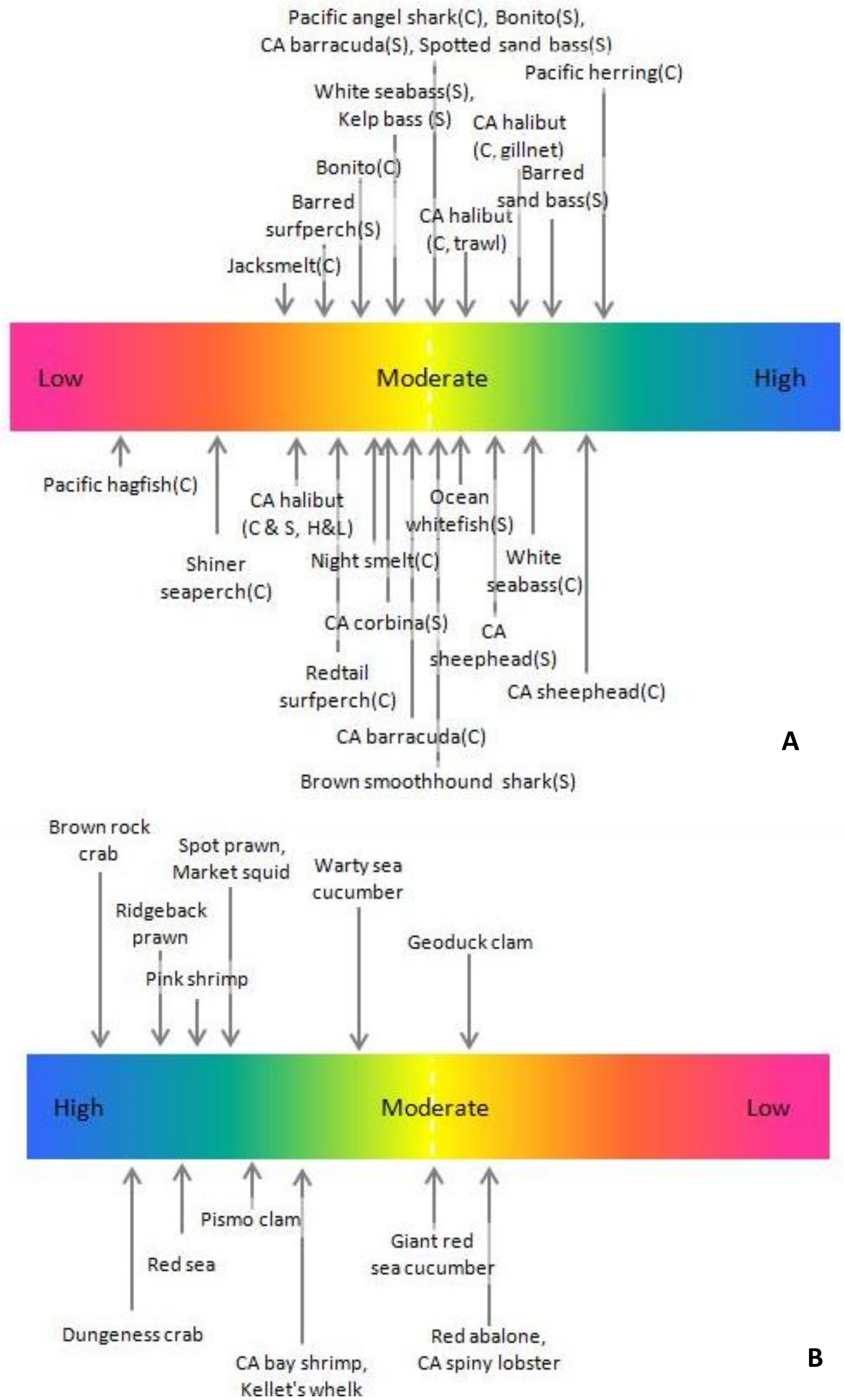
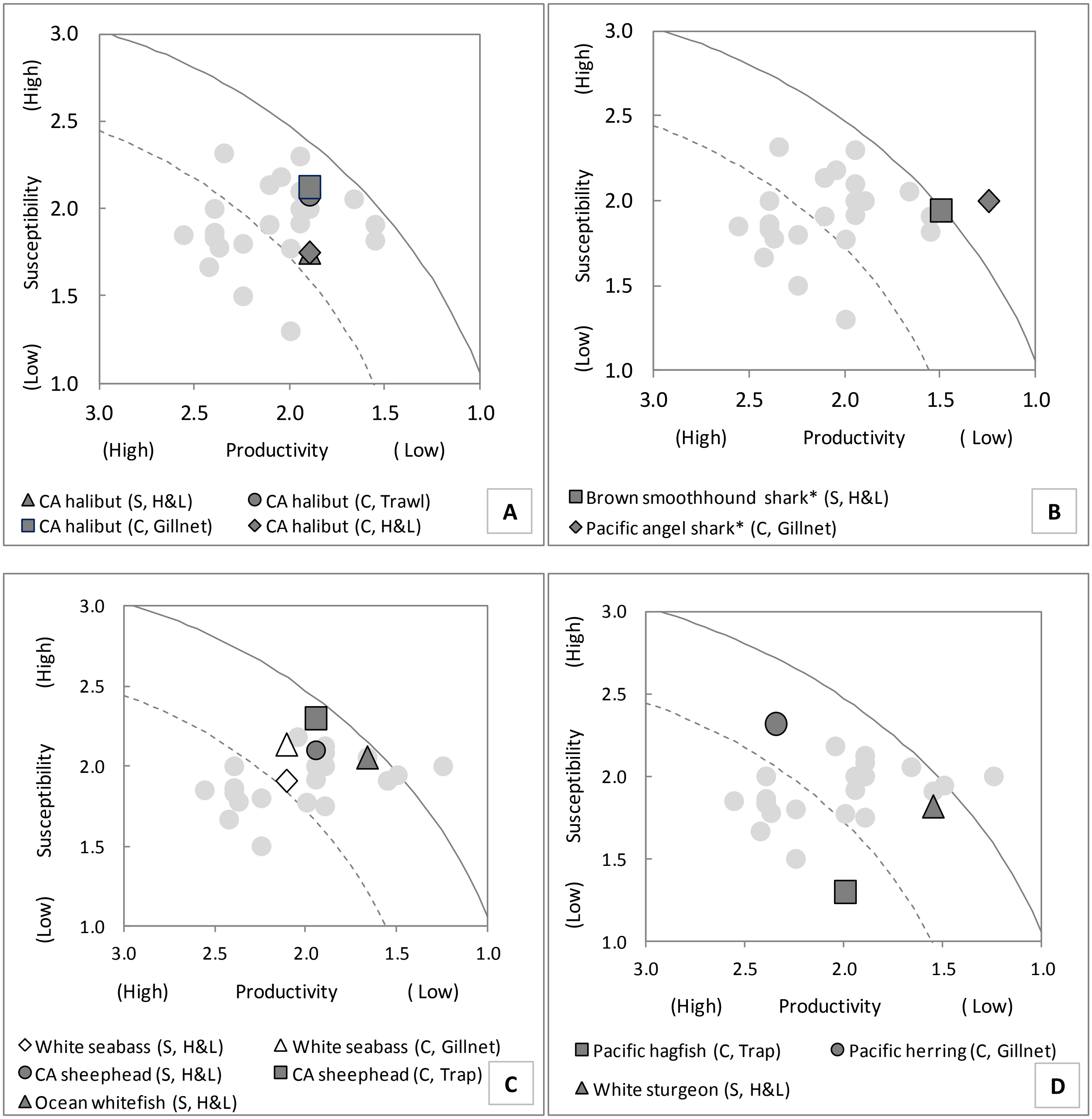
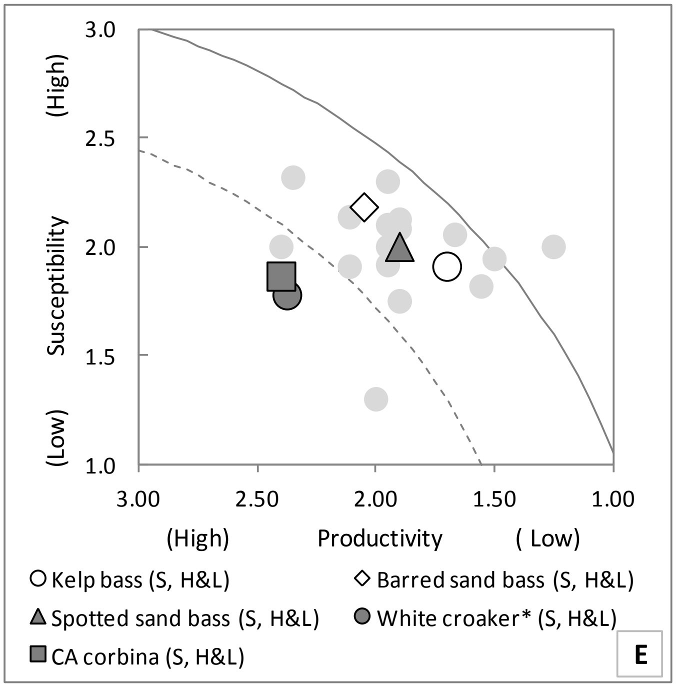
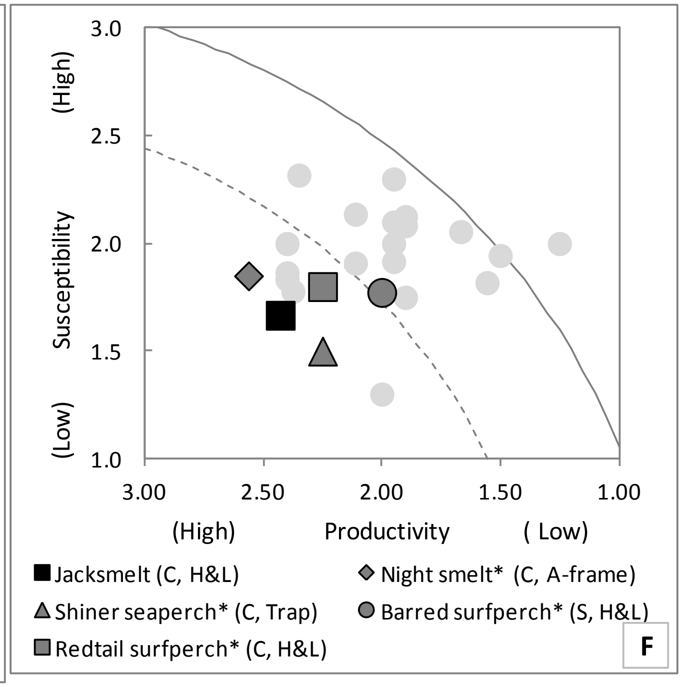


Figure 5. Summarized susceptibility scores across finfish (A) and invertebrate (B) fisheries. Abbreviations include California (CA), commercial (C), sport (S) and hook and line (H&L). Gears provided for CA halibut where three commercial sectors are analyzed. While susceptibility scores are discretely measured as low susceptibility =1, moderate = 2, and high = 3; we provide a comparative visualization to demonstrate the range of overall susceptibility scores.

The axes on PSA charts are oriented to align with how productivity and susceptibility are scored, with the lower left representing lowest vulnerability. Productivity measures across the x-axis, with the origin set at '3' (high productivity = low vulnerability); susceptibility measures along the y-axis with the origin set at '1' (low susceptibility = low vulnerability). Lowest vulnerabilities are those data points that are closest to the origin of the chart; the farther from the origin a data point sits, the higher the vulnerability. Data points that sit on the right side of the chart area measure low productivities; data points that sit towards the top of the chart area measure high susceptibilities. Relative vulnerabilities (*V*) and related data quality are provided for finfish fisheries in Figure 6 and for invertebrate fisheries in Figure 7. The contour lines divide regions of equal risk and group units of similar risk level. Overall data quality of the information used is reflected in the shading of symbols in the charts.


3.0
2.5
2.0
1.5
1.0
(High)
Susceptibility
(Low)
3.0
2.5
2.0
1.5
1.0
(High)
Productivity
(Low)
CA halibut (S, H&L)
CA halibut (C, Trawl)
CA halibut (C, Gillnet)
CA halibut (C, H&L)
A
Brown smoothhound shark* (S, H&L)
Pacific angel shark* (C, Gillnet)
B
White seabass (S, H&L)
White seabass (C, Gillnet)
CA sheephead (S, H&L)
CA sheephead (C, Trap)
Ocean whitefish (S, H&L)
C
Pacific hagfish (C, Trap)
Pacific herring (C, Gillnet)
White sturgeon (S, H&L)
D





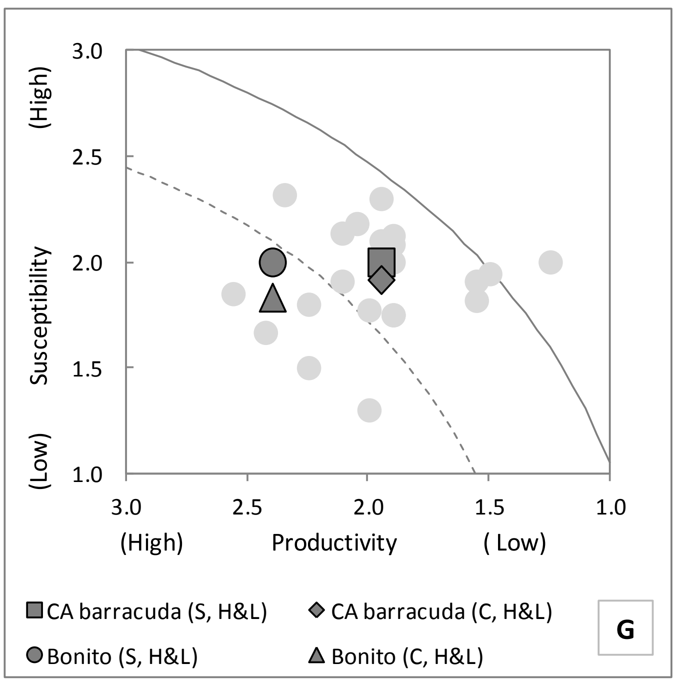


Figure 6. Relative vulnerabilities for finfish species: (A) CA halibut, (B) sharks, (C) white seabass and nearshore finfish (CA sheephead and ocean whitefish), (D) Pacific hagfish, Pacific herring and white sturgeon, (E) seabasses (barred sand bass, kelp bass and spotted sand bass) and nearshore bottom finfish (CA corbina and white croaker), (F) surf perch (shiner seaperch, barred surfperch, redtail surfperch), silversides (jacksmelt) and true smelt (night smelt), and (G) other nearshore pelagic finfish (bonito and CA barracuda). Symbol shading reflects overall data quality (poor >3.5 (solid black); moderate 2.0–3.5 (gray); and good <2.0 (white)). Lightly shaded background circles provide context for all finfish fisheries analyzed. Contours delineate areas of relative vulnerability (*V*, i.e., distance from the origin), with stocks of higher vulnerability above the solid line (*V* = 2.0), those of lower vulnerability below the dotted line (*V* = 1.8). Note that the productivity axis is in descending value in order to make the top right quadrant of the plot the area of greatest vulnerability (i.e., the lowest productivity and highest susceptibility). P and S scores must be considered in concert with data quality for an appropriate assessment of risk from fishing activities and opportunities for increased information to alter the results. Abbreviations include California (CA), commercial (C) fishery, sport (S) fishery, and hook and line (H & L) gear. An * denotes indicator species selected by CDFW for multispecies fisheries.

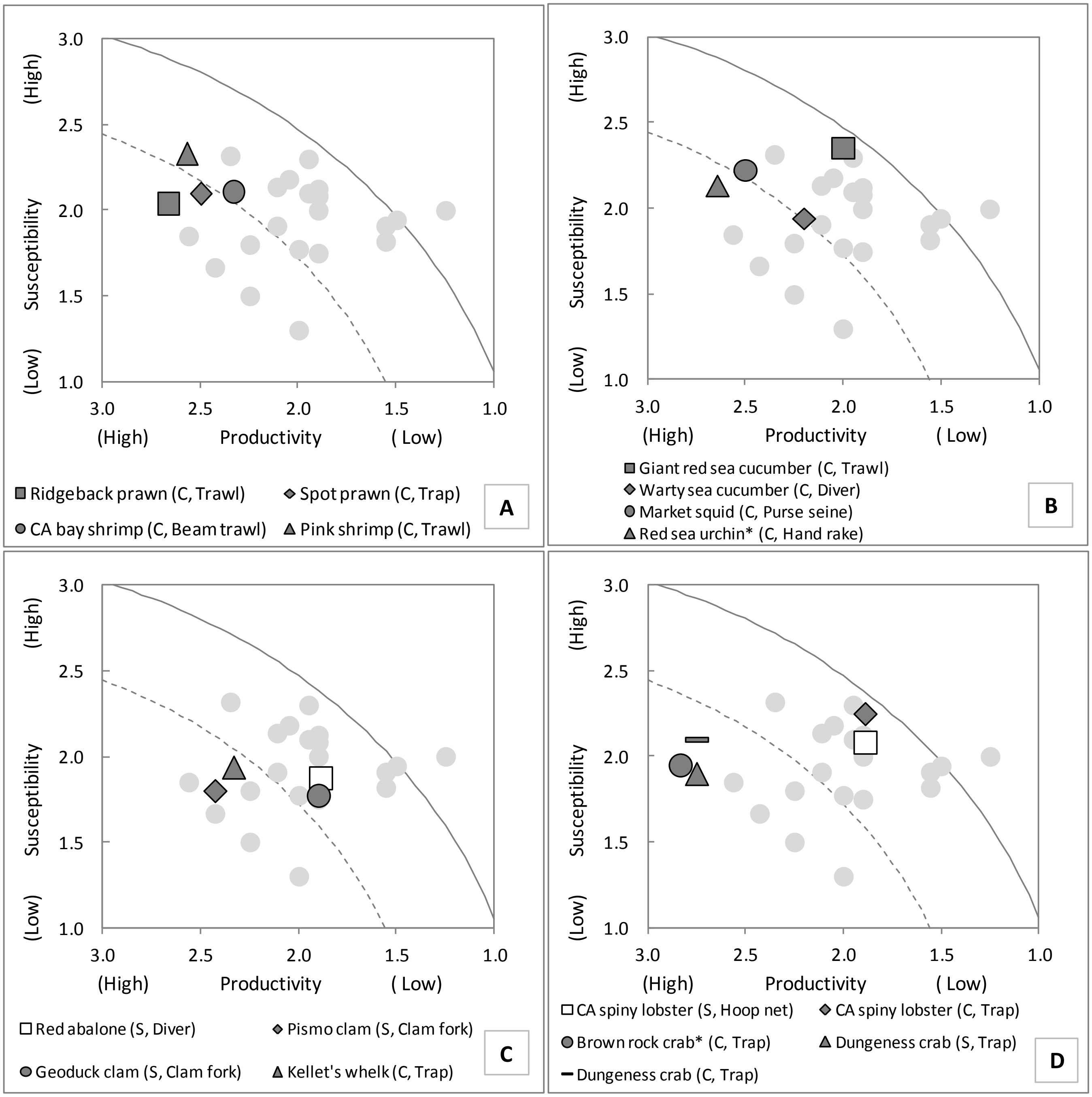


Figure 7. Relative vulnerabilities for invertebrate species: (A) shrimp and prawn, (B) sea cucumber, market squid and sea urchin, (C) red abalone, clam and whelk, and (D) spiny lobster and crab. Symbol shading reflects overall data quality (poor >3.5 (solid black); moderate 2.0–3.5 (gray); and good <2.0 (white)). Lightly shaded background circles provide context for all invertebrate fisheries analyzed. Contours delineate areas of relative vulnerability (*V*, i.e., distance from the origin), with stocks of higher vulnerability above the solid line (*V* = 2.0), those of lower vulnerability below the dotted line (*V* = 1.8). Note that the productivity axis is in descending value in order to make the top right quadrant of the plot the area of greatest vulnerability (i.e., the lowest productivity and highest susceptibility). P and S scores

must be considered in concert with data quality for an appropriate assessment of risk from fishing activities and opportunities for increased information to alter the results. Abbreviations include California (CA), commercial (C) fishery, sport (S) fishery, and hook and line (H & L) gear. An * denotes indicator species selected by CDFW for multispecies fisheries.

4 Discussion

Productivity and Susceptibility Analysis (PSA) is a useful tool for assessing vulnerability of stocks to fishing activities and addressing both data poor and data rich species within the same analysis. The output is straightforward and allows for relatively quick, easy, and cost effective comparison among a large number of stocks, even when life history or fishery information is sparse. Considering limited funding for fishery management and environmental review, identifying the highest risk fisheries offers an opportunity to expend limited funds on the highest needs. Sorting fisheries by risk remains one of the most useful applications of PSA.

This analysis has already taken this preliminary step of grouping species into prioritization categories by identifying their relative vulnerabilities. Initial prioritization of fisheries was undertaken in designating the list of species and fishery sectors for assessments (Table 1); the results of this prioritization indicate:

- Species with low vulnerability which may therefore be a lower priority for further evaluation of management attention or stock status evaluations,
- Species for which management decisions can be deferred, or
- High risk species that likely need to move on to subsequent evaluations with either data rich or data poor methodologies.

PSA results can be used and interpreted in several additional ways as an evaluation planning process, taking into consideration the available resources for the CDFW; the approach can provide information on stock needs in terms of management attention and data improvement. For high risk species (such as those that are highly desirable, vulnerable to fishing activities, highly exploited, exhibit behavioral characteristics (e.g. spawning aggregations) that increase their susceptibility) the PSA highlights the susceptibility attributes which can potentially be altered through management to reduce a species' vulnerability to an identified fishery. Comparing relative vulnerabilities across species can provide information to understand where management might be focused to offer the greatest benefits for at-risk stocks.

Many management systems regulate multispecies fisheries though measures often aimed at indicator species or a small group of commonly co-occurring species, where information is presumed sufficient for management needs. However, PSA analyses and results provide information with which to consider whether managing to the data moderate and rich species is the most appropriate approach. In some circumstances, managing species with similar vulnerability profiles or re-evaluating the indicator species may be useful considerations:

- Fishery stock complexes are a common mechanism employed to manage multispecies fisheries, though these complexes may be based on similar biological characteristics (i.e. species guilds) or co-occurrence, rather than susceptibility to fishing activities. Stocks with similar overall vulnerabilities and characteristics can be grouped into stock complexes, and management considerations can be assessed for the consolidated group. Such an approach would reduce the resource needs for considering management on a fishery by fishery basis and manage to the identified vulnerabilities rather than developing measures that otherwise may not be appropriate for many species in the complex.
- Indicator species in a multispecies fishery are commonly identified as those with sufficient information on which to base management decisions. Given resource constraints of management, an alternate approach would be relying on the results of the PSA and delegating the most vulnerable stock as the indicator species, where possible, as the basis for management; however, analysis should be conducted on all species within a unit to identify the most vulnerable stock(s). This strategy would ensure that management measures would be precautionary enough to protect even the most vulnerable stocks (Patrick et al. 2010). The Department of Fisheries, Western Australia assesses the status of key retained species using PSA, and applies management intervention to the whole resource based on the most vulnerable key species (Fletcher et al., 2010, 2012; DoF 2011).

In terms of data improvement, data quality scores help identify where the greatest uncertainties in information exist. Together, the overall vulnerability and data quality scores suggest where data improvements are needed to understand the stock and fishery and to improve quality of the PSA. It is important for resource managers to consider trade-offs that might exist in efforts to fill data gaps. Directed research could be utilized to fill gaps in understanding a species' productivity but that may be unlikely to alter productivity or overall vulnerability scores. Increased confidence in the impacts from fishing activities are most likely to alter the vulnerabilities, though increased information could result in a higher vulnerability score where certain attributes scores were previously underestimated (such as the estimated areal overlap between the stock and fishing activities compared with actual overlap from improved spatial data). Improving data can be especially useful in data-limited situations and in prioritizing stock assessments (Cope et al. 2011).

Several methodological aspects should be considered when interpreting PSA results. Bias may exist with experts scoring fisheries they manage; an expert may unknowingly underestimate susceptibility scores (e.g. for management strategy), reflecting the expert's perception that the species is well managed. In this case, experts are most likely considering the susceptibility attributes (such as management strategy) of a fishery relative to other California fisheries with which they are familiar rather than to the full suite of management options that are utilized nationally or worldwide. For example, most sport fisheries in California are managed through bag limits, which are a form of catch limit, as well as other measures in many cases, and may be coupled with spatial and temporal closures and even size limits. However, monitoring and enforcement in these fisheries is often inadequate compared with commercial fisheries (e.g. Pacific herring or West Coast groundfish) that employ catch limits with monitoring and accountability measures. Care should be taken to minimize the opportunity for biases to result in susceptibility scores that suggest a fishery is less susceptible than is actually the case. In this analysis, we ensured a consistent and transparent approach through the collaborative review of information inputs and documentation of references. In any approach that evaluates risk over a variety of species, maintaining consistency throughout the process is a critical component in the treatment of the information and utility of the results.

The NMFS PSA approach does not score an attribute with missing data; this is a considerable difference from some other PSA methodologies that default to a high risk score for attributes with missing data as discussed in Section 2.3. An approach that results in lower risk scores may provide less incentive to improve data quality or to reduce vulnerability by improving management. So while the NMFS PSA approach does not equate higher uncertainty with higher risk, which may result in lower vulnerability scores for data-poor species than other PSA approaches, the approach chooses to decouple the treatment of uncertainty from vulnerability allowing managers to decide where to add precaution. This analysis did not compare the results of the NMFS approach with other PSA approaches that default to a high risk score in absence of data; such an evaluation could produce interesting results to compare and consider. It is important to take these results in concert with the suite of attribute scores to isolate those attributes missing information. Additionally important, the PSA depends on how scoring bins are defined as low, moderate, and high for each attribute. These cut-off bins differ slightly among the PSA approaches, though it is unclear whether one approach is more or less conservative than other approaches.

Future steps towards understanding stock vulnerabilities in California fisheries could include expansions of the PSAs. Cumulative PSAs can be applied to look at certain impacts on a species such as various gear types or sectors, bycatch, and takes throughout a species' range. This approach would consider the full spatial range of all fishing activities and related impacts on the stock, and would be the most comprehensive assessment of a stock's vulnerability; however, collectively accounting for all of the variables requires additional resources and there are likely to be larger information gaps across the range of impacts on a stock. The approach employed here is consistent with the NMFS methodology and allows comparison between individual units of assessment and consideration of differences between sectors or gears. There is the risk of underestimating vulnerability by not accounting for cumulative impacts such as full range and overlap of multiple fishing pressures. PSA results can also be applied towards subsequent phases of work including an Ecological Risk Assessment (ERA), which assesses the risk a fishery poses to the ecosystem. The most appropriate next step will depend on needs identified by the CDFW.

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