# Pacific Islands Vulnerability Assessment
# Pelagic Species Narrative

Gabriella N.M. Mukai[1,2], Donald R. Kobayashi[3], Charles Birkeland[2], Johanna Wren[3], Jonatha Giddens[1,4], and Mark Nelson[5]

Pacific Islands Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration

1. Joint Institute for Marine and Atmospheric Research, University of Hawaiʻi at Mānoa
2. School of Life Sciences, University of Hawaiʻi at Mānoa
3. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Pacific Islands Fisheries Science Center
4. National Geographic Society Exploration Technology Lab
5. National Oceanic and Atmospheric Administration, Office of Science and Technology

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 unpublished).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 pelagic 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 Pelagic Species Narrative is accompanied by the Pelagic Species Profile, which provides further information on each biological sensitivity attribute for each species. The Pelagic 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 result of climate change. The inclusion of climate exposure variables followed 4 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 3 or more attributes with a mean ≥ 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, 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 et al. 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**

## Wahoo - *Acanthocybium solandri*

Overall Vulnerability Rank = Moderate

Biological Sensitivity = Low
Climate Exposure = Very High
Data Quality = 86% of scores ≥ 2

| | *Acanthocybium solandri* | Expert Scores | Data Quality | Expert Scores Plots (Portion by Category) |
|---|---|---|---|---|
| Sensitivity attributes | Habitat Specificity | 1.5 | 2.8 | |
| | Prey Specificity | 1.3 | 2.8 | |
| | Adult Mobility | 1.4 | 2.8 | |
| | Dispersal of Early Life Stages | 1.5 | 1.4 | |
| | Early Life History Survival and Settlement Requirements | 2 | 1.4 | |
| | Complexity in Reproductive Strategy | 1.6 | 1.8 | |
| | Spawning Cycle | 1.6 | 2.4 | |
| | Sensitivity to Temperature | 1.8 | 2.4 | |
| | Sensitivity to Ocean Acidification | 1.3 | 2 | |
| | Population Growth Rate | 1.2 | 2 | |
| | Stock Size/Status | 1.2 | 2.6 | |
| | Other Stressors | 1.5 | 1.6 | |
| | Sensitivity Score | Low | | |
| Exposure variables | Bottom Salinity | 1 | 3 | |
| | Bottom Temperature | 1 | 3 | |
| | Current EW | 1.3 | 3 | |
| | Current NS | 1.2 | 3 | |
| | Current Speed | 1.3 | 3 | |
| | Mixed Layer Depth | 1.3 | 3 | |
| | Ocean Acidification | 4 | 3 | |
| | Precipitation | 1 | 3 | |
| | Productivity | 1.4 | 3 | |
| | Sea Surface Temperature | 3.8 | 3 | |
| | Surface Chlorophyll | 1.4 | 3 | |
| | Surface Oxygen | 3.6 | 3 | |
| | Surface Salinity | 1.5 | 3 | |
| | Wind EW | 1.1 | 3 | |
| | Wind NS | 1.1 | 3 | |
| | Wind Speed | 1.1 | 3 | |
| | Exposure Score | Very High | | |
| Overall Vulnerability Rank | | Moderate | | |

Low
Moderate
High
Very High

**Wahoo (*Acanthocybium solandri*)**

<u>Overall Climate Vulnerability Rank</u>: **[Moderate].** (78% certainty from bootstrap analysis).

<u>Climate Exposure</u>: **[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.

<u>Biological Sensitivity</u>: **[Low]**. No sensitivity attributes scored above a 3.0. The highest scores were for Early Life History and Settlement Requirements (2.0) and Sensitivity to Temperature (1.8).

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

<u>Data Quality</u>: 86% of the data quality scores were 2 or greater.

<u>Climate Effects on Abundance and Distribution</u>:

*Acanthocybium solandri* larvae and juveniles are typically found in tropical waters while adults tend to have wider geographic distribution[1]. Adults are considered an oceanic, epipelagic species and are found on average at depths of 20 m, although they can reach depths greater than 250 m [2]. Like other pelagic fish, they may make vertical migrations throughout the day. A study monitoring four wahoo showed that they tend to occur in shallower waters at night (approximately 30 m) and deeper waters during the day (approximately 50 m) [3]. Another study, however, showed that wahoo were at very similar depths (20 m) during the night and day [2]. Wahoo are exposed to temperatures ranging from 11 °C to 28 °C [2]. Wahoo are highly mobile as adults and occur in the Atlantic, Indian, and Pacific Oceans, encompassing tropical and subtropical waters (46° N to 37° S, 180° W to 180° E). Additionally, they are found in northern Baja to Loreto in the Gulf of California, northern Peru, and all of the oceanic islands. They have been seen as far south as 45° S in the southern Atlantic [4]. Wahoo have high genetic connectivity globally.

Adult wahoo are likely to be less sensitive to ocean acidification in regard to prey choice since they prey upon animals that do not have calcium carbonate exoskeletons or shells. However, further research is needed to fully understand the impact of ocean acidification on adult wahoo physiology [5,6]. Wahoo larvae may be susceptible to ocean acidification, but more investigation is warranted to understand its full effect on the species [7,8]. Increased sea surface temperatures and decreased oxygen availability may affect their habitat [9]. Currently, there is no evidence of *A. solandri* being affected by fishing, although local depletions may have occurred [4].

<u>Life History Synopsis</u>**:**

While adults are usually solitary, they will gather to spawn. Females are considered multiple batch spawners, spawning every 2 to 6 days; as much as 20 to 60 times in one season[4,10-12]. Spawning season lasts from at least the spring through autumn which indicates that temperature might be cue for spawning [10-12]. Eggs are found in the pelagic and may drift with the prevailing currents. The planktonic duration is not reported. The main predators of wahoo during their early life history are sharks.

Wahoo display different preferences in prey type at different sizes. In the Gulf of Mexico, smaller wahoo (849–1,160 mm) had greater prey diversity than large wahoo and primarily preyed on exocoetids and carangids [13]. Large wahoo (1,461–1,773 mm) primarily feed on *C. cyrsos, C. hippurus*, and scombrids [13]. Wahoo are listed as Least Concern by the IUCN and are considered stable because of their rapid growth rate and reproductive potential. Catch for wahoo has been increasing over the past two decades [4,14]. Wahoo have a von Bertalanffy growth coefficient of 1.58 $yr^{-1}$ [15]. They reach sexual maturity by their first year and live for 5 to 6 years, maximum 9 years [4,10-10]. The generation length is approximately 3 to 5 years.

**References**


1. Western Pacific Regional Fishery Management Council. 2005. Pelagic fisheries ecosystem plan for Pacific pelagic fisheries of the Western Pacific region.

2. Sepulveda C, Aalbers S, Ortega-Garcia S, Wegner N, Bernal D. 2011. Depth distribution and temperature preferences of wahoo (Acanthocybium solandri) off Baja California Sur, Mexico. Mar Biol. 158:917–926.

3. Theisen TC, Baldwin JD. 2012. Movements and depth/temperature distribution of the ectothermic Scombrid, *Acanthocybium solandri* (wahoo), in the western North Atlantic. Mar Biol. 159: 2249-2258.

4. Collette B, Acero A, Amorim AF, Boustany A, Canales Ramirez C, Cardenas G, Carpenter KE, de Oliveira Jr L, Di Natale A. et al. 2011. Acanthocybium solandri [cited 2017 April 9]. Database: The IUCN Red List of Threatened Species [Internet]. Available from: http://dx.doi.org/10.2305/IUCN.UK.2011-2.RLTS.T170331A6750961.en.

5. Cattano C, Claudet J, Domenici P, Milazzo M. 2018. Living in a high $CO_2$ world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. Ecol Monogr. 88: 320-335.

6. Heuer RM, Grosell M. 2014. Physiological impacts of elevated carbon dioxide and ocean acidification on fish. Am J Physiol Regul Integr Comp Physiol. 307: R1061-R1084.

7. Frommel AY, Margulies D, Wexler JB, Stein MS, Scholey VP, Williamson JE, Bromhead D, Nicol S, Havenhand JN. 2016. Ocean acidification has lethal and sub-lethal effects on larval development of yellowfin tuna, *Thunnas albacares*. J Exper Mar Biol Ecol. 482: 18-24.

8. Stiasny MH, Mittermayer FH, Sswat M, Voss R, Jutfelt F, Chierici M, Puvanendran V, Mortensen A, Reusch TBH, Clemmensen C. 2016. . Ocean acidification effects on Atlantic Cod larval survival and recruitment to the fished population. PlosOne. 11(8): e0155448.

9. Asch R, Cheung W, Reygondeau G. 2018. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. Mar Pol. 88: 285–294.

10. Jenkins KLM, McBride RS. 2009. Reproductive biology of wahoo, Acanthocybium solandri, from the Atlantic coast of Florida and the Bahamas. Mar Freshw Res. 60(9):893–897.

11. Melo ACM, Lessa RPT, Santana FMS. 2011. Determinacao da idade e crescimento da cavala-empinge (Acanthocybium solandri) na regiao do Archipelago de Sao Pedro e Sao Paulo. XIX Encontro Brasileiro de Ictiologia. 788.

12. Oxenford HA, Murray PA, Luckhurst BE. 2003. The biology of wahoo (Acanthocybium solandri) in the Western Central Atlantic. Gulf Caribb Res. 15(1):33–49.

13. Franks JS, Hoffmayer ER, Ballard JR, Garber NM, Garber AF. 2008. Diet of Wahoo, *Acanthocybium solandri*, from the Northcentral Gulf of Mexico. GCFI. 60; 353-362.

14. FAO. 2009. FishStat Plus Version 2.32. Universal Software for Fishery Statistics Time Series. Available from: www.fao.org/fishery/statistics/software/fishstat/en.

15. Zischke MT, Griffiths SP, Tibbetts IR. 2013. Rapid growth of wahoo (Acanthocybium solandri) in the Coral Sea, based on length-at-age estimates using annual and daily increments on sagittal otoliths. ICES J Mar Sci. 70(6):1128–1139.

## Mahimahi - *Coryphaena hippurus*

Overall Vulnerability Rank = Moderate

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

| | *Coryphaena hippurus* | Expert Scores | Data Quality | Expert Scores Plots (Portion by Category) |
|---|---|---|---|---|
| Sensitivity attributes | Habitat Specificity | 1.3 | 2.4 | |
| | Prey Specificity | 1.3 | 2.8 | |
| | Adult Mobility | 1.1 | 3 | |
| | Dispersal of Early Life Stages | 1.7 | 2 | |
| | Early Life History Survival and Settlement Requirements | 1.6 | 1.6 | |
| | Complexity in Reproductive Strategy | 1.4 | 1.8 | |
| | Spawning Cycle | 1.3 | 2.4 | |
| | Sensitivity to Temperature | 1.8 | 2.6 | |
| | Sensitivity to Ocean Acidification | 1.4 | 2.2 | |
| | Population Growth Rate | 1.1 | 2.6 | |
| | Stock Size/Status | 1.3 | 2.6 | |
| | Other Stressors | 1.5 | 2 | |
| | Sensitivity Score | Low | | |
| Exposure variables | Bottom Salinity | 1 | 3 | |
| | Bottom Temperature | 1 | 3 | |
| | Current EW | 1.3 | 3 | |
| | Current NS | 1.2 | 3 | |
| | Current Speed | 1.3 | 3 | |
| | Mixed Layer Depth | 1.3 | 3 | |
| | Ocean Acidification | 4 | 3 | |
| | Precipitation | 1 | 3 | |
| | Productivity | 1.4 | 3 | |
| | Sea Surface Temperature | 3.8 | 3 | |
| | Surface Chlorophyll | 1.5 | 3 | |
| | Surface Oxygen | 3.6 | 3 | |
| | Surface Salinity | 1.5 | 3 | |
| | Wind EW | 1.1 | 3 | |
| | Wind NS | 1.1 | 3 | |
| | Wind Speed | 1.1 | 3 | |
| | Exposure Score | Very High | | |
| Overall Vulnerability Rank | | Moderate | | |

Low
Moderate
High
Very High

**Mahimahi (*Coryphaena hippurus*)**

Overall Climate Vulnerability Rank: **[Moderate].** (87% 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 Dispersal of Early Life Stages (1.7) and Sensitivity to Temperature (1.8).

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

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

Climate Effects on Abundance and Distribution:

Mahimahi, *Coryphaena hippurus*, are found in open waters as well as near coastal areas up to a depth of 85 m. They are highly migratory and are considered so under Annex I of the 1982 Convention on the Law of the Sea [1]. They reside in both tropical and temperate waters such as the Atlantic, Indian, and Pacific Oceans as well as the Mediterranean Sea (47° N to 38° S, 180° W to 180° E). They are found in temperatures ranging from 21 °C to 30 °C [1].

Adult mahimahi may be less sensitive to ocean acidification since they do not rely on calcium carbonate or calcium carbonate-based prey [2]. However, more research is needed to understand the physiological effects of ocean acidification on adult mahimahi [3,4]. Larval mahimahi may be susceptible to ocean acidification, exemplified by impaired larval swimming and hearing ability [5,6]. Increased sea surface temperatures and reduced oxygen availability may affect their habitat [7]. Other environmental stressors for mahimahi are not reported.

Mahimahi are harvested throughout their range. While they can be locally abundant, there were cases of localized overexploitation [8,9]. Overall, there is no indication that there is a significant population decline. Accordingly, mahimahi are listed as Least Concern by the IUCN [1]. Stocks may be differentiated by using sagittal otoliths or morphological characteristics [10,11].

Life History Synopsis**:**

Spawning occurs in open waters at temperatures greater than 21 °C [1]. In temperate areas, spawning typically occurs from spring to mid-summer. However, in tropical areas, spawning occurs year-round. In waters above 24 °C, larvae are found all year with many detected in the spring and fall. Within a spawning period, batch spawning may occur two or more times. In the west central Atlantic, batch fecundity is approximated at 58,000 to 1.5 million eggs and varies with size [12-14].

The larval duration and dispersal are not reported for this species. During early egg development, the melanin pigment and yolk segmentation are not obvious. However, more developed eggs have melanophores and segmented yolk. The food source from the egg is only available for a limited period [15]. Mahimahi are preyed upon at all life stages [15].

Mahimahi are active generalist predators, using high amounts of energy to capture prey in the epipelagic regions. Their diet consists of smaller fishes, zooplankton, crustaceans, and squid [2]. As larvae, mahimahi mostly consume crustaceans, in particular Copepoda [15].

The von Bertalanffy growth coefficient varies from 0.4 to 2.87 $yr^{-1}$ [14,16, 17]. Mahimahi reach maturity at around 4 to 7 months [1]. They can reach a maximum age of 4 years, but it is frequently shorter (~2 years) [13,17,18]. Natural mortality is estimated from 0.6 to 0.8 $yr^{-1}$ [8, 19].

**References**

1. Collette B, Acero A, Amorim AF, Boustany A, Canales Ramirez C, Cardenas G, Carpenter KE, de Oliveira Leite Jr N, Di Natale A, Fox W, et al. 2011. Coryphaena hippurus. [cited 2017 April 10]. Database: The IUCN Red List of Threatened Species [Internet]. http://dx.doi.org/10.2305/IUCN.UK.2011-2.RLTS.T154712A4614989.en.

2. Eschmeyer WN, Herald ES, Hammann H. 1983. A field guide to Pacific coast fishes of North America. Boston: Houghton Mifflin. pp. 336.

3. Cattano C, Claudet J, Domenici P, Milazzo M. 2018. Living in a high $CO_2$ world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. Ecol Monogr. 88:320–335.

4. Heuer RM, Grosell M. 2014. Physiological impacts of elevated carbon dioxide and ocean acidification on fish. Am J Physiol Regul Integr Comp Physiol. 307: R1061-R1084.

5. Bignami SGT. 2013. Effects of ocean acidification on the early life history of two pelagic tropical fish species, Cobia (Rachycentron canadum) and Mahi-mahi (Coryphaena hippurus). Ph.D. Dissertation, University of Miami. Available from: https://scholarship.miami.edu/discovery/fulldisplay/alma991031447233402976/01UOML_INST:ResearchR epository

6. Pimentel M, Pegado M, Repolho T, Rosa R. 2014. Impact of ocean acidification in the metabolism and swimming behavior of the dolphinfish (Coryphaena hippurus) early larvae. Mar Biol. 161: 725–729.

7. Asch R, Cheung W, Reygondeau G. 2018. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. Mar Pol. 88: 285–294.

8. Baset A, Haneef TM, Waris A, Liao B, Memon AM, Karim E, Ismail M. 2020. Maximum sustainable yield of dolphinfish, Coryphaena hippurus (Linnaeus, 1758) fishery in Pakistan. J Anim Sci Res. 4(2): dx.doi.org/10.16966/2576-6457.138

9. Patterson KR, Martinez J. 1991. Exploitation of the dolphin-fish Coryphaena hippurus L. off Ecuador: analysis by length-based virtual population analysis. Fishbyte. 9(2): 21–23.

10. Duarte-Neto P, Lessa R, Stosic B, Morize E. 2008. The use of sagittal otoliths in discriminating stocks of common dolphinfish (Coryphaena hippurus) off northeastern Brazil using multishape descriptors. ICES J Mar Sci. 65(7):1144–1152.

11. Oxenford HA, Hunte W. 1986. Migration of the dolphin ( Coryphaena hippurus ) and its implication for fisheries management in the western Central Atlantic. Proc Gulf Carib Fish Inst. 37:95–111.

12. Gibbs RH, Collette BB. 1959. On the identification, distribution, and biology of the dolphins, Coryphaena hippurus and C. equiselis. Bull Mar Sci Gulf Caribb. 9(961):117–152.

13. Oxenford HA. 1999. Biology of the dolphinfish in the western central Atlantic: a review. Sci Mar. 63(3-4):277–301.

14. Schwenke KL, Buckel JA. 2008. Age, growth, and reproduction of dolphinfish (Coryphaena hippurus) caught off the coast of North Carolina. Fish Bull. 106(1):82–92.

15. Palko BJ, Beardsley GL, Richards WJ. 1982. Synopsis of the biological data on dolphin-fishes, *Coryphaena hippurus* Linnaeus and *Coryphaena equiselis*, Linnaeus. U.S. Dept Commer, NOAA Technical Memorandum. NMFS Circular 443.

16. Benjamin D, Kurup BM. 2012. Stock assessment of dolphinfish Coryphaena hippurus (Linnaeus, 1758) off southwest coast of India. J Mar Biol Ass India. 54: 95–99.

17. Oxenford HA, Hunte W. 1983. Age and growth of dolphin, Coryphaena hippurus, as determined by growth rings in otoliths. Fish Bull. 81:241–44.

18. Uchiyama JH, Burch RK, Kraul Jr SA. 1986. Growth of dolphins, Coryphaena hippurus and C. equiselis in Hawaiian waters as determined by daily increments on otoliths. Fish. Bull. 84(1):186–191.

19. Haupt M. 2018. Life history traits that predispose South African linefishes to overexploitation. M.Sc. Thesis, University of Cape Town.

Striped marlin - *Kajikia audax*

Overall Vulnerability Rank = High

Biological Sensitivity = Moderate

Climate Exposure = Very High

Data Quality = 82% of scores ≥ 2

| | *Kajikia audax* | Expert Scores | Data Quality | Expert Scores Plots (Portion by Category) |
|---|---|---|---|---|
| Sensitivity attributes | Habitat Specificity | 1.2 | 2.8 | |
| | Prey Specificity | 1.1 | 2.8 | |
| | Adult Mobility | 1 | 3 | |
| | Dispersal of Early Life Stages | 1.6 | 1.4 | |
| | Early Life History Survival and Settlement Requirements | 2 | 1 | |
| | Complexity in Reproductive Strategy | 1.6 | 1.6 | |
| | Spawning Cycle | 2 | 2.6 | |
| | Sensitivity to Temperature | 1.5 | 2.8 | |
| | Sensitivity to Ocean Acidification | 1.5 | 1.8 | |
| | Population Growth Rate | 2.6 | 2.2 | |
| | Stock Size/Status | 3.2 | 2.6 | |
| | 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 | 1.2 | 3 | |
| | Current Speed | 1.2 | 3 | |
| | Mixed Layer Depth | 1.4 | 3 | |
| | Ocean Acidification | 4 | 3 | |
| | Precipitation | 1 | 3 | |
| | Productivity | 1.3 | 3 | |
| | Sea Surface Temperature | 3.8 | 3 | |
| | Surface Chlorophyll | 1.4 | 3 | |
| | Surface Oxygen | 3.6 | 3 | |
| | Surface Salinity | 1.4 | 3 | |
| | Wind EW | 1.1 | 3 | |
| | Wind NS | 1.1 | 3 | |
| | Wind Speed | 1 | 3 | |
| | Exposure Score | Very High | | |
| Overall Vulnerability Rank | | High | | |

Low

Moderate

High

Very High

**Striped Marlin (*Kajikia audax*)**

Overall Climate Vulnerability Rank: **[High].** (59% 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 and that is Stock Size/Status (3.2). The next highest score was for Population Growth Rate (2.6).

Distributional Vulnerability Rank: **[Very High].** Three attributes indicated very high 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: 82% of the data quality scores were 2 or greater.

Climate Effects on Abundance and Distribution:

*Kajikia audax* are found in the Indian and Pacific Oceans. They are especially widely distributed in the eastern and northern central Pacific. The central equatorial regions in the western and central Pacific are not considered part of their distribution since there is low and intermittent hook rate. Early longlining data also suggest high abundance in the central north and eastern Pacific and low abundance in the south and western Pacific. Adults are abundant in the south and southwest Pacific during the spring and summer. Striped marlins are typically in cooler water than black or blue marlins [1-3]. Juvenile *K. audax* are not commonly caught in the southwest Pacific Ocean. [4].

Adults are usually found above the thermocline [5]. According to transmitted temperature and depth data, striped marlins spend 80% of their time in the mixed layer; 72% of that time is in the top 5 m, and 75% of their time in temperatures ranging from 20 °C to 24 °C [6]. Their lower depth limit is approximately 300 m. Abundance increases farther away from the continental shelf. They are usually spotted near the shore where deep drop-offs occur [5]. Striped marlins are highly migratory and listed as such in the Annex I of the 1982 Convention on the Law of the Sea [7]. They are usually solitary but will school (groups separated by size) during spawning season [1].

At least four genetically distinct stocks are reported in the Pacific. One of the genetic stocks encompassed Hawaiʻi, Japan, Taiwan, and California [8]. The other three genetic stocks were reported in Australia, Mexico, and Ecuador [8]. Data from Brodziak and Piner [9] suggest that striped marlin populations in the North Pacific (regions north of the equator) have declined by approximately 60% [1]. Striped marlins have globally declined approximately 20 to 25% over the past 16 years [1].

Adult striped marlins may be less sensitive to ocean acidification since they eat a variety of prey and are not dependent on prey with a calcium carbonate shell. However, further research is needed to understand the physiological consequences of ocean acidification on adult striped marlins [10,11]. Striped marlin larvae may also be susceptible to ocean acidification, but additional investigation is necessary to fully understand their vulnerability [12,13]. Increased sea surface temperatures and decreased oxygen availability could influence their habitat [14]. Additional increased warming may affect spawning since temperature may be a potential cue [5]. Other environmental stressors are not reported.

Life History Synopsis**:**

Adults form small schools during spawning seasons that are segregated by size [1]; some spawning sites are found between 10° S and 30° S in the southwest Pacific Ocean [5]. Females are indeterminate batch spawners and develop oocyte asynchronously [15]. Larvae are typically most abundant during early summers corresponding to the presence of mature females. Larvae can tolerate temperatures as low as 24 °C in the Indian and Pacific Oceans [5]. Larvae drift for several weeks to months before they develop into fry [2]; however, other early life stage information such as dispersal and food is not known.

Juveniles consume zooplankton while adults typically consume a variety of epipelagic organisms. Adult striped marlins are considered carnivorous and nonselective feeders, consuming different types of fishes, crustaceans, and squids. A dietary analysis of adults from the southern Gulf of California, Mexico, found that they eat epipelagic organisms from the neritic and oceanic zones. Common prey items were the chub mackerel, California pilchard, and jumbo squid. Their diet includes more epipelagic organisms than the diets of other billfish and larger tunas [1,16,17]. Predators of the striped marlins include great white sharks, killer whales, and humans [1,5].

Striped marlins reach maturity at 210 cm and 170 cm for females and males, respectively, and have a growth coefficient of 0.26 $yr^{-1}$; although, young fish may grow much faster [18-20]. They can potentially live up to a maximum age of approximately 8 to 9 years and have an estimated natural mortality rate of 0.38 $yr^{-1}$ [21,22].

**References**

1. Collette B, Acero A, Boustany A, Canales Ramirez C, Cardenas G, Carpenter KE, Di Natale A, Die D, Fox W, Graves J. et al. 2011. Kajikia audax [cited 2017 April 10]. Database: The IUCN Red List of Threatened Species [Internet]. Available from: http://dx.doi.org/10.2305/IUCN.UK.2011-2.RLTS.T170309A6738801.en.

2. Nakamura I. 1985. Billfishes of the world. An annotated and illustrated catalogue of marlins, sailfishes, spearfishes and swordfishes known to date. FAO species catalogue. No. 125, Vol. 5. Rome:FAO.

3. Ueyanagi S, Wares PG. 1975.Synopsis of biological data on striped marlin, Tetrapturus audax (Philippi), 1887. In: Shomura RS, Williams F, editors. Proceedings of the international billfish symposium, 9-12 August 1972 Part 3. Species Synopses. U.S. Dept Commer, NOAA Technical Report NMFS 675. pp. 132–139.

4. Kopf RK. 2010. Age, growth, and reproductive dynamics of striped marlin, Kajikia audax, in the southwest Pacific Ocean. Ph.D. Dissertation, Charles Sturt University.

5. Kailola PJ, Williams MJ, Stewart PC, Reichelt RE, McNee A, Grieve C. 1993. Australian fisheries resources. Canberra, Australia:Bureau of Resource Sciences.

6. Sippel T, Davie P, Holdsworth J, Block B. 2007. Striped marlin (Tetrapturus audax) movements and habitat utilization during a summer and autumn in the Southwest Pacific Ocean. Fish Oceanogr. 16(5):459–472.

7. FAO, Fisheries Department. World review of highly migratory species and straddling stocks. FAO Fisheries Technical Paper; 1994. No. 337. Rome:FAO. pp. 70.

8. McDowell JR, Graves JE. 2008. Population structure of striped marlin (Kajikia audax) in the Pacific Ocean based on analysis of microsatellite and mitochondrial DNA. Can J Fish Aquat Sci. 65(7):1307–1320.

9. Brodziak J, Piner K. 2010. Model averaging and probable status of North Pacific striped marlin, Tetrapturus audax. Can J Fish Aquat Sci. 67(5):793–805.

10. Cattano C, Claudet J, Domenici P, Milazzo M. 2018. Living in a high $CO_2$ world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. Ecol Monogr. 88: 320–335.

11. Heuer RM, Grosell M. 2014. Physiological impacts of elevated carbon dioxide and ocean acidification on fish. Am J Physiol Regul Integr Comp Physiol. 307: R1061-R1084.

12. Frommel AY, Margulies D, Wexler JB, Stein MS, Scholey VP, Williamson JE, Bromhead D, Nicol S, Havenhand JN. 2016. Ocean acidification has lethal and sub-lethal effects on larval development of yellowfin tuna, *Thunnas albacares*. J Exper Mar Biol Ecol. 482: 18–24.

13. Stiasny MH, Mittermayer FH, Sswat M, Voss R, Jutfelt F, Chierici M, Puvanendran V, Mortensen A, Reusch TBH, Clemmensen C.2016. . Ocean acidification effects on Atlantic Cod larval survival and recruitment to the fished population. PlosOne. 11(8): e0155448.

14. Asch R, Cheung W, Reygondeau G. 2018. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. Mar Pol. 88: 285–294.

15. Kopf RK, Davie PS, Bromhead DB, Young JW. 2012. Reproductive biology and spatiotemporal patterns of spawning in striped marlin Kajikia audax. J Fish Biol. 81(6):1834–1858.

16. Abitia-Cardenas LA, Galvan-Magaña F, Rodriguez-Romero J. 1997. Food habits and energy values of prey of striped marlin, Tetrapturus audax, off the coast of Mexico. Fish Bull. 360–368.

17. Abitía-Cárdenas LA, Muhlia-Melo A, Cruz-Escalona V, Galván-Magaña F. 2002. Trophic dynamics and seasonal energetics of striped marlin Tetrapturus audax in the southern Gulf of California, Mexico. Fish Res. 57(3):287–295.

18. Lee HH, Piner KR, Humphreys R, Brodziak J. 2012.Stock assessment for striped marlin in the Western and Central North Pacific Ocean in 2011. Billfish working group stock assessment workshop. Sapporo: International Scientific Committee for Tuna and Tuna-like Species in the North Pacific. Available from: https://origin-apps-pifsc.fisheries.noaa.gov/library/pubs/IR-12-035.pdf

19. Kopf RK, Davie PS, Bromhead DB, Young JW. 2012. Reproductive biology and spatiotemporal patterns of spawning in striped marlin Kajikia audax. J Fish Biol. 81: 1834–1858.

20. Sun CL, Hsu WS, Su NJ, Yeh SZ, Chang YJ, Chiang WC. 2011. Age and growth of striped marlin (Kajikia audax) in the waters off Taiwan: A revision.Bill working group workshop. Taipei: International Scientific Committee for Tuna and Tuna-like Species in the North Pacific. Available from: http://isc.fra.go.jp/pdf/BILL/ISC11_BILL_2/ISC11BILLWG2_WP07.pdf

21. Kopf RK, Davie PS, Bromhead D, Pepperell JG. 2011. Age and growth of striped marlin (Kajikia audax) in the Southwest Pacific Ocean. ICES J Mar Sci. 68(9): 1884–1895.

22. Piner K, Lee HH. 2011. Correction to meta-analysis of striped marlin natural mortality. International Scientific Committee for Tuna and Tune-like Species in the North Pacific Ocean. Available from: http://isc.fra.go.jp/pdf/BILL/ISC11_BILL_2/ISC11BILLWG2_WP08.pdf

## Skipjack tuna - *Katsuwonus pelamis*

Overall Vulnerability Rank = Moderate

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

| | *Katsuwonus pelamis* | Expert Scores | Data Quality | Expert Scores Plots (Portion by Category) |
|---|---|---|---|---|
| Sensitivity attributes | Habitat Specificity | 1.6 | 2.4 | |
| | Prey Specificity | 1.2 | 2.8 | |
| | Adult Mobility | 1.1 | 3 | |
| | Dispersal of Early Life Stages | 1.5 | 1.6 | |
| | Early Life History Survival and Settlement Requirements | 1.7 | 2.2 | |
| | Complexity in Reproductive Strategy | 1.5 | 1.8 | |
| | Spawning Cycle | 1.1 | 2.8 | |
| | Sensitivity to Temperature | 2 | 2.8 | |
| | Sensitivity to Ocean Acidification | 1.4 | 2 | |
| | Population Growth Rate | 1.4 | 2.4 | |
| | Stock Size/Status | 1.6 | 2.6 | |
| | Other Stressors | 1.5 | 2 | |
| | Sensitivity Score | Low | | |
| Exposure variables | Bottom Salinity | 1 | 3 | |
| | Bottom Temperature | 1 | 3 | |
| | Current EW | 1.3 | 3 | |
| | Current NS | 1.2 | 3 | |
| | Current Speed | 1.3 | 3 | |
| | Mixed Layer Depth | 1.3 | 3 | |
| | Ocean Acidification | 4 | 3 | |
| | Precipitation | 1 | 3 | |
| | Productivity | 1.4 | 3 | |
| | Sea Surface Temperature | 3.8 | 3 | |
| | Surface Chlorophyll | 1.4 | 3 | |
| | Surface Oxygen | 3.6 | 3 | |
| | Surface Salinity | 1.5 | 3 | |
| | Wind EW | 1.1 | 3 | |
| | Wind NS | 1.1 | 3 | |
| | Wind Speed | 1.1 | 3 | |
| | Exposure Score | Very High | | |
| Overall Vulnerability Rank | | Moderate | | |

Low
Moderate
High
Very High

**Skipjack Tuna (*Katsuwonus pelamis*)**

Overall Climate Vulnerability Rank: **[Moderate].** (80% 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 Early Life History and Settlement Requirements (1.7) and Sensitivity to Temperature (2.0).

Distributional Vulnerability Rank: **[High].** All four attributes indicated high 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:

*Katsuwonus pelamis* occur in temperatures from approximately 18 °C to 30 °C across a very large geographic range—at least 40° N to 40° S in the three major oceans [1,2]. The upper temperature skipjack can inhabit may be size-dependent [1]. The range of skipjack extends south of Africa and Australia which, along with the knowledge that skipjack often travel great distances, leads to the conjecture that there is probably genetic connectivity between oceans although there has been indication of distinct stocks within the Indian Ocean [3]. The tendency of Skipjack to travel long distances and tolerate a broad range of temperatures suggests that they can relocate to regions with satisfactory environmental conditions if local conditions become harsh.

As open-ocean pelagic fish that require higher concentrations of dissolved oxygen (3 to 3.5 mL $O_2$/L), skipjack are potentially vulnerable to warming and stratification which lead to reduced oxygen [1,4,5]. If open-ocean conditions become unfavorable, skipjack tend to spend more time in nearshore waters where oxygen is maintained by waves interacting with land masses and where nutrients come to the ocean via terrestrial runoff.

Life History Synopsis**:**

For *Katsuwonus pelamis*, the skipjack tuna, the wide range of temperature tolerance (approximately 15 °C to 30 °C), the potential genetic adaptability through tremendous reproductive output in a short lifespan (they can spawn 80,000 to 2,000,000 eggs per season), and the large, interconnected populations distributed across wide latitudinal ranges (at least 40 °N to 40 °S) around the world may allow this species to adjust to climate change more effectively than many other species [1,2]. Their adaptability may be favored by their tremendous rate of population production and turnover in the huge interconnected circumtropical population. They appear to reach sexual maturity by their second year (approximately 40 to 45 cm) and are estimated to live up to 12 years, but the fish caught are usually 1 to 4 years old [2,6-8]. Skipjack produce a tremendous biomass that provides major support to commercial fisheries, recreational fisheries, and natural predators in all three oceans. The estimated global catch of skipjack in 2009 was 2.5 million tonnes [9]. Over half of all tuna caught globally are skipjack [9].

**References**

1. Barkley RA, Neill WH, Gooding RM. 1978. Skipjack tuna, Katsuwonus pelamis, habitat based on temperature and oxygen requirements. Fish Bull. 76(3): 653–662.

2. Collette BB, Nauen CE. 1983. Scombrids of the world. An annotated and illustrated catalogue of tunas, mackerels, bonitos, and related species known to date. FAO species catalogue. No. 125, Vol. 2. Rome:FAO.

3. Dammannagoda ST, Hurwood DA, Mather PB.2011. Genetic analysis reveals two stocks of skipjack tuna (Katsuwonus pelamis) in the northwestern Indian Ocean. Can J Fish Aquat Sci. 68(2); 210–223.

4. Asch R, Cheung W, Reygondeau G. 2018. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. Mar Pol. 88: 285–294.

5. Lehodey P, Senina I, Calmettes B, Hampton J, Nicol S. 2012. Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. Clim Change. 119: 95–109.

6. Grande M, Murua H, Zudaire I, Goni N, Bodin N. 2014. Reproductive timing and reproductive capacity of the skipjack tuna (Katsuwanus pelamis) in the western Indian Ocean. Fish Res. 156: 14–22.

7. Ashida H, Horie M. 2015. Reproductive condition, spawning season, batch fecundity and spawning fraction of skipjack tuna Katsuwonus pelamis caught around Amami-Oshima, Kagoshima Japan. Fish Sci. 81: 861-869.

8. Andrade HA, Kinas PG. 2004. Estimation of birthdates and catch-at-age using length frequency analysis (LFA), with application for skipjack tuna (Katsuwonus pelamis) caught in the Southwest Atlantic. ICES J Mar Sci. 61(5): 798-811.

9. FAO. Fishery statistical collections. Global tuna catches by stock. 2010. Available from: http://www.fao.org/fishery/statistics/tuna-catches/en

## Yellowfin tuna - *Thunnus albacares*

Overall Vulnerability Rank = Moderate

Biological Sensitivity = Low
Climate Exposure = Very High
Data Quality = 100% of scores ≥ 2

| | *Thunnus albacares* | Expert Scores | Data Quality | Expert Scores Plots (Portion by Category) |
|---|---|---|---|---|
| Sensitivity attributes | Habitat Specificity | 1.3 | 2.8 | |
| | Prey Specificity | 1.1 | 2.8 | |
| | Adult Mobility | 1.2 | 2.8 | |
| | Dispersal of Early Life Stages | 1.7 | 2 | |
| | Early Life History Survival and Settlement Requirements | 1.7 | 2.2 | |
| | Complexity in Reproductive Strategy | 1.7 | 2.6 | |
| | Spawning Cycle | 1.5 | 2.6 | |
| | Sensitivity to Temperature | 1.6 | 2.8 | |
| | Sensitivity to Ocean Acidification | 1.4 | 2.2 | |
| | Population Growth Rate | 1.4 | 2.4 | |
| | Stock Size/Status | 2.2 | 2.8 | |
| | Other Stressors | 1.6 | 2 | |
| | Sensitivity Score | Low | | |
| Exposure variables | Bottom Salinity | 1 | 3 | |
| | Bottom Temperature | 1 | 3 | |
| | Current EW | 1.3 | 3 | |
| | Current NS | 1.2 | 3 | |
| | Current Speed | 1.3 | 3 | |
| | Mixed Layer Depth | 1.3 | 3 | |
| | Ocean Acidification | 4 | 3 | |
| | Precipitation | 1 | 3 | |
| | Productivity | 1.4 | 3 | |
| | Sea Surface Temperature | 3.8 | 3 | |
| | Surface Chlorophyll | 1.4 | 3 | |
| | Surface Oxygen | 3.6 | 3 | |
| | Surface Salinity | 1.5 | 3 | |
| | Wind EW | 1.1 | 3 | |
| | Wind NS | 1.1 | 3 | |
| | Wind Speed | 1.1 | 3 | |
| | Exposure Score | Very High | | |
| Overall Vulnerability Rank | | Moderate | | |

Low
Moderate
High
Very High

**Yellowfin Tuna (*Thunnus albacares*)**

<u>Overall Climate Vulnerability Rank</u>: **[Moderate].** (80% certainty from bootstrap analysis).

<u>Climate Exposure</u>: **[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.

<u>Biological Sensitivity</u>: **[Low]**. No sensitivity attribute scored above a 3.0. The highest score was for Stock Size/Status (2.2).

<u>Distributional Vulnerability Rank</u>: **[Very High].** Three attributes indicated very high 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.

<u>Data Quality</u>: 100% of the data quality scores were 2 or greater.

<u>Climate Effects on Abundance and Distribution</u>:

Yellowfin tuna (*Thunnus albacares*) are expected to experience a range shift, especially at the trailing edge, due to warming from climate change [1]. Shifts of yellowfin tuna will likely then affect fishing efforts [2]. Their vertical migration may also be impacted by stratification and decreased dissolved oxygen levels, which would restrict their vertical migration patterns [3,4]. Additionally, ocean acidification will likely have an impact on adult yellowfin tuna physiology, but further research is needed to understand the species' vulnerability [5,6]. Yellowfin tuna larvae will likely be affected by ocean acidification. As pH decreases, larvae may have increasing kidney, liver, pancreas, eye, and muscle damage as well as reduced survival [7,8].

<u>Life History Synopsis</u>**:**

Yellowfin tuna (*Thunnus albacares*) are circumglobal, highly migratory, and found in tropical and sub-tropical seas (~45° S–45° N) down to depths of at least 400 m [9,10]. They grow to a maximum fork length of ~180 cm and can live for 15–18 years [11-14]. *T. albacares* reach sexual maturity near 98–113 cm in fork length; fish at the smaller end of the spectrum are found near the Philippines and Indonesia and fish towards the larger sizes found near Hawaiʻi [13]. Yellowfin tuna are serial spawners capable of spawning year round every 1–2 days between sunset and sunrise when surface water is warmer than 21.5 °C but with the majority of spawning taking place in waters 24–30 °C [13,15]. In more temperate areas, spawning is limited to the warmer summer months (April–October in the northern hemisphere) with a peak in June–August [13]. Female yellowfin tuna are capable of spawning an average of 2 million pelagic eggs per spawning (range 0.5–10 million), or 55–68 oocytes per gram of body weight [13,15]. The larvae are predominantly found across the tropical oceans in surface waters of less than 22 °C but have been found as far north as Hawaiʻi [16-19]. Recruitment of yellowfin tuna increases during or right after El Niño periods in the eastern tropical Pacific when the surface warm pool is at its greatest extent [17,20].

Larval development patterns are variable and dependent on temperature, density of larvae, and food availability, with the duration of egg and yolk-sack stages being inversely proportional to water temperature [17,21,22]. Post-flexion larvae transition from omnivory to piscivory from 2–3 weeks post hatching and growth rates of feeding larvae increase in higher temperatures with an optimal range for survival between 21–33 °C [21-23].

In the Pacific Ocean, *T. albacares* are managed as a panmictic population [14,24] but there is some evidence that there are subpopulations in the central Equatorial Pacific (see references in [25,26]). Adult yellowfin tuna have long-term core areas of use that rarely exceed 1,000 km in the EPO with very little exchange between northern and southern areas [19,27,28].

Adult *T. albacares* diet consists mainly of fishes, crustaceans, and squid, and in the western Pacific, the ocean anchovy (*Encrasicholina punctifer*) is a major forage source [9,13]. Juvenile yellowfin tuna spend the majority of their time in the mixed layer and above the thermocline. However, when foraging on organisms in the deep scattering layer, adult yellowfin tuna undertake repetitive bounce-diving where they dive to depths of 200–400 m during the day and can spend up to 50% of their time below the thermocline [19,29]. *T. albacares* is sensitive to low oxygen concentrations which limits the depth distribution [13,30,31].

*T. albacares* are commercially valuable fish which can get caught in a variety of gear types ranging from small-scale artisanal fisheries to distant water longline and purse seine fleets [14,24]. *T. albacares* stocks are managed by several regional fisheries management organizations (RFMO) that conduct their own stock assessments and set catch quotas for their region. Global landings have remained stable around 1,000,000 t annually since the 1990s [32]. Heavy fishing over many decades has resulted in an estimated 33% decline in biomass or spawning stock biomass globally between 1998–2008 [9]. *T. albacares* is listed as Near Threatened by the IUCN.

**References**


1. Robinson LM, Hobday AJ, Possingham HP, Richardson AJ. 2015. Trailing edges projected to move faster than leading edges for large pelagic fish habitats under climate change. Deep Sea Res Part II Top Stud Oceanogr. 113: 225–234.
2. Dell JT, Wilcox C, Matear RJ, Chamberlain MA, Hobday AJ. 2015. Potential impacts of climate change on the distribution of longline catches of yellowfin tuna (*Thunnus albacares*) in the Tasman Sea. Deep Sea Res Part II Top Stud Oceanogr. 113: 235–245.
3. Lehodey P, Hampton J, Brill RW, Nicol S, Senina I, Calmettes B, Pörtner H-O, Bopp L, Ilyina T, Bell JD, et al. 2011. Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: Bell JD, Johnson JE, Hobday AJ, Editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Secretariat of the Pacific community, Noumea, New Caledonia. pp.433–492.
4. Asch R, Cheung W, Reygondeau G. 2018. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. Mar Pol. 2018; 88: 285–294.
5. Cattano C, Claudet J, Domenici P, Milazzo M. 2018. Living in a high $CO_2$ world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. Ecol Monogr. 88: 320–335.
6. Heuer RM, Grosell M. 2014. Physiological impacts of elevated carbon dioxide and ocean acidification on fish. Am J Physiol Regul Integr Comp Physiol. 307: R1061-R1084.

7. Frommel AY, Margulies D, Wexler JB, Stein MS, Scholey VP, Williamson JE, Bromhead D, Nicol S, Havenhand JN. 2016. Ocean acidification has lethal and sub-lethal effects on larval development of yellowfin tuna, *Thunnas albacares*. J Exper Mar Biol Ecol. 482: 18–24.
8. Bromhead D, Scholey V, Nicol S, Margulies D, Wexler J, Stein M, Hoyle S, Lennert-Cody C, Williamson J, Havenhand J, et al. 2015. The potential impact of ocean acidification upon eggs and larvae of yellowfin tuna (*Thunnus albacares*). Deep Sea Res Part II Top Stud Oceanogr. 113: 268–279.
9. Collette B, Acero A, Amorim AF, Boustany A, Canales Ramirez C, Cardenas G, Carpenter KE, de Oliveira Leite Jr N, Di Natale A, Fox W, et al. 2011. Coryphaena hippurus. [cited 2017 April 9]. Database: The IUCN Red List of Threatened Species [Internet]. http://dx.doi.org/10.2305/IUCN.UK.2011-2.RLTS.T154712A4614989.en.
10. Riede K. 2004. Global register of migratory species - from global to regional scales. Federal Agency for Nature Conservation. Final Report of the R&D-Projekt 808 05 081.
11. Andrews AH, Pacicco A, Allman R, Falterman BJ, Lang ET, Golet W. 2020. Age validation of yellowfin (Thunnus albacares) and bigeye (Thunnus obesus) tuna of the northwestern Atlantic Ocean. Can J Fish Aquat Sci. 77(4):637–643.
12. Farley J, Krusic-Golub K, Eveson P, Clear N, Roupsard F, Sanchez C, Nicol S, Hampton J. 2020. Age and growth of yellowfin and bigeye tuna in the western and central Pacific Ocean from otoliths. Western and Central Pacific Fisheries Commission.
13. Itano DG. 2000. The reproductive biology of yellowfin tuna (*Thunnus albacares*) in Hawaiian waters and the western tropical Pacific Ocean: project summary. SOEST 00-01 JIMAR Contribution 00-328. Pelagic Fisheries Research Program, JIMAR, University of Hawaii. pp. 69.
14. Vincent M, Ducharme-Barth N, Hamer P, Hampton J, Williams P, Pilling G. 2020. Stock assessment of yellowfin tuna in the western and central Pacific Ocean. Western and Central Pacific Fisheries Commission.
15. Schaefer KM. 1998. Reproductive biology of yellowfin tuna Thunnus albacares in the eastern Pacific Ocean. Inter-Amer Trop Tuna Comm Bull. 21:201–272.
16. Boehlert GW, Mundy BC. 1996. Ichthyoplankton vertical distributions near Oahu, Hawaiʻi, 1985-1986: Data Report. U.S. Dept Commer, NOAA Technical Memorandum. NMFS-SWSC-235. pp. 148.
17. Muhling BA, Lamkin JT, Alemany F, García A, Farley J, Ingram GW, Berastegui DA, Reglero P, Carrion RL. 2017. Reproduction and larval biology in tunas, and the importance of restricted area spawning grounds. Rev Fish Biol Fish. 27(4):697–732.
18. Reglero P, DP T, Álvarez-Berastegui D, Aparicio-González A, Worm B. 2014. Worldwide distributions of tuna larvae: revisiting hypotheses on environmental requirements for spawning habitats . Mar Ecol Prog Ser. 501:207–224.
19. Schaefer KM, Fuller DW, Aldana G. 2014. Movements, behavior, and habitat utilization of yellowfin tuna (Thunnus albacares) in waters surrounding the Revillagigedo Islands Archipelago Biosphere Reserve, Mexico. Fish Oceanogr. 23(1):65–82.
20. Lehodey P, Chai F, Hampton J. 2003. Modelling climate-related variability of tuna populations from a coupled ocean–biogeochemical-populations dynamics model. Fish Oceanogr. 12(4-5):483–94.
21. Margulies D, Sutter JM, Hunt SL, Olson RJ, Scholey VP, Wexler JB, Nakazawa A. 2007. Spawning and early development of captive yellowfin tuna (Thunnus albacares). Fish Bull. 105:249–265.

22. Wexler JB, Margulies D, Scholey VP. 2011. Temperature and dissolved oxygen requirements for survival of yellowfin tuna, Thunnus albacares, larvae. J Exp Mar Biol Ecol. 404:63–72.
23. Llopiz JK, Richardson DE, Shiroza A, Smith SL, Cowen RK. 2010. Distinctions in the diets and distributions of larval tunas and the important role of appendicularians. Limnol Oceanogr. 55:983–996.
24. Minte-Vera C, Xu H, Maunder MN. 2019. Stock status indicators for yellowfin tuna in the eastern Pacific Ocean. Inter-Amer Trop Tuna Comm. 19:19–32.
25. Moore BR, Adams T, Allain V, Bell JD, Bigler M, Bromhead D, Clark S, Davies C, Evans K, Faasili Jr U, et al. 2020. Defining the stock structures of key commercial tunas in the Pacific Ocean II: Sampling considerations and future directions. Fish Res. 230:105524.
26. Moore BR, Bell JD, Evans K, Farley J, Grewe PM, Hampton J, Marie AD, Minte-Vera C, Nicol S, Pilling GM, et al. 2020. Defining the stock structures of key commercial tunas in the Pacific Ocean I: Current knowledge and main uncertainties. Fish Res. 230:105525.
27. Bayliff WH. 1984. Migrations of yellowfin and skipjack tuna released in the central portion of the eastern Pacific Ocean, as determined by tagging experiments. Inter-Amer Trop Tuna Comm Bull. 18:1–107.
28. Fink BD, Bayliff WH. 1970. Migrations of yellowfin and skipjack tuna in the Eastern Pacific Ocean as determined by tagging experiments, 1952–1964. Inter-Amer Trop Tuna Comm Bull. 15:1–227.
29. Schaefer KM, Fuller DW, Block BA. 2009. Vertical movements and habitat utilization of skipjack (Katsuwonus pelamis), yellowfin (Thunnus albacares), and bigeye (Thunnus obesus) tunas in the equatorial eastern Pacific Ocean, ascertained through archival tag data. In: Nielsen JL, Arrizabalaga H, Fragoso N, Hobday A, Lutcavage M, Sibert J, editors. Tagging and tracking of marine animals with electronic devices. Dordrecht: Springer. pp. 121–144.
30. Bushnell PG, Brill RW, Bourke RE. 1990. Cardiorespiratory responses of skipjack tuna (Katsuwonus pelamis), yellowfin tuna (Thunnus albacares), and bigeye tuna (Thunnus obesus) to acute reductions of ambient oxygen. Can J Zool. 68(9):1857–1865.
31. Holland KN, Brill RW, Chang RKC. 1990. Horizontal and vertical movements of yellowfin and bigeye tuna associated with fish aggregating devices. Fish Bull. 88:493–507.
32. FAO. FishStat Plus Version 2.32. Universal Software for Fishery Statistics Time Series. 2009. Available from: www.fao.org/fishery/statistics/software/fishstat/en.

## Bigeye tuna - *Thunnus obesus*

Overall Vulnerability Rank = Moderate

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

| | *Thunnus obesus* | Expert Scores | Data Quality | Expert Scores Plots (Portion by Category) |
|---|---|---|---|---|
| Sensitivity attributes | Habitat Specificity | 1.4 | 2.4 | |
| | Prey Specificity | 1.4 | 2.6 | |
| | Adult Mobility | 1 | 3 | |
| | Dispersal of Early Life Stages | 1.6 | 1.2 | |
| | Early Life History Survival and Settlement Requirements | 1.6 | 1.4 | |
| | Complexity in Reproductive Strategy | 1.4 | 2.2 | |
| | Spawning Cycle | 1.1 | 2.8 | |
| | Sensitivity to Temperature | 1.4 | 2.6 | |
| | Sensitivity to Ocean Acidification | 1.3 | 2 | |
| | Population Growth Rate | 1.5 | 2.6 | |
| | Stock Size/Status | 2 | 2.8 | |
| | Other Stressors | 1.4 | 2 | |
| | Sensitivity Score | Low | | |
| Exposure variables | Bottom Salinity | 1 | 3 | |
| | Bottom Temperature | 1 | 3 | |
| | Current EW | 1.3 | 3 | |
| | Current NS | 1.2 | 3 | |
| | Current Speed | 1.3 | 3 | |
| | Mixed Layer Depth | 1.3 | 3 | |
| | Ocean Acidification | 4 | 3 | |
| | Precipitation | 1 | 3 | |
| | Productivity | 1.4 | 3 | |
| | Sea Surface Temperature | 3.8 | 3 | |
| | Surface Chlorophyll | 1.5 | 3 | |
| | Surface Oxygen | 3.7 | 3 | |
| | Surface Salinity | 1.5 | 3 | |
| | Wind EW | 1.1 | 3 | |
| | Wind NS | 1.1 | 3 | |
| | Wind Speed | 1.1 | 3 | |
| | Exposure Score | Very High | | |
| Overall Vulnerability Rank | | Moderate | | |

Low
Moderate
High
Very High

**Bigeye Tuna (*Thunnus obesus*)**

Overall Climate Vulnerability Rank: **[Moderate].** (96% 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 the life stages.

Biological Sensitivity: **[Low]**. No sensitivity attributes scored above 3.0: Stock Size/Status scored the highest at 2.0.

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

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

Climate Effects on Abundance and Distribution:

Bigeye tuna longline fishery may be at risk of increasing natural mortality as temperatures increase in the tropical regions of the distribution [1,2]. However, reducing fishing may mitigate the consequences of climate change [1]. Additionally, warmer surface water temperatures due to climate change may lead to reduced foraging success if bigeye tuna attempt to capture prey at deeper depths [3]. Increasing temperatures occurring bigeye tuna habitat may also be accompanied by decreasing dissolved oxygen concentrations [4]. However, bigeye tuna may not be susceptible to these decreases since they can tolerate relatively low concentrations of dissolved oxygen (0.4-0.5 mL $O_2$/L) [3]. Ocean acidification may have an impact on adult bigeye tuna's physiology and reproduction, but research is needed to fully understand any potential consequences of ocean acidification [5,6]. Bigeye tuna larvae will likely be affected by ocean acidification. Organ damage and reduced survival may be potential impacts of ocean acidification [7,8].

Life History Synopsis**:**

Bigeye tuna are a pelagic highly migratory species that occur in the tropical and subtropical Pacific, Indian, and Atlantic oceans (45° N–43° S) where they spend most of their time above the thermocline during the night (0–100 m) and below during the day (300–500 m), in temperatures ranging 13 °C–29 °C and oxygen levels above 2 mL/L [9-13]. Bigeye reach sexual maturity around 2–4 years of age depending on region [14,15], and spawning occurs mainly in the tropics (15° N–15° S). Bigeye are serial spawners with year-round spawning and no strong spawning seasons [16], although increased spawning has been observed during March–November in the central and eastern Pacific [17] and February–-September for the western Pacific [18]. Female bigeye spawn on average every 2.6 days and release an estimated 2.9–6.3 million eggs per spawning [14,16,18]. Pacific spawning is thought to be linked to temperature and takes place in waters warmer than 24 °C with the greatest reproductive potential in the eastern Pacific [10,18,19-21]. Bigeye spawn pelagic eggs that hatch after ~21–24 hours [22]. The larvae are predominantly found across the tropical Pacific but have been encountered as far north as 30 °N near Hawaiʻi and along the western Pacific basin [23-25]. Juvenile bigeye tuna show regional fidelity to seamounts and FADs [26-29] with core areas spanning less than 300 km [12,28]. Adult bigeye feed on cephalopods, crustaceans, gelatinous organisms, and fish in the deep scattering layer [13,30,31]; juveniles likely have a similar diet. Ontogenetic movement and migration patterns in bigeye tuna are unclear but tagging and otolith microchemistry studies suggest that bigeye spawn in equatorial waters, migrate north as juveniles or sub-adult to feed near islands and seamounts, then migrate back towards the equator to spawn as mature adults [32,33]. Bigeye live for about 10 years and grow to around 180–200 cm in the Pacific Ocean but max size varies from region to region [34-36]. Pacific bigeye are considered one panmictic population, but two Regional Fisheries Management Organizations (RFMO) managed them as two separate stock; the Inter-American Tropical Tuna Commission (IATTC) manages bigeye tuna east of 150° W and the Western and Central Pacific Fisheries Commission (WCPFC) manages bigeye west of 150° W. The WCPFC adopted a new growth function in their 2017 stock assessment resulting in western and central Pacific (WCP) bigeye tuna not being in an overfished state [37]. However, under the old growth function, WCP bigeye are considered overfished with overfishing taking place [37,38]. The IATTC's most recent stock assessment indicates that the eastern Pacific bigeye stock is not overfished and that overfishing is not taking place [39]. The IUCN red list lists bigeye tuna as Vulnerable with Atlantic and Indian Ocean stocks considered Fully Exploited, and the EPO and WCPO stocks considered Over-exploited [10,40].

**References**


1. Woodworth-Jefcoats PA, Blanchard JL, Drazen JC. 2019. Relative impacts of simultaneous stressors on a pelagic marine ecosystem. Front Mar Sci. 6: 383.

2. Lehodey P, Senina I, Sibert J, Bopp L, Calmettes B, Hampton J, Murtugudde R. 2010. Preliminary forecasts of Pacific bigeye tuna population trends under the A2 IPCC scenario. Prog Oceanogr. 86(1-2): 302–315.

3. Lehodey P, Hampton J, Brill RW, Nicol S, Senina I, Calmettes B, Pörtner H-O, Bopp L, Ilyina T, Bell JD, et al. 2011. Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: Bell JD, Johnson JE, Hobday AJ, Editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Secretariat of the Pacific community, Noumea, New Caledonia.pp.433–492.

4. Asch R, Cheung W, Reygondeau G. 2018. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. Mar Pol. 88: 285–294.

5. Cattano C, Claudet J, Domenici P, Milazzo M. 2018. Living in a high $CO_2$ world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. Ecol Monogr. 88: 320–335.

6. Heuer RM, Grosell M. 2014. Physiological impacts of elevated carbon dioxide and ocean acidification on fish. Am J Physiol Regul Integr Comp Physiol. 307: R1061–R1084.

7. Frommel AY, Margulies D, Wexler JB, Stein MS, Scholey VP, Williamson JE, Bromhead D, Nicol S, Havenhand JN. 2016. Ocean acidification has lethal and sub-lethal effects on larval development of yellowfin tuna, *Thunnas albacares*. J Exper Mar Biol Ecol. 482: 18–24.

8. Bromhead D, Scholey V, Nicol S, Margulies D, Wexler J, Stein M, Hoyle S, Lennert-Cody C, Williamson J, Havenhand J, et al. 2015. The potential impact of ocean acidification upon eggs and larvae of yellowfin tuna (*Thunnus albacares*). Deep Sea Res Part II Top Stud Oceanogr. 113: 268–279.

9. Bushnell PG, Brill RW, Bourke RE. Cardiorespiratory responses of skipjack tuna (Katsuwonus pelamis), yellowfin tuna (Thunnus albacares), and bigeye tuna (Thunnus obesus) to acute reductions of ambient oxygen. Can J Zool. 1990;68(9):1857–1865.

10. Collette B, Acero A, Amorim AF, Boustany A, Canales Ramirez C, Cardenas G, Carpenter KE, de Oliveira Leite Jr N, Di Natale A, Fox W, et al. 2011. Coryphaena hippurus. [cited 2017 May 26]. Database: The IUCN Red List of Threatened Species [Internet]. https://dx.doi.org/10.2305/IUCN.UK.2011-2.RLTS.T21859A9329255.en

11. Dagorn L, Bach P, Josse E.2000. Movement patterns of large bigeye tuna (Thunnus obesus) in the open ocean, determined using ultrasonic telemetry. Mar Biol. 136(2):361–371.

12. FAO, Fisheries Department. World review of highly migratory species and straddling stocks. FAO Fisheries Technical Paper; 1994. No. 337. Rome:FAO. pp. 70.

13. Howell EA, Hawn DR, Polovina JJ. 2010. Spatiotemporal variability in bigeye tuna (Thunnus obesus) dive behavior in the central North Pacific Ocean. Prog Oceanogr. 86(1):81–93.

14. Farley JH, Clear NP, Leroy B, Davis TLO, McPherson G. 2006. Age, growth and preliminary estimates of maturity of bigeye tuna, Thunnus obesus, in the Australian region. Mar Freshw Res. 57(7):713–724.

15. Nootmorn P. 2004. Reproductive biology of bigeye tuna in the Eastern Indian Ocean. IOTC Proc. 7:1–5.

16. Schaefer KM, Fuller DW, Miyabe N. 2006. Reproductive biology of bigeye tuna *Thunnus obesus* in the eastern and central Pacific Ocean. Inter-Amer Trop Tuna Comm Bull. 23:3–31.

17. Zhu G, Dai X, Xu L, Zhou Y. 2010. Reproductive biology of Bigeye Tuna, Thunnus obesus, (Scombridae) in the eastern and central tropical Pacific Ocean. Environ Biol Fishes.88(3):253–260.

18. Sun CL, Yeh SZ, Chang YJ, Chang HY, Chu SL. 2013. Reproductive biology of female bigeye tuna Thunnus obesus in the western Pacific Ocean. J Fish Biol. 83(2):250–271.

19. Kailola PJ, Williams MJ, Stewart PC, Reichelt RE, McNee A, Grieve C. 1993. Australian fisheries resources. Canberra, Australia:Bureau of Resource Sciences.

20. Kikawa S. 1966. The distribution of maturing bigeye and yellowfin and an evaluation of their spawning potential in different areas in the tuna longline grounds in the Pacific. Rep Nankai Reg Fish Res Lab. 23:131–208.

21. Nikaido H, Miyabe N, Ueyanagi S. 1992. Spawning time and frequency of bigeye tuna, *Thunnus obesus*. Bull Natl Res Inst Far Seas Fish. 28:47–73.

22. Houde ED, Richards WJ. 1969. Rearing larval tunas in the laboratory. Comml Fish Rev. 31:32–34.

23. Boehlert GW, Mundy BC. 1996. Ichthyoplankton vertical distributions near Oahu, Hawaiʻi, 1985-1986: Data Report. U.S. Dept Commer, NOAA Technical Memorandum. NMFS-SWSC-235. pp. 148.

24. Paine MA, McDowell JR, Graves JE. 2008. Specific identification using COI sequence analysis of scombrid larvae collected off the Kona coast of Hawaii Island. Ichthyol Res. 55:7–16.

25. Reglero P, DP T, Álvarez-Berastegui D, Aparicio-González A, Worm B. 2014. Worldwide distributions of tuna larvae: revisiting hypotheses on environmental requirements for spawning habitats . Mar Ecol Prog Ser. 501:207–224.

26. Adam MS, Sibert J, Itano D, Holland K. 2003. Dynamics of bigeye (Thunnus obesus) and yellowfin (T. albacares) tuna in Hawaii's pelagic fisheries: Analysis of tagging data with a bulk transfer model incorporating size-specific attrition. Fish Bull. 101(2):215–228.

27. Hampton J, Gunn J. 1998. Exploitation and movements of yellowfin tuna (Thunnus albacares) and bigeye tuna (T. obesus) tagged in the north-western Coral Sea. Mar Freshw Res. 49(6):475–489.

28. Itano DG, Holland KN. 2000. Movement and vulnerability of bigeye (Thunnus obesus) and yellowfin tuna (Thunnus albacares) in relation to FADs and natural aggregation points. Aquat Living Resour. 13(4):213–223.

29. Sibert JR, Musyl MK, Brill RW. 2003. Horizontal movements of bigeye tuna (Thunnus obesus) near Hawaii determined by Kalman filter analysis of archival tagging data. Fish Oceanogr. 12(3):141–151.

30. Potier M, Marsac F, Lucas V, Sabatié R, Hallier J, Ménard F. 2004. Feeding partitioning among tuna taken in surface and mid-water layers: the case of yellowfin ( Thunnus albacares ) and bigeye ( T. obesus ) in the Western Tropical Indian Ocean. West Indian Ocean J Mar Sci. 3(1):51–62.

31. Schaefer KM, Fuller DW. 2010. Vertical movements, behavior, and habitat of bigeye tuna (Thunnus obesus) in the equatorial eastern Pacific Ocean, ascertained from archival tag data. Mar Biol. 157(12):2625–2642.

32. Rooker JR, David Wells RJ, Itano DG, Thorrold SR, Lee JM. 2016. Natal origin and population connectivity of bigeye and yellowfin tuna in the Pacific Ocean. Fish Oceanogr. 25(3):277–291.

33. Schaefer K, Fuller D, Hampton J, Caillot S, Leroy B, Itano D. 2015. Movements, dispersion, and mixing of bigeye tuna (Thunnus obesus) tagged and released in the equatorial Central Pacific Ocean, with conventional and archival tags. Fish Res. 161:336–355.

34. Aires-da-Silva AM, Maunder MN, Schaefer KM, Fuller DW. 2015. Improved growth estimates from integrated analysis of direct aging and tag–recapture data: An illustration with bigeye tuna (Thunnus obesus) of the eastern Pacific Ocean with implications for management. Fish Res. 163:119–126.

35. Kume S, Joseph J. 1969. The Japanese longline fishery for tunas and billfishes in the eastern Pacific Ocean east of 130 W, 1964-1966. Inter-American Trop Tuna Comm Bull. 13:275–418.

36. Sun C-L, Huang C-L, Yeh S-Z. 2001. Age and growth of the bigeye tuna, Thunnus obesus, in the western Pacific Ocean. Fish Bull. 99:502.

37. McKechnie S, Pilling G, Hampton J. 2017. Stock assessment of bigeye tuna in the Western and Central Pacific Ocean. Noumea, New Caledonia: The Pacific Community.

38. Harley S, Davies N, Hampton J, McKechnie S. 2014. Stock assessment of bigeye tuna in the Western and Central Pacific Ocean. Noumea, New Caledonia: The Pacific Community.

39. Aires-da-Silva A, Minte-Vera C, Maunder MN. 2017. Status of bigeye tuna in the eastern Pacific Ocean in 2016 and outlook for the future. Inter-Amer Trop Tuna Comm. SAC-08-04a.

40. Majkowski J. 2007. Global fishery resources of tuna and tuna-like species. FAO Fisheries Technical Paper; No. 483. Rome:FAO. pp. 54.