Pycnopodia helianthoides - (Brandt, 1835)

ANIMALIA - ECHINODERMATA - ASTEROIDEA - FORCIPULATIDA - ASTERIIDAE - Pycnopodia - helianthoides

Common Names: Sunflower Seastar (English), Rag Mop (English), Slime Star (English), Sunflower Sea Star (English), Sunflower Star (English), Sunflower Starfish (English)
Synonyms: Asterias helianthoides Brandt, 1835

Taxonomic Note:
The genus *Pycnopodia* is monophyletic, and *Pycnopodia helianthoides* is the only species in the genus. *Pycnopodia helianthoides* is one of only two species in the sub-family Pycnopodiinae, the other is *Lysastrosoma anthosticta* from Japan (Accessed through: WoRMS, World Register of Marine Species at: http://www.marinespecies.org/aphia.php?p=taxdetails&id=240764 on 2020-08-04).

Red List Status	
CR - Critically Endangered, A2ace (IUCN version 3.1)	
Possibly Extinct:	No
Possibly Extinct in the Wild:	No
Date Last Recorded (in the wild):	

Red List Assessment

Assessment Information

Reviewed?	Date of Review:	Status:	Reasons for Rejection:	Improvements Needed:
true	2020-08-31	Passed	-	-

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Assessment Rationale

Pycnopodia helianthoides has experienced dramatic decreases in population size and range after enduring a global disease outbreak of sea star wasting syndrome (SSWS). From 2013-2017, *Pycnopodia* and other sea star species were devastated by SSWS, which affected a variety of sea star species across more than 5,000 km of the western coast of North America (Hewson *et al.* 2014, 2019; Menge *et al.* 2016; Montecino-Latorre *et al.* 2016; Miner *et al.* 2018; Harvell *et al.* 2019; Konar *et al.* 2019). Prior to 2013, *Pycnopodia* was regularly found in a variety of shallow marine habitats from the Pacific Coast of Baja California, Mexico to the Aleutian Islands, Alaska, United States. It is a non-harvested, generalist species and had few major threats prior to the disease outbreak.

After the rapid loss of *Pycnopodia* to SSWS from 2013-2017, we compiled 31 datasets including 61,043 surveys that showed that *Pycnopodia* population size declined by 90.6% from its historic to its current population size. Additionally, the area of occupancy has declined 57.6% from 4,052 km² before the outbreak (2003-2012) to 1,716 km² afterward. The species is now extremely rare across much of the outer coast of the contiguous United States and Mexico, a swath of 2500 km of coastline. Since the initial outbreak subsided around 2016-17, *Pycnopodia* populations have not begun to recover, are still declining in many regions, and have reached near-zero densities along the outer coasts of the contiguous United States and Mexico. Further, there is evidence that the disease is still present in remaining populations, and warming water from global climate change seems to contribute to disease severity.

The decline of this predatory sea star species may have ecosystem-wide implications. Evidence in some locales suggests that the loss of predatory *Pycnopodia* on rocky reefs can substantially reduce their predation on sea urchins, allowing urchins populations to grow and overgraze kelp. Kelp are the foundational species in kelp forest ecosystems and provide habitat and food to many organisms, including those in important fisheries (e.g. abalone, rockfish). However, it is not yet known whether the role of *Pycnopodia* as a sea urchin predator is a key driver of kelp forest health in North America or whether their role is important only under certain circumstances. In places where *Pycnopodia* does benefit kelp, the recovery of *Pycnopodia* may be a valuable management tool for maintaining healthy kelp forest ecosystems in the future.

Pycnopodia meets the qualification for Critically Endangered under Criterion A2ace on the basis of its 90.6% global decline. Additionally, it qualifies for Vulnerable under Criterion B2ab as its current area of occupancy is less than 2,000 km², its number of locations could be as low as 1, and there is evidence for continuing population declines. *Pycnopodia* qualifies as Least Concern under Criteria C and D, and Data Deficient under Criterion E. For further details see the Supplementary Materials.

Distribution

Geographic Range

Range Description
Pycnopodia helianthoides is commonly found in marine waters ranging from the Aleutian Islands, Alaska, United States to San Diego, California, United States (Herrlinger 1983). However, this global analysis shows that the historical southern limit of *Pycnopodia* extends to Isla Natividad, Baja California, Mexico (27.84501°N, 115.1428°W). From there, it used to be common northward throughout the Pacific coastline of North America. Our northernmost observation is in Bettles Bay near Anchorage Alaska, United States (60.95496°N, 148.29942°W). From our data, it also extends westward along the Aleutian Island chain to the Fox Islands near Nikolski, Alaska (52.63844°N, 169.1337°W), and researchers have observed it as far west as Kuluk Bay, Adak Island, in the Andreanof Islands in 2006 (S. Jewett pers. comm. 2020). Other than a single, and perhaps misidentified, observation near St. George Island, Alaska (56.67678°N, 169.5519°W), the species does not appear to extend into the Bering Sea.

Depth Range
Our analysis and historical records show that the depth range of *Pycnopodia* is from 0 to 455 m (0–1,493 ft) with the highest abundance between 0 and 25 m deep. They are rare deeper than 120 m (394 ft) (Fisher 1928, Lambert 2000, Hemery *et al.* 2016).

Number of Locations
The primary threat to *Pycnopodia* is sea star wasting syndrome, which appears to have caused declines in all populations globally within three years. Thus, the minimum number of locations (defined by IUCN as a geographically or ecologically distinct area in which a single threatening process can rapidly affect all occurrences of an ecosystem type) could be as low as 1. However, considering the species' broad geographic range and the finding

that populations in the northwestern edge of its range may have been less affected by the disease, the number of locations may be as high as 10.

Elevation / Depth / Depth Zones

Depth Lower Limit (in metres below sea level): 455

Depth Upper Limit (in metres below sea level): 0

Depth Zone: Shallow photic (0-50m), Deep Photic (51-200m), Bathyl (201-4,000m)

Map Status

Map Status	Use map from previous assessment	How the map was created, including data sources/methods used:	Please state reason for map not available:	Data Sensitive?	Justification	Geographic range this applies to:	Date restriction imposed:
Done	-	-	-	-	-	-	-

Occurrence

Countries of Occurrence

Country	Presence	Origin	Formerly Bred	Seasonality
Canada	Extant	Native	-	Resident
Canada -> British Columbia	Extant	Native	-	Resident
Mexico	Possibly Extant	Native	-	Resident
Mexico -> Baja California	Possibly Extant	Native	-	Resident
Mexico -> Baja California Sur	Possibly Extant	Native	-	Resident
United States of America	Extant	Native	-	Resident
United States of America -> Alaska	Extant	Native	-	Resident
United States of America -> Aleutian Is.	Extant	Native	-	Resident
United States of America -> California	Extant	Native	-	Resident
United States of America -> Oregon	Extant	Native	-	Resident
United States of America -> Washington	Extant	Native	-	Resident

Large Marine Ecosystems (LME) Occurrence

	Presence	Origin	Formerly Bred	Seasonality
2.2.3. Westerlies Biome -> Pacific Provinces -> Gulf of Alaska	Extant	Native	-	Resident

4.5.2. Coastal Biome -> Pacific Coastal Provinces -> California Current	Extant	Native	-	Resident

FAO Area Occurrence

	Presence	Origin	Formerly Bred	Seasonality
67. Pacific - northeast	Extant	Native	-	Resident
77. Pacific - eastern central	Extant	Native	-	Resident

Population

Historical Abundance
Literature on *Pycnopodia* abundance before the 2013–2017 sea star wasting disease outbreak suggests that they were fairly common throughout their range. These include studies from Alaska, United States (Duggins 1983, Konar *et al.* 2019), British Columbia, Canada (Montecino-Latorre *et al.* 2016, Schultz *et al.* 2016, Burt *et al.* 2018), Oregon, United States (Hemery *et al.* 2016), and California, United States (Herrlinger 1983, Eckert 2007, Rassweiler *et al.* 2010, Bonaviri *et al.* 2017, Rogers-Bennett and Catton 2019, Eisaguirre *et al.* 2020). The most geographically comprehensive study was done by Harvell *et al.* (2019) from Alaska to California. For details on each of these studies, please see the Supplementary Material: *Pycnopodia* Populations in the Literature.

The Outbreak of Sea Star Wasting Syndrome
Many of the studies referenced above detail the recent declines in *Pycnopodia* populations caused by the outbreak of sea star wasting syndrome (SSWS) that began in 2013 (Montecino-Latorre *et al.* 2016, Schultz *et al.* 2016, Bonaviri *et al.* 2017, Burt *et al.* 2018, Harvell *et al.* 2019, Konar *et al.* 2019, Rogers-Bennett and Catton 2019, Eisaguirre *et al.* 2020). Harvell *et al.* (2019) showed a 100% decline in Oregon and California and a 99.2% decline in Washington due to SSWS. SSWS is the largest marine epizootic on record (Harvell *et al.* 2019) and affected over 20 species of sea stars (Hewson *et al.* 2014). *Pycnopodia* was especially vulnerable (Montecino-Latorre *et al.* 2016, Schultz *et al.* 2016) because it was the most susceptible of the sea star taxa affected by the multi-host SSWS pathogen (Harvell *et al.* 2019). SSWS was first observed in the Olympic Coast of Washington in June 2013 followed by Central California and the Salish Sea in summer 2013. It quickly expanded south to Mexico and slowly northward, arriving in the Aleutian Islands by 2016. While the cause of SSWS is unclear (Hewson *et al.* 2018), it causes lesions, arm loss, and ultimately death within days to weeks, and very few individuals recover once symptoms appear (Hewson *et al.* 2014).

Estimating Population Sizes over Time
We assessed the global population of *Pycnopodia* using 31 datasets (Supp. Fig.1 and Supp. Table 1) from the Aleutian Islands, Alaska to the Baja California Peninsula, Mexico. These included 61,043 surveys spanning from 1967 to 2020 and distributed from the rocky intertidal to the bathyal plain at 984m deep. Since the *Pycnopodia* decline followed an abrupt non-linear pattern (Supp. Fig. 2), we elected to compare the population decline before versus after sea star wasting syndrome (see Supplementary Material for more detail on this timeline). To estimate global population trends (Supp. Fig. 3), we first the estimated seafloor surface area among regions and depths to quantify available habitat (Supp. Tables 2 and 3). We then determined how densities (1987-2019) of *Pycnopodia* varied by region, depth, and outbreak phase (Supp. Fig. 4 and Supp. Tables 2 and 5). We then multiplied density by habitat area to calculate the estimated population size before and after the SSWS outbreak (Supp. Fig. 3 and Supp. Table 2). For further details on these methods, please refer to Supplementary Material: Population Data and Methods for IUCN Assessment.

Global Decline
Our global analysis confirms the declines caused by sea star wasting syndrome documented in many of the studies above. Indeed, many of the datasets in the references above were included in our global analyses. We calculated a 90.6% global decline in *Pycnopodia* population size when comparing before (1987-2013) to after (2014, 2015 or 2017-2019, depending on the region) the SSWS outbreak (Supp. Fig. 3 and Supp. Table 2). The decline extended to all depths, with a 92.9% decline in deep depths (>25m) and a 93.8% decline in shallow depths (<25m) (Supp. Table 2). The global post-decline population estimate is 594,251,528 (average between 2014/2015/2017 and 2019, depending on timing of the decline in each region). However, the global estimate for 2019 is 80,627,721.

Region-Specific Declines

Among regions in shallow waters (where the vast majority of animals are found), the most severe declines occurred in the Pacific coast of the Baja California Peninsula and the outer coast of the western continental United States, where the decline ranged from 97.2% - 99.8% (Supp. Fig. 3 and Supp. Table 2). Severe declines also occurred in many northern regions, including a 91.9% decline in the Salish Sea, a 94.7% decline in southeast Alaska, and a 94.9% decline in the eastern Gulf of Alaska.

The western Gulf of Alaska and the Aleutian Islands showed more moderate population declines (61.1% decline, Supp. Table 2), and observations by contributors suggest the disease was less severe in these regions (B. Konar, pers. comm. 2020). However, sparse observations make these estimates uncertain (Supp. Table 2; N = 7 surveys after the SSWS-induced decline). We present two estimates of decline for the north, central and coastal British Columbian coast. The first compares before and after the Aug 1 2015 pre-/post-crash cutoff (matches analysis use for other regions) and indicates a moderate decline (67.4%). However, we believe this number is an underestimate because it incorporates the data from juvenile animals that recruited to Calvert Island, British Columbia shortly after SSWS. This population then experienced a second decline in 2018, presumably due to another SSWS outbreak, and most did not reach adult size (A. Gehman pers. obs. 2020). We were not able to separate these juveniles from adults, so we narrowed our post-decline population estimate using data from 2018-2019 only, when the second outbreak had subsided and the remaining animals were generally nearing adult size. Using this method, we estimated that the decline in this region was 89.9% (Supp. Table 2).

Continued Declines

The remaining populations are primarily in the northern half of the species' previous range and are patchily-distributed populations in the Aleutians, the Gulf of Alaska, north, central and coastal British Columbia, and the Salish Sea (Supp. Fig. 3 and Supp. Table 2). Very few animals remain along the outer coast of the United States and Mexico (Supp. Fig. 3 and Supp. Table 2). Importantly, there is little indication that *Pycnopodia* is in the process of recovering from the outbreak (Supp. Fig. 5 and Supp. Table 4). Indeed, most regions with remaining populations, including much of Alaska and British Columbia (including the Salish Sea), have exhibited continuing declines since 2017. Regions on the outer coast of the contiguous United States and Mexico, have "flat lined" at extremely low densities (Supp. Fig. 5; Washington outer coast, Oregon, North, Central, Southern and Baja California). *Pycnopodia* is now very rare along this > 2500 km stretch of coastline, and seem to be decreasing. Notably, in all of the United States and Mexican contiguous outer coast, only 20 of 3976 total surveys recorded an animal between 2018-2019, with only 7 in California, and most of these were lone individuals. No animals have been recorded in Baja California since 2015, and none in California in 2019 (Supp. Table 4).

Population Information

Continuing decline in mature individuals?	Qualifier	Justification
Yes	-	-

Habitats and Ecology

Habitats

Pycnopodia appears to be a habitat generalist, occurring on many different types of marine habitats including mud, sand, shell, gravel, rocky bottoms, kelp forests, and the lower rocky intertidal (Fisher 1928, Mauzey *et al.* 1968, Lambert 2000). Previous work on *Pycnopodia* has shown variable associations with one or another habitat types depending on life stage and region (Shivji *et al.* 1983). Our analysis of habitat preferences showed that no clear associations of *Pycnopodia* with particular habitat or substrate types in California (see Supplementary Material: Data Analysis: Depth and Habitat Patterns for more information). Because of this finding, we did not incorporate habitat type into our population estimates.

Depths

Previous sources have identified the depth range of *Pycnopodia* to be from 0 - 435 m (0 - 1427 ft) and typically no more than 120 m (394 ft) (Fisher 1928, Lambert 2000, Hemery *et al.* 2016). In our global analysis, we found that *Pycnopodia* was most abundant before the sea star wasting syndrome outbreak in shallow nearshore waters less than 25 m (82 ft), less abundant in middle depths 25 m to 50 m (164 ft), and present but rare to depths up to 300 m (Mean ± SD: 39,077 ± 226,556 km^{-2}, 1,996 ± 5,573 km^{-2}, and 204 ± 740 km^{-2}, respectively). The large standard deviations in these averages are because *Pycnopodia* tends to be patchily distributed. *Pycnopodia* was very rare below 300 m depth, with only 12 records. The deepest record was 455 m (1493 ft), though it is possible that this and other deep

records were actually misidentified *Rathbunaster californicus*, a species that looks similar and extends deeper. The upper depth range extends into the low intertidal zone to around 0 m above mean lower low water, especially along the Alaskan coast (Konar *et al.* 2019). Regarding depth preferences in shallower waters within the range of SCUBA (<30 m or <100 ft), no pattern in densities (Bonaviri *et al.* 2017) nor sizes (Shivji *et al.* 1983) with depth have been noted in the literature. We also detected no pattern in densities within this shallower range (up to 25 m).

Environmental Range
The large geographic range of this species indicates it can inhabit a wide variety of environments. Along the Oregon coast, correlations between *Pycnopodia* distributions and environmental conditions suggest that their abundances are driven most strongly by annual mean daily water temperature (peak at 9-11.5 °C), depth (peak at 0 to 75m) and annual mean daily salinity (peak at 33.0-33.4 PSU), in that order (Hemery *et al.* 2016). Within the 12-16°C gradient in mean annual water temperature along the Channel Islands, California, *Pycnopodia* was more abundant at the cooler western islands (San Miguel and Santa Rosa Islands) than the warmer eastern islands (Anacapa and Santa Barbara Islands), and 14°C seemed to be strong cutoff driving abundance (Bonaviri *et al.* 2017).

Diet and Ecological Role
Pycnopodia is a generalist and opportunistic predator that consumes a large number of prey taxa including but not limited to gastropods, echinoderms, and crustaceans (Supp. Fig. 6; Mauzey *et al.* 1968, Herrlinger 1983, Beas-Luna *et al.* 2014). *Pycnopodia* is usually considered a macroinvertivore since the bulk of its prey fit this category. Preferred prey items vary due to local abundance, climate, latitude, and habitat gradients. For example, Mytilus trossulus (formerly M. edulis) has been reported to be a favorite prey item in the Gulf of Alaska (Paul and Feder 1975), gastropods in British Columbia (Shivji *et al.* 1983), sea urchins in northern California (Rogers-Bennett and Catton 2019) and gastropods and crustaceans in central California (Herrlinger 1983). Interestingly, very few species feed on *Pycnopodia* (Supp. Fig. 6; Mauzey *et al.* 1968).

As a generalist predator, *Pycnopodia* can regulate the structure of nearshore benthic communities and are considered a keystone predator in some areas across its distribution (Duggins 1983, Herrlinger 1983). *Pycnopodia* preys on sea urchins (Strongylocentrotus purpuratus, S. droebachiensis, and Mesocentrotus franciscanus) and can create small, urchin-free zones through direct predation or by causing sea urchin "stampedes" (Paine and Vadas 1969, Duggins 1983, Watson and Estes 2011). Since sea urchins feed on kelp (primarily Macrocystis pyrifera, and Nereocystis luetkeana) the short-term existence of prey-free patches can influence algal diversity, community primary productivity, and kelp forest community structure (Paine and Vadas 1969, Dayton 1975, Duggins 1983, Herrlinger 1983). Since the SSWS outbreak began in 2013, several papers have identified further evidence of the potential ecological role *Pycnopodia* can play in kelp forest ecosystems. The loss of this predator was associated with a 311% increase in the abundance of medium-sized urchins and a 30% decline in kelp densities in British Columbia, suggesting *Pycnopodia* exerts top-down control over urchin populations (Burt *et al.* 2018). A similar phenomenon has been observed in southern British Columbia, Northern California, and southern California (Schultz *et al.* 2016, Rogers-Bennett and Catton 2019, Eisaguirre *et al.* 2020). The potential for *Pycnopodia* to play a role in regulating kelp forest community structure and dynamics may be strongest in regions lacking other sea urchin predators, such as otters.

Life History and Reproduction
Pycnopodia has separate sexes and broadcast spawn to produce free-swimming, feeding, pelagic larvae (Greer 1962, Morris *et al.* 1980). The larvae develop for 50-146 days before settling and metamorphosing (Strathmann 1978, J. Hodin pers. comm. 2020). Beyond this basic information, little is understood about the reproductive ecology, growth rates, physiology, and longevity of *Pycnopodia*. They exhibit indeterminate growth and have not been individually tagged successfully nor reared in captivity from birth through adulthood, so determining lifespan and growth rates is challenging. We interviewed aquarists and larval ecologists, gathered size distribution data and used models to estimate the generation time for *Pycnopodia*. We found generation time to be in the range of 20.5 – 65 years, with the middle-most estimates providing a narrower range of 27 – 37 years range (Supp. Figs. 7 and 8 and Supp. Table 6). For more information on reproduction, life history, and generation time modeling, see Supplementary Materials: Habitats and Ecology: Life History and Ecology & Determination of Generation Time.

IUCN Habitats Classification Scheme

Habitat	Season	Suitability	Major Importance?
9.2. Marine Neritic -> Marine Neritic - Subtidal Rock and Rocky Reefs	Resident	Suitable	Yes

9.3. Marine Neritic -> Marine Neritic - Subtidal Loose Rock/pebble/gravel	Resident Suitable	Yes
9.4. Marine Neritic -> Marine Neritic - Subtidal Sandy	Resident Suitable	Yes
9.5. Marine Neritic -> Marine Neritic - Subtidal Sandy-Mud	Resident Suitable	Yes
9.6. Marine Neritic -> Marine Neritic - Subtidal Muddy	Resident Suitable	Yes
9.7. Marine Neritic -> Marine Neritic - Macroalgal/Kelp	Resident Suitable	Yes
9.9. Marine Neritic -> Marine Neritic - Seagrass (Submerged)	Resident Suitable	Yes
11.1.1. Marine Deep Benthic -> Marine Deep Benthic - Continental Slope/Bathyl Zone (200-4,000m) -> Hard Substrate	Resident Marginal	-
11.1.2. Marine Deep Benthic -> Marine Deep Benthic - Continental Slope/Bathyl Zone (200-4,000m) -> Soft Substrate	Resident Marginal	-
12.1. Marine Intertidal -> Marine Intertidal - Rocky Shoreline	Resident Marginal	-
12.6. Marine Intertidal -> Marine Intertidal - Tidepools	Resident Marginal	-
15.11. Artificial/Aquatic & Marine -> Artificial/Marine - Marine Anthropogenic Structures	Resident Suitable	No

Life History

Generation Length	Justification	Data Quality
27-37	-	-

Age at maturity: female or unspecified
5 Years

Size at Maturity (in cms): Female
30

Maximum Size (in cms)
110

Movement Patterns

Movement Patterns: Not a Migrant

Systems

System: Marine

Use and Trade

General Use and Trade Information

No targeted fisheries exist for *Pycnopodia*. Although most regions allow recreational harvest of *Pycnopodia*, the harvest rate is likely extremely low. However, *Pycnopodia* is routinely encountered as bycatch in bottom-contacted pot and trap fisheries as well as trawl and seine fisheries (Supp. Figs. 9 and 10). The encounter rate and survival rate as bycatch is unclear. They are difficult to disentangle without injury, so handling may decrease survival. There is no evidence that this species is widely traded as a live animal in the aquarium trade. Their large size and predatory behavior probably deter nearly all aquarists. Although not pervasive, dried "sunflower sea stars" are commercially sold individually online as decor. For details, see the Supplementary Material: Use and Trade.

Subsistence:	Rationale:	Local Commercial:	Further detail including information on economic value if available:
No	-	No	-

National Commercial Value: Yes

International Commercial Value: Yes

End Use	Subsistence	National	International	Other (please specify)
10. Wearing apparel, accessories	-	true	true	-

Is there harvest from captive/cultivated sources of this species? No

Threats

Disease
Without question, disease is currently the greatest threat to *Pycnopodia* populations. This global analysis and many published works (Hewson *et al.* 2014, Montecino-Latorre *et al.* 2016, Schultz *et al.* 2016, Burt *et al.* 2018, Harvell *et al.* 2019, Konar *et al.* 2019, Rogers-Bennett and Catton 2019, Eisaguirre *et al.* 2020) demonstrate that this species' precipitous decline corresponds to the outbreak of sea star wasting syndrome in 2013-2017. Though the global outbreak appears to have subsided, localized outbreaks continue to occur in *Pycnopodia* and other sea star species. The pathogen or agent that causes SSWS remains unknown (Hewson *et al.* 2016, 2019). While disease is the proximate threat, there is also evidence that climate change in the form of increasing temperatures exacerbates or may have triggered the disease (see Climate Change below). It is imperative that we understand disease etiology and dynamics in coordination with any attempts to mitigate disease effects or aid *Pycnopodia* recovery. For more information see Supplementary Material: Threats.

Climate Change
There is evidence that warmer temperatures speed the progression and increase mortality from SSWS in the laboratory (Eisenlord *et al.* 2016, Kohl *et al.* 2016). Anomalously warm water temperature has been associated with region-specific timing of SSWS outbreaks in *Pycnopodia* (Eisenlord *et al.* 2016, Harvell *et al.* 2019, Aalto *et al.* 2020). Understanding the mechanistic relationship between temperature and SSWS will help to understand the continued risks for *Pycnopodia* and inform recovery efforts. For more on the interaction of climate change and SSWS threats, please see the Supplementary Material: Threats.

It also is likely that warming waters with global climate change may directly decrease *Pycnopodia* densities. Along the Oregon coast, Hemery *et al.* (2016) found strong effects of temperature, with peak abundances occurring at 9–11.5°C. Similarly, in Southern California warmer water temperature was associated with decreasing density of *Pycnopodia*, and 14°C seemed to be a strong cutoff driving abundance (Bonaviri *et al.* 2017). Overall, it is possible that ocean warming from human-caused climate change could drive decreases in *Pycnopodia* density in surviving populations or prohibit recovery.

Fishing and Trade
While bycatch of *Pycnopodia* occurs in multiple fisheries (i.e. trap, seine, and trawl), more information is needed to determine whether this is a threat to *Pycnopodia* populations. Similarly, we do not know whether dried *Pycnopodia* traded by online retailers represents a threat. Finally, there are anecdotal observations that refuge populations of *Pycnopodia* in the fjords of British Columbia may be disrupted by the practice of "log dumping", where timber is

felled into the fjords before transport (T. Blaine, pers. comm.). The threat this poses to these refuge populations is unknown. When population sizes of *Pycnopodia* are large, it is unlikely that any of these external sources of mortality from fishing and trade pose a substantial threat to the species. However, these activities could hinder population recovery in areas with severely reduced population sizes. Further investigation of these potential threats is needed.

Conservation

Determining the Cause of SSWS
The cause of SSWS is an essential question that should be answered before we can determine the advisability of *Pycnopodia* recovery efforts. The persistence of SSWS, especially in other species, may potentially negate or greatly reduce the efficacy of any *Pycnopodia* captive rearing and reintroduction efforts outlined below. Further, we have no diagnostic test for SSWS to ensure that sea stars that we may introduce to the wild are not a danger to wild *Pycnopodia* or to other sea stars.

Captive Rearing and Reintroduction
Captive rearing is the most viable recovery option for locales with few or no *Pycnopodia* that are far from surviving populations (i.e. the outer Pacific coasts of the United States and Mexico). While this conservation action does not address the underlying threats to *Pycnopodia* (disease and climate change), it can be used to restore populations in suitable areas that may not otherwise recover on their own. Drawing from aquaculture practices, captive rearing of *Pycnopodia* has the potential for cost-effective high production on a relatively quick timescale. Captive rearing efforts could provide a reservoir of individuals to maintain genetic diversity, maintain population numbers, and aid in the recovery of the species. Further, captive rearing programs can have the simultaneous benefit of being scientific resources to study SSWS and to gather information on the life history and environmental niche of *Pycnopodia*, which could aid subsequent recovery efforts. To this end, the Nature Conservancy and the University of Washington have collaborated to begin the captive rearing of *Pycnopodia*, have demonstrated its feasibility, and have accumulated valuable life history information (e.g., growth rates, environmental conditions, diets) that will inform future conservation actions.

Reducing Lethal Take
While we assume direct harvest is relatively low (see Use and Trade), even a small amount of take in this critically endangered species can hinder recovery. Currently, there are few protections against harvest of *Pycnopodia* in most regions and we have little information on harvest statistics. Enacting specific regulations that disallow the targeted harvest of *Pycnopodia* could reduce this source of mortality, which could be particularly important for small, remnant populations.

Reducing bycatch, particularly in trap fisheries, is an additional potential conservation action to aid recovery of *Pycnopodia*. Since the threat posed by bycatch to *Pycnopodia* is unclear (see Use and Trade and Threats), the first conservation action should be to determine its magnitude. If bycatch indeed can cause decline or hinder recovery (particularly in vulnerable populations), public engagement with the recreational and commercial fleets about best practices for catch and release would be a logical next step.

Localized Protections
The recovery of isolated or sparse populations of adult *Pycnopodia* or the success of new recruitment events may also benefit from locally focused protection from take or disturbance. For example, one of the few surviving populations of *Pycnopodia* in the contiguous United States occurs in Hood Canal, Washington, where bycatch from the local crab fishery could have a negative impact on persistence or recovery. Similarly, there are surviving populations in the fjords of Central British Columbia (T. Blaine pers. comm. 2020) where the practice of "log dumping" (felling or storing trees in the marine environment for later transport), could have detrimental effects on those populations. Some localized, and perhaps temporary, protections against human activity for these survivors may aid local recovery. Further, there is modest evidence that juvenile *Pycnopodia* utilize nearshore seagrass beds as a nursery habitat (A. Gehman and M. Miner pers. obs. 2020). Seagrass beds are highly susceptible to habitat degradation (Orth *et al.* 2006) so protecting these habitats may aid *Pycnopodia* recovery. Finally, the recovery of this species in severely affected areas is contingent on recruitment from remote source populations. Since recruitment of *Pycnopodia* is often episodic and mortality of juveniles quite high (Sewell and Watson 1993), the success of a recruitment event may hinge on the local rates of mortality from human activities like fishing and habitat destruction.

Marine Protected Areas (MPAs) may also serve as a viable, but less targeted, conservation action. While the spatially explicit protection afforded by MPAs does not necessarily protect *Pycnopodia* from its two most important threats, SSWS and climate change, MPAs can mitigate harvest, pollution, and habitat degradation. Multiple MPAs already exist in Canada, the United States, and Mexico, and comprise ~1.55% of the range of *Pycnopodia* (5,377,374 km²; see

Supplemental Material: Conservation Actions for details on these MPAs). These MPAs could also serve as target areas for the restoration and re-establishment of *Pycnopodia* by affording space-based protections during recovery. (see Supplemental Material: Conservation Actions and https://docs.google.com/spreadsheets/d/10UM662HazRfvtnCrXdUJAszUn6jvoOk-Yj5XiHETU30/edit?usp=sharing for details on these MPAs).

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