Pacific Islands Vulnerability Assessment
Invertebrate Species Narrative

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The Pacific Islands Fisheries Science Center conducted a climate change vulnerability assessment for six species groups in the Pacific Islands region (Giddens et al. unpublished). This data report summarizes the following assessments of each species in the invertebrate species group: overall climate vulnerability rank (certainty determined by bootstrap following Hare et al. 2016), climate exposure, biological sensitivity, distributional vulnerability rank, data quality, climate effects on abundance and distribution, and life history (see Morrison et al. 2015 for further details).

Biological sensitivity and climate exposure were evaluated and scored by experts for each species. Biological sensitivity is representative of a species' capacity to respond to environmental changes in reference to a biological attribute. The Invertebrate Species Narrative is accompanied by the Invertebrate Species Profile, which provides further information on each biological sensitivity attribute for each species. The Invertebrate Species Profile was used to help experts evaluate biological sensitivity. Experts were also encouraged to use their own expertise and knowledge when evaluating. Climate exposure is defined as the degree to which a species may experience a detrimental change in a physical variable as a result of climate change. The inclusion of climate exposure variables followed four guidelines: 1) the variables are deemed to be ecologically meaningful for the species and geography in question, 2) the variables should be available on the NOAA ESRL Climate Change Data Portal for consistency across different CVAs, 3) the variables are available in the temporal and spatial domains suitable for inclusion, and 4) the quality of the modeled product was judged to be adequate for inclusion. By following these guidelines, the exposure scoring was therefore a quantitative exercise, in that future values could be compared to historical values while incorporating observed patterns of natural variability. This allowed determination of likely severity of future changes in exposure on a species and area specific basis for each exposure variable. Scoring for biological sensitivity and climate exposure is based on scale from 1–4 (Low, Moderate, High, Very High) and scoring for data quality is ranked from 0–3 (No Data, Expert Judgement, Limited Data, Adequate Data). A high score for biological sensitivity and climate exposure indicates greater vulnerability. Expert Score Plots show the variation in expert scoring (5 experts per species). Scoring was completed in 2018. The mean score for each sensitivity attribute or exposure variable was calculated and a logic model was used to determine the component score for biological sensitivity and climate exposure. For example, if there are three or more attributes with a mean greater than or equal to 3.5, the sensitivity or exposure component score would be a 4 (Very High). Please see Morrison et al. 2015 for remaining logic model's criteria. Overall climate vulnerability was determined by multiplying sensitivity and exposure component scores and the possible range of these scores was between 1 and 16. The numerical values for the climate vulnerability rank were the following: 1–3 (Low), 4–6 (Moderate), 8–9 (High), and 12–16 (Very High).

Hare JA, Morrison WE, Nelson MW, Stachura MM, Teeters EJ, Griffis RB, Alexander MA, Scott JD, Alde L, Bell RJ, et al. 2016. A Vulnerability Assessment of Fish and Invertebrates to Climate Change on the Northeast U.S. Continental Shelf. PLoS One. 11: e0146756.

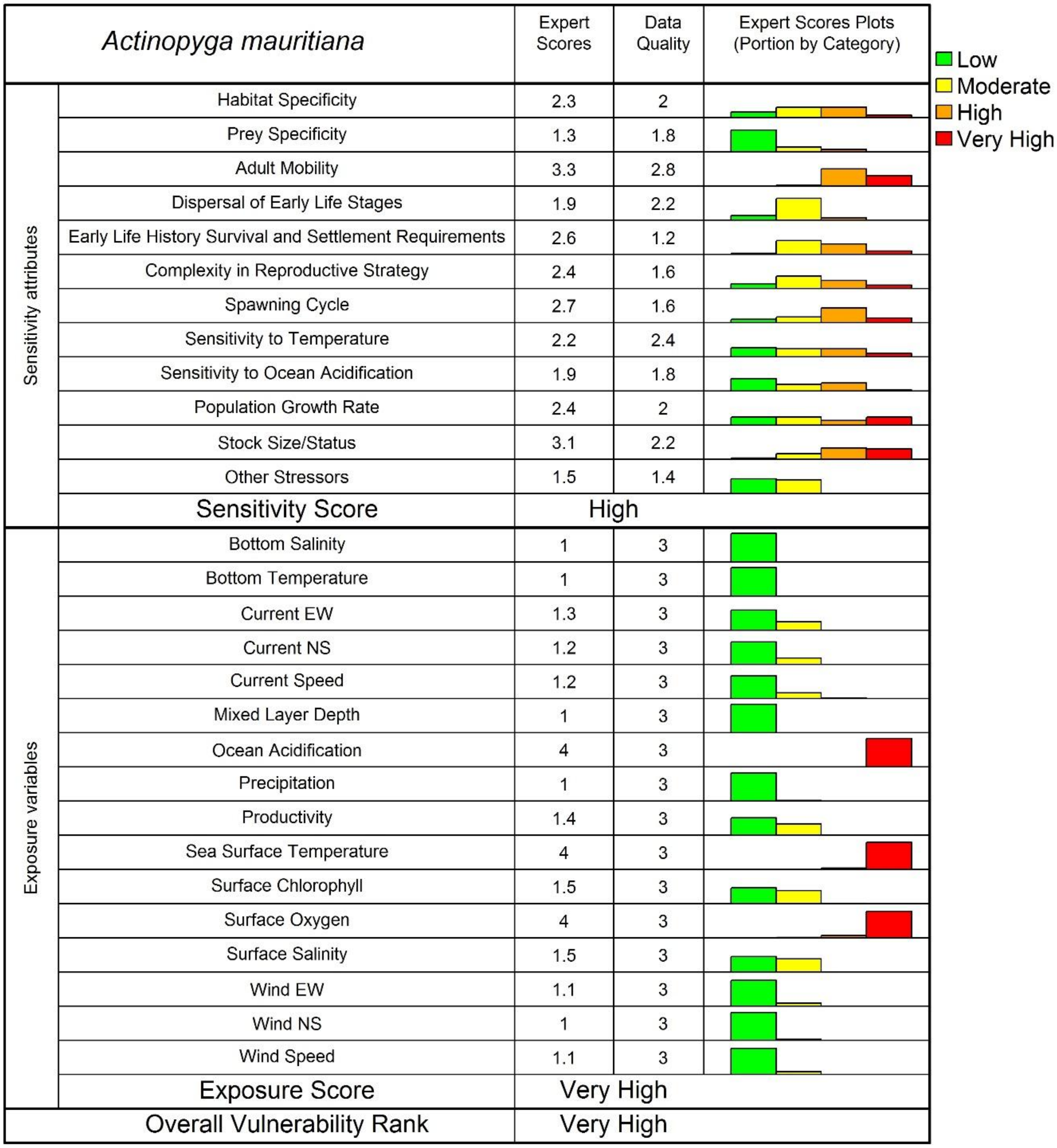
Morrison WE, Nelson MW, Howard JF, Teeters EJ, Hare JA, Griffis RB, Scott JD, Alexander MA. 2015. Methodology for Assessing the Vulnerability of Marine Fish and Shellfish Species to a Changing Climate. U.S. Dept of Commer, NOAA. NOAA Technical Memorandum NMFS-OSF-3, 48 p.

Contents

Surf redfish - *Actinopyga mauritiana*

Overall Vulnerability Rank = Very High🟥

Biological Sensitivity = High🟧
Climate Exposure = Very High🟥
Data Quality = 79% of scores ≥ 2



	Actinopyga mauritiana	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	2.3	2	
	Prey Specificity	1.3	1.8	
	Adult Mobility	3.3	2.8	
	Dispersal of Early Life Stages	1.9	2.2	
	Early Life History Survival and Settlement Requirements	2.6	1.2	
	Complexity in Reproductive Strategy	2.4	1.6	
	Spawning Cycle	2.7	1.6	
	Sensitivity to Temperature	2.2	2.4	
	Sensitivity to Ocean Acidification	1.9	1.8	
	Population Growth Rate	2.4	2	
	Stock Size/Status	3.1	2.2	
	Other Stressors	1.5	1.4	
	Sensitivity Score	High		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.3	3	
	Current NS	1.2	3	
	Current Speed	1.2	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.4	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.5	3	
	Surface Oxygen	4	3	
	Surface Salinity	1.5	3	
	Wind EW	1.1	3	
	Wind NS	1	3	
	Wind Speed	1.1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		Very High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Surf Redfish (*Actinopyga mauritiana*)

Overall Climate Vulnerability Rank: **[Very High].** (74% certainty from bootstrap analysis).

Climate Exposure: [Very High]. Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[High]**. Two sensitivity attributes scored above a 3.0: Adult Mobility (3.3) and Stock Size/Status(3.1).

Distributional Vulnerability Rank: **[Moderate].** Three attributes indicated moderate vulnerability to distribution shift: limited early life stage dispersal, relatively high habitat specialization, and sensitivity to temperature. However, adult mobility was scored as low which may mitigate the propensity of the species to shift distribution.

Data Quality: 79% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

A risk management approach assessment of a multi-species sea cucumber fishery in the Torres Strait predicted a general decline in biomass projections for the surf redfish due to climate change effects independent of fishing pressure [1]. For the eight species modeled by Plagányi et al. [1], temperature was predicted to have a positive effect on sea cucumber growth, which was offset by increased larval and juvenile mortality. There have been no studies pertaining to surf redfish distributional changes as a result of climate change, although it can be assumed that a decrease in the coral-dominated surge zones of barrier reefs, the preferred habitat of the species [2], would have a negative influence on the abundance and distribution of the species.

Life History Synopsis**:**

The surf redfish inhabits high-energy surge zones of intertidal and subtidal coral reefs, rigidly attached to surfaces exposed to breaking surf [2], with its prime habitat including barrier reefs down to about 6 m on the outer reef slope [3,4]. The surf redfish is distributed in the Indo-Pacific Region from the Pitcairn Islands into the Red Sea [5]. On Saipan in the Northern Mariana Islands, Trianni and Tenorio [6] documented the range of measured surf redfish length to be from 6 cm to 37 cm and measured wet weight range from 50 to 1100 g. From New Caledonia mark-recapture data, Conand [7] estimated asymptotic length to be 34.0 cm with a von Bertalanffy growth coefficient, which indicates how fast maximum length is reached, of 0.12 yr^{-1} and annual natural mortality rate of 1.45 yr^{-1}. No subsequent estimates of these parameters have been made for this species in part because growth rings are not identifiable from calcareous structures or other hard parts, as with other sea cucumber species. The peak reproductive activity of surf redfish in Guam, as observed by increased mean gonadal somatic index values, is during the spring and summer, corresponding to increased day length and warmer ocean temperatures [2]. This was similar to findings by Conand [8] in New Caledonia and by Ramofafia et al. [9] in the Solomon Islands. Although the surf redfish exhibits annual reproduction, individuals lacking or having indeterminate gonads were found to be present year-round in the populations studied by both Hopper et al. [2] and Ramofafia et al. [9]. Hopper et al. [2] concluded that given the differences in the seasonal range of temperature and seasonal photoperiod between New Caledonia and Guam, and the similar resting periods and periods of elevated gonadal index for the surf redfish in both locations, temperature and photoperiod appear to influence reproductive synchrony in an absolute rather than a relative manner. The mean absolute fecundity for surf redfish from Guam was estimated to be to be 33.6 × 10^6 [2], higher than fecundity estimated from New Caledonia by Conand [8]. Ramofafia et al. [10] reared surf redfish to the auricularia and doliolaria stages, with the auricularia stage being reached by 40–70 hours and subsequent transformation to the doliolaria stage in 12–22 days. There is no information on size of settlement for surf redfish, and observation of juveniles in the field is uncommon, although estimates from a New Caledonia reef flat were 2–3 cm [11]. Surf redfish are broadcast spawners, releasing unfertilized gametes into the water column. The distance between the sexes may be negatively correlated with reproductive success [12]; therefore, the species may be susceptible to Allee dynamics [13]. Trianni and Tenorio [6] estimated population size for a recovered surf redfish population utilizing a stratified random sampling approach and generated an average population growth rate from previously harvested habitats of 0.95. Estimated densities from previously harvested barrier reef habitats ranged from 0.3 to 11.8 individuals per 100 m^2 [6], encompassing the range of habitat density estimates from an unharvested population on Tinian Island that ranged from 0.3 to 5.7 individuals per 100 m^2 [13].

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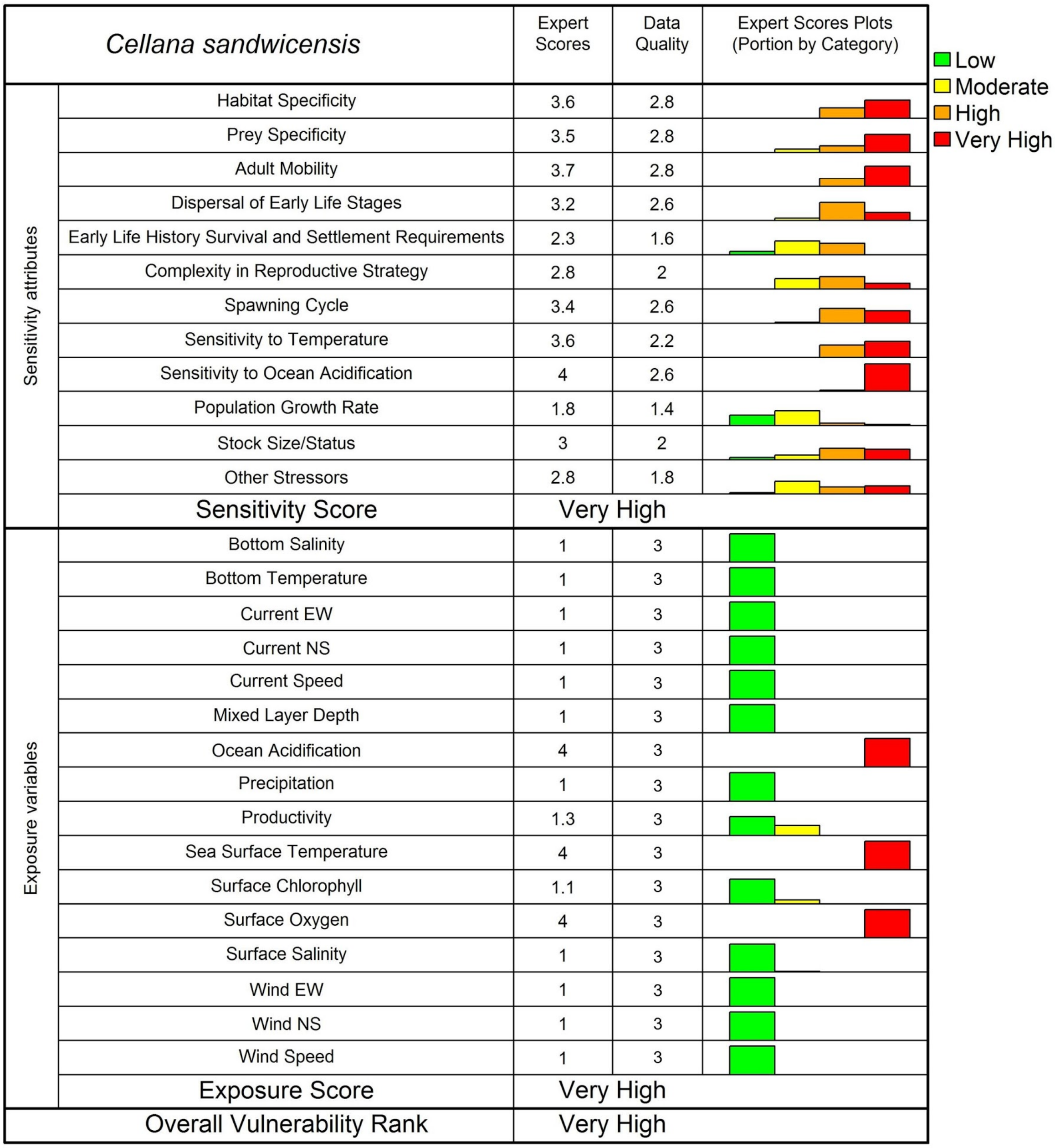
Limpet - *Cellana sandwicensis*

Overall Vulnerability Rank = Very High 🟥

Biological Sensitivity = Very High 🟥
Climate Exposure = Very High 🟥
Data Quality = 32% of scores ≥ 2



Cellana sandwicensis		Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	3.6	2.8	
	Prey Specificity	3.5	2.8	
	Adult Mobility	3.7	2.8	
	Dispersal of Early Life Stages	3.2	2.6	
	Early Life History Survival and Settlement Requirements	2.3	1.6	
	Complexity in Reproductive Strategy	2.8	2	
	Spawning Cycle	3.4	2.6	
	Sensitivity to Temperature	3.6	2.2	
	Sensitivity to Ocean Acidification	4	2.6	
	Population Growth Rate	1.8	1.4	
	Stock Size/Status	3	2	
	Other Stressors	2.8	1.8	
	Sensitivity Score	Very High		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1	3	
	Current NS	1	3	
	Current Speed	1	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.3	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.1	3	
	Surface Oxygen	4	3	
	Surface Salinity	1	3	
	Wind EW	1	3	
	Wind NS	1	3	
	Wind Speed	1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		Very High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Limpet (*Cellana sandwicensis*)

Overall Climate Vulnerability Rank: **[Very High].** (100% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[Very High]**. Seven sensitivity attributes scored above a 3.0. The highest scores were for Habitat Specificity (3.6), Adult Mobility (3.7), and Sensitivity to Ocean Acidification (4.0).

Distributional Vulnerability Rank: **[Low].** Three attributes indicated low vulnerability to distribution shift: adult mobility, limited early life stage dispersal, and high habitat specialization. Sensitivity to temperature was the only attribute ranked high.

Data Quality: 32% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Cellana sandwicensis a benthic species, resides in the rocky intertidal region in the lower to mid-intertidal zone and is one of three endemic limpet species in Hawaiʻi . They have been identified from the island of Hawaiʻi (19°00ʹN, 155°40ʹW) to Puhahonu (25°01ʹN, 167°59ʹW) [1]. Sea level rise, development, pollution, and loss of habitat are anticipated threats to *C. sandwicensis*. Sea level rise could cause shifts in their habitat. They are especially vulnerable to changes to their habitat since adults are not highly mobile. Ocean acidification is also a potential threat as their shells are made of calcium carbonate. Although not reported, their limited mobility would necessitate sufficient population densities for reproduction (K Springer, personal communication). Consequently, climate effects on adult abundance may in turn effect reproduction. Climate effects would be further compounded by heavy fishing pressure. More research is needed to understand the impacts of nearshore habitat disturbance and destruction.

Life History Synopsis**:**

Spawning for *Cellana sandwicensis* (ʻOpihi ʻĀlinalina in Hawaiian) occurs around December, with gonadosomatic index increasing from October to February [2]. The spawning period is thought to be near the new moon [3]. When spawning occurs, gametes are released into the water where external fertilization takes place [4]. *C. sandwicensis* are believed to be gonochoristic; however, Mau [2] reported the presence of a hermaphrodite. This may indicate *C. sandwicensis* are sequential hermaphrodites, but further investigation is needed [2]. The larval duration is short, with lecithotrophic larvae settling within 4 days [2,4]. After settling in the lower to mid-intertidal zone, they grow 4 to 5 mm per month until they reach 20 mm [5]. The limpets then grow 2 to 3 mm per month [5]. According to the study from Mau [2], *C. sandwicensis* reach maturity at around 21 mm or 8 to 9 months and can grow to nearly 70 mm. *C. sandwicensis* consume crustose coralline algae and benthic substrate (K Springer, personal communication). The von Bertalanffy growth coefficient, which indicates how fast maximum length is reached, was reported to be 0.0371 yr^{-1} [2]. Natural mortality was not reported. Known predators include *Neothais harpa*, *Purpura aperta*, *Drupa morum*, and *Drupa ricina* (K Springer, personal communication).

C. sandwicensis have a weaker population structure within the main Hawaiian Islands and between the main Hawaiian Islands and the Northwestern Hawaiian Islands. Biogeographical range and microhabitat use were associated with dispersal estimates. However, minimum pelagic larval duration was a poor predictor of population partitioning [1].

References

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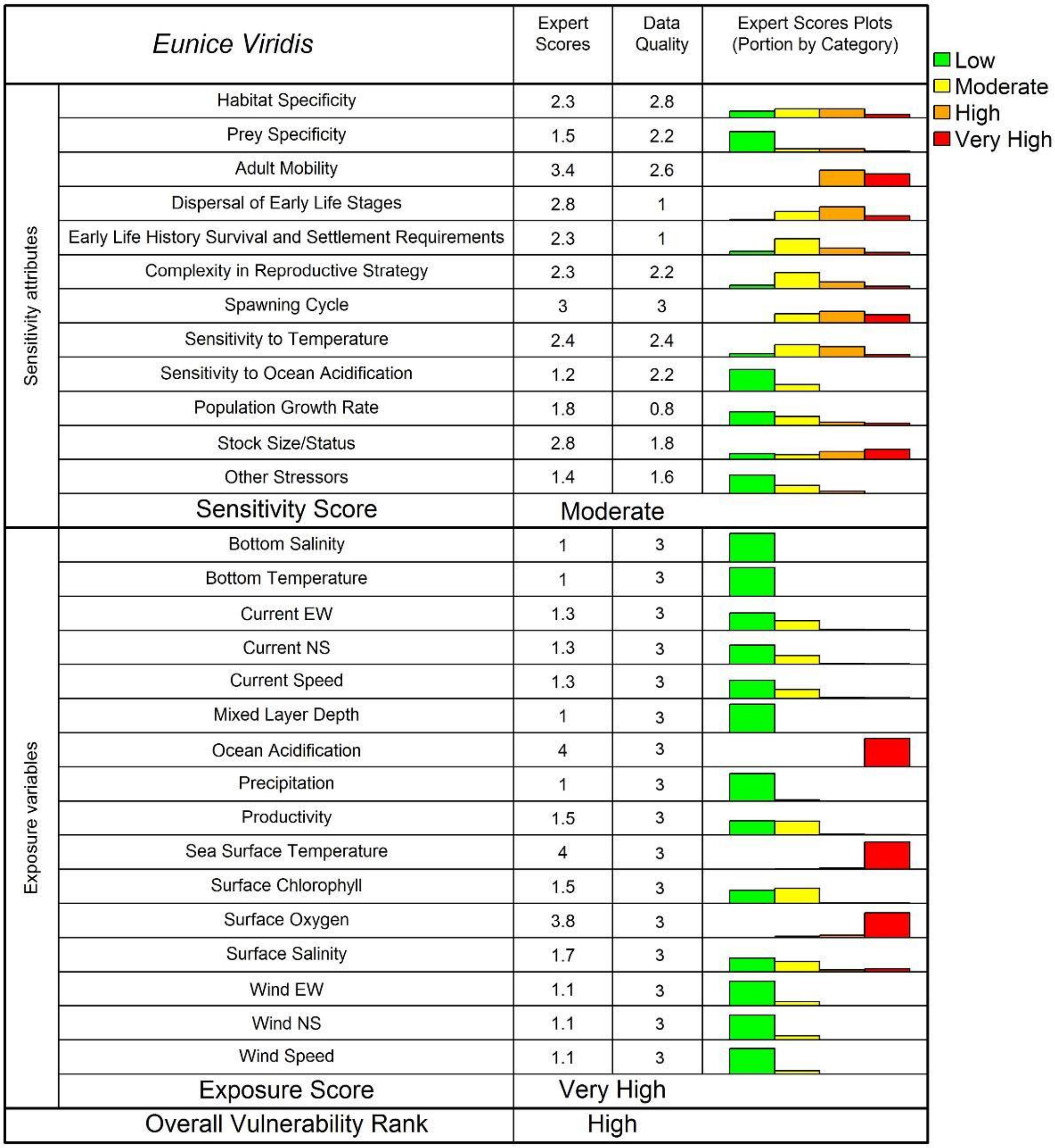
Palolo worm - *Eunice Viridis*

Overall Vulnerability Rank = High🟧

Biological Sensitivity = Moderate 🟨
Climate Exposure = Very High🟥
Data Quality = 25% of scores ≥ 2



	Eunice Viridis	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	2.3	2.8	
	Prey Specificity	1.5	2.2	
	Adult Mobility	3.4	2.6	
	Dispersal of Early Life Stages	2.8	1	
	Early Life History Survival and Settlement Requirements	2.3	1	
	Complexity in Reproductive Strategy	2.3	2.2	
	Spawning Cycle	3	3	
	Sensitivity to Temperature	2.4	2.4	
	Sensitivity to Ocean Acidification	1.2	2.2	
	Population Growth Rate	1.8	0.8	
	Stock Size/Status	2.8	1.8	
	Other Stressors	1.4	1.6	
	Sensitivity Score	Moderate		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.3	3	
	Current NS	1.3	3	
	Current Speed	1.3	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.5	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.5	3	
	Surface Oxygen	3.8	3	
	Surface Salinity	1.7	3	
	Wind EW	1.1	3	
	Wind NS	1.1	3	
	Wind Speed	1.1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Palolo Worm (*Eunice viridis*)

Overall Climate Vulnerability Rank: **[High].** (63% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[Moderate]**. One sensitivity attribute scored above a 3.0: Adult Mobility (3.4). Dispersal of Early Life Stages (2.8) and Stock Size/Status (2.8) also ranked high.

Distributional Vulnerability Rank: **[Low].** All four attributes indicated low vulnerability to distribution shift: adult mobility, limited early life stage dispersal, relatively high habitat specialization, and sensitivity to temperature.

Data Quality: 25% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Eunice viridis live in the shallow waters of tropical coral reefs and inhabits crevices and cavities within the reef. The palolo worm can be found in Indonesia, Vanuatu, Fiji, Samoa, and American Samoa [1]. Over-harvesting is thought to have caused local extinction in northwestern Upolu [1,2]. This species may not be directly affected by ocean acidification, but further investigation is needed to understand potential consequences. *E. viridis* inhabit tunnels in coral limestone which would be impacted by ocean acidification [3]. Other potential environmental stressors on the palolo worm are not reported.

Life History Synopsis**:**

Aggregations of *E. viridis* spawn during the second or third day after the third quarter of the moon in October or November in a synchronized manner. The worms develop segments which become engorged with sperm and eggs. At sunrise, the segments separate and rise to the surface where the gametes are released. Spawning occurs for several nights. The mechanisms or triggers that induce spawning are not known [1,4]. During spawning, the segments can be harvested for consumption [1,3]. Other early life history traits are not reported for *E. viridis*. Adult palolo worms gnaw long tunnels through coral limestone where symbiotic algae occur [3]. It is thought that the algae is the main source of nutrition [3]. Adults are mobile but limited by physical constraints.

References

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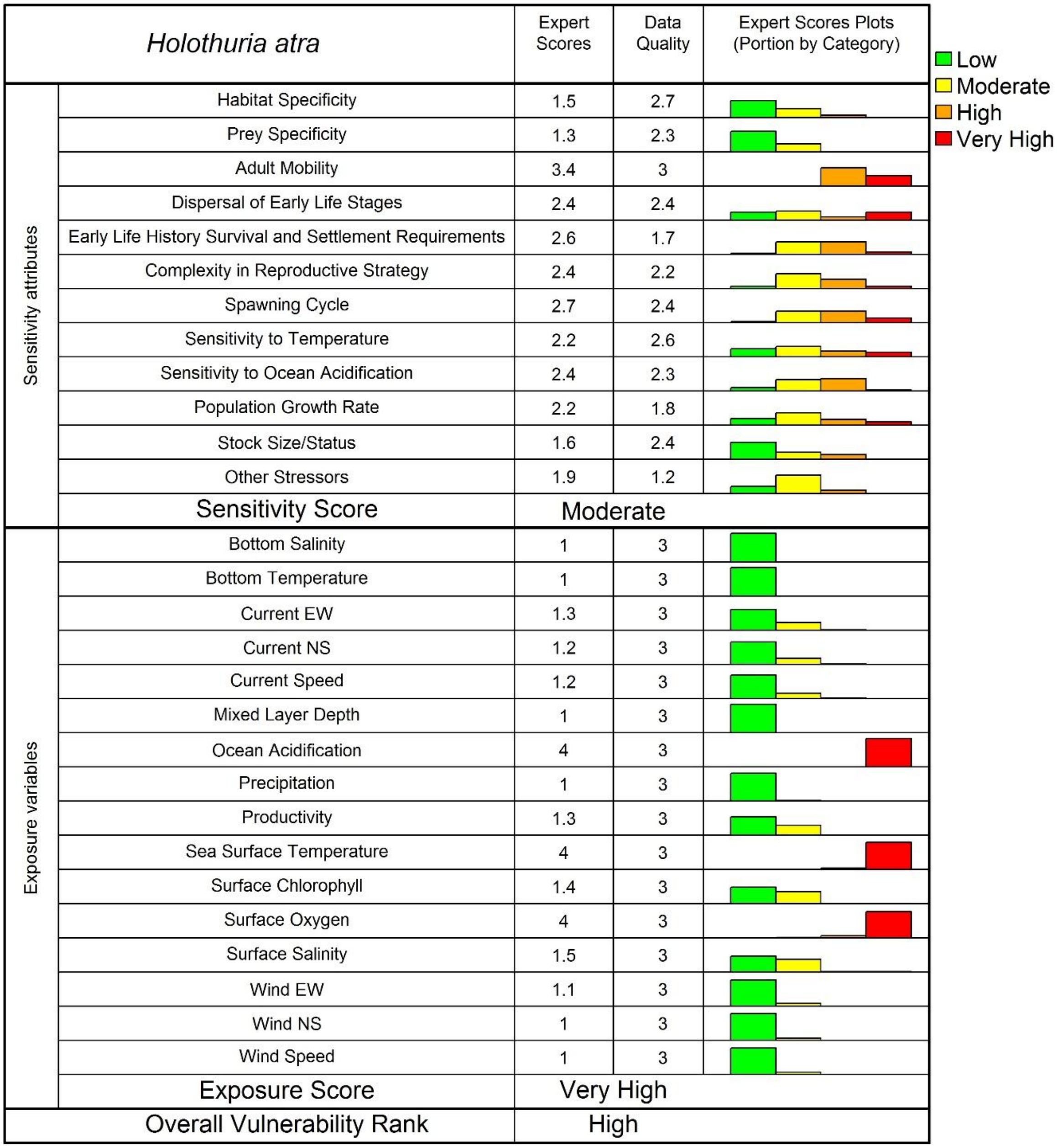
Black sea cucumber - *Holothuria atra*

Overall Vulnerability Rank = High🟧

Biological Sensitivity = Moderate 🟨
Climate Exposure = Very High 🟥
Data Quality = 89% of scores ≥ 2



	Holothuria atra	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	1.5	2.7	
	Prey Specificity	1.3	2.3	
	Adult Mobility	3.4	3	
	Dispersal of Early Life Stages	2.4	2.4	
	Early Life History Survival and Settlement Requirements	2.6	1.7	
	Complexity in Reproductive Strategy	2.4	2.2	
	Spawning Cycle	2.7	2.4	
	Sensitivity to Temperature	2.2	2.6	
	Sensitivity to Ocean Acidification	2.4	2.3	
	Population Growth Rate	2.2	1.8	
	Stock Size/Status	1.6	2.4	
	Other Stressors	1.9	1.2	
	Sensitivity Score	Moderate		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.3	3	
	Current NS	1.2	3	
	Current Speed	1.2	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.3	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.4	3	
	Surface Oxygen	4	3	
	Surface Salinity	1.5	3	
	Wind EW	1.1	3	
	Wind NS	1	3	
	Wind Speed	1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Black Sea Cucumber (*Holothuria atra*)

Overall Climate Vulnerability Rank: **[High].** (95% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[Moderate]**. Adult mobility is the only Sensitivity Attribute that scored above a 3.0 due to the limited home range of this species.

Distributional Vulnerability Rank: **[High].** Three attributes indicated moderate vulnerability to distribution shift: adult mobility, limited early life stage dispersal, and relatively high habitat specialization.

Data Quality: 67% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Holothuria atra, the most abundant [1] and most widely distributed of all commercially exploited holothuroids, are found all the way from the Red Sea and Madagascar in the west to Mexico and the Galápagos Islands in the east [2]. Asexual reproduction by fission is especially prevalent in shallow habitats for *H. atra* [1]. This form of reproduction is much more reliable in maintaining local populations, even when overexploited, than periodic spawning of gametes. Also, the populations in shallow water are frequently subjected to warm water and, therefore, have adapted to fluctuations in water temperature. However, spawning most often occurs in the warm season and fission in the cool season. Warming may have greater effect on asexual reproduction because fission is associated with relatively cool water. Therefore, it is ironic that the warming climate will likely directly affect the traits that make *H. atra* different from most other holothuroids and make it the most abundant holothuroid. Warm seawater will force *H. atra* into deeper water where it grows larger and relies more on reproduction by spawning.

Life History Synopsis**:**

Holothuria atra, *H. edulis*, and *Stichopus chloronotus* characteristically reproduce asexually by fission when in shallow water and tend to reproduce sexually by broadcast spawning in deeper waters where they grow larger. This may make them less susceptible to the Allee effect than most other holothuroid species because they can more reliably maintain local populations in greater abundance by asexual reproduction.

H. atra are widely distributed locally among habitats from the inner reef flats and lagoons to the forereef slopes, usually from 0 to 20 m depth, but occasionally down to 30 m. *H. atra* have been naturally exposed to high seawater temperatures at low tides on inner reef flats. At depth on the forereef slope, *H. atra* tend to grow larger and reproduce sexually. On the reef flats or other nearby inshore waters, this species is usually abundant, but individuals remain small and do not reproduce sexually even though their gonads may be mature. Harsh conditions are often found in shallow water in the shoreward edge of the reef flat, perhaps allowing preadaptation to widespread climate change.

H. atra are relatively resilient to overharvesting due to asexual reproduction by fission and not being a favored species to harvest for food. *H. atra* are commonly taken when other species are scarce, but seldom mentioned in articles discussing the various species of holothuroids taken for food [3]. In others they are categorized as having low commercial value [4]. Unfortunately, when other species are extirpated by overharvest, *H. atra* are then taken in abundance.

References

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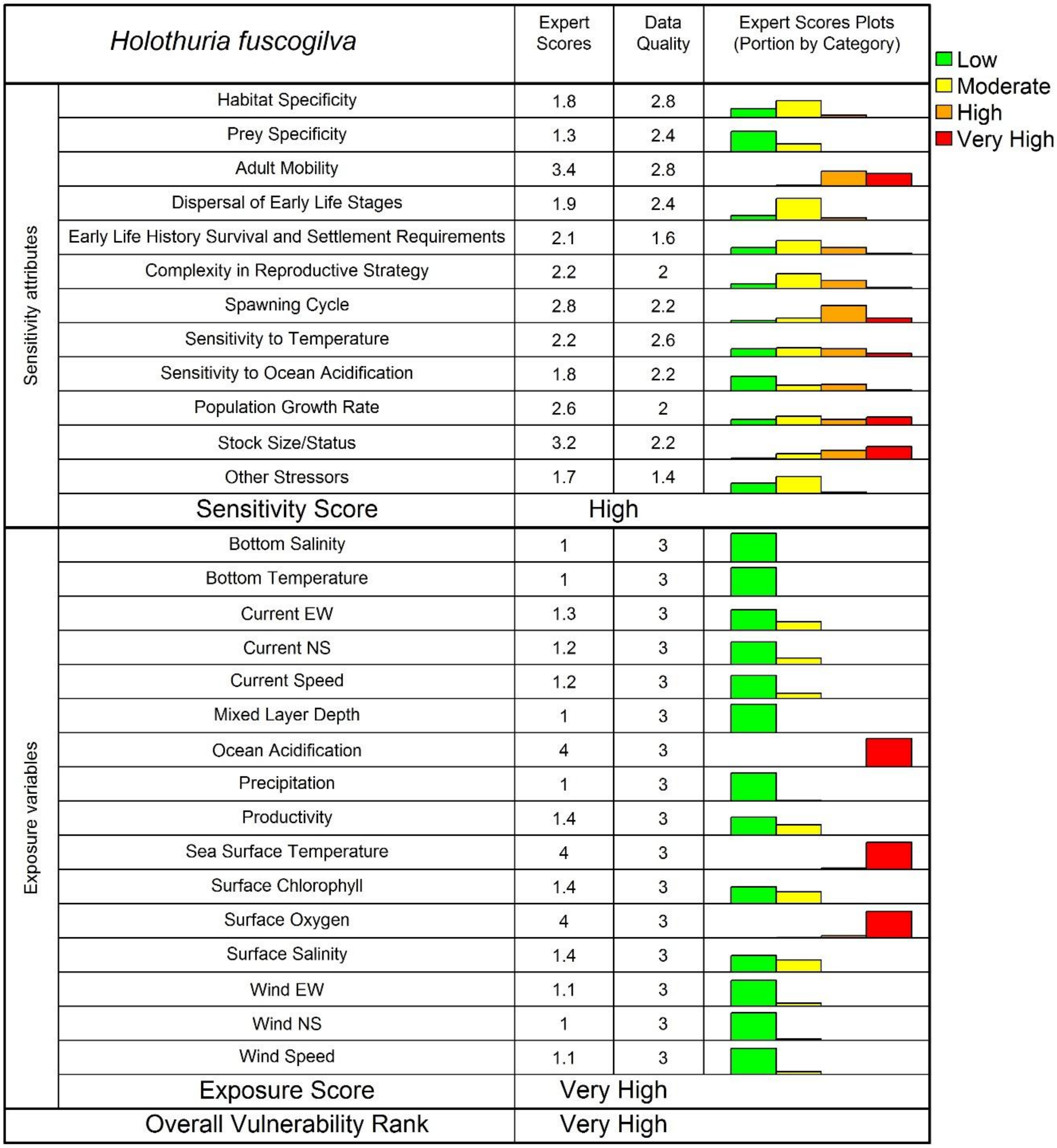
White teatfish - *Holothuria fuscogilva*

Overall Vulnerability Rank = Very High🟥

Biological Sensitivity = High🟧
Climate Exposure = Very High🟥
Data Quality = 93% of scores ≥ 2



	Holothuria fuscogilva	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	1.8	2.8	
	Prey Specificity	1.3	2.4	
	Adult Mobility	3.4	2.8	
	Dispersal of Early Life Stages	1.9	2.4	
	Early Life History Survival and Settlement Requirements	2.1	1.6	
	Complexity in Reproductive Strategy	2.2	2	
	Spawning Cycle	2.8	2.2	
	Sensitivity to Temperature	2.2	2.6	
	Sensitivity to Ocean Acidification	1.8	2.2	
	Population Growth Rate	2.6	2	
	Stock Size/Status	3.2	2.2	
	Other Stressors	1.7	1.4	
	Sensitivity Score	High		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.3	3	
	Current NS	1.2	3	
	Current Speed	1.2	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.4	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.4	3	
	Surface Oxygen	4	3	
	Surface Salinity	1.4	3	
	Wind EW	1.1	3	
	Wind NS	1	3	
	Wind Speed	1.1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		Very High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

White Teatfish (*Holothuria fuscogilva*)

Overall Climate Vulnerability Rank: **[Very High].** (88% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[High]**. Two sensitivity attributes scored above a 3.0: Adult Mobility (3.4) and Stock Size/Status (3.2).

Distributional Vulnerability Rank: **[High].** Three attributes indicated high vulnerability to distribution shift: limited early life stage dispersal, relatively high habitat specialization, and sensitivity to temperature. However, adult mobility was scored as low which may temper the propensity of the species to shift distribution.

Data Quality: 93% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Holothuria fuscogilva are remarkably widely distributed in the Pacific and Indian Oceans from the Red Sea and Madagascar in the west to Easter Island and Pitcairn Island in the east, with latitudes extending from 22°N (Hong Kong) to 31.5°S (Lord Howe Island). However, the IUCN report on endangered species notes that overharvesting of *H. fuscogilva* has severely fragmented populations and CITES [1] calculated from several studies that "For the species *Holothuria (Microthele) fuscogilva*, the density of its populations does not exceed 40 individuals per hectare", which is 0.004 per m^2 or one every 250 m^2 in the Indo-Pacific. *H. fuscogilva* are slow moving and potentially vulnerable to Allee effects which reduces the chance for successful fertilization during spawning if the population is too sparse to effectively aggregate for spawning. *H. fuscogilva* will be substantially more resilient to climate change if management allows populations to remain at densities that allow aggregations of at least 0.06–0.25 per m^2 that allow them to spawn within 2–4 m of each other for successful fertilization and population recovery 2-5].

Life History Synopsis**:**

H. fuscogilva, listed as Vulnerable in the IUCN Red List of threatened species[6], are especially vulnerable because of their reproductive biology. Compared to most other holothuroids, they have late sexual maturity, low fecundity, and spawn only once or twice a year [7,8]. However, the most serious detrimental trait is their low motility. Sessile marine animals need to be within 2–4 m of each other for successful fertilization [2-5]. Although holothuroids are motile, they are very slow and are thought not to travel large distances. *H. scabra* aggregate in aquaria for spawning in response to the lunar cycle [9]. This surely happens in the field under natural or unharvested conditions, but when populations of large holothuroids are harvested on or near coral reefs, they are reduced to densities of less than 0.004 per m^2 [1].

H. fuscogilva species are high-priced tropical benthic resources with an average price in Hong Kong of U.S.$ 192 kg^{-1} and with prices up to U.S.$ 274 kg^{-1} [10]. They have been overharvested throughout most of their range. The biology of holothuroids makes the economics of extractive harvest favor overharvesting or even liquidation. When harvested on a large scale, it takes decades for the population to recover (for documentation, refer to the discussion of *H. whitmaei*). The rates of recruitment are too irregular and the growth of holothuroids is too slow to sustain the overhead of the process of harvesting, transporting, and marketing. The average growth in interest of the capital gained by selling the holothurians is greater than the recruitment and growth of the holothurian population so economics favors liquidation of the resource (Anonymous 2000). Subsistence does not involve the major expenses of travel, transporting to market, or marketing. If the harvest of holothuroids is confined to subsistence, it might be possible to have a sustainable use of holothuroid resources.

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Black teatfish - *Holothuria whitmaei*

Overall Vulnerability Rank = Very High🟥

Biological Sensitivity = High🟧
Climate Exposure = Very High🟥
Data Quality = 89% of scores ≥ 2

Holothuria whitmaei		Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	1.7	2.6	
	Prey Specificity	1.1	2.4	
	Adult Mobility	3.5	2.8	
	Dispersal of Early Life Stages	1.8	2.6	
	Early Life History Survival and Settlement Requirements	2.1	1.6	
	Complexity in Reproductive Strategy	3.2	2	
	Spawning Cycle	2.6	2.4	
	Sensitivity to Temperature	2.5	2.8	
	Sensitivity to Ocean Acidification	2	2.4	
	Population Growth Rate	2.6	1.8	
	Stock Size/Status	3.4	2.2	
	Other Stressors	2	1.6	
	Sensitivity Score	High		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.2	3	
	Current NS	1.1	3	
	Current Speed	1.1	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.3	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.4	3	
	Surface Oxygen	3.9	3	
	Surface Salinity	1.6	3	
	Wind EW	1.1	3	
	Wind NS	1	3	
	Wind Speed	1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		Very High		

Black Teatfish (*Holothuria whitmaei*)

Overall Climate Vulnerability Rank: **[Very High].** (100% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[High]**. Three sensitivity attributes scored above a 3.0. These were: Adult Mobility (3.5), Complexity in Reproductive Strategy (3.2), and Stock Size/Status (3.4).

Distributional Vulnerability Rank: **[High].** Three attributes indicated moderate vulnerability to distribution shift: limited early life stage dispersal, and relatively high habitat specialization, and sensitivity to temperature. However, adult mobility was scored as low which may mitigate the propensity of the species to shift distribution.

Data Quality: 89% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Holothuria whitmaei are widely distributed in the tropical Pacific, with a range extending from western Australia to Hawaiʻi, south to Lord Howe Island 31.5°S, and as far east as Pitcairn and Easter islands. DNA studies found that populations of *H. whitmaei* on reefs in the Great Barrier Reef are interconnected and populations in western Australia and on reefs in the Coral Sea are possibly the sources of recruits [1,2]. This is remarkable considering the low motility of adults and the relatively short pelagic larval duration. Recent studies on the potential effects of climate change on fisheries species including holothuroids determined that, being a winter spawner, the reproductive success of black teatfish may be negatively affected by seawater warming. These effects will be evident first in areas nearer the equator [3,4].

Life History Synopsis**:**

Listed as Endangered on the IUCN Red List, *Holothuria whitmaei* [5] is one of the most commercially valuable holothuroid species (average price in Hong Kong is U.S.$ 180 kg^{-1}, maximum U.S.$ 230 kg^{-1} [6]) and has been overharvested throughout most of its range. A moratorium has been put on harvesting this species on the Great Barrier Reef as it was reduced there by 80%. There has not yet been any sign of recovery which has been predicted to take decades [7]. Likewise, harvesting *H. whitmaei* was banned in the Torres Strait in 2003, yet there are no signs of recovery to date. Records from 1922–1936 showed 30,743,460 holothuroids taken from Micronesia, especially from Chuuk. In 1988, eight sites around Chuuk were surveyed for holothuroids, but only two individuals of *H. whitmaei* (called *H. nobilis* in the records but now known to be separate species) were found [8], indicating no recovery for at least 42 years. Furthermore, a survey conducted in 2013 reported only a few individuals of *H. whitmaei* in Chuuk [9].

It is probably the reproductive biology of *H. whitmaei* that led to the species becoming Endangered. Compared to most other holothuroids, they mature slowly, have low fecundity, and spawn only once or twice a year [10]. However, the most serious detrimental trait is low motility. Sessile marine animals need to be within 2–4 m of each other for successful fertilization [11-14]. *H. scabra* have been found to aggregate in aquaria for spawning in response to the lunar cycle [15]. This surely happens in the field under natural or unharvested conditions, but when populations of large holothuroids are harvested on or near coral reefs, they are reduced to densities of less than 0.004 per m^2 [16]. Kinch et al. [17]

determined the population density of *H. whitmaei* in the Pacific to be no more than 12 individuals per hectare, or 0.0012 per m^2 or one individual per 833 m^2. Large benthic holothuroids can move but the distances required to find each other and aggregate from a population of 0.0012 individuals per m^2 are too great and holothuroids do not move fast enough to produce an aggregation to spawn effectively, i.e., "…due to reduction in population density caused by fishing, individuals may be unable to reproduce, the distance between males and females being too large" [16].

Growth rates of sea cucumbers are not well known, but a study of *H. whitmaei* shows slow growth and low overall productivity [7]. Aging of holothurians in the wild has not been possible, but modeling by Uthicke et al. [7] indicated that *H. whitmaei* are long-lived (potentially several decades), with low and sporadic recruitment. This is consistent with the slow rate of population recovery after overfishing.

The *H. whitmaei* species is an especially high-priced tropical benthic resource with slow recovery after having been overfished which thins the populations to densities that are insufficient for successful fertilization. *H. whitmaei* have been overharvested throughout most of their range [5]. As discussed for *H. fuscogilva*, the biology of holothuroids makes the economics of extractive harvest favor overharvesting or even liquidation. Large-scale harvesting results in populations requiring decades to recover. Since recruitment is variable and holothuroids have slow growth, overhead of harvesting, transporting, and marketing cannot be met; consequently, overexploitation of the resource is likely (Anonymous 2000). Confining the harvest of holothuroids to subsistence may lead to sustainable use of holothuroid resources as it does not involve the major expenses of travel, transporting, or marketing.

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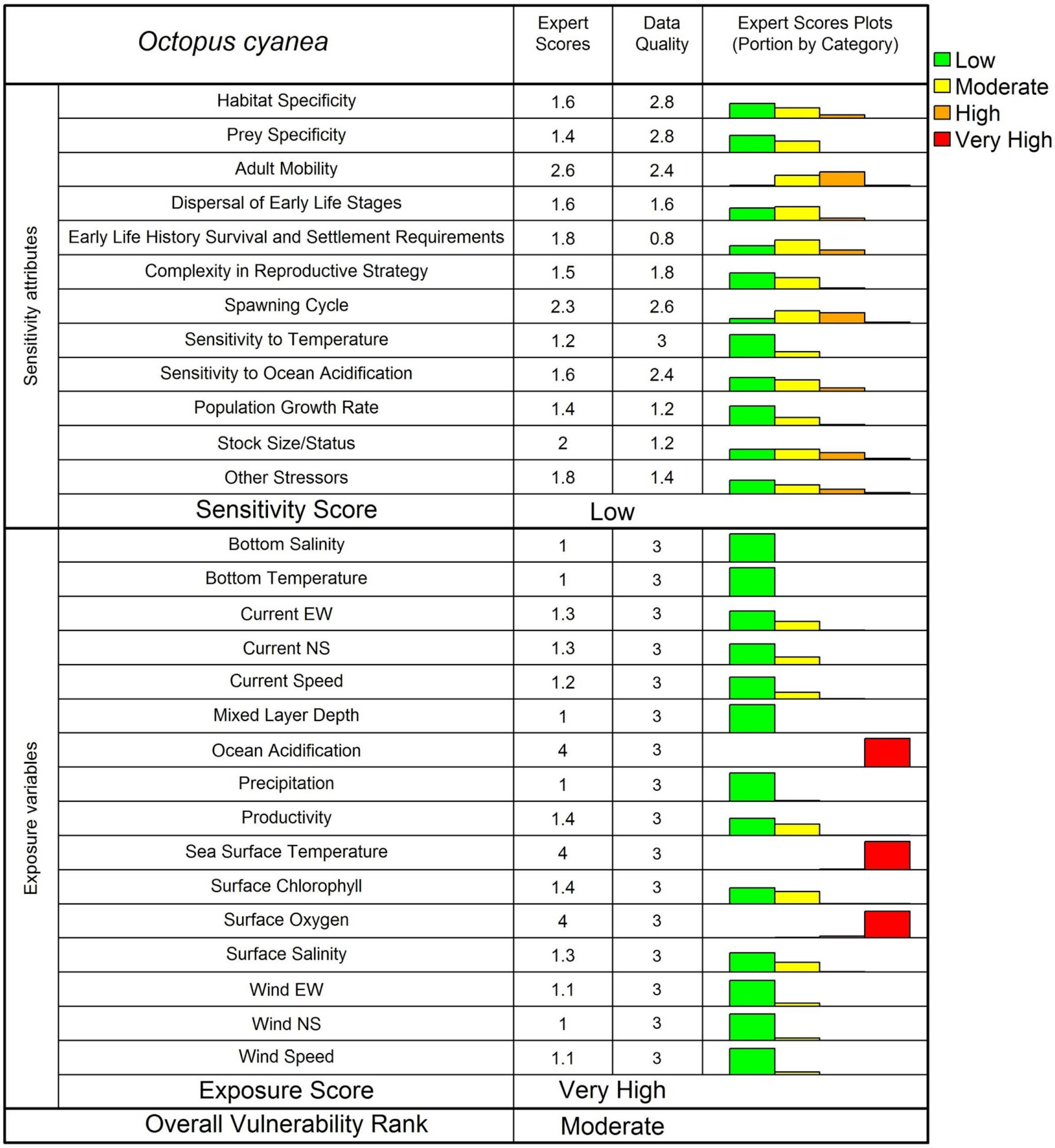
Blue octopus - *Octopus cyanea*

Overall Vulnerability Rank = Moderate 🟨

Biological Sensitivity = Low 🟩
Climate Exposure = Very High 🟥
Data Quality = 21% of scores ≥ 2



	Octopus cyanea	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	1.6	2.8	
	Prey Specificity	1.4	2.8	
	Adult Mobility	2.6	2.4	
	Dispersal of Early Life Stages	1.6	1.6	
	Early Life History Survival and Settlement Requirements	1.8	0.8	
	Complexity in Reproductive Strategy	1.5	1.8	
	Spawning Cycle	2.3	2.6	
	Sensitivity to Temperature	1.2	3	
	Sensitivity to Ocean Acidification	1.6	2.4	
	Population Growth Rate	1.4	1.2	
	Stock Size/Status	2	1.2	
	Other Stressors	1.8	1.4	
	Sensitivity Score	Low		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.3	3	
	Current NS	1.3	3	
	Current Speed	1.2	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.4	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.4	3	
	Surface Oxygen	4	3	
	Surface Salinity	1.3	3	
	Wind EW	1.1	3	
	Wind NS	1	3	
	Wind Speed	1.1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		Moderate		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Blue Octopus (*Octopus cyanea*)

Overall Climate Vulnerability Rank: **[Moderate].** (95% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[Low]**. No sensitivity attributes scored above a 3.0. The highest scores were for Adult Mobility (2.6) and Spawning Cycle (2.3).

Distributional Vulnerability Rank: **[High].** Three attributes indicated high vulnerability to distribution shift: adult mobility, limited early life stage dispersal, and relatively high habitat specialization.

Data Quality: 21% of the data quality scores were 2 or greater. Early Life History and Settlement Requirements was particularly data deficient (0.8)

Climate Effects on Abundance and Distribution:

The shallow-water benthic blue octopus (*Octopus cyanea*) are found in coral bedrock, live and dead coral heads, excavations in sand or rubble as well as in naturally occurring holes in rocks or dens [1,2]. They occur from eastern Africa to the Hawaiian Islands and can be found in a depth range of 0 to 150 m. *O. cyanea* are not migratory, typically stay near their shelter [1], and prefer temperatures ranging from 24.7 °C to 29.1 °C. Climate effects, specifically temperature, are expected to increase the rates of food intake, growth, and metabolism [3]. Additionally, low light intensity and elevated temperatures are thought to induce early spawning and thus short life-spans [3]. The blue octopus are not directly affected by ocean acidification and are not dependent on other species affected by ocean acidification since it consumes a variety of prey; although they inhabit live and dead coral heads [1,3].

Life History Synopsis**:**

In captivity, *Octopus cyanea* can spawn year round. Males may mate with several females, after which the suckers on the edge of his webbing expand in size over two or three months until he dies. Females deposit their eggs in a den and remain near them until they hatch, dying soon after [4]. After hatching, embryos enter the planktonic stage, however, the duration is not reported [5]. After developing into juveniles, *O. cyanea* rapidly form homes and defend against conspecifics [6]. Lifespan is reported to be around 12 to 15 months after settling from the planktonic larval state [4].

Adults primarily eat bivalves, gastropods, and xanthid crabs. They are considered to be an opportunistic predator and use tactile foraging methods. Blue octopus pounce to capture crabs and other prey items or hunt by using an interbranchial web to cover coral heads, rocks, or algae clumps. Then they explore the object with the tips of their arms [1,3]. *O. cyanea*'s growth curve is nearly exponential and they can convert prey into new growth with an efficiency greater than 50% [3].

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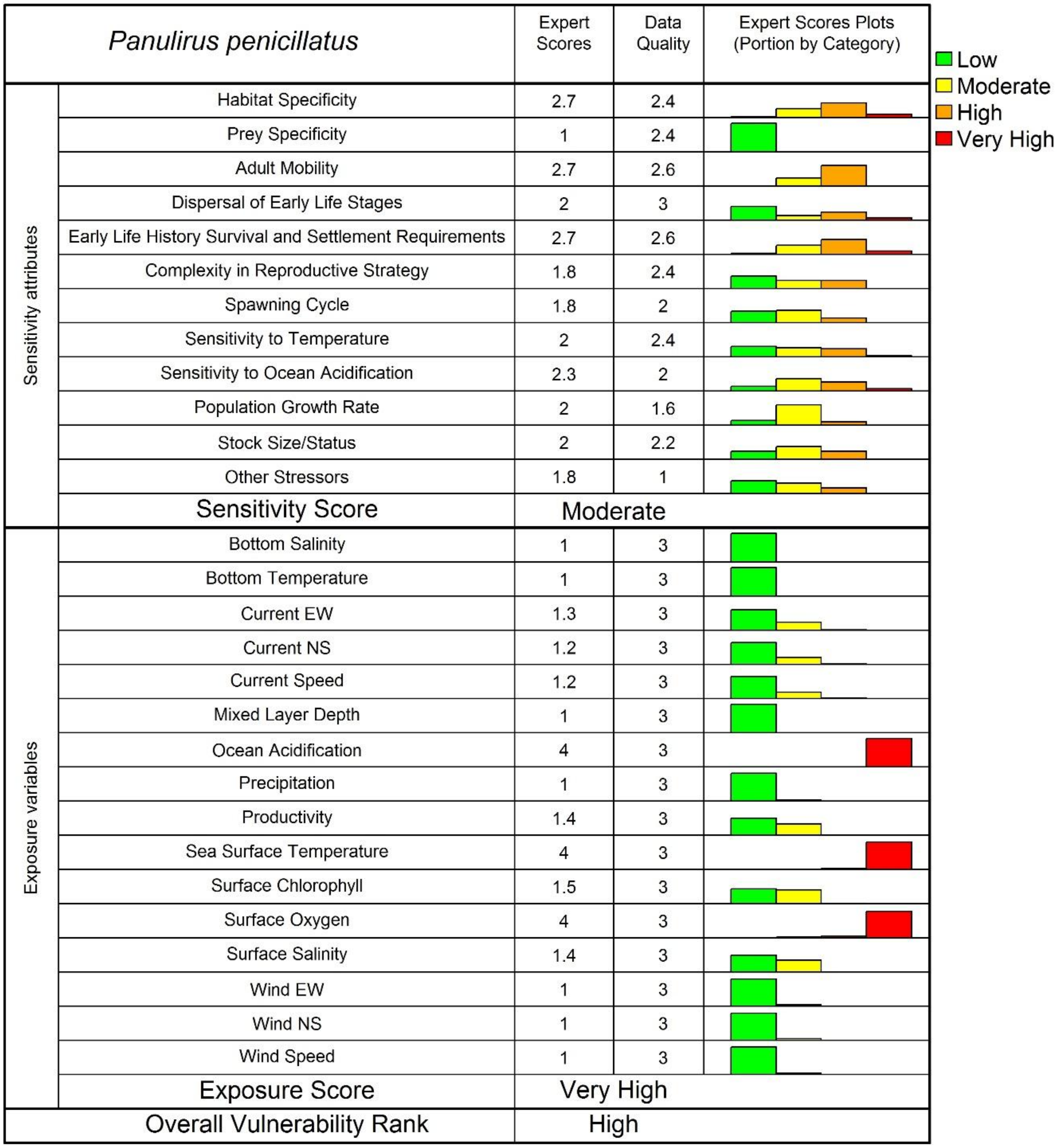
Spiny lobster - *Panulirus penicillatus*

Overall Vulnerability Rank = High 🟧

Biological Sensitivity = Moderate 🟨
Climate Exposure = Very High 🟥
Data Quality = 93% of scores ≥ 2



	Panulirus penicillatus	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	2.7	2.4	
	Prey Specificity	1	2.4	
	Adult Mobility	2.7	2.6	
	Dispersal of Early Life Stages	2	3	
	Early Life History Survival and Settlement Requirements	2.7	2.6	
	Complexity in Reproductive Strategy	1.8	2.4	
	Spawning Cycle	1.8	2	
	Sensitivity to Temperature	2	2.4	
	Sensitivity to Ocean Acidification	2.3	2	
	Population Growth Rate	2	1.6	
	Stock Size/Status	2	2.2	
	Other Stressors	1.8	1	
	Sensitivity Score	Moderate		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.3	3	
	Current NS	1.2	3	
	Current Speed	1.2	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.4	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.5	3	
	Surface Oxygen	4	3	
	Surface Salinity	1.4	3	
	Wind EW	1	3	
	Wind NS	1	3	
	Wind Speed	1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Spiny Lobster (*Panulirus penicillatus*)

Overall Climate Vulnerability Rank: **[High].** (98% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[Moderate]**. No sensitivity attributes scored above a 3.0. The highest scores were for Habitat Specificity (2.7), Adult Mobility (2.7) and Early Life History and Settlement Requirements (2.7).

Distributional Vulnerability Rank: **[Low].** All four attributes indicated low vulnerability to distribution shift: adult mobility, limited early life stage dispersal, relatively high habitat specialization, and sensitivity to temperature.

Data Quality: 93% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Panulirus penicillatus have a wide distribution that includes regions in the Indo-West Pacific and east Pacific, south of the Red Sea, South and East Africa, Madagascar, Indian Ocean, South China Sea, Japan, the Philippines, Indonesia Hawaiʻi, Samoa, Tuamotu Archipelago, northern and eastern Australia, the Galapagos, Revillagigedo Archipelagos, Cocos and Clipperton Islands, Sinaloa, Nayarit, Guerrero. Spiny lobster's preferred temperature ranges from 20.1 °C to 28.3 °C [1,2]. Spiny lobsters typically inhabit outer reef slopes, subtidal zones, or surge channels and can occur on small islands or near arid coasts. They are nocturnal and are found in depths of 1 to 4 m (maximum 16 m). *P. penicillatus* flourish in rough water habitats and those in the coral reef are usually found on the forereef or scoured shorelines in windward surf zones since they require clear, clean, and highly oxygenated water [1,3,4]. Adult range on average is less than 2 km [5].

P. penicillatus are common off the coasts of the U.S., Mexico, and Mozambique, while scarce in South Africa [4]. The population density is approximately 95 individuals per km in the tropical west Pacific [6]. Intense fishing pressure from commercial and subsistence fisheries appear to have reduced the lobster's abundance. Declines are localized and have not been studied across its entire range. The species is likely ecologically extinct on O'ahu, and stocks are depleted on the outer islands in Hawaiʻi (M. Iacchei, personal communication) [4,6-8].

Spiny lobsters have exoskeletons composed of carbohydrate chitin and consume crustose coralline algae to increase calcium which hardens into new shell after molting (M. Iacchei, personal communication). The role of calcium and dependence on crustose coralline algae as a food and calcium source is anticipated to make spiny lobster more sensitive to ocean acidification. Other potential stressors to *P. penicillatus* are not reported.

Life History Synopsis**:**

Spiny lobster females are reproductive year round, with peaks occurring in the summer months when temperatures increase [3,9,10]. Brood and pelagic duration last from 1 month to 7.5 months [11,12]. Larvae are relatively large and capable of dynamic movement. The phyllosoma and puerulus stages are active within the pelagic, with phyllosoma demonstrating diel vertical migration and horizontal movement. Additionally, pueruli exhibit rapid swimming, navigation to the coast, and habitat preferences. When larvae metamorphose into pueruli, they resemble a clear-colored baby lobster and are non-feeding. Their fast swimming ability allows them to cross the shelf, settle into adult habitat, and molt into the juvenile stage and begin feeding (M. Iacchei, personal communication).

Larvae can be found in the ocean, 4,000 km from the nearest adult habitat. The dynamic larval behavior indicates that the long planktonic larval duration may only rarely disperse larvae across the full species range. The "Johnson's model" of lobster larval dispersal suggests that the majority of phyllosoma and pueruli are retained locally in gyres or eddies near the coastline and recruitment is dependent on local production [13].

Larvae and adult spiny lobsters grow by molting. When they outgrow their current body and shed their current exoskeleton, they are soft tissued and, consequently, vulnerable for up to a week. During this period of vulnerability, they hide in shelters, eat crustose coralline algae to increase calcium to harden a new shell. Adults molt approximately once per year; the frequency decreases as the lobster gets older (M. Iacchei personal communication). Spiny Lobsters in the Galapagos have a von Bertalanffy growth coefficient (K), which indicates how fast maximum length is reached, of 0.264 and 0.201 yr^{-1} for females and males, respectively [14]. While the age of maturity for *P. penicillatus* is not known, other Palinurid lobsters reach sexual maturity by 3 to 4 years. Their maximum age ranges from 10 to 14 years [15]. Natural mortality (M) in the Marshall Islands was calculated as approximately 0.24 yr^{-1} [6].

Larvae likely feed on soft-bodied organisms such as appendicularians, salps, and cnidarians while in the open ocean for 9 months. Spiny lobster adults are omnivores, preferentially eating gastropods, bivalves, chitons, crustaceans, crustose coralline, and fleshy algae. It is thought that they will also move into the intertidal zone and consume echinometra urchins (M. Iacchei personal communication)[16,17]. Their predators consist of octopuses and jacks. At smaller sizes, their predators include other invertivores (M. Iacchei, personal communication).

A significant genetic structure was observed at multiple spatial scales throughout its range, from the Red Sea to the east Pacific Ocean. Population subdivisions frequently corresponded with provincial biogeographic boundaries, and a potential species-level disjunction occurred across the east Pacific Barrier. Some sites were highly isolated within broader regions of minimal genetic discontinuity [13].

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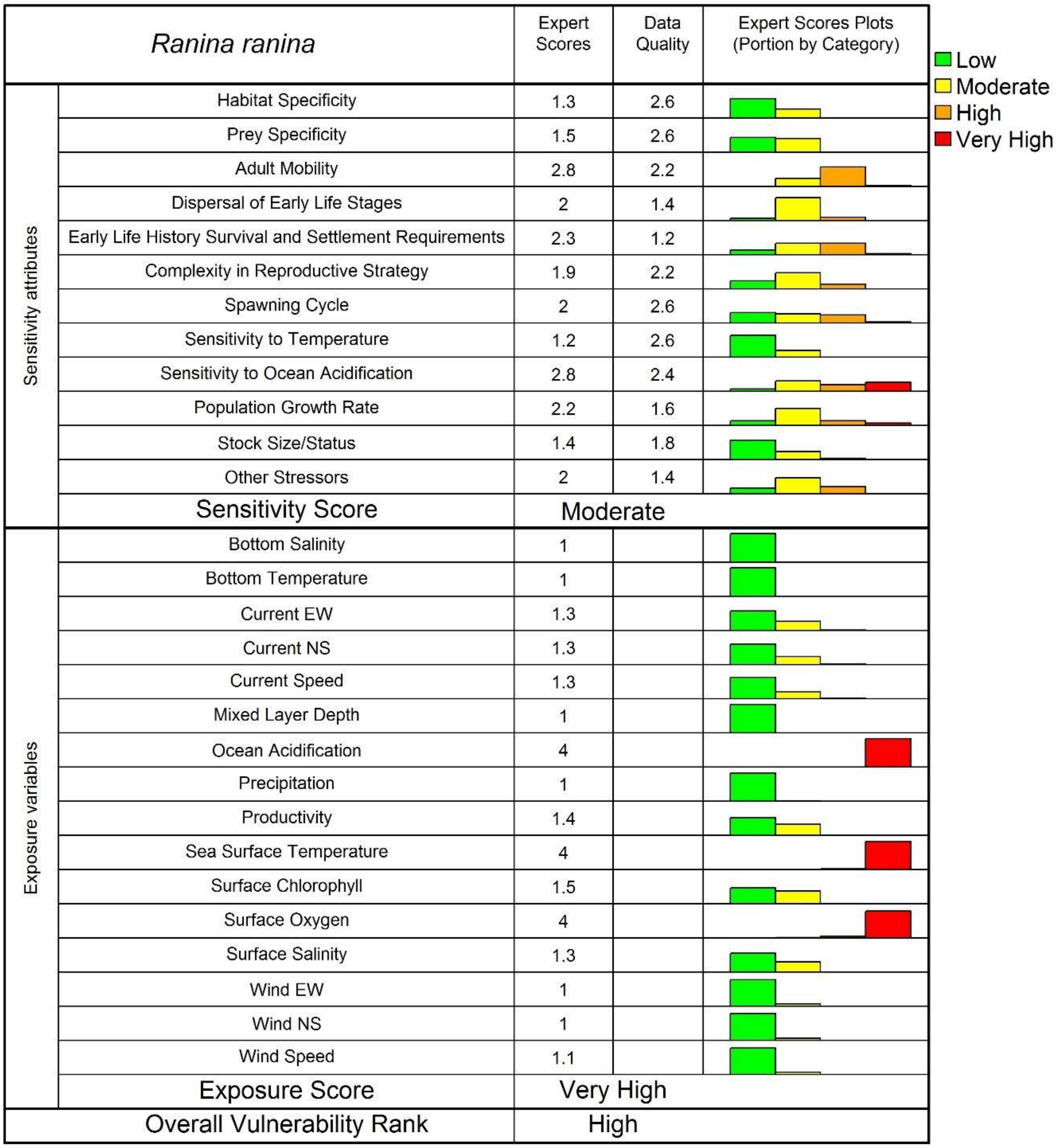
Kona crab - *Ranina ranina*

Overall Vulnerability Rank = High🟧

Biological Sensitivity = Moderate 🟨
Climate Exposure = Very High 🟥
Data Quality = 25% of scores ≥ 2



	Ranina ranina	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	1.3	2.6	
	Prey Specificity	1.5	2.6	
	Adult Mobility	2.8	2.2	
	Dispersal of Early Life Stages	2	1.4	
	Early Life History Survival and Settlement Requirements	2.3	1.2	
	Complexity in Reproductive Strategy	1.9	2.2	
	Spawning Cycle	2	2.6	
	Sensitivity to Temperature	1.2	2.6	
	Sensitivity to Ocean Acidification	2.8	2.4	
	Population Growth Rate	2.2	1.6	
	Stock Size/Status	1.4	1.8	
	Other Stressors	2	1.4	
	Sensitivity Score	Moderate		
Exposure variables	Bottom Salinity	1		
	Bottom Temperature	1		
	Current EW	1.3		
	Current NS	1.3		
	Current Speed	1.3		
	Mixed Layer Depth	1		
	Ocean Acidification	4		
	Precipitation	1		
	Productivity	1.4		
	Sea Surface Temperature	4		
	Surface Chlorophyll	1.5		
	Surface Oxygen	4		
	Surface Salinity	1.3		
	Wind EW	1		
	Wind NS	1		
	Wind Speed	1.1		
	Exposure Score	Very High		
Overall Vulnerability Rank		High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Kona Crab (*Ranina ranina*)

Overall Climate Vulnerability Rank: **[High].** (94% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[Moderate]**. No sensitivity attributes scored above a 3.0. The highest scores were for Adult Mobility (2.8) and Sensitivity to Ocean Acidification (2.8).

Distributional Vulnerability Rank: **[Moderate].** Three attributes indicated moderate vulnerability to distribution shift: adult mobility, limited early life stage dispersal, and relatively high habitat specialization. However, sensitivity to temperature was scored as low which may mitigate the propensity of the species to shift distribution.

Data Quality: 25% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Unusually high temperatures might affect the physiological condition of Kona crab (*Ranina ranina*) larvae. A study examined the temperature effects on larval development of *R. ranina* where zoeas were exposed to temperature treatments encompassing 17 to 33 °C. Survival decreased with decreasing temperature and the ideal temperature range for survival constricted at later developmental stages [1]. Time between molting events increased as temperature declined. Food consumption increased as development progressed; additionally, consumption increased at higher temperatures for instars I-V but reached its maximum at 25 °C during instar VII [1]. Kona crabs and a variety of soft shelled mollusks they feed on have an exoskeleton made of protein, chitin, and calcium which makes them sensitive to ocean acidification [2,3]. It was observed that when Kona crabs were exposed to elevated temperatures during early development, they had reduced growth and delay of morphogenesis, despite consuming a large amount of food [1].

Life History Synopsis**:**

Kona crabs are found in the Indo-Pacific ranging from East Africa, Japan, Australia, and Hawaiʻi. It is a reef-associated and tropical species [2]. Their preferred habitat is sand although they are also associated with coral reefs [2,4-6].

There are no reported habitat requirements reported for juvenile Kona Crab. Adult crabs tend to occupy the sublittoral zone at depths up to 200 m in open sand areas that are subject to strong currents, and adjacent to coral reefs [2,4-6]. Kona crabs are opportunistic scavengers that feed on a variety of worms and soft shelled mollusks. Kona crabs are moderately limited in mobility and spend the majority of time buried in the sand to avoid predators and emerge only to feed and mate [2,7,8].

In Hawaiʻi, females are ovigerous from May to September. Larger females to ovulate at least twice each season, with the primary effort going into the first ovulation [5,9]. Pelagic larval duration is not reported for this species in particular, but for the Samoan crab (*Scylla serrata*), experimental work by Nurdaini and Zeng [10] estimated a mean larval development time to the megalopa stage ranging from 20.6 to 22.6 days at 25 °C, shortened by several days at higher temperatures.

Kona crab has been commercially fished in Hawai‘i, Japan, the Philippines, the Seychelles, and more recently along the east coast of Australia. A study in Australia displayed a reduction in the amount of targeted large male crabs (110 to 119 mm carapace length) over a 2-year period at two sites [11]. Fishery-independent surveys in Australia displayed a Kona crab abundance that varied significantly by time period, location, and depth. Catches, in particular females, were reduced from October to December each year which aligned with spawning periods [11]. In Hawai‘i, an interdecadal decline in crab catch rate was observed for O'ahu but not for other islands [8].

Kona crabs are slow growers [12,13]. Males appeared to reach their maximum asymptotic size (L_{max}) at about 140 mm, whereas in females L_{max} may be greater than 110 mm [4]. Age at maturity is not reported for this species, but the Samoan crab becomes sexually mature within the first two years of life [14,15]. The carapace length where 50% of female Kona crabs were ovigerous during spawning season was 70–75 mm, and the mean length of ovigerous females was 86±8mm [5]. The von Bertalanffy growth coefficient (K), which indicates how fast maximum length is reached, was estimated to be 0.29 yr^{-1} for females and 0.23 yr^{-1} for males [13].

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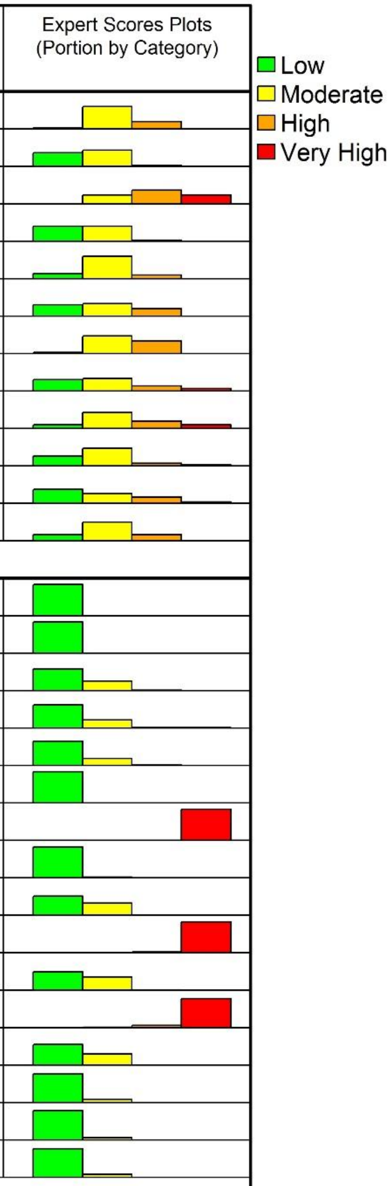
Samoan crab - *Scylla serrata*

Overall Vulnerability Rank = Moderate🟨

Biological Sensitivity = Low🟩
Climate Exposure = Very High🟥
Data Quality = 89% of scores ≥ 2

	Scylla serrata	Expert Scores	Data Quality
Sensitivity attributes	Habitat Specificity	2.2	2.8
	Prey Specificity	1.6	2.6
	Adult Mobility	3	2.4
	Dispersal of Early Life Stages	1.6	2.8
	Early Life History Survival and Settlement Requirements	2	2.2
	Complexity in Reproductive Strategy	1.9	2.4
	Spawning Cycle	2.4	2.6
	Sensitivity to Temperature	2	2.4
	Sensitivity to Ocean Acidification	2.4	2.4
	Population Growth Rate	1.8	1.6
	Stock Size/Status	1.8	1.4
	Other Stressors	2	1.6
	Sensitivity Score	Low	
Exposure variables	Bottom Salinity	1	3
	Bottom Temperature	1	3
	Current EW	1.3	3
	Current NS	1.3	3
	Current Speed	1.2	3
	Mixed Layer Depth	1	3
	Ocean Acidification	4	3
	Precipitation	1	3
	Productivity	1.4	3
	Sea Surface Temperature	4	3
	Surface Chlorophyll	1.4	3
	Surface Oxygen	4	3
	Surface Salinity	1.3	3
	Wind EW	1.1	3
	Wind NS	1	3
	Wind Speed	1.1	3
	Exposure Score	Very High	
Overall Vulnerability Rank		Moderate	



Samoan Crab (*Scylla serrata*)

Overall Climate Vulnerability Rank: **[Moderate].** (74% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[Low]**. No sensitivity attributes scored above a 3.0. The highest scores were for Spawning Cycle (2.4) and Sensitivity to Ocean Acidification (2.4).

Distributional Vulnerability Rank: **[Moderate].** All four attributes indicated moderate vulnerability to distribution shift: adult mobility, limited early life stage dispersal, relatively high habitat specialization, and sensitivity to temperature.

Data Quality: 89% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Scylla serrata, also known as Samoan crab, is native to the Indo-Pacific but was introduced to areas such as Florida and Hawaiʻi (34°N to 37°S, 22°E to 134°W). It occurs in temperatures ranging from 20 °C to 30 °C and in depths ranging from 0 to 70 m [1-3]. *S. serrata* digs burrows in mangroves or in soft substrate in the shallow and intertidal waters [2]. They are expected to be affected by ocean acidification since their exoskeleton is composed of calcium and their diet consists of molluscs and crustaceans, which rely on calcium as well [4]. Other environmental stressors are not reported for this species.

Life History Synopsis**:**

S. serrata males initiate copulation when the female is about to molt [1]. The male delivers non-motile spermatozoa into the female, which she retains for several weeks to months before they fertilize her eggs [5]. Females bear egg masses on their pleopods and migrate offshore where millions of eggs will hatch. *S. serrata* have an extended larval duration, with the megalopa stage lasting approximately 21 days at 25 °C [5-8]. It is thought that the elongated larval period allows for greater dispersal to populations throughout the Indo-Pacific, including Japan, Indonesia, the Red Sea, the Philippines, and East and South Africa [6,9]. Juvenile crabs are usually found in the upper intertidal area and adults occur in the subtidal [1]. Differences in habitat use based on life stage may be a mechanism for smaller individuals to avoid cannibalism from larger conspecifics [1]. Samoan crabs become sexually mature in the first two years of life [10,11]. Samoan crabs can grow up to 3.5 kg and have a shell width of 24 cm. Berried females are typically found from November to April with more found in December and February [12].

Larvae survive at salinities higher than 20‰ which corresponds with the migration of egg-bearing females to offshore waters. At 15‰, larval mortality was 100% [8]. Adults are euryhaline and are able to persist in high and low salinities [13]. Adults are also eurythermal, with larvae having a slightly narrower thermal tolerance. Adults were successfully raised at 25 °C to 36 °C while larvae experienced mortality at temperatures above 25 °C [14,15] Samoan crabs forage during the night and feed on small invertebrates as well as shrimps, crabs, fishes, and bivalves [4].

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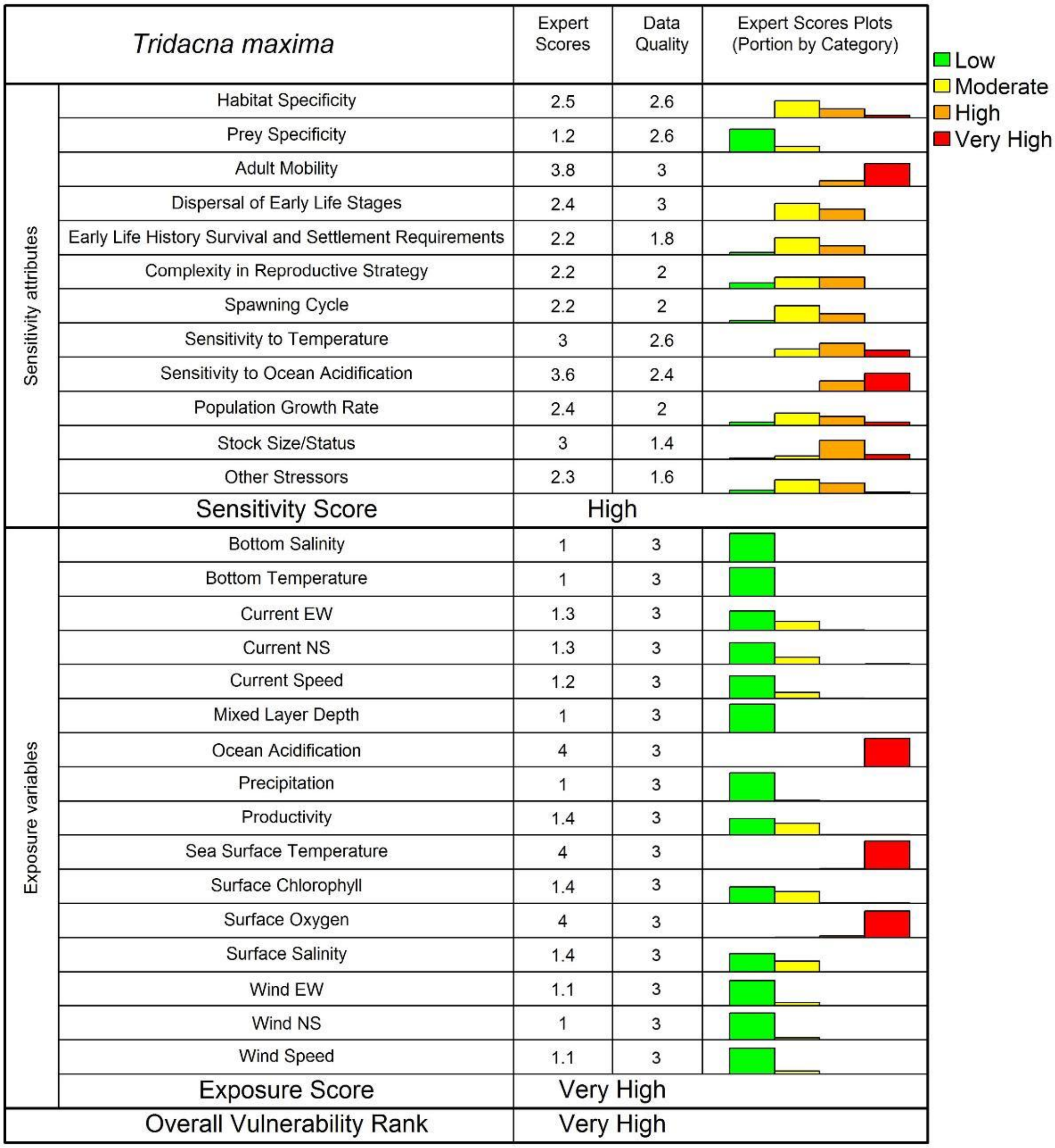
Maxima clam - *Tridacna maxima*

Overall Vulnerability Rank = Very High 🟥

Biological Sensitivity = High 🟧
Climate Exposure = Very High 🟥
Data Quality = 32% of scores ≥ 2



Tridacna maxima		Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	2.5	2.6	
	Prey Specificity	1.2	2.6	
	Adult Mobility	3.8	3	
	Dispersal of Early Life Stages	2.4	3	
	Early Life History Survival and Settlement Requirements	2.2	1.8	
	Complexity in Reproductive Strategy	2.2	2	
	Spawning Cycle	2.2	2	
	Sensitivity to Temperature	3	2.6	
	Sensitivity to Ocean Acidification	3.6	2.4	
	Population Growth Rate	2.4	2	
	Stock Size/Status	3	1.4	
	Other Stressors	2.3	1.6	
	Sensitivity Score	High		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.3	3	
	Current NS	1.3	3	
	Current Speed	1.2	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.4	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.4	3	
	Surface Oxygen	4	3	
	Surface Salinity	1.4	3	
	Wind EW	1.1	3	
	Wind NS	1	3	
	Wind Speed	1.1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		Very High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Maxima Clam (*Tridacna maxima*)

Overall Climate Vulnerability Rank: **[Very High].** (100% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[High]**. Two sensitivity attributes scored above a 3.0: Adult Mobility (3.8) and Sensitivity to Ocean Acidification (3.6).

Distributional Vulnerability Rank: **[Moderate].** Three attributes indicated moderate vulnerability to distribution shift: limited early life stage dispersal, high habitat specialization, and sensitivity to temperature. However, adult mobility was scored as low which may mitigate the propensity of the species to shift distribution.

Data Quality: 32% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Maxima clams (*Tridacna* maxima) are found in the tropics (28°N to 37°S, 31°E to 128°W) in temperatures ranging from 23 °C to 30 °C [1]. *T. maxima* is found in the coral reef flats of shallow areas, reef areas of lagoons, and in the intertidal region. They are sometimes found on the surface of the reef or sand, sometimes embedded in the coral. They typically occur in well-lit areas since they have a symbiotic relationship with photosynthetic organisms [2,3]. Depth ranges from 0 to 20 m [4]. Wild stocks are depleted and certain populations in Southeast Asia and South Pacific are locally extirpated [5]. *T. maxima* has a calcium carbonate shell which makes them sensitive to ocean acidification.

Life History Synopsis**:**

Maxima Clams in Anae Island, Guam, are most likely spawn in November to March and peak in February. Spawning also occurs in August and September. Reproduction is stimulated by the lunar cycle, time of day, and presence of other gametes in the water. Additionally, elevated temperature may be a factor which induces spawning [6,7]. Larval dispersal along present-day ocean surface currents cannot be assumed since other mechanisms may be the cause of the dispersal [8]. Within 12 hours of fertilization, embryos develop into trochophore larvae and are able to filter feed [6]. The trochophore larvae then develop into bivalve veligers [7,9]. At the final larval stage, a foot develops and allows the larva to swim and rest on substrate [6]. Veligers metamorphose to juveniles, which in one study occurred 11 days post fertilization [7,9]. After metamorphosis, juveniles become more sedentary and acquire zooxanthellae (*Symbiodinium microadriaticum*), from which they receive nutrition. Nutrient uptake of dissolved matter also occurs through their epidermis [6,10]. Sessile adults can be found attached to rocks or dead coral [6,7,9]. *T. maxima* siphons water through its body to filter for phytoplankton and extract oxygen with its gills [6].

Veliger shell growth rate and shell growth rate after settlement until day 40 are low, after which growth rate increases to 6.8 μm/day. The sharp increase in growth rate corresponds to when juveniles acquire their zooxanthellae [7]. Juveniles mature into males after 2 or 3 years and become hermaphroditic at around 15 cm in length [1,7]. The von Bertalanffy growth coefficient, which indicates how fast maximum length is reached, is approximately 0.1 yr^{-1} and asymptotic mean size is estimated at 27–30 cm [11,12].

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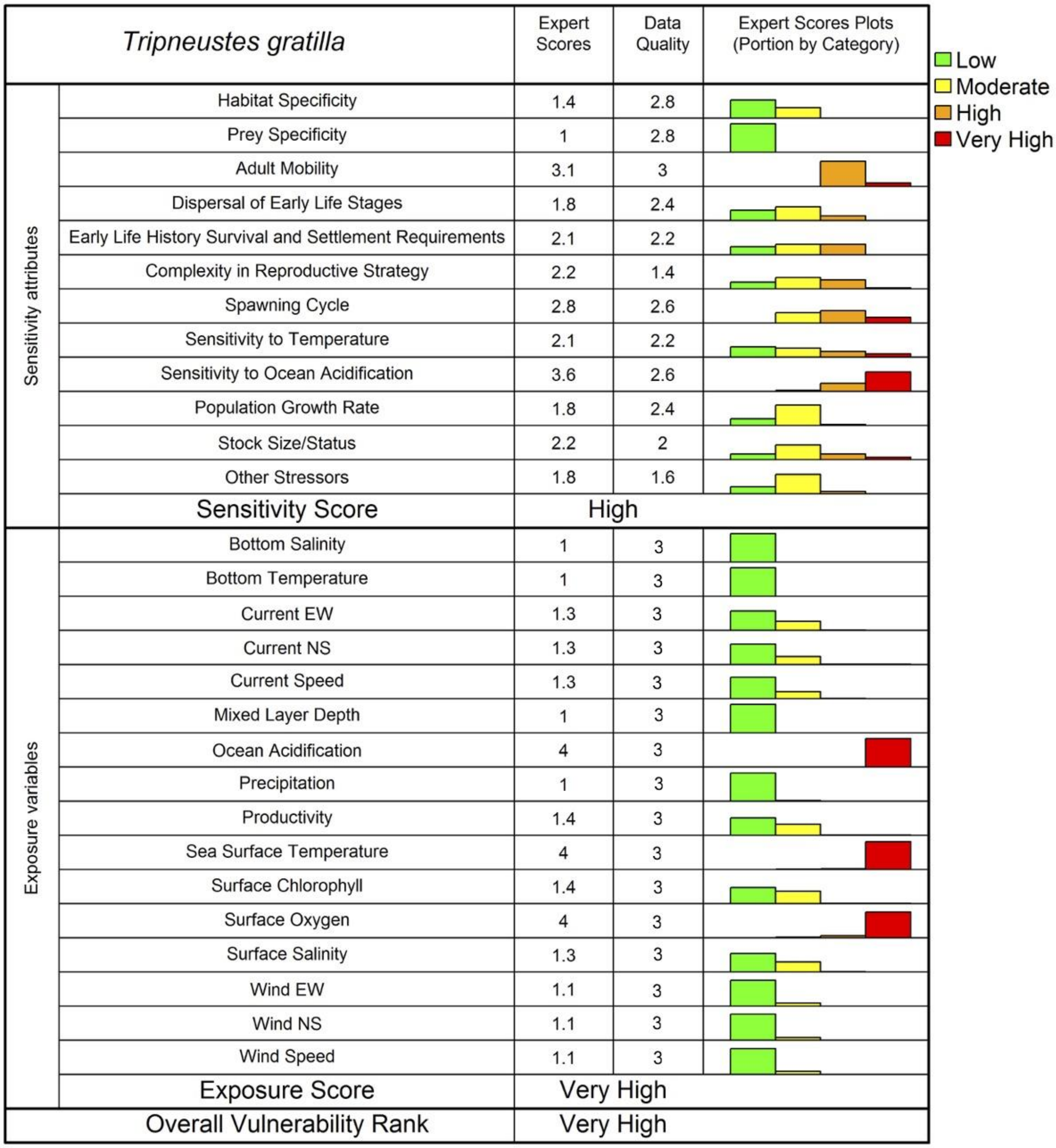
Collector urchin - *Tripneustes gratilla*

Overall Vulnerability Rank = Very High 🟥

Biological Sensitivity = High 🟧
Climate Exposure = Very High 🟥
Data Quality = 36% of scores ≥ 2



	Tripneustes gratilla	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	1.4	2.8	
	Prey Specificity	1	2.8	
	Adult Mobility	3.1	3	
	Dispersal of Early Life Stages	1.8	2.4	
	Early Life History Survival and Settlement Requirements	2.1	2.2	
	Complexity in Reproductive Strategy	2.2	1.4	
	Spawning Cycle	2.8	2.6	
	Sensitivity to Temperature	2.1	2.2	
	Sensitivity to Ocean Acidification	3.6	2.6	
	Population Growth Rate	1.8	2.4	
	Stock Size/Status	2.2	2	
	Other Stressors	1.8	1.6	
	Sensitivity Score	High		
Exposure variables	Bottom Salinity	1	3	
	Bottom Temperature	1	3	
	Current EW	1.3	3	
	Current NS	1.3	3	
	Current Speed	1.3	3	
	Mixed Layer Depth	1	3	
	Ocean Acidification	4	3	
	Precipitation	1	3	
	Productivity	1.4	3	
	Sea Surface Temperature	4	3	
	Surface Chlorophyll	1.4	3	
	Surface Oxygen	4	3	
	Surface Salinity	1.3	3	
	Wind EW	1.1	3	
	Wind NS	1.1	3	
	Wind Speed	1.1	3	
	Exposure Score	Very High		
Overall Vulnerability Rank		Very High		

🟩 Low
🟨 Moderate
🟧 High
🟥 Very High

Collector Urchin (*Tripneustes gratilla*)

Overall Climate Vulnerability Rank: **[Very High].** (100% certainty from bootstrap analysis).

Climate Exposure: **[Very High].** Three exposure factors contributed to this score: Ocean Acidification (4.0), Sea Surface Temperature (4.0), and Ocean Oxygen (4.0). Exposure to all three factors occurs during all life stages.

Biological Sensitivity: **[High]**. Two sensitivity attributes scored above a 3.0; Adult Mobility (3.1) and Sensitivity to Ocean Acidification (3.6).

Distributional Vulnerability Rank: **[High].** Three attributes indicated high vulnerability to distribution shift: limited early life stage dispersal, high habitat specialization, and sensitivity to temperature. However, adult mobility was scored as low which may mitigate the propensity of the species to shift distribution.

Data Quality: 36% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

Tripneustes gratilla has a remarkably large geographic range, extending from east Africa to western America. It was formerly thought that the 5,000 km distance across very deep water between the central and eastern Pacific that caused the greatest separation within other genera of urchins also led to a separation between *T. gratilla* and *T. depressus*, but genetic analysis determined that they are a single species, *T. gratilla,* throughout the Indo-Pacific and eastern Pacific [1]. *T. ventricosus* occurs throughout the tropical Atlantic from Central America to Africa. The high fecundity and dispersal of *T. gratilla* keep little genetic structure from Africa to western America. This, along with the acceptance of *T. gratilla* of several habitats, a large depth range, and broad diet as a generalist herbivore and detritus feeder, suggest it is potentially less affected by climate change than most other invertebrates. Although embryonic development from egg through early larval stages is normal between 22 °C and 29 °C [2], seawater warming above 29 °C might possibly have negative effects.

Life History Synopsis**:**

Intuitively, it would seem that echinoderms such as *Tripneustes gratilla* would be especially vulnerable to low pH because the basic frameworks of both adult and larval urchins are made of $CaCO_3$ which could dissolve at low pH. However, research has indicated that for urchins previously studied, about 150 genes are involved in upregulating calcium transport. These genes are activated in low pH conditions [3]. These genes were found in urchins but not in corals suggesting that urchins are possibly better able to function normally at low pH than corals. In fact, the echinoids were diverse in the Cretaceous and early Cenozoic Periods when the ocean pH was as low as 7.4–7.6 [4-6]. Although scleractinian corals were also diverse and common in the Cretaceous, they left fossil calices, but did not build reefs as extensively as they do now.

Laboratory experiments with echinoid larvae at low pH also showed that larval morphology was not changed in form and larval survival was not affected until the pH was below 7.0 [7]. The pH of the oceans will never go below 7.4–7.6 so it is unlikely that direct effects of low pH on larval *T. gratilla* will ever occur. However, the larvae raised at low pH with normal temperatures grew more slowly [8]. Although their survival in laboratory experiments was not directly affected, growing slower or smaller in nature extends the especially vulnerable stages of larval lives at lower sizes, which likely increases risk of predation. On the other hand, increased CO_2 tends to lead to warmer seawater as it leads to lower pH, and the larvae tend to grow faster in warmer temperatures. Laboratory experiments demonstrated that the effects of lower pH and concomitantly warmer waters on speed of larval growth tend to cancel each other [8]. However, it is possible that early embryonic and larval development might be adversely affected when the water temperature goes above 29 °C.

Adult *T. gratilla* may be more resilient in a changing climate than many invertebrates because of their broad niche requirements. *T. gratilla* live in a variety of habitats; their depth distribution is to at least 75 m [9], and they are generalist herbivores and deposit feeders. This species has moderate motility and can travel hundreds of meters [10] which potentially allows it to continue to gather to reproduce effectively at relatively low abundances, unlike sessile or slow-moving animals such as holothuroids.

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