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Supplementary Material

Vulnerability of 14 elasmobranchs to various fisheries in the southern Gulf of Mexico

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PSA attributes selection for approach 1

A multicriteria analysis was carried out to select the attributes to estimate P and S indices for approach 1. The set of attributes included in the analysis was obtained from Patrick *et al*. (2010), McCully Phillips *et al*. (2015), Furlong-Estrada *et al*. (2017), and Bravo-Zavala (2018). The multicriteria analysis is based on a Hierarchical Analytical Process (AHP) technique (Moreno-Jiménez 2002; Rosas Ávila *et al*. 2015). The AHP compares the attributes with each other according to five criteria, a) data redundancy; which refers to the correlation with other attributes; b) data reliability; if there is more or less confidence in the source to produce the attribute in comparison to the others (e.g. data in a scientific paper or recorded by the authors of the present study have the highest confidence); c) data easiness; if the attribute needs more or less data series or calculations to produce it in comparison to the others (e.g. attributes needing few data or calculations are easiest to produce it); d) data relevance; if the presence of the attribute is more or less relevant for determining the index in comparison to the others (e.g. some attributes can be more relevant than others, such as *r* or age-related attributes for estimating P); and, e) data availability; if there is more or less information in the literature or databases in comparison to other attributes. The comparisons of attributes with each other were made by assigning values ranging from 1 to 5 for the five criteria. These comparisons are based on available literature and the authors' expertise. For example, when comparing redundancy of 'maximum age' against the other 13 P attributes resulted in one of the following values depending on the attribute to which it is compared: 1) very little redundancy, 2) little redundancy, 3) moderate redundancy, 4) high redundancy, and 5) very high redundancy (e.g. 'maximum age' is highly redundant to 'age at maturity'). According to the criteria, the comparisons resulted in a paired scored matrix to establish which attribute was better than another.

The multicriteria analysis was carried out using the 'Definite' software from the Spatial Information Laboratory (https://spinlab.vu.nl/support/tools/definite-bosda/). The model to calculate the value of each attribute through this analysis was:

$$Aj = \sum_{i=1}^{I=5} \beta i \, \theta ij$$

where Aj is the value for attribute j of J attributes, β_i is the weighting for criterion i of I criteria, and θ_{ij} is the classification of attribute j based on criterion i. After paired comparisons, each attribute resulted in a global value from 0 to 1, where the score closest to one represented the best attributes. A total of 31 attributes were evaluated, 14 for P (Table S1) and 17 for S (Table S2). The attributes with the highest values were used in the sensitivity tests.

Table S1. Productivity attributes and rankings used to determine the vulnerability of a species.

Productivity attribute	Definition	Risk score ranking High (3)	Moderate (2)	Low (1)
Intrinsic rate of population growth (r)[1]	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	0.16–0.5	<0.16
Maximum age (years)[1]	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	10–20	>20
Maximum size (cm)[1]	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	<150[A]	150–250[A]	>250[A]
von Bertalanffy growth coefficient (*k*)[1]	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*	>0.3[A]	0.05–0.3[A]	<0.05[A]
Estimated natural mortality (*M*)[1]	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	>0.3[A]	0.1–0.3[A]	<0.1[A]
Measured fecundity[1]	Average number of the offspring by female	>15[A]	4–15[A]	<4[A]
Breeding strategy[1]	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	0	1–3	>4
Recruitment pattern (% of recruitment success)[1]	Stocks with sporadic and infrequent recruitment success often are long lived and thus may be expected to have lower levels of productivity	>75	10–75	<10
Age at maturity (years)[1]	Age at maturity tends to be positively related with maximum age (α^{max}); long-lived, lower productivity stocks will have higher ages at maturity than short-lived stocks	<2	2–4	>4
Mean trophic level[1]	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	>3.5
Size at maturity (cm)[3]	Size at maturity tends to be positively related with maximum age (α^{max}); long-lived, lower productivity stocks will have higher sizes at maturity than short-lived stocks	<100	100–150	>150
Reproductive cycle[3]	Lower productivity stocks will have longer reproductive cycles	Biannual	Annual	Biennial
Reproductive strategy[2]	Lower productivity stocks will have reproductive strategies related to the production of few offspring	Oviparous/ pelagic spawning	Oviparous/ demersal spawning	Viviparous
Genetic diversity[2]	Lower productivity stocks will have lower genetic diversity	More than a species in its genera	Unique species in its genera	Unique species in its family

Attributes proposed by 1: Patrick *et al*. (2010); 2: McCully Phillips *et al*. (2015); 3: Furlong-Estrada *et al*. (2017).

[A]Ranking modified according to Furlong-Estrada *et al*. (2017).

Table S2. Description of the risk categories for calculating susceptibility with approach 1.

Susceptibility attributed	Definition	Risk score ranking Low (1)	Moderate (2)	High (3)
Areal overlap[1]	The extent of geographic overlap between the known distribution of a stock and the distribution of the fishery	<25% of stock present in the area fished	Between 25 and 50% of the stock present in the area fished	>50% of stock present in the area fished
Geographic concentration[1]	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[1]	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 present in the depths fished	Between 25 and 50% of the stock present in the depths fished	>50% of stock present in the depths fished
Seasonal migrations[1]	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 behavioural responses[1]	Behavioural responses of both individual fish and the stock in response to fishing	Behavioural responses of fish decrease the catchability of the gear	Behavioural responses of fish do not substantially affect the catchability of the gear	Behavioural responses of fish increase the catchability of the gear
Morphological characteristics affecting capture[1]	The ability of the fishing gear to capture fish based on their morphological characteristics	Species shows low susceptibility to gear selectivity	Species shows moderate susceptibility to gear selectivity	Species shows high susceptibility to gear selectivity
Desirability or value of the fishery[1]	The assumption that highly valued fish stocks are 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; <33% retention	Stock is moderately valued or desired by the fishery; 33–66% retention	Stock is highly valued or desired by the fishery; >66% retention
Management strategy[1]	The susceptibility of a stock to overfishing may largely depend on the effectiveness of fishery management procedures used to control catch	Catch prohibited[A]	Closed seasons[A]	No measures[A]
Fishing rate relative to M[1]	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	<0.5	0.5–1.0	>1
Relative biomass of mature or other proxies[1] Note: originally known as Biomass of spawners (SSB)	The extent to which fishing has depleted the biomass of a stock in relation to expected	B is >40% of B^0 (original biomass)	B is between 25 and 40% of B^0	B is <25% of B^0

	unfished levels offers information on realised susceptibility			
Survival after capture and release[1]	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%	Probability of survival 33–67%	Probability of survival <33%
Impact of fisheries on essential fish habitat or habitat in general for nontargeted fish[1]	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
Size of the fishing fleet[3,4]	Number of fishing small-scale boats (SSB) or medium-scale boats (MSB)	<100 SSB or 10 MSB	100–300 SSB or 10–30 MSB	>300 SSB or >30 MSB
Fisheries seasonality[4]	Number of months in which the fishing fleet operates	<4	4–8	>8
Fisheries target[4]	Target or by-catch species	By-catch species (null or low value)	By-catch species (medium or high value)	Target species
Gear selectivity[4]	Fishing gear efficiency to capture the species	Gear is not effective to capture the species	Gear is moderately effective to capture the species	Gear is effective to capture the species
Stock monitoring[2]	Stock status to inform management	Sufficient data to inform the status	Insufficient data that show trends	Insufficient data to inform the status

Attributes proposed by 1: Patrick *et al*. (2010); 2: McCully Phillips *et al*. (2015); 3: Furlong-Estrada *et al*. (2017); 4: Bravo-Zavala (2018).

[A]Ranking modified according to Bravo-Zavala (2018).

Table S3. Description of the risk categories for calculating susceptibility with approach 2 according to Tovar-Ávila *et al*. (2010) and Hobday *et al*. (2011).

	Risk score ranking		
Component or attribute	**Low (0.33)**	**Moderate (0.66)**	**High (1.00)**
Availability 1. Overlap of species range with fishery. 2. Global distribution	Fishery range < one-third of the species range. Globally distributed	Fishery range >one-third but <two-thirds of the species range. Restricted to same hemisphere/ocean basin as the fishery.	Fishery range >two-thirds of the species range. Restricted to the same country as the fishery.
Encounterability	Low probability of encountering the gear (e.g. pelagic species encountering demersal gears).	Moderate probability of encountering the gear (e.g. pelagic species encountering mid-water gears).	High probability of encountering the gear (e.g. demersal species encountering demersal gears).
Selectivity	Low probability of being caught by the gear (e.g. filter feeder species taking a baited hook).	Moderate probability of being caught by the gear (e.g. fast swimming species taken by demersal trawl).	High probability of being caught by the gear (e.g. species with protruding structures taken by gill-net).
Post-capture mortality	High probability of survival after capture (e.g., discarded demersal species with spiracles and robust structure).	Moderate probability of survival after capture (e.g. discarded species with a fragile structure and ram ventilation).	Low probability of survival after capture (e.g. retained target and by-product species).

Table S4. Life-history parameters by species used to estimate productivity (P).

Species	Maximum size (cm)	Reproductive cycle	Size at maturity (cm)	Fecundity	Maximum age (years)	Trophic level	Age at maturity (years)	***k***	***r***
R. terraenovae	113(13)	Annual(13)	80(13)	4(13)	10(16)	4(29)	3(1)	0.63(6)	0.218
S. tiburo	125(1)	Annual(30)	72(30)	11(30)	12(24)	3.2(29)	3(30)	0.28(24)	0.657
S. lewini	350(1)	Annual(1)	245(1)	31(3)	30(1)	4.1(29)	15(1)	0.09(25)	0.239
C. falciformis	276(1)	Biennial(15)	246(1)	12(1)	22(15)	4.2(29)	12(1)	0.09(26)	0.177
C. leucas	271(2)	Biennial(16)	204(2)	12(1)	28(2)	4.3(29)	10(2)	0.12(2)	0.206
C. porosus	110(1)	Biennial(1)	85(1)	7(1)	12(3)	4.1(29)	6(3)	0.076(23)	0.265
C. plumbeus	234(1)	Biennial(1)	190(1)	14(16)	35(16)	4.1(29)	16(3)	0.12(27)	0.137
C. acronotus	137(1)	Annual(1)	103(1)	5(1)	16(17)	4.2(29)	6(4)	0.35(17)	0.204
C. limbatus	200(1)	Biennial(1)	156(1)	6(1)	14(18)	4.2(29)	6(18)	0.14(18)	0.164
S. mokarran	430(1)	Biennial(1)	315(1)	42(3)	44(5)	4.3(29)	6(5)	0.11(5)	0.492
H. americanus	115(29)	Annual(11)	76(11)	7(11)	13(29)	3.5(31)	6(6)	0.08(28)	0.362
A. narinari	230(9)	Annual(20)	135(12)	4(9)	25(19)	3.2(31)	6(7)	0.13(21)	0.273
R. bonasus	106(10)	Annual(8)	89(10)	1(10)	18(8)	3.2(31)	5(8)	0.19(22)	0.113
R. brasiliensis	102(14)	Biennial(14)	89A(10)	1(14)	18A(8)	3.6(31)	5A(8)	0.19A(22)	0.038

k: von Bertalanffy growth coefficient; *r*: intrinsic rate of population growth. Cited references (in numerical order and denoted by superscript numbers in parentheses): 1, Castro (2011); 2, Cruz-Martínez *et al*. (2005); 3, Compagno *et al*. (2005); 4, Carlson *et al*. (2007); 5, Piercy *et al*. (2010); 6, Cailliet and Goldman (2004); 7, Kyne *et al*. (2006); 8, Neer and Thompson (2005); 9, Last *et al*. (2016); 10, Pérez-Jiménez (2011); 11, Ramírez Mosqueda *et al*. (2012); 12, Tagliafico *et al*. (2012); 13, Morín (2010); 14, Vooren and Lamónaca (2004); 15, Bonfil (2008); 16, Fowler *et al*. (2005); 17, Carlson *et al*. (1999); 18, Tovar-Ávila *et al*. (2009); 19, Dubick (2000); 20, Cuevas-Zimbrón *et al*. (2011); 21, Utrera López (2015); 22, Fisher *et al*. (2013); 23, Lessa and Santana (1998); 24, Carlson and Parsons (1997); 25, Piercy *et al*. (2007); 26, Bonfil *et al*. (1993) ; 27, Hale and Baremore (2013); 28, Hernández Lazo (2012); 29, Cortés (1999); 30, Berthiaume (2010); 31, R. Froese and D. Pauly, 'Fishbase', version 12/2019, see www.fishbase.org.

[A] Data taken from *Rhinoptera bonasus*

Table S5. Database used for the estimation of the rebound potential.

Species	*a*	*w*	*b*
Rhizoprionodon terraenovae	3	10	2
Sphyrna tiburo	3	12	5.5
Carcharhinus acronotus	6	16	2.5
Rhinoptera bonasus	5	18	0.5
Rhinoptera brasiliensis	5[A]	18[A]	0.25
Sphyrna mokarran	6	44	10.5
Aetobatus narinari	6	25	2
Carcharhinus leucas	10	28	3
Hypanus americanus	6	13	3.5
Carcharhinus plumbeus	16	35	3.5
Carcharhinus limbatus	6	14	1.5
Sphyrna lewini	15	30	15.5
Carcharhinus falciformis	12	22	3
Carcharhinus porosus	6	12	1.75

Data for *a* (age at maturity in years), *w* (maximum reproductive age in years), and *b* (fecundity) were obtained from Table S4.

[A]Data taken from *Rhinoptera bonasus*.

Table S6. Estimations of natural mortality (*M*) used for the estimation of the rebound potential.

Species	Jensen's First Estimator	Modified Hewitt and Hoeing Estimator	Reciprocal of lifespan	Dulvy and Forrest (2010)	Hoenig (1983)	Average
R. terraenovae	0.55	0.422	0.154	0.265	0.421	0.362
S. tiburo	0.55	0.352	0.133	0.118	0.35	0.300
S. lewini	0.11	0.141	0.044	0.038	0.139	0.094
C. falciformis	0.137	0.192	0.059	0.038	0.19	0.123
C. leucas	0.165	0.151	0.053	0.050	0.149	0.113
C. porosus	0.275	0.352	0.111	0.032	0.35	0.224
C. plumbeus	0.103	0.120	0.039	0.050	0.119	0.086
C. acronotus	0.275	0.263	0.091	0.147	0.262	0.208
C. limbatus	0.275	0.301	0.10	0.059	0.30	0.207
S. mokarran	0.275	0.096	0.04	0.046	0.094	0.110
H. americanus	0.275	0.325	0.105	0.033	0.323	0.212
A. narinari	0.275	0.169	0.064	0.055	0.167	0.146
R. bonasus	0.330	0.234	0.087	0.080	0.232	0.193
R. brasiliensis	0.330	0.234	0.087	0.080	0.232	0.193

Table S7. Multicriteria estimates of biological productivity attributes (P) ordered from highest to lowest total value.

Attributes	Total value	Data redundancy	Data reliability	Data easiness	Data relevance	Data availability
1. Maximum size	0.82	0.60	0.80	1.00	0.70	1.00
2. Size at maturity	0.70	0.59	0.62	0.80	0.73	0.76
3. Maximum age	0.59	0.65	0.61	0.50	0.75	0.45
4. Reproductive cycle	0.58	0.30	0.70	0.60	0.50	0.80
5. Fecundity	0.55	0.30	0.65	0.55	0.59	0.67
6. Trophic level	0.52	0.55	0.55	0.50	0.35	0.65
7. Intrinsic rate of population growth (*r*)	0.51	0.65	0.40	0.25	0.85	0.40
8. Age at maturity	0.50	0.60	0.45	0.35	0.60	0.50
9. von Bertalanffy growth coefficient (*k*)	0.50	0.45	0.50	0.35	0.65	0.55
10. Reproductive strategy	0.49	0.30	0.70	0.60	0.16	0.70
11. Natural mortality	0.47	0.60	0.30	0.35	0.70	0.40
12. Genetic diversity	0.35	0.45	0.30	0.30	0.35	0.35
13. Recruitment pattern	0.23	0.45	0.14	0.15	0.28	0.11
14. Breeding strategy	0.22	0.45	0.12	0.18	0.21	0.13

Table S8. Multicriteria estimates of susceptibility attributes (S) ordered from highest to lowest total value.

Attributes	Total value	Data redundancy	Data reliability	Data easiness	Data relevance	Data availability
1. Fisheries target	0.81	0.35	1.00	1.00	0.70	1.00
2. Fisheries seasonality	0.67	0.34	0.65	0.93	0.60	0.84
3. Desirability or value of the fishery	0.63	0.35	0.94	0.74	0.49	0.65
4. Size of the fishing fleet	0.60	0.45	0.60	0.70	0.60	0.65
5. Gear selectivity	0.54	0.50	0.55	0.39	0.61	0.65
6. Vertical overlap	0.53	0.39	0.65	0.55	0.50	0.57
7. Areal overlap	0.52	0.40	0.60	0.51	0.52	0.55
8. Stock monitoring	0.50	0.30	0.70	0.60	0.45	0.45
9. Management strategy	0.43	0.23	0.55	0.54	0.28	0.55
10. Impact of fisheries on habitat	0.41	0.35	0.45	0.35	0.45	0.45
11. Schooling, aggregation	0.41	0.36	0.38	0.45	0.45	0.40
12. Survival after capture and release	0.33	0.30	0.40	0.15	0.55	0.25
13. Geografic concentration	0.32	0.25	0.35	0.35	0.40	0.23
14. Fishing rate relative to *M*	0.27	0.35	0.20	0.10	0.45	0.26
15. Morphology affecting capture	0.27	0.14	0.35	0.30	0.35	0.20
16. Seasonal migrations	0.26	0.19	0.35	0.17	0.30	0.30
17. Biomass of mature	0.22	0.30	0.22	0.15	0.35	0.10

Table S9. Scores for the productivity attributes (P) by species.

Attributes	***R. terraenovae***	***S. tiburo***	***C. acronotus***	***C. porosus***	***C. leucas***	***C. plumbeus***	***C. falciformis***	***C. limbatus***	***S. lewini***	***S. mokarran***	***H. americanus***	***A. narinari***	***R. bonasus***	***R. brasiliensis***
Maximum size	***3***	***3***	***3***	***3***	1	*2*	1	*2*	1	1	*2*	*2*	***3***	***3***
Reproductive cycle	*2*	*2*	*2*	1	1	1	1	1	*2*	1	*2*	*2*	*2*	1
Size at maturity	***3***	***3***	*2*	***3***	1	1	1	1	1	1	***3***	*2*	***3***	***3***
Fecundity	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	***3***	***3***	*2*	1	1	1
Maximum age	*2*	*2*	*2*	*2*	1	1	1	*2*	1	1	1	1	*2*	*2*
Reproductive strategy	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Trophic level	1	*2*	1	1	1	1	1	1	1	1	*2*	*2*	*2*	1
r	*2*	***3***	*2*	*2*	*2*	1	*2*	1	*2*	*2*	*2*	*2*	1	1
Age at maturity	*2*	*2*	1	1	1	1	1	1	1	1	1	1	1	1
k	***3***	*2*	***3***	*2*	1	*2*	1	1	1	*2*	*2*	*2*	*2*	*2*

The codes and fonts are as follows: 1 (roman), low; 2 (italic), moderate; and 3 (italic and bold), high.

Table S10. Data quality value and category for each species' estimated productivity (P) and susceptibility (S) scores.

Species	P data quality value	P data quality category	S data quality value	S data quality category
R. terraenovae	1.61	Good	1.44	Good
S. tiburo	1.61	Good	1.53	Good
S. lewini	2.08	Moderate	1.81	Good
C. falciformis	2.08	Moderate	1.81	Good
C. leucas	1.97	Good	1.81	Good
C. porosus	2.08	Moderate	2.19	Moderate
C. plumbeus	2.08	Moderate	2.19	Moderate
C. acronotus	2.08	Moderate	1.63	Good
C. limbatus	1.75	Good	1.63	Good
S. mokarran	2.19	Moderate	2.00	Moderate
H. americanus	1.39	Good	2.00	Moderate
A. narinari	2.44	Moderate	2.19	Moderate
R. bonasus	2.17	Moderate	2.19	Moderate
R. brasiliensis	3.11	Moderate	2.19	Moderate

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