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An assessment of vulnerability in Alaska groundfish

Olav A. Ormseth*, Paul D. Spencer

Alaska Fisheries Science Center, National Marine Fisheries Service, 7600 Sand Point Way NE, Seattle, WA 98115, USA

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ABSTRACT

Federal fishery management rules in the United States have recently changed, necessitating an examination of which fish stocks require annual catch limits and how appropriate stock complexes are formed. We used an analytical approach termed productivity–susceptibility analysis (PSA) to analyze the vulnerability of federally managed Alaska groundfish stocks to overfishing. The focus of the effort was non-target stocks that have limited data available for determining stock status and vulnerability. The PSA approach was originally created to assess risks to bycatch in Australian trawl fisheries and compares productivity attributes (e.g. life-history traits) to factors that determine a stock's susceptibility to fishing impacts, producing a combined score indicative of a stock's relative vulnerability to overfishing. We used a form of the PSA developed by a working group from the U.S. National Marine Fisheries Service specifically for use in assessing vulnerability in federally managed fisheries. Alaska groundfish displayed a wide range of vulnerability scores, and this result was mainly due to variability in productivity scores. Susceptibility scores varied less than productivity scores and were centered on an intermediate value. The inclusion of target stocks in the PSA was valuable for assessing the relative vulnerability of the non-target stocks. Sensitivity analyses indicated that PSAs respond differently to changes in attribute scores depending on their initial conditions, and managers should be careful in interpreting changes in PSA results when stocks are re-evaluated.

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1. Introduction

The primary law governing federal fishery management in the United States, the Magnuson-Stevens Fishery Conservation and Management Act, was strengthened in 2006 to reduce the potential for overfishing of commercial fish stocks. The most significant change was a requirement for annual catch limits (ACLs) for all fish stocks vulnerable to overfishing. Determining vulnerability can be relatively straightforward for target stocks for which data regarding stock status and fishing impacts are generally available. For data-limited non-target stocks, however, the determination of vulnerability may be more difficult.

To ameliorate this problem, in 2008 a working group of scientists from the U.S. National Marine Fisheries Service (NMFS) developed a process for estimating the vulnerability of marine fish stocks (Patrick et al., 2010). The process uses a semi-quantitative approach termed productivity–susceptibility analysis (PSA), which was originally created to analyze bycatch issues in Australian fisheries (Milton, 2001; Stobutzki et al., 2001). Although different versions of PSAs exist, the common characteristic is that they compare attributes of productivity (*P*), e.g. life-history traits such as natural mortality and age at 50% maturity, with attributes of susceptibility to fishing impacts (*S*), including spatial overlap with fisheries and fishing gear selectivity (Table 1). The mean *P* and *S* scores are used to produce a vulnerability score indicative of the likelihood that a stock may be overfished in the absence of conservation measures. Most PSAs also include some assessment of uncertainty or data quality.

The PSA approach is conceptually similar to other semi-quantitative risk assessments that evaluate extinction risk based upon biological productivity and categorization of life-history parameters (e.g. Musick, 1999; Roberts and Hawkins, 1999; Cheung et al., 2005). However, the PSA differs from these approaches in that it addresses vulnerability to overfishing by considering not only the biological productivity of the stock, but also the degree to which fisheries can impose mortality upon the stock. While the utility of the PSA is more limited than fully quantitative methods, such as the Sustainability for Fishing Effects model (Zhou and Griffiths, 2008), it is also more widely applicable in situations where information is limited.

The goal of the NMFS working group was to develop a version of the PSA which could be applied broadly to federally managed fisheries in the United States. Two key features distinguish the NMFS PSA from other similar approaches (Patrick et al., 2009, 2010). All attributes in the analysis are treated additively, i.e. the *P* and *S* scores are weighted averages of the individual attribute values. This

* Corresponding author. Tel.: +1 206 526 4242; fax: +1 206 526 6723.
E-mail address: olav.ormseth@noaa.gov (O.A. Ormseth).

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Table 1
Description of productivity and susceptibility attributes included in the analysis.

Productivity attributes	Susceptibility attributes
r	Management strategy
Maximum age	Areal overlap
Maximum size	Geographic concentration
Growth rate (k)	Vertical overlap
Natural mortality	Fishing rate relative to natural mortality (F/M)
Measured fecundity	Biomass of spawners (SSB) or other proxies
Breeding strategy	Seasonal migrations
Recruitment pattern	Schooling/aggregation and other behaviors
Age at maturity	Gear selectivity
Mean trophic level	Survival after capture and release
	Desirability/value of the fishery
	Fishery impact to habitat

differs from other PSAs where some attribute scores are treated multiplicatively, magnifying their effect on the overall vulnerability score (Hobday et al., 2007). The NMFS approach also treats data quality separately from the vulnerability score. In the original PSA approach, missing data results in an increase in the vulnerability score due to the increase in uncertainty (Stobutzki et al., 2001). To allow the vulnerability score to reflect the best possible estimate of P and S, data quality scores in the NMFS PSA are included for interpretation of the vulnerability scores but are not factored into its estimation (Patrick et al., 2009).

The goal of this paper was to use the NMFS PSA approach to evaluate the relative vulnerability of fish stocks in federal waters off the state of Alaska. In Alaska, groundfish stocks in federal waters (from 3 nm to 200 nm from shore) have been managed using ACLs for over 30 years (DiCosimo et al., 2010). However, the new federal rules have posed several challenges for the management of non-target stocks. Under the new guidelines, stocks vulnerable to overfishing are classified as “in the fishery” in fishery management plans (FMPs). The FMPs may also include an ecosystem components category made up of less-vulnerable stocks for which ACLs are not required but monitoring and limitation of incidental catches are warranted. Classifying stocks into these two categories is one challenge for federal managers in Alaska.

The guidelines for creating stock complexes, which include several species managed as a group, have also been strengthened. Complexes must be composed of stocks with similar vulnerability to overfishing. In Alaska, a core group of non-target stocks were historically managed as a single “Other Species” group (Reuter et al., 2010). This group consisted generally of five stock complexes (squids, octopuses, sharks, skates, and sculpins) although the exact makeup of the group varied by area and evolved over time.[1] The North Pacific Fishery Management Council, which oversees federal fishery management in Alaska, separated the Other Species category into its constituent stock complexes in 2010. However, it remains to be determined whether the individual complexes comprise stocks of similar vulnerability.

To inform the classification of stocks within the Alaska groundfish FMPs and to evaluate the composition of stock complexes, we performed PSAs for the two federal fisheries management areas in Alaska: the Bering Sea/Aleutians Islands (BSAI) region and the Gulf of Alaska (GOA) region. Separate analyses were conducted for each region because each is vast in its geographic extent and constitutes a separate marine ecosystem. While similar species and species groups exist in both areas, there are major differences in the natural environment, activity by humans, and behavior of fishing fleets between the areas. In this analysis, our objectives were to:

(1) Evaluate the vulnerability of all groundfish stocks included in the FMPs.
(2) Compare the vulnerability of target and non-target stocks.
(3) Compare methods for analyzing fisheries caught using different gear types.
(4) Analyze the sensitivity of the PSA to changes in attribute scores.

2. Methods

The analysis included most of the stocks contained in the groundfish fishery management plans for the GOA and BSAI. For the shark, skate, and sculpin complexes, catches contain multiple species from within the complexes, so species were analyzed individually. In contrast, catches of squids are almost entirely *Berryteuthis magister* and catches of octopus are dominated by *Enteroctopus dofleini*. Therefore, these two species were chosen to represent the squid and octopus complexes, respectively, even though other members of the complex may have different life-history characteristics.

2.1. Vulnerability analysis

This analysis was designed specifically as an application of the NMFS PSA approach, which has been thoroughly described elsewhere (Patrick et al., 2009, 2010). We limit our description to a brief overview of the general methodology combined with an explanation of procedures specific to the Alaska groundfish analysis.

The PSA considered ten P attributes and twelve S attributes (Table 1). Each attribute was scored on a three-point scale, indicating low (1), medium (2), and high (3) values. Each attribute score was then weighted according to the analyst's interpretation of the relevance of each attribute. In the Alaska groundfish PSA, all attributes were weighted equally with the exception of recruitment pattern (a measure of the frequency of recruitment success). A preliminary analysis of known recruitment indices suggested that there was little relationship between those indices and productivity in Alaska, so that attribute received a weight half that of the other attributes. The individual weighted attribute scores were used to calculate mean scores for P and S that were used in two ways:

(1) The scores were depicted graphically in a scatter plot, with P on the x-axis and S on the y-axis. This provided a strong visual appreciation of differences among stocks. In addition, the x-axis was reversed (i.e. it starts at 3 and ends at 1), so that the area of the plot close to the origin (which was at 3, 1) corresponded to high-productivity, low-susceptibility stocks. Such stocks are considered to have low vulnerability. The further a stock was from the origin, the more vulnerable to fishing it was likely to be.
(2) Following on (1), the Euclidean distance from the origin to the stock's datapoint was calculated and used as a measure of the stock's overall vulnerability. The distance was calculated as:

$$\sqrt{(P-3)^2+(S-1)^2}$$

where P = productivity and S = susceptibility.

Each attribute score was also evaluated for the quality of the data used to determine the score. Data quality scores ranged from 1 to 5 as follows:

[1] In the Gulf of Alaska (GOA) management area, skates have been managed as a separate category since 2004 due to the emergence of a directed fishery (Ormseth and Matta, 2009). In the Bering Sea/Aleutian Islands (BSAI) management area, squids have been managed separately for several decades and skates were moved to a separate category in 2009 (Ormseth et al., 2009).

1: (Best data): Information is based on established and substantial data.
2: (Adequate data): Information with limited coverage and corroboration.
3: (Limited data): Limited confidence; may be based on similar taxa.
4: (Very limited data): Expert opinion or based on the general literature review.
5: (No data): No information on which to base score.

For attributes with a data quality score of 5, no attribute score was given (i.e. that attribute did not factor into the overall vulnerability score) but the attribute-specific data quality score was included in the mean data quality score to ensure that it included the full range of data quality for that stock. The mean data quality scores for *P* and *S* were reported in tables and the mean overall data quality scores were used to define data quality categories (high: <2, medium: ≥2 and <3, low: ≥3) for each stock that were depicted in the scatter plots.

A separate PSA was conducted for each management area. There are stock assessments or reports prepared regularly for all the included stocks, and the authors of those reports were asked to provide attribute scores for the stocks for which they were responsible. These attribute scores were then compiled to produce the PSA, and two-tailed *t*-tests were used to compare PSA results between target and non-target stocks.

2.2. Multiple-gear analyses

When one stock is captured in different fisheries using different gear types, it can be difficult to determine which data to use in estimating susceptibility to the fishery. The original working group document recommended that a separate PSA be performed for each gear type and the results combined according to the proportion represented by each gear type in the total catch. In contrast, the analysis presented here scored attributes conservatively according to the fishery and gear type with the highest proportion of the total catch – e.g. squids were evaluated relative to midwater trawl gear, where most of the incidental catch occurs.

To test the difference between these two approaches, we conducted two separate PSAs for each of two BSAI stocks: Pacific cod and Alaska skate. Pacific cod are captured in longline, trawl, and pot fisheries; Alaska skates are captured in longline and trawl fisheries. For each stock, a PSA was conducted for each gear type. An average of the resulting *P* and *S* scores, weighted by the proportion of catch by gear type, was used to estimate vulnerability.

2.3. Sensitivity tests

To test the sensitivity of the PSA to changes in the attribute scores, we conducted a series of limited PSAs based on two different scenarios. Each PSA focused on only one hypothetical stock. Because *S* attributes are the most likely to change in the short term, in each scenario all *P* values for the stock were held at a score of 2 and only *S* values were changed.

In scenario 1, the *S* analysis included all 12 attributes. Vulnerability scores were calculated for successive increases in the number of changed attribute scores (i.e. the effect of changing one attribute score vs. the effect of changing all 12 attribute scores). Furthermore, four types of changes were considered: (1) all attributes starting at 1 and increasing to 2; (2) all attributes starting at 2 and increasing to 3; (3) all attributes starting at 1 and increasing to 3; (4) a net result of all attributes increasing from 1 to 2.5 (a result that could be achieved through different combinations of changes to individual attributes).

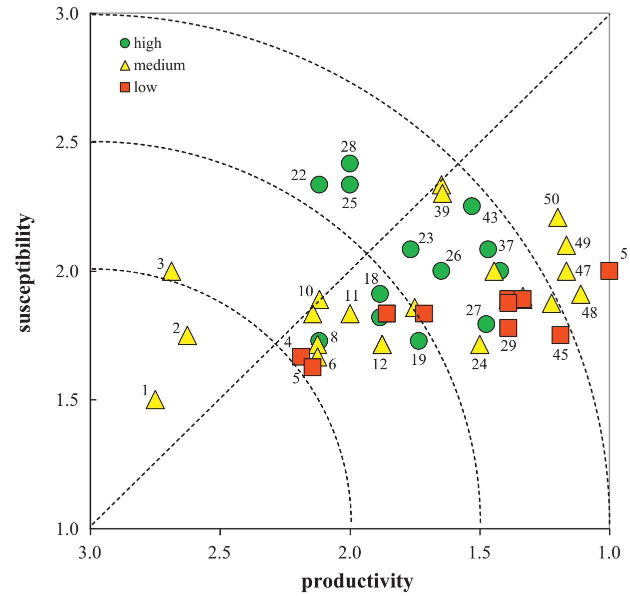

Fig. 1. Results of the productivity–susceptibility analysis for the Bering Sea/Aleutian Islands management area. Colors and symbol shapes indicate data quality scores. Numbers indicate stocks listed in Table 2. For clarity, not all stocks are labeled. Dashed lines indicate isopleths (i.e. points equidistant from the origin). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Scenario 2 considered only the change of *S* attribute scores from 1 to 3 but examined the effects of that change on PSAs using different numbers of total attributes. Vulnerability scores were calculated for successive changes of up to 4 attributes for PSAs using 12 (full), 8, or 4 total attributes.

3. Results

Stocks in the BSAI and GOA had a wide range of *P* scores and a narrower range of *S* scores (Tables 2 and 3, and Figs. 1 and 2). In both areas, *P* scores ranged from 1.00 to 2.75 and *S* scores ranged from 1.5 to 2.42. The values resulted in vulnerability scores from 0.56 to 2.24 in the BSAI and 0.56 to 2.37 in the GOA. Data quality scores were 1.37–3.65 in the BSAI and 1.18–3.65 in the GOA.

Target stocks produced different results from non-target stocks. In both areas mean *P* scores were similar between target and non-target stocks but *S* scores for target stocks were significantly higher (Table 4). Vulnerability scores were not significantly different (Table 4). In both areas, data quality was significantly higher for target stocks (Table 4).

Multiple-gear analysis produced slightly different vulnerability scores than the approach using a single fishery. For Pacific cod, vulnerability decreased from 1.73 to 1.71 using the multiple-gear approach (Table 5). For the Alaska skate, vulnerability estimated using multiple gears was 1.79 compared to 1.87 estimated using the single-gear approach.

Sensitivity tests revealed different responses from the PSA depending on initial conditions. Under Scenario 1, vulnerability scores increased with the number of individual attribute scores that were changed (Fig. 3). The increase in vulnerability was greatest for the PSAs where *S* scores were changed from 1 to 3. In addition, PSAs with higher initial *S* scores produced a greater absolute change in vulnerability than those with lower *S* scores: PSAs where *S* increased from 2 to 3 had greater increases in vulnerability than those where *S* increased from 1 to 2, even though the *S* score was increased by the same amount. In Scenario 2, PSAs with fewer total

Table 2
Results of the productivity–susceptibility analysis for the Bering Sea/Aleutian Islands management area. Target stocks are listed in bold and italicized text. P = productivity and S = susceptibility.

ID #	Stock name	*P*	*S*	Vulnerability	Data quality		
					P	*S*	Mean
1	Capelin	2.75	1.50	0.56	2.58	3.08	2.83
2	Squid	2.63	1.75	0.84	2.37	3.33	2.85
3	Eulachon	2.69	2.00	1.05	2.68	2.25	2.47
4	Starry flounder	2.19	1.67	1.05	3.21	3.08	3.15
5	Octopus	2.14	1.63	1.06	2.89	3.67	3.28
6	Rex sole	2.13	1.67	1.10	2.53	3.08	2.80
7	Red irish lord	2.13	1.71	1.13	2.47	2.75	2.61
8	Alaska plaice	2.12	1.73	1.14	1.74	1.67	1.70
9	Threaded sculpin	2.14	1.83	1.20	2.37	3.25	2.81
10	***Flathead sole***	***2.12***	***1.89***	***1.25***	***2.05***	***2.00***	***2.03***
11	Longfin Irish lord	2.00	1.83	1.30	2.37	3.33	2.85
12	Great sculpin	1.88	1.71	1.33	1.95	2.75	2.35
13	Plain sculpin	1.88	1.71	1.33	1.95	2.75	2.35
14	Warty sculpin	1.88	1.71	1.33	2.26	2.67	2.46
15	***Yellowfin sole***	***1.88***	***1.82***	***1.39***	***1.74***	***1.67***	***1.70***
16	Spinyhead sculpin	1.86	1.83	1.41	2.79	3.42	3.10
17	Thorny sculpin	1.86	1.83	1.41	3.00	3.42	3.21
18	***Northern rock sole***	***1.88***	***1.91***	***1.44***	***1.74***	***1.67***	***1.70***
19	Arrowtooth flounder	1.73	1.73	1.46	2.05	1.67	1.86
20	Yellow Irish lord	1.75	1.86	1.52	1.63	2.67	2.15
21	Armorhead sculpin	1.71	1.83	1.53	2.68	3.42	3.05
22	***Atka mackerel***	***2.12***	***2.33***	***1.60***	***1.95***	***1.92***	***1.93***
23	***Sablefish***	***1.76***	***2.08***	***1.64***	***1.63***	***1.25***	***1.44***
24	Bigmouth sculpin	1.50	1.71	1.66	1.95	2.75	2.35
25	***Walleye pollock***	***2.00***	***2.33***	***1.67***	***1.53***	***1.21***	***1.37***
26	***Pacific ocean perch***	***1.65***	***2.00***	***1.68***	***1.84***	***1.58***	***1.71***
27	Giant grenadier	1.47	1.79	1.72	2.00	1.92	1.96
28	***Pacific cod***	***2.00***	***2.42***	***1.73***	***1.53***	***1.42***	***1.47***
29	Whitebrow skate	1.39	1.78	1.79	2.89	3.17	3.03
30	Butterfly skate	1.39	1.78	1.79	2.89	3.42	3.16
31	Roughshoulder skate	1.39	1.88	1.83	3.00	3.42	3.21
32	Commander skate	1.39	1.89	1.84	2.89	3.17	3.03
33	Whiteblotched skate	1.39	1.89	1.84	2.79	3.17	2.98
34	Roughtail skate	1.39	1.89	1.84	2.68	3.17	2.93
35	Mud skate	1.39	1.89	1.84	2.79	3.17	2.98
36	Bering skate	1.44	2.00	1.85	1.63	2.83	2.23
37	Alaska skate	1.42	2.00	1.87	1.26	2.08	1.67
38	Northern rockfish	1.47	2.08	1.88	2.37	1.58	1.98
39	Dusky rockfish	1.64	2.30	1.88	3.21	2.25	2.73
40	Big skate	1.33	1.89	1.89	1.63	3.33	2.48
41	Deepsea skate	1.33	1.89	1.89	2.89	3.33	3.11
42	Aleutian skate	1.33	1.90	1.89	1.53	2.92	2.22
43	***Greenland turbot***	***1.65***	***2.33***	***1.90***	***2.42***	***2.42***	***2.42***
44	***Pacific halibut***	***1.53***	***2.25***	***1.93***	***1.68***	***1.42***	***1.55***
45	Salmon shark	1.19	1.75	1.96	3.21	3.67	3.44
46	Longnose skate	1.22	1.88	1.98	1.53	3.58	2.55
47	***Shortraker rockfish***	***1.17***	***2.00***	***2.09***	***3.11***	***1.92***	***2.51***
48	Spiny dogfish	1.11	1.91	2.10	1.84	3.00	2.42
49	Shortspine thornyhead	1.17	2.10	2.14	3.63	2.25	2.94
50	***Rougheye rockfish***	***1.20***	***2.21***	***2.17***	***2.68***	***2.00***	***2.34***
51	Sleeper shark	1.00	2.00	2.24	3.63	3.67	3.65

attributes included in the analysis were much more sensitive to changes in the value of individual attributes (Fig. 4)

4. Discussion

The PSA for Alaska groundfish provided an effective means to summarize the diverse fish stocks included in the FMPs. Productivity scores varied widely, demonstrating that managed stocks in Alaska possess a number of different life history strategies. Susceptibility scores varied less and tended toward an intermediate value (i.e. 2). This result is consistent with the intent of federal groundfish management in two ways. With the exception of giant grenadier all stocks included in the PSA are listed as managed species in the FMPs, indicating that there was at least some level of conservation concern for those stocks when the FMPs were created. Because of this, all stocks should display some susceptibility to commercial fishing. Conversely, the lack of high susceptibility scores may be indicative of successful management practices. No Alaska groundfish stocks are overfished and careful management including catch limits and in-season catch accounting have been practiced for over two decades. The PSA includes several metrics relative to management practices in the S attributes (e.g. management strategy, fishing rate relative to M), and the intermediate S scores are likely indicative of how management practices have limited the impact of fishing on target species.

The lower S scores observed in the non-target stocks are consistent with the greater exploitation of target stocks, which results in higher scores for some S attributes. Impact on populations is greater for target stocks (i.e. F/M ratios are higher), and attributes such as areal overlap and gear selectivity should also be higher for stocks that are actively targeted by fisheries. While mean P did not differ between targets and non-targets, this result obscured actual patterns of productivity. The target species tended to have intermediate P values, while non-targets were more likely to have extreme

Table 3
Results of the productivity–susceptibility analysis for the Gulf of Alaska management area. Target stocks are listed in bold and italicized text. P = productivity and S = susceptibility.

ID #	Stock name	P	S	Vulnerability	Data quality		
					P	S	Mean
1	Capelin	2.75	1.50	0.56	2.58	3.08	2.83
2	Squid	2.63	1.71	0.81	2.79	3.33	3.06
3	***Starry flounder***	***2.19***	***1.63***	***1.03***	***3.21***	***3.08***	***3.15***
4	Eulachon	2.69	2.00	1.05	2.68	2.25	2.47
5	Octopus	2.14	1.63	1.06	2.89	3.67	3.28
6	***Flathead sole***	***2.12***	***1.70***	***1.13***	***2.05***	***2.00***	***2.03***
7	Great sculpin	1.88	1.71	1.33	3.11	3.00	3.05
8	Plain sculpin	1.88	1.71	1.33	3.11	3.00	3.05
9	***Dover sole***	***1.71***	***1.36***	***1.34***	***1.63***	***1.58***	***1.61***
10	***Rex sole***	***1.87***	***1.73***	***1.35***	***1.32***	***1.58***	***1.45***
11	***Yellowfin sole***	***1.88***	***1.82***	***1.39***	***1.74***	***2.25***	***1.99***
12	Arrowtooth flounder	1.73	1.64	1.42	2.05	1.75	1.90
13	***Northern rock sole***	***1.88***	***1.90***	***1.43***	***1.74***	***2.50***	***2.12***
14	***Walleye pollock***	***2.29***	***2.25***	***1.44***	***1.63***	***1.83***	***1.73***
15	***Atka mackerel***	***2.12***	***2.20***	***1.49***	***1.95***	***3.17***	***2.56***
16	Yellow Irish lord	1.75	1.86	1.52	3.11	3.00	3.05
17	***Greenland turbot***	***1.65***	***1.78***	***1.56***	***2.42***	***3.25***	***2.84***
18	***Sablefish***	***1.76***	***2.08***	***1.64***	***1.11***	***1.25***	***1.18***
19	Bigmouth sculpin	1.50	1.71	1.66	3.11	3.00	3.05
20	***Pacific cod***	***2.00***	***2.42***	***1.73***	***1.53***	***1.42***	***1.47***
21	Giant grenadier	1.44	1.79	1.75	2.05	1.92	1.98
22	***Pacific ocean perch***	***1.74***	***2.29***	***1.81***	***1.47***	***1.38***	***1.42***
23	***Rougheye rockfish***	***1.30***	***1.68***	***1.83***	***1.95***	***1.63***	***1.79***
24	Big skate	1.33	1.90	1.89	1.63	2.83	2.23
25	Aleutian skate	1.33	1.90	1.89	1.53	2.92	2.22
26	***Pacific halibut***	***1.53***	***2.25***	***1.93***	***1.68***	***1.42***	***1.55***
27	Salmon shark	1.19	1.75	1.96	1.95	3.50	2.72
28	***Northern rockfish***	***1.33***	***2.08***	***1.99***	***2.16***	***1.63***	***1.89***
29	Longnose skate	1.22	1.90	1.99	1.53	3.08	2.30
30	Spiny dogfish	1.11	1.91	2.10	1.84	3.00	2.42
31	***Dusky rockfish***	***1.20***	***2.08***	***2.10***	***2.05***	***1.63***	***1.84***
32	***Sharpchin rockfish***	***1.14***	***2.00***	***2.11***	***2.58***	***2.04***	***2.31***
33	***Widow rockfish***	***1.17***	***2.10***	***2.14***	***1.58***	***2.29***	***1.94***
35	Sleeper shark	1.00	2.00	2.24	3.63	3.67	3.65
36	***Harlequin rockfish***	***1.00***	***2.00***	***2.24***	***2.68***	***2.13***	***2.40***
37	***Shortraker rockfish***	***1.00***	***2.09***	***2.28***	***2.89***	***2.13***	***2.51***
38	***Yellowtail rockfish***	***1.00***	***2.10***	***2.28***	***1.58***	***2.29***	***1.94***
39	***Yelloweye rockfish***	***1.00***	***2.27***	***2.37***	***1.47***	***2.13***	***1.80***

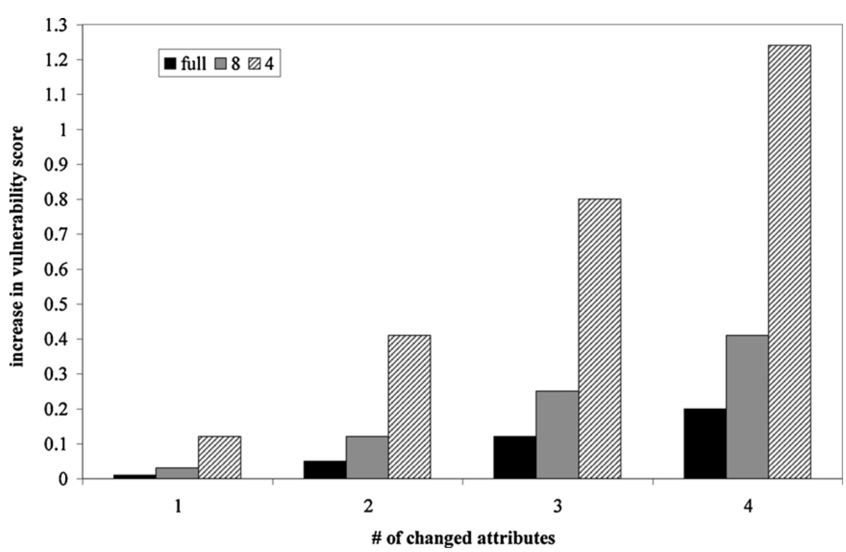

Fig. 4. Effect of increasing susceptibility scores from 1 to 3 on vulnerability scores for productivity–susceptibility analyses with different numbers of changed attributes and different numbers of total attributes included in the analysis.

values. This is also consistent with commercial fisheries targeting species with intermediate life histories.

The inclusion of target stocks in the PSA was valuable for interpreting the vulnerability of non-target stocks. One limitation of the PSA approach is that it produces estimates of relative vulnerability, and the lack of clearly defined thresholds is a challenge for decision-making. While some authors have suggested that vulnerabilities of 1.8 (Patrick et al., 2009) or 2.4 (Jason Cope, NMFS/NWFSC, pers. comm.) are associated with stocks experiencing overfishing, the level of vulnerability that should trigger management actions is difficult to define and may vary by region. In the Alaska analysis, for example, there are a number of species with vulnerabilities above 1.8 yet none of these are experiencing overfishing. The inclusion of target stocks provides a way of assessing the vulnerability of non-target stocks relative to stocks for which independent, quantitative assessments of vulnerability exist. Non-target stocks with similar vulnerability scores to target stocks likely require equivalent management approaches. Stocks with lower vulnerability may require less oversight, e.g. they may be included in the FMP as ecosystem components.

The results of the PSAs have implications for non-target stocks. Forage fishes (capelin and eulachon) and squids had much lower vulnerability scores than the other stocks, largely as a result of high productivity. Forage fishes are not currently managed using catch limits: directed fishing for them is banned and they have been included in the revised Alaska groundfish FMPs as ecosystem components. The PSA results suggested that this is a valid approach and that squids may be a candidate for similar management measures. The remaining non-target stocks had vulnerability scores that were similar to (e.g. sculpins) or exceeded (e.g. sharks) those of the target stocks. Such stocks likely require similar management to the target stocks, i.e. remaining "in the fishery" and having annual catch limits. Giant grenadier had similar vulnerability to several major target species, Pacific cod and walleye pollock, suggesting that it should be added to the FMPs and have annual catch limits. The PSA also underscored the vulnerability of long-lived species such as sharks and some rockfishes.

The PSA results can also inform the creation of stock complexes. Under the new federal guidelines, species included in stock complexes should have similar vulnerability scores. The analysis presented here indicated that some complexes, e.g. skates, contain species with similar vulnerability. In contrast, groupings such as the sculpin complex may require further consideration. Sculpin vulnerability varied considerably, mainly as a result of differences

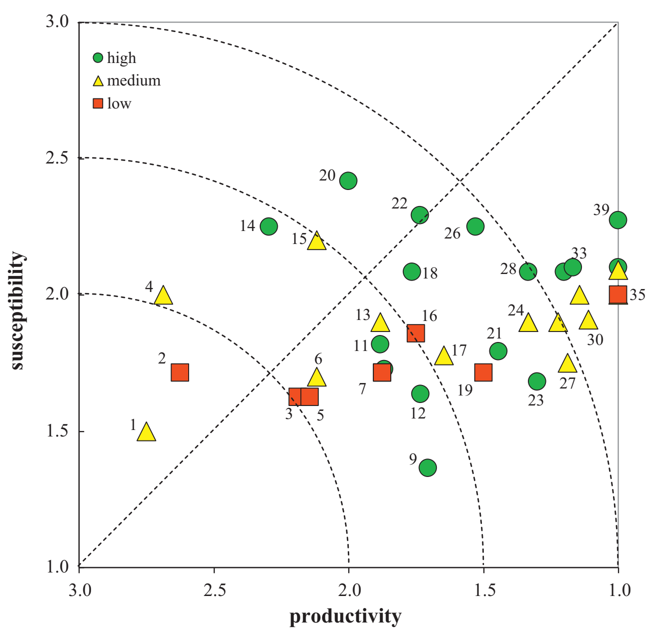

Fig. 2. Results of the productivity–susceptibility analysis for the Gulf of Alaska management area. Colors and symbol shapes indicate data quality scores. Numbers indicate stocks listed in Table 3. For clarity, not all stocks are labeled. Dashed lines indicate isopleths (i.e. points equidistant from the origin). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

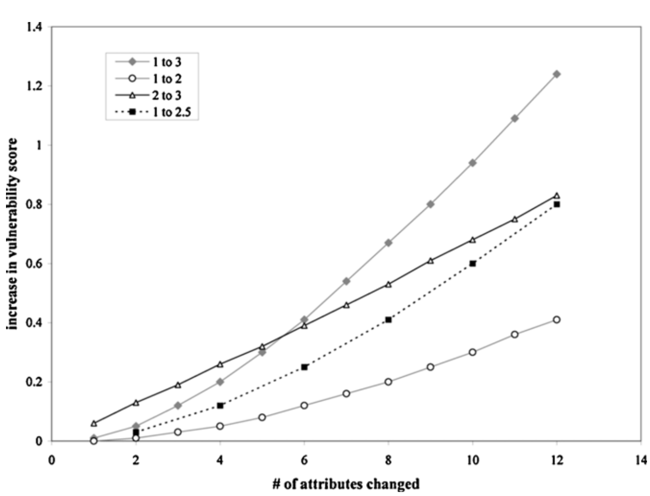

Fig. 3. Effects of increasing susceptibility scores on the overall vulnerability score of a single-stock productivity–susceptibility analysis (PSA) where all attributes are included in the analysis. Legend indicates the nature of the change in attribute score as described in the methods.

Table 4
Comparison of the results of productivity–susceptibility analysis for target and non-target stocks in the Bering Sea/Aleutian Islands and Gulf of Alaska management areas.

	Means (±SD)		Test statistics	
	Target	Nontarget	*t*	*p*
BSAI				
Productivity	1.75 ± 0.32	1.69 ± 0.44	0.507	0.617
Susceptibility	2.13 ± 0.21	1.84 ± 0.15	4.565	0.000
Vulnerability	1.71 ± 0.28	1.58 ± 0.39	1.286	0.210
Mean data quality	1.85 ± 0.40	2.69 ± 0.49	−6.082	0.000
GOA				
Productivity	1.59 ± 0.43	1.72 ± 0.57	−0.811	0.424
Susceptibility	1.99 ± 0.26	1.79 ± 0.14	3.053	0.004
Vulnerability	1.75 ± 0.40	1.53 ± 0.49	1.478	0.151
Mean data quality	1.98 ± 0.49	2.71 ± 0.50	−4.472	0.000

Table 5
Comparison of vulnerability scores for Pacific cod and Alaska skate in the Bering Sea/Aleutian Islands management area using two different approaches to the productivity–susceptibility analysis.

	Trawl	Longline	Pot
Pacific cod			
% Of catch	30%	59%	11%
P	2.00	2.00	2.00
S	2.50	2.33	2.33
Proportional *P*	0.60	1.19	0.22
Proportional *S*	0.75	1.39	0.25
# Attributes changed	3		
Total combined *P*	2.00		
Total combined *S*	2.38		
Multi-gear vulnerability	1.71		
Single gear vulnerability	1.73		
	Trawl	Longline	
Alaska skate			
% Of catch	18%	82%	
P	1.42	1.42	
S	2.00	1.80	
Proportional *P*	0.25	1.17	
Proportional *S*	0.35	1.48	
# Attributes changed	2		
Total combined *P*	1.42		
Total combined *S*	1.84		
Multi-gear vulnerability	1.79		
Single gear vulnerability	1.87		

in *P* scores. Although the species in the complex had similar susceptibility to fishing, their differences in life history traits may require the formation of separate complexes. The results of the PSA will inform an impending review of stock complexes in the Alaska FMPs.

The vulnerability scores produced using the multiple-gear approach were similar to those using the single-gear approach. This is likely due to the fact that *P* scores are the same regardless of gear type. In addition, the *S* attribute categories are fairly broad, so susceptibility to different gear types must vary substantially to produce large differences in vulnerability scores. More importantly, there is no effective way to parse out some of the attributes to individual gear types. For example, the *F*/*M* attribute must consider all fisheries simultaneously to avoid underestimating the impact of fisheries on a stock. Three different gear types might each have low *F*/*M* ratios, but the stock is experiencing the cumulative effect of that fishing mortality. It is interesting to note that the fisheries with a lower portion of total catch (e.g. the Pacific cod trawl fishery, Table 5) produced a higher susceptibility score. This is due to characteristics of the gear itself (e.g. habitat disruption and wider size selectivity); in contrast, the lower proportion of catch is not captured because the analysis considers the population as a whole.

The sensitivity analysis indicated that the response of a PSA to changes in attribute scores depends on its initial conditions. The vulnerability score for a stock with low vulnerability will respond more slowly to increases in susceptibility than the score for a stock with higher initial vulnerability. This has implications for periodic review of stock vulnerability: managers need to be aware that subtle changes in stock vulnerability may be indicative of larger changes in susceptibility. The large changes in vulnerability scores for PSAs that include few attributes were not surprising but underscored the need to make the PSA as complete as possible, even if that requires the inclusion of lower-quality data.

While the analyses described in this paper provided useful information for Alaska groundfish management, the results also underscored some of the limitations of the PSA approach. The multi-gear and sensitivity tests suggested that the NMFS PSA is fairly insensitive: large changes in attribute scores must occur for large changes in vulnerability to be observed. This insensitivity may limit the PSA's usefulness for ongoing monitoring of vulnerability status. Furthermore, the extent of the change in vulnerability depends heavily on the starting conditions of the analysis. These observations are consistent with results from analyses in Australian elasmobranch fisheries, where PSAs were unable to capture important changes in susceptibility due to the limited number and range of the included attributes (Griffiths et al., 2006).

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