Roadmap to Recovery for the Sunflower Sea Star

ALONG THE WEST COAST OF NORTH AMERICA

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

The Nature Conservancy

TRILATERAL COMMITTEE for Wildlife and Ecosystem Conservation and Management

Roadmap to Recovery for the Sunflower Sea Star

ALONG THE WEST COAST OF NORTH AMERICA

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SPECIES NAME

Sunflower sea star,
Pycnopodia helianthoides

SPECIES RANGE

Baja California, Mexico, to Alaska, US

CONSERVATION STATUS

International Union for Conservation of Nature (IUCN) Critically Endangered, December 2020; petition for US Endangered Species Act (ESA) listing filed on August 18, 2021, and status review in progress; status report being compiled for consideration by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC).

Purpose of this Document

This document articulates a multi-faceted and multi-partner Roadmap to Recovery (Roadmap) for the sunflower sea star (*Pycnopodia helianthoides*) along the West Coast of North America. The species has experienced catastrophic declines across much of its range, principally due to sea star wasting disease. This Roadmap provides an overview of key near- and medium-term steps to arrest further declines and to foster recovery of populations that in turn can support species-level viability. This Roadmap also provides a range-wide overview of regional differences in declines to promote linkages among federal, state, and tribal efforts throughout the range of sunflower sea stars, which includes Mexico, the US, Canada, and the lands and waters of American Indian tribes and indigenous First Nations.

SUGGESTED CITATION

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EXECUTIVE SUMMARY

The sunflower sea star (*Pycnopodia helianthoides*) is among the largest sea stars in the world, ranging from Baja California, Mexico, to the Aleutian Islands of Alaska in the US. Adults are found in a wide range of depths and habitats. Even though they were once common and abundant, surprisingly little is known about the species' life history and ecology, including the role of sunflower sea stars in maintaining healthy kelp forest ecosystems through predation of grazers and how this varies geographically.

A sea star wasting disease (SSWD) event beginning in 2013 reduced the global population of sunflower sea stars by an estimated ninety-four percent, triggering the International Union for the Conservation of Nature (IUCN) to classify the species as Critically Endangered. Declines of ninety-nine to one hundred percent were estimated in the outer coast waters of Baja California, California, Oregon, and Washington. From the Salish Sea to the Gulf of Alaska, declines were greater than eighty-seven percent; however, there is uncertainty in estimates from Alaska due to limited sampling. A range-wide species distribution analysis showed that the importance of temperature in predicting sunflower sea star distribution rose over fourfold following the SSWD outbreak, suggesting latitudinal variation in outbreak severity may stem from an interaction between disease severity and warm waters. Given the widespread, rapid, and severe declines of sunflower sea stars, the continued mortality from persistent SSWD, and the potential for the disease to intensify in a warming future ocean, there is a need for a Roadmap to Recovery to guide scientists and conservationists as they aid the recovery of this Critically Endangered species.

The purpose of this document is to identify key questions and the sequencing of potential actions to prepare for, initiate, and accelerate the recovery of sunflower sea star populations throughout their range. This Roadmap was developed by leading experts to highlight these key questions, immediate and near-term actions, and any important sequencing among seven primary Objectives to streamline and coordinate collective action. Below we synthesize a set of prioritized actions among these seven primary Objectives. The degree of need and timeline of some recovery actions may vary by region. However, given global declines, continued mortality from persistent SSWD, and likelihood of future declines, the need for each region to begin preparing for actions in each of the seven Objectives is clear.

SSWD, epidemiology, risk mitigation

The area of greatest concern and need for immediate action common to all geographic regions is understanding disease prevalence and disease risk. Here we use the term "disease" to describe SSWD, also known as Sea Star Wasting Syndrome or Asteroid Idiopathic Wasting Syndrome, which affects some twenty species of sea stars and the cause(s) of which remain unknown and under debate in the literature. Much work is needed to improve our understanding of SSWD, the cause(s) of SSWD, how SSWD impacts wild sunflower sea stars, SSWD dynamics in a multi-host system, and to discover and develop measures to mitigate SSWD impacts and risks associated with conservation actions.

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2017–2020

5.75 billion
sunflower sea stars died of SSWD

94.3% (± 0.9%)
global decline
(Mean ± SE)
(Gravem et al. 2021, Hamilton et al. 2021)

2,700 km of coastline
showing declines of 99–100% from Baja California, Mexico to Cape Flattery, WA, USA

Declines
greater than 87.8% during this time in the rest of their range from the Salish Sea to the Gulf of Alaska

Key epidemiology actions include:

Key action	Conservation relevance
Identify the causative agent(s) should one or more exist	Enable disease mitigation measures including identification, containment, abatement, prevention
If present, determine sunflower sea star immune response to SSWD	Enable support for resistance and prevention
If a causative agent is identified, investigate how transcriptomics of immunity vary between susceptible and resistant sea star species	Uncover resistance mechanisms in resistant species potentially to be applied to sunflower sea stars, to inform mitigation measures and inform multi-species disease dynamics
Investigate multi-host dynamics	Model multi-host distribution and disease dynamics and how these may affect sunflower sea star population trends to inform conservation actions
Investigate, determine, and communicate disease mitigation measures	May minimize disease impacts, risks, and spread associated with conservation actions
Conduct research to better understand how life history and/or environmental factors may affect disease transmission, population declines, and recovery potential	Inform population modeling and life history or environmentally specific conservation actions

Insights gained from research in epidemiology and disease ecology will be foundationally important to many, if not all, of the actions among the other Objectives. In particular, this affects immediate and near-term work in expanding captive rearing and experiments to determine best approaches for outplanting. In captive rearing settings, there is an immediate need for establishing protocols for the identification of disease and non-disease indicators and appropriate response for each to be communicated among all parties rearing sunflower sea stars. Another immediate need identified is to hold a workshop to explore uncertainties, consider important immediate next steps, and propose best paths forward for disease research, disease mitigation, and immediate conservation actions, including the expansion of captive rearing efforts and experiments to determine best outplanting approaches. Outcomes and assumptions of this roundtable discussion should be clearly articulated to the community of practice working on sunflower sea star research and recovery quickly via the Pycnopodia Recovery Working Group and other outlets to facilitate actions in these areas.

Develop recovery goals, criteria, and thresholds; conduct population modeling

Demographic and genetic recovery criteria are needed to inform if natural recovery is occurring and when and where management actions are needed to guide the recovery of sunflower sea star populations. The IUCN assessment highlighted great variation among the twelve identified regions of the species range. Guidance on a regional scale may require consideration of local environmental and oceanographic features that may drive connectivity or isolation of populations, genetic population structure, and disease prevalence. Goals, criteria, and thresholds should be considered in a nested model: local forcing nested in regions and regional forcing nested in geography irrespective of jurisdictional boundaries.

While there are data gaps identified, there is enough information to begin establishing regionally based goals and criteria and modeling population dynamics. Work should begin on this immediately. As new information is gained to fill spatial and topical gaps, it should be incorporated into regional modeling in an adaptive management framework. This work will be foundational to guiding appropriate and

coordinated recovery, but the challenge of doing so should not be underestimated, as this will require dedicated leads, staff, and funding to accomplish.

Information to direct population modeling and conservation actions

We urge that research priority be given to answering questions important to assessing and monitoring population status, modeling population dynamics, assessing threats, and bettering our understanding of SSWD. Focusing on these topics will illuminate how actions can affect populations of sunflower sea stars.

Population monitoring and data needs

Tracking populations over time is key to estimating losses, monitoring trends, and designing and informing recovery interventions. There are large spatio-temporal gaps in the collection of data needed to inform population dynamics. Notably, Alaska contains the largest portion of the species range yet has very sparse population monitoring data. Improving the spatial and temporal resolution of monitoring density and size frequency has been identified as one of the highest priorities for Alaska. Other regions should also assess their coverage and determine gaps that need filling. All geographies should increase and maintain efforts to monitor populations of sunflower sea stars; this will require continued or increased funding, support, and capacity. Other means of gaining information about the local status of sunflower sea stars, such as the use of eDNA or citizen science efforts, should be pursued, particularly in remote areas and along the outer waters of Washington, Oregon, California, and Baja California where few sunflower sea stars have been recorded in scientific surveys in years.

Genetic structure and diversity

It is also essential to determine the spatial genetic structure of sunflower sea stars. This will enable informed assessment of genetic diversity, degree of local adaptation, and effective population size of populations. These in turn will inform recovery criteria and any translocation projects.

Life history and environmental influences on reproduction, growth, and survival

Understanding natural and anthropogenic sources of mortality and how those vary by life stage and region will likely be key to understanding population dynamics and potential drivers of population resilience. Basic life history attributes, including growth and survival among life stages, generation time, and adult densities needed for spawning will inform demographic processes and population trajectories. Determining if any habitats are disproportionately important to spawning success, recruitment, growth, or survival can inform spatial components of population modeling as well as actions such as habitat protection or restoration that may enhance sunflower sea star population recovery or resilience. This research will need to be conducted in the northern portion of the range where in some locations sunflower sea stars are still relatively common. Fortunately, the mosaic of environmental differences and sunflower sea star habitat variation among and within the Salish Sea, British Columbia, and Alaska may allow projection of results to more southern locations where depletion of sunflower stars preclude most studies.

Expand captive rearing—capture and maintain genetic diversity

Captive rearing provides two benefits to the recovery of sunflower sea stars by 1) providing a scientific platform to research the basic biology, life history, environmental requirements, and disease dynamics for the species to inform population monitoring and recovery goals and thresholds; and 2) the ability to maintain the genetic stock and diversity of the species and produce large numbers of individuals to recover populations that have been wiped out or suffered dramatic declines. Unlike transplanting, captive rearing for outplanting does not deplete population numbers from one area to benefit another.

There is an immediate need to increase the number of facilities that captively rear sunflower sea stars. This will lower the risk of overall culturing failure and will enhance diversity of expertise in a network to expand our knowledge and understanding through scientific research. A network of partners including academic researchers, marine field stations, Association of Zoos and Aquariums (AZA) accredited aquariums, private programs, tribal representatives, state agencies, and federal agencies will provide a diversity of expertise and approaches to develop protocols for captive rearing, establish SSWD risk mitigation protocols, communicate disease identification and response, and answer key questions to inform conservation management and actions. Ideally this network could also provide facilities to represent the local genetic stock and diversity of each region as insurance from further SSWD losses in the wild.

Begin preparing for potential rescue and enhancement

With few sunflower sea stars observed in the outer coast waters of Washington, Oregon, California, and Baja California since 2017 and no clear signs of natural recovery, it appears that assisted recovery measures such as transplanting or outplanting may be necessary to recover populations in this area. Citizen science recorded sunflower sea stars on the Mendocino coast of California in 2021, highlighting 1) the unpredictable nature of marine population dynamics, which is in large part due to the large but spatially variable dispersal of planktonic larvae; 2) the importance of focused work to inform when and where outplanting is appropriate; and 3) the importance of citizen science to inform the recovery of the species. More work is needed to improve our understanding of the current population status, genetic population structure, degree of local adaptation, and disease dynamics among all regions, to inform whether or not outplanting of captively reared sunflower sea stars is merited for population recovery and maintenance. A high priority and area of immediate action is exploring and determining SSWD risk mitigation and protocols associated with captive rearing and outplanting to be ready if and when such actions are merited.

We suggest each region at least begin to prepare for potential captive rearing and ideally establish facilities to maintain genetic diversity and local adaptations. While numbers may appear relatively high now, an estimated ninety-four percent of the global population was lost in less than five years, and it can take years to establish a captive rearing program.

Given the risk of further declines, we recommend an emergency response plan be prepared in each region. The plan should carefully lay out triggers for responses and describe the facilities and personnel that are available should rescue be needed to avoid mortality in the wild due to SSWD or heatwaves.

Considerable investment will be necessary to assess, guide, and act on the need for management and conservation actions to recover and maintain populations of sunflower sea stars throughout the species range. Many information gaps need to be filled and challenges overcome as soon as possible to prepare for and accelerate recovery actions. There are several recovery efforts of other marine invertebrate and fish species to learn from, highlight challenges, and develop resolutions in advance to accelerate recovery timelines for populations of sunflower sea stars. It will also be important to dedicate funding and capacity towards scientific research and monitoring among all aspects of sunflower sea star recovery as well as use information gained in an adaptive management approach. Coordination between the Pycnopodia Recovery Working Group and a consortium of state, tribal, indigenous, and federal representatives will be instrumental in implementing this Roadmap and ensuring efforts and outcomes are aligned and more effective. While differences in population status may give rise to differences in immediate priority actions, all locations should prepare for action in all Objectives.

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BACKGROUND

This background section provides a summary of conservation-relevant information regarding the sunflower sea star (*Pycnopodia helianthoides*), drawn from the International Union for Conservation of Nature (IUCN) Red List report (Gravem et al. 2021), a synthesis of sea star wasting disease (SSWD) effects on sunflower sea star populations (Hamilton et al. 2021), and literature that describes the range, life history, habitats, threats, declines, and areas of conservation impact.

Species Range and Current Status

Historically, sunflower sea stars were commonly found in marine waters ranging from the Aleutian Islands, Alaska, US, to Isla Natividad, Baja California, Mexico (Herrlinger 1983; Gravem et al. 2021). While the northernmost observation for sunflower sea stars is reported from Bettles Bay near Anchorage, Alaska, their range extends westward along the Aleutian Island chain to the Fox Islands near Nikolski, Alaska. The depth range of sunflower sea stars extends from zero to 455m, with the highest abundance between zero and twenty-five meters (Gravem et al. 2021), and individuals are rarely observed deeper than 120m (Fisher 1928; Lambert 2000; Hemery et al. 2016). A range-wide species distribution analysis showed that sunflower sea star distribution prior to the 2013-2016 SSWD outbreak was driven most strongly by depth (peak at zero-100m), followed by weaker associations with salinity (peak at thirty-two to thirty-five PSU) and the 90th percentile of sea surface temperature (wide peak at twelve to twenty degrees Celsius), in that order (Hamilton et al. 2021). After the SSWD outbreak, temperature became much more strongly associated with the species' distribution, shifting the peak to colder waters (eight to ten degrees Celsius for 90th percentile of sea surface temperature), while depth remained an important predictor (Hamilton et al. 2021). Overall, the SSWD outbreak is estimated to have killed over 5.75 billion sunflower sea stars, causing a 94.3 ± 0.9% decline (Mean ± SE) in the global population (Gravem et al. 2021, Hamilton et al. 2021). Notably, the declines reached ninety-nine to one hundred percent across 2,700 km of coastline from Baja California, Mexico, to Cape Flattery, Washington, US, and declines of greater than 87.8% in the rest of their range from the Salish Sea to the Gulf of Alaska from 2017-2020. The decline resulted in an IUCN listing of Critically Endangered (Gravem et al. 2021).


Spawning © Alexis Schneider


Juvenile © Janna Nichols

Life History

Surprisingly little is known about the life history of sunflower sea stars. Below we summarize what is known and identify areas in need of further research.

Reproduction and Recruitment

Gonad development in sunflower sea stars typically occurs in the winter season, and spontaneous spawning of captive sea stars has been observed in March through May (Hodin et al. 2021). Sunflower sea stars have separate sexes but are not sexually dimorphic, and they broadcast spawn sperm and eggs to produce embryos and free-swimming, pelagic larvae (Greer 1962, Morris et al. 1980, Hodin et al. 2021). This spawning strategy suggests that adults must be within a few meters of one another for successful fertilization to take place (Lundquist and Botsford 2004). Given the prolonged severe reduction in population densities of sunflower sea stars, there is concern about densities falling below threshold for successful reproduction, with this "Allee effect" (Allee 1931) preventing natural recovery in areas with severe declines. It is unknown if sunflower sea stars aggregate to spawn, but they are highly mobile with speeds of up to 160 cm/minute and are often found in groups, so this remains a possibility (Mauzey et al. 1968).

Substantial uncertainty and variability exist regarding the seasonality of reproduction in sunflower sea stars. Older literature suggests a reproductive peak in late spring to summer (reviewed in Strathmann 1978). In contrast, more recent observations point to an earlier annual onset of reproductive maturity (late fall to early winter), with spawning occurring from January to June in the Salish Sea (J. Hodin and J. Kocian pers. comm. 2022). Regional variation in the timing of gonad development and spawning is likely and, while no studies have been conducted specifically on the age of maturity of sunflower sea stars, Gravem et al. (2021) estimate it to be at least five years; however reproduction could be possible as early as two to three years (J. Hodin pers. comm. 2022).

After fertilization, embryos quickly develop into swimming, bilaterally symmetrical larvae that progress through the typical echinoderm larval phases of bipinnaria and brachiolaria prior to metamorphosing (Greer 1962; Strathman 1978; Hodin et al. 2021). The larvae feed on single-celled phytoplankton (Greer 1962) and develop for forty-two to 146 days before settling and metamorphosing (Strathmann 1978; J. Hodin pers. comm. 2020); this larval duration is temperature dependent. The majority of larvae cultured between ten and fourteen degrees Celsius are competent to metamorphose after sixty to seventy days into a juvenile sea star with five arms, and they grow more arms over time (Greer 1962). However, larval cloning is common, resulting in prolonged larval duration and delayed metamorphosis in a subset of larvae within a clutch.



Larvae © Ralph Pace

When larvae obtain competence to settle (as indicated by the "helmet" of juvenile structures visible at the posterior end), they have been observed to settle readily on a diversity of substrates in the lab. Settlement rates were observed to be especially high on an articulated coralline alga (*Calliarthron tuberculosum*) and adult-associated biofilm; as the larvae age, they will increasingly settle "spontaneously" on the sides of the larval rearing vessels or other large particulate matter in the cultures (Hodin et al. 2021).

Beyond this basic information, little is understood about the reproductive ecology, growth rates, physiology, and longevity of sunflower sea stars. The species exhibits indeterminate growth and has not been individually tagged successfully nor reared in captivity from birth through adulthood, so determining lifespan and growth rates is challenging. Anecdotal evidence suggests that thirty captive mid-sized sunflower sea stars (sizes thirty to sixty centimeters diameter) in Washington, US, grew at a median rate of roughly two centimeters per year (J. Hodin, pers. comm. 2020). Further studies are needed to better understand sunflower sea star life history, how it varies in the wild, and what characteristics may affect population declines or recovery, as outlined in Objective 2.

Survivorship and Causes of Mortality

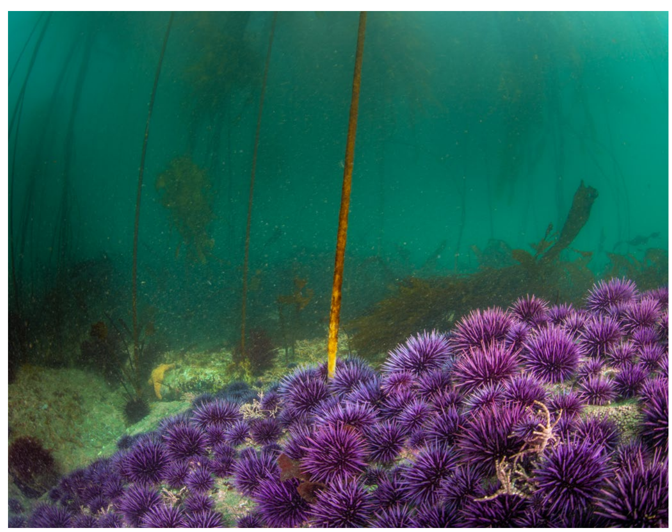
Little is known about causes of natural mortality, including predation, on sunflower sea stars among life stages. Research into these key information gaps of population vital rates will better inform demographic modeling and how natural, disease, and human-induced impacts affect individual survival and population parameters (Morris and Doak 2002). Other factors also inform population viability analyses, including genetics, demographic stochasticity, density dependence (e.g., Allee effect), and environmental stochasticity (Morris and Doak 2002), which in turn may inform recovery actions that reduce mortality at key life stages or when and where to bolster populations via transplanting or outplanting of captively reared individuals. When population sizes of sunflower sea stars are large, it is unlikely that non-disease-related sources of mortality pose a substantial threat to the species. However, these impacts could hinder population recovery in areas with severely reduced population sizes. Research needed to help fill these important gaps and to inform population trajectories is further outlined in Objectives 1 and 2.

Ecological Role

Prior to the SSWD outbreak, sunflower sea stars were recognized as an important generalist mesopredator across Northeastern Pacific nearshore food webs, where they can be an effective predator of small- and medium-sized sea urchins on rocky reefs (Bonaviri et al. 2017; Burt et al. 2018; Eisaguirre et al. 2020). Sunflower sea stars can promote kelp abundance via top-down pressure on sea urchins by affecting sea urchin abundance, behavior, and grazing rates (Duggins 1983; Schultz et al 2016; Burt et al. 2018; Eisaguirre et al. 2020). Further research is needed to explore the ecological role of sunflower sea stars as a predator in maintaining healthy ecosystems, including foundational habitats such as kelp forests, and how this role varies geographically.

Habitats

Adult sunflower sea stars appear to be habitat generalists, occurring on many different types of marine habitats including mud, sand, shell, gravel, rocky bottoms, kelp forests, seagrass beds, and the lower rocky intertidal (Fisher 1928; Mauzey et al. 1968; Lambert 2000; A. Gehman and M. Miner pers. obs. 2020; Hamilton et al. 2021). However, more work is needed to investigate potential habitat relationships among sunflower sea star life stages, and if this varies regionally. Hodin et al. (2021) have shown in the lab that articulate coralline algae (*Calliarthron tuberculosum*) may provide settlement cues and higher rates of successful settlement of sunflower sea stars relative to other substrates. Observations suggest that juvenile sunflower sea stars may utilize seagrass beds and sugar kelp beds as a nursery habitat (A. Gehman and M. Miner pers. obs. 2020; K. Collins and S. Gravem pers. obs. 2022). More research is needed to determine how different habitat types influence growth and survival of different life stages and reproduction of sunflower sea stars and their resulting impacts on populations (Objectives 1 and 2).



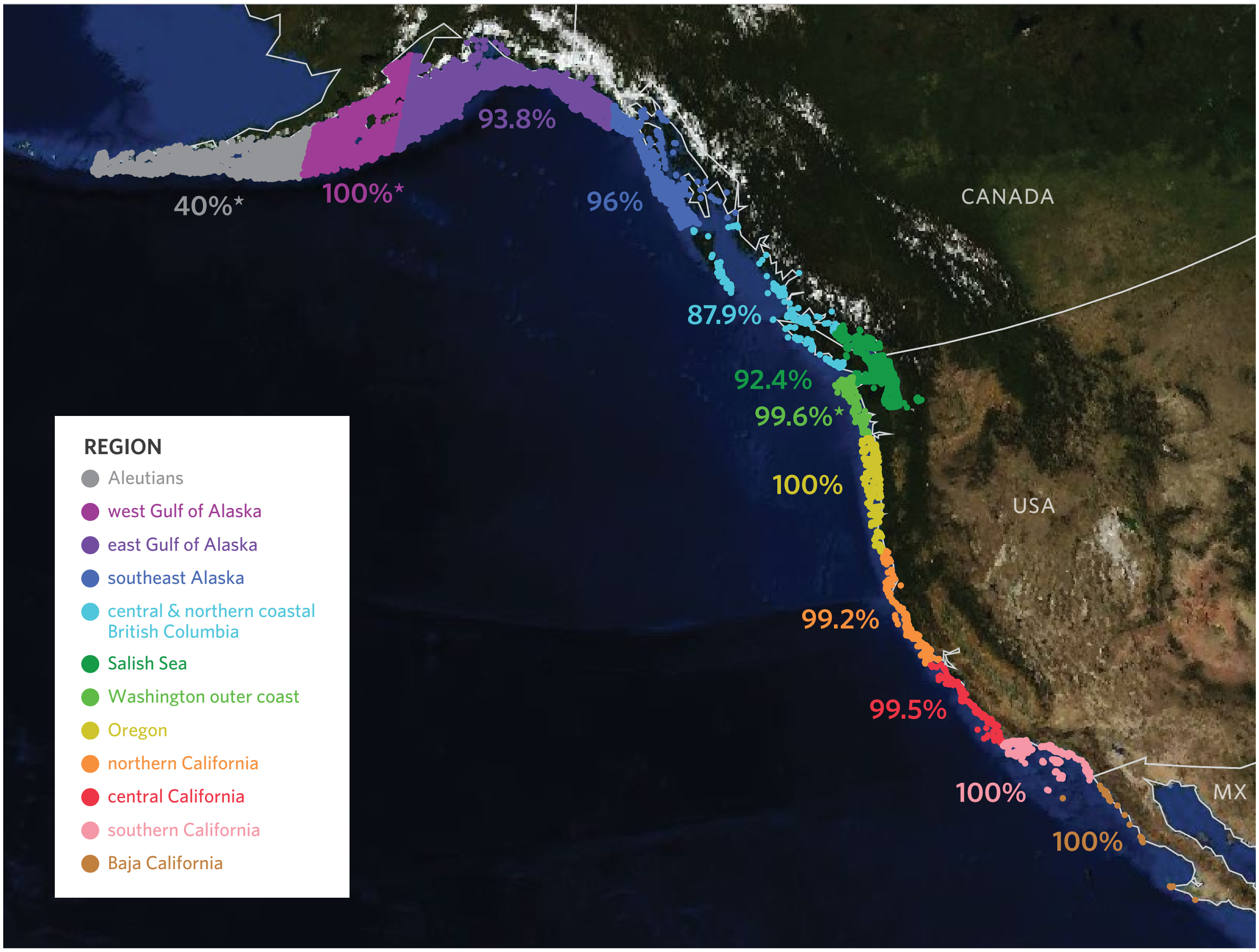


Figure 1. The estimated percent declines in sunflower sea star population density due to the SSWD outbreak in 2013-2017. Map adapted from Gravem et al. 2021, with points indicating where incidence surveys have been performed. Percent decline estimates from Hamilton et al. 2021.
** indicate low confidence due to small sample sizes for density.*

Threats

Disease

Here we use the term "disease" to describe SSWD, which is currently the greatest threat to sunflower sea star populations. 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; Gravem et al. 2021; Hamilton et al. 2021) demonstrate that the species' precipitous decline corresponds to the outbreak of SSWD starting in 2013. This SSWD epidemic began in 2013 and was documented to affect approximately twenty species of sea stars along the Pacific coastline from Mexico to the Aleutian Islands (Hewson et al. 2014, Miner et al. 2018), although it may also have affected additional species. Sunflower sea stars appear to be the species most impacted by SSWD, with declines in some areas reaching ninety-nine to one hundred percent (Montecino-Latorre et al. 2016; Schultz et al. 2016; Harvell et al. 2019; Gravem et al. 2021; Hamilton et al. 2021). Localized outbreaks continue to occur in sunflower sea stars and other sea star species (seastarwasting.org) and the cause and/or disease agent(s) remains unknown (Hewson et al. 2014, 2019). While SSWD is the proximate threat, there is some evidence that increasing temperatures exacerbate or may have triggered the disease outbreak (Harvell et al. 2019; Hamilton et al. 2021). There are many information gaps and questions regarding SSWD that are in need of action as outlined in Objective 3; findings from this area of research are important to many, if not all, aspects of research and actions towards the recovery of sunflower sea stars.

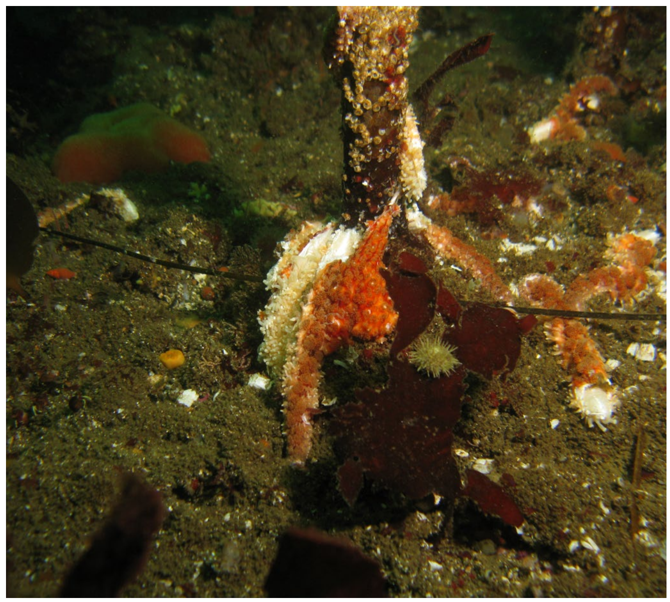
After the outbreak of SSWD starting in 2013, sunflower sea star density declined range-wide by an estimated 94.3% ± 0.9%, and the magnitude of this decline was similar in both shallow and deep waters (92.5% and 96.5%, respectively; Hamilton et al. 2021). In shallow depths where the majority of animals are found, the magnitude and significance of the decline differed among twelve geographic regions defined by Gravem et al. (2021) (Fig. 1). Estimated density declines were greater than 87.9% in eleven of twelve regions, and were greater than 99.2% from the Washington outer coast southward, with no sunflower sea stars observed in Oregon, southern California, or Baja California between 2017 and 2021 (Hamilton et al. 2021).

Temperature and Climate Change

SSWD killed a greater percentage of populations more quickly in the southern half of the species' range, and seawater temperature became four times more important in predicting the abundance of sunflower sea stars after the outbreak (Hamilton et al. 2021). These observations suggest an interaction between disease severity and warmer waters (Hamilton et al. 2021) that may potentially be exacerbated by further climate change. There is also evidence for another sea star, the ochre sea star (*Pisaster ochraceus*), that warmer temperatures speed the progression and increase mortality from SSWD in the laboratory (Eisenlord et al. 2016; Kohl et al. 2016). Anomalously warm water temperature has been associated with region-specific timing of SSWD outbreaks in sunflower sea stars (Harvell et al. 2019; Aalto et al. 2020). However, data from Miner et al. (2018) and Menge et al. (2016) suggest that warmer temperatures were unrelated to regional outbreaks. Overall, it is clear that warmer temperatures increase disease severity, but it is not clear whether the outbreak was triggered by a warming climate. It is probable that ocean warming from human-caused climate change has exacerbated the decreases in sunflower sea star densities, and climate change may hinder recovery, especially in the warmer southern end of the species' range.

Other Anthropogenic Threats

Sunflower sea stars have not suffered anthropogenic impacts typical of imperiled species to drive population declines such as over harvest, bycatch, pollution, or destruction of critical habitat. The known driver of population declines is SSWD. However, due to the dramatic decline of sunflower sea star populations globally, there is concern that other threats, impacts, or causes of mortality that historically have been insignificant may push depressed populations further towards extirpation or prevent natural recovery. Therefore, assessing the degree of mortality associated with anthropogenic impacts such as bycatch or impacts to habitat, the scale of these impacts, and the degree to which these impacts could affect population stability or recovery at different population densities and geographies, should be explored as outlined in Objective 1.



Need for Recovery Action

Given the scale and intensity of global declines, continued observations of SSWD-related mortality, and likelihood of further declines, we assert a need to act immediately and swiftly to inform and direct potential recovery actions. This range-wide Roadmap will highlight key questions and actions, inform sequencing for consideration, and link regional efforts on research and actions throughout the international range of this species. While there are many unknowns in need of investigation for this species, there is enough known to begin planning and acting as a coordinated consortium of state, tribal, indigenous, federal, and non-governmental representatives. Given the many different decision-making groups throughout the extensive species range, the many areas in need of investigation, and the need for accelerated action, a structured decision making framework may prove useful to further guide actions within and among regions throughout the species range (Keeney, 2004; Moore & Runge, 2012; Conroy & Peterson, 2013; Johnson et al., 2015).

Given the scale and intensity of global declines, continued observations of SSWD-related mortality, and likelihood of further declines, we assert a need to act immediately and swiftly to inform and direct potential recovery actions.

A first step to informing whether natural recovery may occur or if, when, and where conservation interventions are needed, is to establish regionally based recovery goals, demographic criteria, and assessment of threats (Objective 1). This should be acted on immediately with information at hand and improved upon as new information is gained. Continued and enhanced monitoring and research will be necessary to model population trajectories and responses to threats and recovery actions, thereby further informing the degree of natural recovery or need for interventions among regions (Objective 2). SSWD is known to be the primary driver of population declines throughout the species range, yet little is known about SSWD and how to mitigate disease risk. Research on SSWD and disease mitigation will be important to all aspects of research and conservation actions (Objective 3). It has been established that captive rearing is possible for sunflower sea stars. There is an immediate need to increase the number of captive rearing facilities for risk reduction, genetic representation, and to advance scientific research given a diversity of expertise among a network of facilities (Objective 4). There is little known, however, on best methods for outplanting captive reared sunflower sea stars to effectively enhance and maintain depleted populations, particularly given concerns of SSWD risk. Therefore, immediate research on this topic is needed to prepare for if and when the need for assisted recovery is determined (Objective 5). Permitting for research and recovery actions is required, particularly given

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biosecurity concerns of SSWD; therefore, consideration of sequencing of actions and advanced coordination among agencies and others involved in research or recovery will be needed to streamline the work (Objective 6). Many areas in need of research and action are identified throughout the range of sunflower sea stars, from Alaska to Mexico, highlighting the need for coordination and communication of the work conducted among all Objectives as well as public engagement and outreach (Objective 7). The Pycnopodia Recovery Working Group is a community of practice initiated in 2019, with agency and non-governmental members from three countries, four US states, American Indian tribes, and indigenous First Nations that meet three times a year to network, share lessons learned, facilitate collaboration, and catalyze research and recovery action (described further in Objective 7). Coordination between the Pycnopodia Recovery Working Group and a consortium of state, tribal, indigenous, and federal representatives will be instrumental in implementing this Roadmap and ensuring efforts and outcomes are aligned and more effective.

This Roadmap was developed and reviewed in close collaboration with the US National Marine Fisheries Service (NMFS), California Department of Fish and Wildlife, Oregon Department of Fish and Wildlife, Washington Department of Fish and Wildlife, and Alaska Department of Fish and Game to ensure this Roadmap is as useful and relevant as possible to each jurisdiction and provides a unifying overview connecting federal and state efforts throughout the species range. Fisheries and Oceans Canada (DFO) Science and Parks Canada were also consulted about processes and information for potential recovery in Canada, but as consideration for protection in Canada is in the early stages, no formal recovery actions will be established at this time until a formal listing occurs. Given the broad nature of this Roadmap, the participation of agency staff in developing this Roadmap does not necessarily constitute those agencies' support for all aspects and actions in this document.

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PRIORITY OBJECTIVES AND ACTIONS FOR INFORMING RECOVERY

In this document, we consider recovery as restoring and maintaining population viability throughout the sunflower sea star's range so that it may re-assume its role in its ecological community. To achieve recovery, there are three key aims to be met:

- Increase the abundance, productivity, local spatial structure/distribution, and genetic diversity of sunflower sea star populations to levels that support the species' long-term survival and viability.
- Increase the abundance, productivity, local spatial structure/distribution, and genetic diversity of sunflower sea star populations so that sunflower sea stars recover to the point where they resume their role as a key member of the subtidal ecological community along the West Coast of temperate North America.
- Assure that genetic structure, diversity, and population size of sunflower sea stars are sufficient to confer resilience to existing and emerging threats.

Given the widespread, rapid, and severe declines of sunflower sea stars, the continued mortality from persistent SSWD, and the potential for the disease to intensify in a warming future ocean, below we highlight seven priority Objectives and associated actions needed to inform management and policy in advance of that goal:

OBJECTIVE 1
Develop Recovery Goals, Demographic Criteria, and Assessments of Threats

OBJECTIVE 2
Maintain and Enhance Research and Monitoring to Inform Population Trajectories

OBJECTIVE 3
Continue, Refine, and Expand Research on Disease and Disease Mitigation

OBJECTIVE 4
Continue and Expand Captive Rearing Efforts for Scientific Research and Potential Population Recovery

OBJECTIVE 5
Determine How Best to Translocate or Outplant Sunflower Sea Stars to Recover Populations

OBJECTIVE 6
Identify and Address Permitting and Biosecurity Challenges

OBJECTIVE 7
Develop and Implement Public Outreach and Communications.

TERMS as used in this Roadmap

Aims = High level attributes that need to be targeted to direct and determine recovery goals and objectives

Goals = Targeted states of local and regional population recovery and interactions necessary to confer species recovery

Objectives = What needs to be achieved in working towards recovery

Actions = Specific actions identified as necessary to accomplish objectives

Criteria = Specific values used to measure progress towards recovery

Thresholds = Quantified measures identifying critical transitions, e.g. in population trajectories or threats

OBJECTIVE 1

Develop Recovery Goals, Demographic Criteria, and Assessments of Threats

Recovery goals as well as demographic, genetic, and threat-based criteria are needed to inform where natural recovery processes may be sufficient and if and where assisted recovery approaches like captive rearing and outplanting will be necessary. The IUCN assessment highlighted great variation in sunflower sea star status among the twelve regions of the species' range (Figure 1). Guidance on a regional scale may require consideration of local environmental and oceanographic features that may drive connectivity of populations, spatial genetic structure, and disease prevalence. Goals and criteria should be considered in a nested model: local forcing nested in regions and regional forcing nested in geography irrespective of jurisdictional boundaries. A consortium of state, tribal, indigenous, and federal representatives would be well suited to work within this framework. This work will be foundational to guiding appropriate and coordinated recovery, but the challenge of doing so should not be underestimated, as this will require dedicated leads, staff, and funding to accomplish. **While there are many identified data gaps, there is sufficient information to begin establishing regionally based goals and quantifiable criteria and to initiate modeling of population dynamics.** As new information is gained to fill spatial and topical gaps, it should be incorporated into regional modeling, providing adaptive management of the recovery framework. We strongly recommend that this effort should be acted on as soon as possible to inform where populations appear stable and where there is need for recovery actions. Here we outline important considerations for developing recovery goals, demographic criteria, and threat-based criteria among three key actions:

ACTIONS NEEDED to support Objective 1

ACTION 1.1 ▪ Develop regionally specific demographic and genetic recovery goals, criteria, and thresholds.

ACTION 1.2 ▪ Assess threats and develop regionally specific threat-based thresholds and recovery criteria.

ACTION 1.3 ▪ Develop, evaluate, and, as appropriate, implement plans to restore sunflower sea stars by enhancing local populations and/or supporting natural recovery.

ACTION 1.1

Develop regionally specific demographic and genetic recovery goals, criteria, and thresholds.

Demographic and genetic recovery criteria are needed to inform if, when, and where management actions are needed to facilitate the maintenance and recovery of sunflower sea star populations. Demographic criteria, including minimum viable population size and population growth rates needed for recovery and stability, can be informed by long-term monitoring data (Action 2.1). Understanding population connectivity and local genetic adaptation (Action 2.3) will be important to inform the probability of natural recovery as well as best practices for any actions towards population enhancement. Gravem et al. (2021) found variation in sunflower sea star population declines in response to SSWD among the twelve regions assessed for the IUCN population assessment. Hamilton et al. (2021) further refined these regional estimates, corroborating regional variability and highlighting the need for region-specific demographic and genetic recovery criteria. Continued and expanded monitoring and research to collect demographic and genetic data (Objective 2) in a coordinated and collaborative effort among federal agencies, state agencies, university researchers, non-governmental organizations, American Indian tribes and indigenous First Nations, and other governments and institutions will be needed to inform and develop regionally specific demographic and genetic recovery criteria throughout the range of the species, as well as to monitor population trends and recovery actions in relation to these established criteria.

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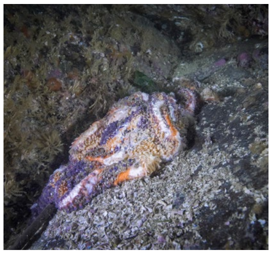
ACTION 1.2

Assess threats and develop regionally specific threat-based thresholds and recovery criteria.

Wasting disease is the primary factor for the species' decline. We should continue to gauge the disease's effects throughout the species' range and better understand how disease expression varies among sites, with latitude, among years, and under different oceanographic conditions, including El Niño/La Niña cycles, decadal cycles (e.g., Pacific Decadal Oscillation, Interdecadal Pacific Oscillation), and long-term climate change. Factors including temperature, food availability and quality, competitors, and predators may influence disease expression, reproductive output, and survival. Conducting periodic, standardized observations and sampling will allow us to observe acute changes, identify long-term trends in health, and detect other diseases that may emerge in wild populations. More work and consideration are needed to determine if the current and future threat of SSWD, and thus the threat-based criteria, should differ among regions. An understanding of regionally specific SSWD disease dynamics and how water temperature tolerances affect growth and survival among life stages and subsequent population trajectories is needed to inform thresholds of these threats that may signal changes in population status or needs for changes in management actions. Key questions and actions regarding SSWD are further outlined in Objective 3.

Other threats to sunflower sea star population stability and recovery should also be assessed, including mortality associated with bycatch in trap and trawl fisheries, and impacts to habitat including dredging, water intakes, and log dumping. The degree of mortality associated with these threats should be assessed as well as whether this degree of impact is at a scale to impact population stability or recovery, considering demographic criteria and thresholds such as minimum viable population size. The concern with each of these human induced threats, while small in scale, is that even small causes of mortality or prevention of reproduction or population connectivity could push small, isolated populations below critical thresholds or prevent recovery. Similarly, an understanding of how any threats or impacts may or may not interact synergistically and how these synergies vary by region is needed.

While bycatch of sunflower sea stars occurs in multiple fisheries (i.e., trap and trawl), more information is needed to determine the degree to which bycatch results in mortality and whether this is a threat to sunflower sea star populations. In most cases individuals encountered as bycatch can be released with minimal harm, but variability in handling practices across fishing sectors and geography is largely undocumented. If bycatch is assessed to result in significant mortality at a scale to affect populations, measures to



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reduce bycatch may be an additional conservation action to aid recovery of sunflower sea stars. Such measures could be initiated through public outreach, education, and engagement as outlined in Objective 7.

Research to determine how different habitat types influence growth and survival of different life stages, reproduction, and recruitment of sunflower sea stars and their resulting impacts on populations (Action 2.4) will inform whether mitigating threats to these habitats (Action 1.3) may be important. For example, there are anecdotal observations that sunflower sea star refuge populations 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. 2019). Since recruitment of sunflower sea stars is often episodic and mortality of juveniles is quite high (Sewell and Watson 1993; Hodin et al. 2021), any measures to enhance these critical transitions in life history will be important to population recovery and maintenance.

ACTION 1.3

Develop, evaluate, and, as appropriate, implement plans to restore sunflower sea stars by enhancing local populations and/or supporting natural recovery.

Plans are needed to guide and implement restoration efforts to meet identified regionally specific demographic and genetic recovery goals (Action 1.1). Plans are further informed by threat-based criteria and thresholds (Action 1.2), including information gained from SSWD research (Objective 3) to inform how disease may affect recovery actions and recovery potential. Further research will be needed to assess the relationship of habitat to demographic processes (Action 2.4) to inform potential restoration actions, including the protection or enhancement of spawning habitat, recruitment habitat, or nursery habitat. Restoration efforts may include approaches to enhance recruitment, aggregation, and translocation of individuals to increase local densities, as well as captive breeding (Objective 4) and outplanting (Objective 5) to increase densities and/or reintroduce individuals in locations where densities have fallen below identified thresholds or they have been extirpated.

KEY QUESTIONS in need of further research

- What are threshold population metrics that may identify whether a population is stable, threatened, endangered, or at risk of extirpation?
- What is the spatial distribution and frequency of continued SSWD outbreaks?
- What is the spatial distribution and trajectory of recovery of populations that were impacted by SSWD outbreaks?
- How do natural and SSWD-related mortality rates affect population trajectories?
- What other threats impact sunflower sea star populations and what actions may mitigate these impacts?
- What environmental factors affect growth, survival, and reproduction? And can actions to protect or enhance these habitat values also facilitate sunflower sea star recovery?

While plans for recovery actions will best be developed and implemented at regional scales, there is an identified need to maintain and enhance multinational coordination among recovery efforts. Identified genetic structure, population trends, and population impacts may occur across interstate and international borders, thereby necessitating coordination between Canada, Mexico, American Indian tribes, indigenous First Nations, the US, and the four US states. Regular communication and collaboration on research, monitoring, and funding opportunities will be important to evaluate the species' status and to support recovery throughout its range. Coordinated and strategic public outreach and education plans (Objective 7) can establish a groundswell of support and capacity to implement recovery actions. The Pycnopodia Recovery Working Group will continue to be an important forum for communication, opportunity for networking, and avenue to facilitate international collaboration. Similarly, this Roadmap was presented to the Trilateral Committee for Wildlife and Ecosystem Conservation and Management to continue to facilitate international collaboration on the recovery of sunflower sea stars throughout their range.

OBJECTIVE 2

Maintain and Enhance Research and Monitoring to Inform Population Trajectories

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In order to assess population trajectories (stable, declining, increasing), appropriate data must be collected at relevant spatio-temporal scales to assess differences within and among regions throughout the full range of sunflower sea stars. Continuation of existing monitoring programs and expansion of new survey activities are required to fill data gaps in key geographies identified by Gravem et al. (2021) and Hamilton et al. (2021) and outlined below in Action 2.1. Further, these authors noted that even within some existing long-term monitoring programs, the type and quality of data collected may need to be enhanced beyond presence-absence to collecting density and size structure data in order to enable demographic analyses and the tracking of population trajectories.

It is also important to determine how survival, growth, and reproduction at different life stages are affected by life history attributes, environmental factors, and community interactions. It is likely that such factors vary among regions, and this regional variation should be investigated further to better inform recovery actions within and among regions. The dearth of basic biological and ecological information available for sunflower sea stars limits assessment of demographic parameters. For instance, the authors of the IUCN Red List Report for this species struggled to make a meaningful estimate of generation time, because insufficient data was available on lifespan, size at age, juvenile growth rates, mortality rates, age at maturity, or fecundity (Gravem et al. 2021). While recent efforts have begun adding to our understanding of key sunflower sea star population processes, we still lack answers to key questions that will be critical to recovery efforts.

KEY QUESTIONS in need of further research

- What are the growth rates of sunflower sea stars, and what is the relationship between size and age?
- At what age do sunflower sea stars become reproductively mature? This question can be addressed in the laboratory with captive rearing programs (Objective 4), and indeed may be answered as soon as 2023, but should also be determined for wild populations.
- Once mature, what is the frequency of spawning, and how does fecundity vary with age and size?
- Are sunflower sea stars subject to Allee effects (Allee 1931) at low densities? If so, what threshold densities are needed to ensure reproductive success?
- What is the average and maximum lifespan of sunflower sea stars?
- What are mortality rates among life stages?
- How do life history characteristics and relationships to the environment vary among regions?
- How does adult movement and larval dispersal give rise to population connectivity and recovery?
- What is the degree of local genetic adaptation?
- What are natural and SSWD-related mortality rates at different life stages?
- Do any local-scale environmental conditions contribute to population-level resilience in the face of SSWD?

Answering these questions will be important to informing decline and recovery trajectories, developing and refining recovery criteria, defining appropriate conservation and management interventions, and evaluating how each varies among regions. Indeed, designing data collection and interpreting results to answer the above questions will be foundational to inform recovery goals, Objectives, and demographic and threat-based criteria as described in Objective 1. In addition to answering basic biological and ecological questions, ongoing monitoring into population status in each region will be necessary to calibrate regional recovery efforts based on population trends (including initial losses) and processes relevant to that area. For instance, Hamilton et al. (2021) estimated ninety-nine percent declines along the conterminous US and Mexico, considering these regions as functionally extinct, whereas in certain areas of the Salish Sea, much of British Columbia, and Alaska, the species could still be found at densities similar to pre-outbreak. Such localized differences in decline (Hamilton et al. 2021), apparent sensitivity to temperature (Hemery et al. 2016; Hamilton et al. 2021), and the relationship between decline and temperature (Hamilton et al. 2021) raise questions about genetic bases for disease resistance and temperature tolerances and potential genetic population structure of sunflower sea stars that will be important to consider when tracking populations and informing conservation and management interventions. Further, this natural variation in sunflower sea stars and relative impact of SSWD sets the stage for natural experiments to investigate factors influencing disease dynamics and population resilience in the face of disease and warming oceans. With the goals of informing population trajectories and resulting management actions, we outline the following key actions.

ACTIONS NEEDED to support Objective 2

ACTION 2.1 ■ Ensure monitoring (including size frequency, density data, and genomics) at appropriate spatio-temporal scales required to inform population status and trends within and among regions.

ACTION 2.2 ■ Investigate life history attributes and environmental factors that affect survival, population dynamics, and recovery.

ACTION 2.3 ■ Evaluate the genetic structure and diversity of wild sunflower sea stars across spatial scales, including the genetics of disease susceptibility and resistance.

ACTION 2.4 ■ Investigate potential habitats critical to key life stages.

ACTION 2.5 ■ Establish data management protocols and access across multiple state, tribal, and federal jurisdictions.

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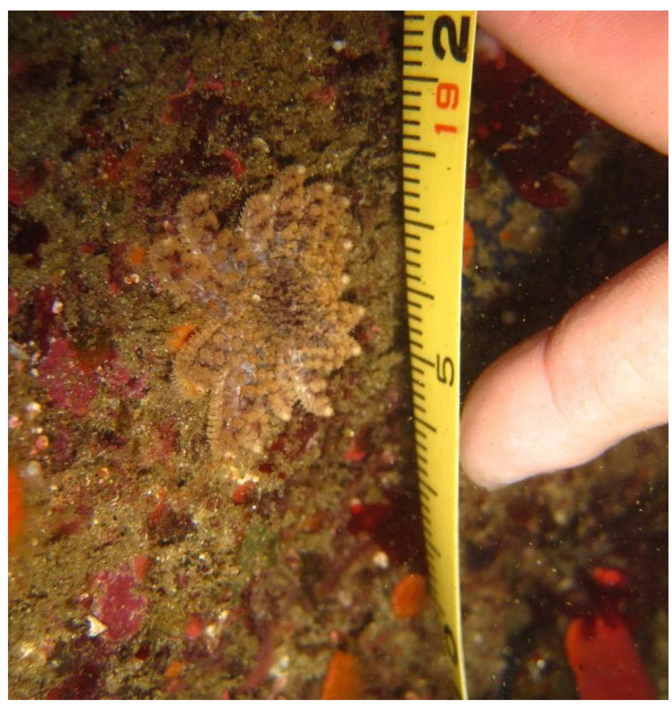

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ACTION 2.1

Ensure monitoring (including size frequency and density data) at appropriate spatio-temporal scales required to inform population status and trends within and among regions.

Tracking populations over time is key to designing and informing recovery interventions. There is an identified need for continued support for existing and expanded long-term monitoring and research to evaluate population trends in relation to recovery criteria over time (Objective 1), including density, recruitment patterns, size structure, spatial structure (e.g., nearest neighbor), growth rates, sex ratios, and habitat characteristics. This includes developing approaches for non-invasive, minimally harmful tools to evaluate population demographics (e.g., sex ratios, reproductive condition), and disease status. The long-term monitoring program is a high priority because it provides critical information to inform all of the other actions, address threats, and prevent extinction.

Along the West Coast of North America, many spatial data gaps exist, particularly in British Columbia and Alaska, but also on the outer coasts of Washington, Oregon, and northern California. A first step is to determine the spatial resolution of data collection required to inform population trajectories within each region. Filling these gaps is an important priority to recognize how local dynamics contribute to regional and population-level declines and recovery trajectories. These determinations should be conducted in a coordinated fashion to inform local and regional dynamics, as well as global population dynamics, and to facilitate research on how environmental gradients influence resilience. Further, identifying and confirming any population strongholds that suffered lower magnitude declines than other areas or that may show signs of recovery will provide insights into population resilience and potential management or recovery actions.

Another challenge to monitoring population-level trajectories identified by Gravem et al. (2021) is that some of the available data are in the form of presence/absence data or coarse abundance groupings. While these data can be useful for some analyses (see Hamilton et al. 2021), data on density, size frequency, and genetic diversity yield outsized insights into population processes critical to recovery. Further, data on size-specific growth, birth, and death rates will inform demographics and population viability analyses (Morris and Doak 2002). Size frequency information can be used to populate size-based models to estimate both mortality rates and the rate at which new individuals are entering the population, either through migration or recruitment (Williams, Nichols, and Conroy 2002).

While thoughtful planning of scientific research coordinated among academic and agency partners is needed to inform local, regional, and range-wide population trajectories, there also exists an important role for citizen science and observational contributions. For example, no sunflower sea stars were observed in scientific surveys in Oregon, southern California, or Baja California between 2017 and 2020 (Hamilton et al. 2021). However, there have been a handful of observations of sunflower sea stars reported in Oregon since 2020, and in November of 2021 a citizen observed healthy sunflower sea stars during extreme low tides on the Mendocino Coast of California, all reported to the MARINe Sea Star Wasting Syndrome Observation Reporting website (seastarwasting.org), resulting in confirmed sightings. Observations like these document the presence of healthy individuals in the wild, which scientific surveys may not pick up, and inform the spatial distribution of remaining wild individuals to help conservation decisions. Another approach that may be useful to inform the presence of sunflower sea stars in remote areas or areas where the species has not been observed in years is the use of eDNA.

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ACTION 2.2

Investigate life history attributes and environmental factors that affect survival, population dynamics, and recovery.

The lack of basic information about sunflower sea stars limits our ability to understand the timescales for recovery, the best seasons for various recovery interventions, and environmental variables that could influence recovery. Understanding how environmental variables, including water temperature and habitat type, influence survival among life stages could help inform environmental protection or restoration measures that could enhance the natural recovery of sunflower sea stars as well as identify appropriate areas and life stages for outplanting efforts in regions where this is deemed necessary. Important areas in need of research include 1) degree of density dependence on reproductive success and population maintenance; 2) age at reproductive maturity; 3) size-based fecundity and duration of reproductive viability; 4) periodicity of spawning; 5) growth rates at various life stages; 6) generation time; and 6) natural mortality rates among life stages or sizes. Of important consideration is whether behavior or life history traits affect disease dynamics, including, for example, the observed gregarious behavior in the lab (Hodin et al. 2021) and/or the potential for spawning aggregations. Improved understanding is needed regarding the relationship of these attributes to environmental factors such as habitat type, water temperature, oceanic currents, or biological interactions such as predation, competition, symbioses, or other community interactions. Further, understanding is needed of how the presence or absence of SSWD modifies these relationships. A challenge to addressing these research topics will be determining if there are any manners to mark individual sunflower sea stars without harm to enable unique identification and determination of individual growth, movement, and survival rates among life stages. Addressing this challenge sooner rather than later will facilitate research needed to inform the monitoring of populations.

Some work has begun to investigate and inform these questions, including insights gained from captive rearing (further outlined in Objective 4; Hodin et al. 2021), and research on size-based and seasonality of reproduction (S. Gravem, Oregon State University) and recruitment, cohort growth, habitat use, and ecological interactions (e.g. K. Collins, Unaffiliated; A. Gehman, Hakai Institute; K. Kroeker, University California, Santa Cruz; P. Raimondi, University California, Santa Cruz). Researchers have been investigating SSWD, genetics, and environmental influences on SSWD as outlined further in Objective 3. More work is urgently needed to inform demographic processes, life history influences on these processes, and how these vary with environmental conditions and geography. Findings will help to inform potential for local extirpation, decline and recovery trajectories, and conservation actions to maintain and enhance sunflower sea star populations at local, regional, and range-wide scales.

← ***Work in Progress***

ACTION 2.3

Evaluate the genetic structure and diversity of wild sunflower sea stars across local and broad spatial scales, including the genetics of disease susceptibility and resistance.

Population genetic data provides insight into the scales of population connectivity and levels of genetic diversity throughout sunflower sea stars' range, thereby directing conservation actions. The genetic structuring of natural populations can be used to understand the connectivity among groups of individuals, both across and within study sites. Because connectivity is mediated by larval dispersal, evaluating genetic structure across sites (macroscale) and within sites (microscale) could provide a deeper understanding of larval dispersal, recruitment dynamics, immigration, and emigration. Additionally, genetic monitoring provides the opportunity to detect genetic associations with SSWD (e.g. Schiebelhut et al. 2018) and putative resistance. Researchers are working on collecting and sequencing genetic data throughout the species' range to inform population genetics, epigenetics, and individual and population level genetic associations with SSWD (Schiebelhut and Dawson in prep). This work is a high priority and merits further support and effort to promote sound conservation action.

The Roadmap identifies the need to address 1) methods for non-lethal collection of genetic samples; 2) appropriate sample design (e.g., number of samples per site, size, and life stage to sample, frequency of sampling); 3) maintaining and archiving samples; and 4) guidance to coordinate future use of the samples. We should also pursue methods to assess the historical genetic structure of populations, if samples of sufficient quality and quantity are available. Understanding population connectivity and local genetic adaptation can inform the probability of natural recovery as well as best practices for any actions towards population enhancement.

Severe density declines over a broad spatial scale, like those caused by the SSWD epidemic, have the potential to lead to substantial loss of genetic diversity (e.g., Gurgel et al. 2020); however, until we learn more about genetic diversity or structure, little can be implied. Loss of genetic diversity can limit adaptive capacity and lead to inbreeding depression. The rate of recovery may determine the genetic impacts on the species, and with a long generation time, detection of the genetic consequences of a mass mortality event can be delayed (Keller et al., 2001; Nunziata and Weisrock, 2017). There may be a genetic impact of the SSWD-related mass mortality of sunflower sea stars (Schiebelhut et al. 2018; Ruiz-Ramos et al. 2020); however, scientists do not yet have a good grasp on whether or how genetic mechanisms may influence individual resistance and resilience to SSWD. Thus, understanding the genetics of sunflower sea stars takes on even greater importance. Evaluating genetic structure and diversity of sunflower sea stars across their range will help inform recovery efforts. As a first step, a survey of range-wide spatial genetic structure is needed using contemporary and historical samples from the southern distribution of sunflower sea stars where populations were largely wiped out. The initial description of population genetic structure and assessment of genetic associations with SSWD in sunflower sea stars is currently being done by Drs. Lauren Schiebelhut and Michael Dawson (University of California, Merced) with support from Revive & Restore. Knowledge gained from this work will help guide where to target animals for captive breeding programs, where to translocate or reintroduce wild or captive-bred animals, and where to focus limited recovery resources in the face of ongoing incidence of SSWD, while keeping the focus on harnessing adaptive loci to preserve adaptive potential without compromising the natural selective process of wild survivors through outbreeding depression (Hohenlohe et al. 2019).

← *Work in Progress*

ACTION 2.4

Investigate potential habitats critical to key life stages.

Adult sunflower sea stars are thought of as habitat generalists; however, this does not preclude the potential for there being habitats that hold disproportionate importance to certain life stages through enhanced survival, growth, reproduction, or recruitment success. For example, in marine environments, some habitats provide a nursery role by providing enhanced growth and/or survival to juveniles that migrate into and use these habitats; while these habitats are typically a smaller proportion of types used by all juveniles, they provide a majority of individuals that survive to adulthood and thus are disproportionately important to population maintenance (Beck et al. 2001). At this point, little is known of the potential for such important habitats to sunflower sea stars and more research is needed to inform this potentially important aspect of population maintenance.

There is evidence that articulate coralline algae may provide cues and/or provide enhanced recruitment relative to other substrates (Hodin et al. 2021). If so, conserving or restoring articulated coralline algae, which are impacted by trampling and warming waters (Micheli et al. 2016; Vásquez-Elizondo and Enriquez 2016), may be important to recover and maintain densities and distributions needed for the maintenance of sunflower sea star populations and meta-populations, particularly at the southern end of the sunflower sea star's range. More work is needed to inform how this potential habitat relationship affects population growth and how that varies among regions to inform potential management actions (Action 1.3).

A number of field observations from the Salish Sea, British Columbia, and Alaska have noted elevated densities of juvenile sunflower sea stars in seagrass and sugar kelp beds (A. Gehman, M. Miner, and P. Raimondi pers. obs. 2020; K. Collins and S. Gravem pers. obs. 2022). In addition, juvenile sunflower sea stars have also been observed within beds of eelgrass located in the marine-dominated regions of estuaries in Oregon (S. Rumrill, pers. obs. 2022). A study of nursery habitats among fifteen commercially important and imperiled fish and invertebrate species found seagrass to be the single most important nursery habitat among species throughout Washington, Oregon, and California (Hughes et al. 2014). Determining if seagrasses, sugar kelps, or other habitats provide nursery habitat for sunflower sea stars could inform synergistic conservation efforts, as any work to restore and enhance these habitats could simultaneously and disproportionately benefit population maintenance and recovery of sunflower sea stars.

KEY QUESTIONS in need of further research

- Are there habitats that are disproportionately important to sunflower sea star spawning, recruitment, or growth and survival of key life stages?
- Are some habitats occupied only during certain seasons or under certain conditions?
- What habitats support high enough densities to allow for successful reproduction?
- Are certain geographies more important to reproductive success or dispersal due to oceanic currents and/or bathymetry?
- How do any habitat influences on population dynamics vary regionally?

ACTION 2.5

Establish data management protocols and access across multiple state, tribal, and federal jurisdictions.

Gravem et al. (2021) have started a data set by collecting, aggregating, and analyzing data from over 48,000 surveys to inform the IUCN sunflower sea star (Pycnopodia helianthoides) Global Population Assessment. This was a significant undertaking that serves as a core dataset upon which we may build an ongoing database. However, moving forward there will be a need to develop a database management system for updated population assessments at focused geographic scales and for the global population as new data are available and conditions change. There is a need for these data to be collected, entered, and formatted in a similarly replicable fashion to facilitate data integration, combination, and compilation at geographic scales of interest. Ideally this database would be flexible enough to incorporate data taken at different degrees of complexity, from simple presence observations to detailed size structure and disease data. It should also be updated regularly, with sufficient quality control measures to ensure that data are not duplicated nor overlooked. Ideally these data should be held in a publicly available repository to facilitate data investigation by any interested person or group.

A well-maintained public database would facilitate regular updates to population assessments at different scales and assessments of population responses to novel temperature or disease events. Importantly, it would also enable assessment of the efficacy of any recovery actions undertaken as described throughout this Roadmap. The Pycnopodia Recovery Working Group has also discussed a set of strategies for improving the visualization, analysis, and data exploration features of the database that are dynamic, useful, and user-friendly. Results of this effort could provide the foundation of available data to inform population trends, population genetics, disease dynamics, and ecological interactions but will require focused concerted effort, dedicated funding, dedicated staffing, and an agreed upon lead to house and maintain such a useful database.

OBJECTIVE 3:

Continue, Refine, and Expand Research on Disease and Disease Mitigation

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Underlying the current IUCN Critically Endangered status of sunflower sea stars was a mass mortality event, driven by as-yet unidentified causative agent(s). Effective management of sunflower sea stars is unlikely to be successful without concurrent disease research and management, which requires knowledge of the disease agent and interactive conditions that exacerbate disease transmissibility, lethality, and adaptability (Cleaveland et al. 2007; Groner et al. 2016). Here we use the term "disease" to describe SSWD, also known as Sea Star Wasting Syndrome or Asteroid Idiopathic Wasting Syndrome which is currently the greatest threat to sunflower sea star populations. Importantly, increased knowledge of the disease mechanisms will help to mitigate any unintended consequences that could arise from conservation actions (Chauvenet et al. 2011; Stringer and Linklater 2014; O'Bryan et al. 2020), a risk that is particularly high in a multi-host system with hosts that have varying disease response. The multi-host nature of SSWD highlights the potential importance of identifying species-level variance in susceptibility and transmission potential to identify reservoir or super-spreading hosts (McCallum 2012). Importantly, rather than aiming for the potentially unachievable goal of disease-elimination, integrating disease modeling into population viability analyses can enable the establishment of threshold levels of disease prevalence, multi-host dynamics, and other key parameters that give rise to population stability or recovery (Cleaveland et al. 2007). Through integration of field research, field and lab experiments, and epidemiological modeling (e.g., Aalto et al. 2020), we can begin to estimate the potential for recovery of sunflower sea stars given different disease management measures, which can include the cost/benefit tradeoffs associated with inaction (Gortazar et al. 2015). Below, we summarize key actions to address these knowledge gaps and inform accelerated recovery, as well as aspects of caution warranted within these actions and among other Objectives for the recovery of sunflower sea stars.

ACTIONS NEEDED to support Objective 3

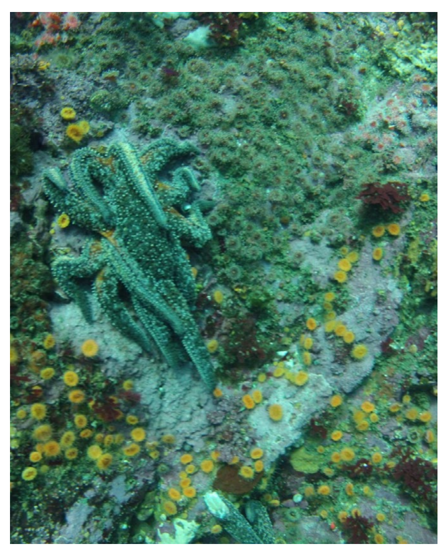
ACTION 3.1 ■ Perform challenge experiments to identify the causative agent(s), should one or more exist.

ACTION 3.2 ■ Conduct research to better understand how life stage and/or environmental factors affect disease transmission, population declines, and recovery potential.

ACTION 3.3 ■ Conduct research on sunflower sea star immune response to SSWD. Investigate how transcriptomics of immunity vary between susceptible and resistant species to uncover key resistance mechanisms and inform multi-species disease dynamics.

ACTION 3.4 ■ Investigate multi-species disease dynamics—i.e. susceptibility, harboring, and transmission among species. Follow up will be modeling dynamics in the wild to inform population dynamics and recovery potential.

ACTION 3.5 ■ Investigate SSWD mitigation measures, including enhancing the immunity of sunflower sea stars, genetics of resistance, genetic selection to improve immunity, and in-lab treatments to prevent outbreaks in captive rearing and outplanting. Identify feasible cost-effective disease control measures.



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ACTION 3.1

Perform challenge experiments to identify the causative agent(s), should one or more exist.

The causative agent(s) remain unknown and under debate in the literature yet determining if and what the causative agent(s) are could enlighten disease mitigation measures and inform recovery actions. Early work suggested that disease signs were associated with injection of viral sized particles, and a putative virus (sea star associated densovirus [SSaDV]) was suggested as the driver of the disease (Hewson et al. 2014). SSaDV has been refuted as causal to SSWD across various sea star species (Hewson et al. 2019, 2021; Aquino et al. 2021), but challenge experiments still suggest a disease transmissible through water, direct contact, and injection (Hewson et al. 2014; DelSesto 2015; Fuess et al. 2015; Kay et al. 2019; Gehman, Crandall, Hershberger and Harvell in prep). The epidermal microbiome has also been implicated in the progression of disease in ochre sea stars (Lloyd and Pespeni 2018), but whether microbial changes associated with the disease are causative or a response to disease signs remains to be explored. A collaborative group of researchers, including The Nature Conservancy, the Friday Harbor Labs, and the Hakai Institute, supported by US Geological Survey (USGS) and the Washington Department of Fish and Wildlife, are working on Action 3.1. Year one trial experiments were completed in 2021, replicating early experiments to confirm that disease transmission can be induced through injection of cells from diseased individuals. Injectate and tissue samples were collected and are currently being processed to identify candidate pathogens. Building on year one, future experiments will work to delineate the size fraction of the disease agents and explore alternative modes of transmission.

Work in Progress

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ACTION 3.2

Conduct research to better understand how life stage and/or environmental factors affect disease transmission, population declines, and recovery potential.

In the field, smaller sunflower sear stars and ochre sea star individuals appeared to have higher survival in response to wasting outbreaks (Eisenlord et al. 2016; Gehman et. al., *in prep*). The underlying mechanism behind this higher survival rate remains unknown. Variation between life stages could provide clues to disease traits, potential for host resistance, and/or identification of causative agent(s). However, preliminary lab work with sunflower sea stars suggests that small individuals are just as susceptible to disease (Davis, Gehman, Crandall and Harvel, ongoing), so an increase in replication of laboratory studies could be necessary, and the use of lab-reared sunflower sea stars in research could be more practicable. Further work is needed to understand how disease susceptibility and resistance varies among life stages.

Field observations suggest that environmental variables interact with disease outcomes, with suggestions that temperature and oxygen could be important stressors that exacerbate SSWD (Kohl et al. 2016; Harvell et al. 2019; Aalto et al. 2020; Aquino et al. 2021; Hamilton et al. 2021). Impacts of variation in these parameters are inconsistent, however, suggesting that interactions among variables, on both the micro and macro scale, likely affect disease prevalence and progression. Future work exploring the interaction between environmental drivers and disease traits could help to delineate what habitats are important for recovery of sunflower sea stars. For example, the relationship between temperature and sunflower sea star occurrence changed from before wasting to after wasting, with the pre-wasting highest occurrence found around sixteen degrees Celsius locations, and post-wasting increasing occurrence below ten degrees Celsius (Hamilton et al. 2021). These cooler habitats could be temperature refuges for sunflower sea stars in the face of disease, and preserving those habitats could be important to sunflower sea star recovery. Indeed, Bonaviri et al. (2017) found temperature to be the primary environmental driver of sunflower sea star abundance, with higher abundances in water temperatures lower than fourteen degrees Celsius and lower abundances at higher temperatures. Ecological niche and species distribution modeling showed temperature, salinity, and depth to be the primary determinants of sunflower sea star occurrence prior to the 2013 SSWD outbreak, indicating the important role of these abiotic factors in determining habitable environments for this species (Hemery et al. 2016). There are many questions to address in relation to SSWD and sunflower sea star recovery (Box—Additional SSWD Questions; pg 27).

Additional **SSWD QUESTIONS** to be addressed

- Does susceptibility to SSWD vary by life stage, genetics, or geography?
- Are there density dependent disease dynamics? I.e. does infection rate and proportion of population infected increase with sunflower sea star population density?
- What environmental factors influence SSWD dynamics?
- Is upwelling important to the delivery of novel disease agents or to dispersing or maintaining the prevalence of existing disease agents?
- What role do oceanic currents play in transporting disease agents and influencing epidemic dynamics?
- Are there any other symbionts (mutualists, commensalists, parasites) of sunflower sea stars that were lost during SSWD; are these important to sunflower sea star recovery or ecosystem function?

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ACTION 3.3

Conduct research on sunflower sea star immune response to SSWD. Investigate how transcriptomics of immunity vary between susceptible and resistant species to uncover key resistance mechanisms and inform multi-species disease dynamics.

An increased understanding of the immune response of sunflower sea stars to SSWD will provide insight into the host-pathogen relationship, which could be integral to identifying causative agent(s) and managing the disease. Early histological research found results suggestive of immune responses, including aggregation, adhesion, and degeneration of coelomocytes within the water vascular system of wasting stars (N. Harley, personal communication). Research focusing on immune capabilities of sunflower sea stars is underway, both with field observational work and laboratory experiments. Early work showed that individuals exposed to disease in the lab responded with increased expression of genes associated with immune pathways, including melanization, Toll pathways, complement cascade, and arachidonic acid metabolism (Fuess et al. 2015). Work to compare microbial communities from healthy and diseased field population during the early outbreak in southeast Alaska will begin soon at the University of Vermont (M. Pespeni, U Vermont; A. Gehman, Hakai Institute, pers comm). Similarly, field and laboratory work are being conducted to evaluate transcriptomics of extant populations of sunflower sea stars in investigating evidence of resistance capabilities (L. Schiebelhut, University of California, Merced; M. Dawson, University of California, Merced; A. Gehman, Hakai Institute; G. Crandall, University of Washington; and S. Roberts, United States Geological Survey).

← Work in Progress

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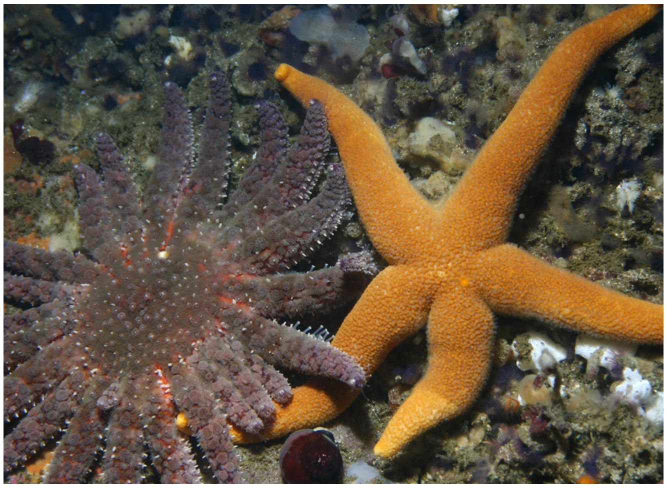

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ACTION 3.4

I investigate multi-species disease dynamics—i.e. susceptibility, harboring, and transmission among species. Follow up will be modeling dynamics in the wild to inform population dynamics and recovery potential.

SSWD affects approximately twenty species of sea stars (Hewson et al. 2014), with no significant phylogenetic clustering (Schiebelhut et al. in review), and there is evidence from mortality in the field and the lab that SSWD infection and mortality varies among species (Kay et al. 2019). Since many of the host species interact in space and time, either as competitors, predators, or prey, it is likely that interactions among species will influence disease transmission at the community level. As mentioned above, the existence of reservoir hosts (hosts that can harbor and transmit the disease agent with little to no negative host effect) in a multi-host system can make populations of other host species much more vulnerable to extinction (McCallum 2012). Practically, research into reservoir hosts can only be conducted following identification of the causative agent(s) of disease (Action 3.1.). However, work can be done now to explore the variability in susceptibility, transmission potential, and progression of disease between different species of sea stars and evaluate, through injection and transcriptomics, any resistance mechanisms of more resistant stars, such as the leather star (*Dermasterias imbricata*), the blood star (*Henricia leviuscula*), or other *Henricia* spp. Comparative whole genome analyses are underway in Dr. Michael Dawson's lab (University of California, Merced) building on previous work (e.g., Ruiz-Ramos et al. 2020) to explore genes of interest in more and less susceptible asteroid species. Observational work exploring the relationship between community diversity and observed SSWD dynamics varying across space could give insight into whether community composition influences disease dynamics in this system.

Work in Progress

ACTION 3.5

Investigate SSWD mitigation measures, including enhancing the immunity of sunflower sea stars, genetics of resistance, genetic selection to improve immunity, and in-lab treatments to prevent outbreaks in captive rearing and outplanting. Identify feasible cost-effective disease control measures.

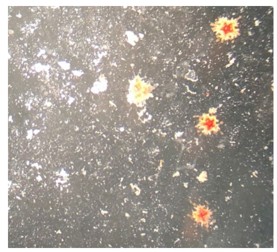
Building on the work from actions 3.1-3.5, both theoretical and experimental exploration of the potential for mitigation of disease in sunflower sea stars is needed. This can include management strategies that reduce disease potential, captive breeding practices that could increase immunity or resistance to disease, and in-lab practices that mitigate disease transmission. In an ideal world, disease management strategy development would come after identification of the causative agent(s) and case definition. Further, identification of the causative agent would facilitate selection for resistant sunflower sea stars and, thus, selective captive breeding. However, the rapid pace of sunflower sea star population change makes it infeasible to wait until after these steps have been taken. In the absence of isolation of a causative agent, identifying genetic associations with greater survivorship or population persistence may be a valuable step in identifying populations of sunflower sea stars for potential sources for captive breeding stock and/or translocations, as permitted by various jurisdictions. Drs. Dawson and Schiebelhut (University of California, Merced) are developing the capacity to screen individuals for loci of interest. In the long-term, if causative agents and/or genes enhancing resistance can be identified in sunflower sea stars, or in other, less severely affected species, gene editing would be an avenue for future research, depending on perceived or realized risks and benefits. As such, a working group of researchers addressing the question of how to develop potential disease mitigation measures that scale across our knowledge of the disease is urgently needed. This objective would be best served by a collaborative working group of researchers across sectors and is currently a key missing step in the response to the recovery of sunflower sea stars.

Work in Progress

OBJECTIVE 4

Continue and Expand Captive Rearing Efforts for Scientific Research and Potential Population Recovery

Captive rearing yields two types of benefits for species recovery. The first benefit involves gaining a more detailed understanding of every life stage between embryo and reproductive adult, which can be critical for population recovery. Sunflower sea stars—like the majority of marine invertebrates—have a biphasic life cycle with a planktonic larval stage that settles into the benthos as a small juvenile, which then grows several orders of magnitude into a reproductive adult. Captive rearing provides access to all life stages, allowing for observations and experiments related to issues as diverse as sensitivity to environmental conditions, disease resistance, life history seasonality, growth rates, feeding behaviors, and prey preferences. The second benefit of captive rearing is the ability to grow large numbers of individuals in an aquaculture setting to maintain genetic diversity, act as reservoirs of genetic stock and abundance as insurance against further losses in the wild, and for the long-term prospect of release into the wild to restore the species to areas where they have disappeared or are at low enough densities to merit population enhancement. In the case of sunflower sea stars, populations have all but vanished in the southern half of their range, from the outer coast of Washington to Baja California. While any enhancement activities would need to be carefully evaluated to weigh the benefits of outplanting against the potential detriments of impacts to local gene pools (Objectives 1 and 2) and could take years to obtain permits for (Objective 6), demonstrating capacity to successfully support a broad-scale enhancement effort is fundamental to securing long-term support.



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Before the SSWD outbreak in 2013, there had been very few publications describing pre-adult life stages of sunflower sea stars. More recently, a small-scale sunflower sea star captive rearing program in the Salish Sea has been established at the University of Washington's marine biology center, Friday Harbor Laboratories. Their published (Hodin et al. 2021) and preliminary findings have elucidated reproductive seasonality and spawning protocols, established basic methods for full life cycle rearing, determined growth rates and temperature sensitivities of various life stages, and identified particular life stages that are the most challenging to rear in a captive setting. This work now points to the following actions in the years ahead.

← ***Work in Progress***

ACTIONS NEEDED to support Objective 4

ACTION 4.1 ▪ Increase the number of facilities and levels of production in partnership with aquariums, academic institutions, and government agencies; maintain communication among this network to advance captive rearing protocols and our understanding of the species.

ACTION 4.2 ▪ Establish, communicate, and ensure the utilization of standard and effective captive rearing protocols; communicate and update with advancements.

ACTION 4.3 ▪ Maintain genetic diversity. Include genetic assessment in all captive rearing facilities to understand genetic structure and diversity, and genetic risk factors for disease; establish biobanking and cell lines of representative genomic diversity from wild and captive populations, especially representatives collected from putatively extirpated populations.

ACTION 4.4 ▪ Ensure that a certain percentage of stock is reserved for scientific research while maintaining a percentage for outplanting.

ACTION 4.5 ▪ Given risk of further declines, develop an "emergency response plan" and identify groups and facilities to rescue healthy sunflower sea stars in response to events such as warm water blobs or SSWD outbreaks.

ACTION 4.1

Increase the number of facilities and levels of production in partnership with aquariums, academic institutions, and government agencies; maintain communication among this network to advance captive rearing protocols and our understanding of the species.

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At this point, the Friday Harbor Labs has the only captive rearing program, raising all life stages of sunflower sea stars from gametes to adults. Several aquariums, however, have adult sunflower sea stars in their care. It is critically and immediately important to increase the number of full life cycle captive rearing facilities for redundancy and risk reduction, and for genetic and geographic representation. It will be important to determine the number of facilities necessary to meet recovery goals (Actions 1.3); however, of immediate importance is increasing beyond one facility for risk reduction. Expanding efforts of full life cycle captive rearing to multiple facilities will create a network of facilities to test a variety of rearing conditions for suitability, thereby advancing and optimizing rearing protocols.

The Friday Harbor Labs captive rearing program is approaching successful full life cycle culture, yet there are specific stages—especially the early juvenile stage—that remain problematic, with slow growth and high mortality. Therefore, one crucial need for additional facilities is to increase the capacity to collectively explore a variety of rearing and food conditions as possible solutions for optimized progression through these problematic life stages. As such, these different facilities would ideally utilize different methodologies for captive rearing, including water type (artificial versus natural), filtration or treatment (raw filtered, sub-micron filtered, UV-treated), and circulation (flow through, recirculating), to better understand optimal conditions among life stages. These facilities would increase the potential output beyond what the small facility in Friday Harbor can produce. Immediate side benefits include spreading the risk of loss and the ability to maintain genetic diversity: ideally diversity that is aligned with historical genetic structure of the populations near the facilities in question. Important questions in need of answering include the minimum number of adult individuals (broodstock) each breeding facility should hold, and which facilities might house wild-origin broodstock vs. those of captive-origin (from one or more generations of captive breeding).

As an integral part of this action, we recommend pursuing and maintaining key partnerships with public aquarium facilities for a variety of reasons. *Work in → Progress* The Nature Conservancy, Friday Harbor Labs, and partners are engaging facilities accredited by the Association of Zoos and Aquariums (AZA) interested in captively rearing sunflower sea stars. A number of aquariums have live sunflower sea stars in their exhibits that were collected before the 2013 pandemic, including several collected in California where very few are known to still exist in the wild. These animals are thus potentially critical broodstock for ongoing and proposed captive rearing efforts to maintain genetic composition and representation. The AZA holds expert aquarists with technical expertise in rearing a variety of organisms, including endangered species for restoration efforts, to take on different challenges of sunflower sea star full life cycle rearing, as well as expertise in imperiled species maintenance and recovery. Aquariums are also trusted institutions by the public for communicating scientific and environmental information. The group is working with aquarium partners to establish an AZA Saving Animals from Extinction (SAFE) program focused on sunflower sea stars. The program, if established, would bring together AZA members interested in collaborating on recovery of this species. AZA SAFE programs often involve a variety of coordinated activities, such as research, captive rearing and release, policy, and outreach and education (Objective 7). Other facilities will need to be involved in recovery efforts of sunflower sea stars including academic institutions, state, federal, and private facilities. This range of facilities and approaches would provide differing expertise to help in addressing the diversity of challenges of captively rearing sunflower sea stars to learn more about and recover the species.

The range of sunflower sea stars crosses three international borders, and thus efforts involved in recovering the species should truly be international (Action 1.3). A network of captive rearing facilities should thus include representatives from Mexico, Canada, American Indian tribes, indigenous First Nations, and the US, including Alaska, Washington, Oregon, and California, as ideally captive rearing efforts will be occurring across the entire historical range of the species. We recommend creating a collaborative network of academic, private, and aquarium institutions to promote information sharing and coordination of diverse efforts to captively rear sunflower sea stars. This network could meet regularly with a rotating schedule of lead presenters from the various institutions in the network to share challenges, lessons learned, advancements, and key next steps.

ACTION 4.2

Establish, communicate, and ensure the utilization of standard and effective captive rearing protocols; communicate and update with advancements.

We propose a shared online platform (e.g., wiki) to house—and identify responsible parties to maintain—the most up-to-date versions of protocols, while allowing community access to add comments and updates. As part of this process, it is also necessary to establish and maintain regular communication channels among those engaged in captive production, e.g., through email and regular teleconference meetings as outlined in Action 4.1. As outlined in Action 2.5, a data management and access platform agreed upon and used by this network will streamline collaboration among facilities and between captive rearing and outplanting programs, if and when that time comes.

An area in need of exploration, determination, and communication of standard protocols is the identification of, and proper response to, disease in various life stages of sunflower sea stars held in captivity. There is uncertainty whether symptoms, or indeed small changes in appearance or behavior, are caused by SSWD, a different disease, or other factors such as water quality, injury, or stress. However, discerning these different causes of affliction will be important in directing appropriate responses. Some aquaria may only have one or few sunflower sea stars making the identification of symptoms and appropriate response critical. The response to affliction could determine not only the fate of the individual but also other sunflower sea stars, or even other species, within the facility. This highlights the importance of epidemiological research and communicating findings (Objective 3). This also highlights the need to develop a network of facilities with sunflower sea stars in captivity that communicate and share findings and lessons learned.

As we envision increasing the number and scale of sunflower sea star captive rearing programs across their range, it is important to be cognizant of the potential for inadvertent spread of SSWD, including potential novel variants and other diseases. In this effort, we can follow protocols used with other marine invertebrates, those with more established captive rearing programs and that are susceptible to their own suite of diseases, such as white abalone. For example, it may be found that captive rearing facilities for sunflower sea stars should sterilize any outflowing water back into the wild. In some jurisdictions, discharge of water, even after sterilization, may not be allowed and alternative disposal mechanisms will need to be developed. More investigation should be done to determine the degree of threat from outflows and the relative benefits of these types of action. Protocols should be established for at least some "clean" rearing facilities, where the incoming water is also sterilized. These sterile facilities could rear entire life cycles within controlled environments and test how sterile, probiotic, or disease challenged scenarios affect growth, survival, and reproduction among different life stages or genetic compositions in captive populations. Facilities like these will also be important to test disease mitigation measures. Furthermore, selective breeding programs with inbreeding control can improve disease resistance, as has been reported in mollusks (Hollenbeck & Johnston 2018). Genotyping-informed outplanting could allow for selection of individuals with greater resistance to SSWD or temperature stress while simultaneously avoiding a severe genetic bottleneck, a potential outcome if natural recolonization occurred stepwise (Slatkin & Excoffier 2012) or if reintroduction used standard selective breeding to establish disease resistance (Leberg & Firmin 2008). Finally, it is worth noting that effective disease prevention will be greatly enhanced by progress in identifying the cause or causes of SSWD (see Objective 3, above).

The network of private, academic, and agency aquarium facilities described throughout Objective 4 would be a useful forum for the sharing of information and protocols across borders. The Pycnopodia Recovery Working Group described in Objective 7 and the Trilateral Committee for Wildlife and Ecosystem Conservation and Management with whom this work has been shared will each be useful networks to ensure international collaboration.

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ACTION 4.3

Maintain genetic diversity. Include genetic assessment in all captive rearing facilities to understand genetic structure and diversity, and genetic risk factors for disease; establish biobanking and cell lines of representative genomic diversity from wild and captive populations, especially representatives collected from putatively extirpated range populations.

For this effort, it will be important to identify responsible parties to track individuals and populations, as well as to establish communication channels for monitoring populations, including databases where information on captive broodstock and subsequent generations derived from them are cataloged. In addition, it is important to identify entities responsible for holding and documenting genetic samples, including advising how many locations of wild origin broodstock should be held in order to maximize the production of distinct genetic lines and minimize the risk of a catastrophic event (e.g., a natural disaster or a wasting outbreak) impacting a rearing facility. A related goal is then to establish decision-making protocols for selecting crosses to optimize genetic diversity, including informing on possible sharing of broodstock (or their gametes) across facilities in different geographic locations. *Work in → Progress* Drs. Dawson and Schiebelhut (University of California, Merced) are developing a targeted sequencing approach to screen individuals for loci of interest, an approach that seems likely to yield useful information on genetic risk and resistance factors.

Work in → Progress Drs. Dawson and Schiebelhut (University of California, Merced), with support from Revive & Restore, are also initiating a biobanking project, targeting specific individuals held in public aquariums that were collected pre-2013 from the most heavily impacted southern part of the range (see Action 4.1). Museum specimens could also be important and helpful in this regard. And finally, with respect to establishing stable cell lines, such work in echinoderms is currently in its infancy, but those involved in recovery efforts for sunflower sea stars should monitor emerging findings to determine if and when they could be applicable to forming a "seed bank."

ACTION 4.4

Ensure that a certain percentage of stock is reserved for scientific research while maintaining a percentage for outplanting.

Captive rearing has both scientific and applied goals, and indeed these goals inform one another. As the techniques for cultivating sunflower sea stars advance, large-scale aquaculture facilities will be needed to generate the large numbers of individuals required for any impactful outplanting effort. At the same time, a certain proportion of facilities and captive rearing programs should be maintained with a scientific focus throughout to continue to advance captive rearing protocols, learn more about the basic biology of the species, and answer questions important to conservation and recovery as identified in Objectives 1-5. These facilities too will need dedicated funding, capacity, and ample enough numbers of sunflower sea stars for robust scientific investigations. These latter experimental approaches are absolutely critical for developing the knowledge bases needed for any successful wild reintroduction, particularly given the substantial knowledge gap for recovery of this species.

ACTION 4.5

Given risk of further declines, develop an "emergency response plan" and identify groups and facilities to rescue healthy sunflower sea stars in response to events such as warm water blobs or SSWD outbreaks.

As sunflower sea star populations decline to identified thresholds (Objective 1), and with continued SSWD or environmental anomalies, such as marine heat waves, there may be a need to rescue stars that might otherwise perish under those extreme conditions. With advances in our understanding of epidemiology (Objective 3), there may come a time where sick sunflower sea stars could be collected to be treated and held for recovery. At this point, the objective would be to collect healthy stars from the wild and keep them healthy and safe while these adverse conditions persist, to be released once conditions improve or into more suitable areas. To be prepared in advance for such needs, we recommend establishing a network of facilities and associated crews that could collect and transport threatened sunflower sea stars to an appropriate, nearby holding facility. This will require established facilities, whether within or in addition to existing captive rearing facilities, with established tanks with appropriate water systems and quarantine ability to hold any rescued sunflower sea stars. If rescue is conducted in the midst of a wasting outbreak, this will require isolated individual housing for at least a two-week quarantine period following collection. This will require collaboration with state and federal agencies to get protocols, permits, and processes agreed upon in advance (Objective 6). Trained volunteers may need to be ready and on-call to quickly respond to such events and the need for rescue actions as a means of enhancing capacity within funding limitations (highlighting the need for outreach and communication outlined in Objective 7). Finally, and as appropriate, tissue samples (such as tube feet in a healthy star, or a variety of tissues in a dying star) should be taken, processed appropriately and shared with the groups studying the disease (see Objective 3) to assist in these efforts. The emergency response plan should also include protocols to determine when rescued individuals are no longer needed to be held in captivity and best practices for release as developed in Objective 5.

OBJECTIVE 5

Determine How Best to Translocate or Outplant Sunflower Sea Stars to Recover Populations

A primary goal of sunflower sea star recovery is restoring populations in the wild such that the species is able to re-assume its role in its ecological community. To accomplish this goal, there may be a need to translocate or outplant individuals to areas that have either suffered complete losses or where densities have dropped below levels where populations can replenish naturally. Here, we consider three main types of translocation actions: reintroduction, reinforcement, and rescue (Box 5.0).

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Box 5.0: Translocation and Outplanting Actions

Reintroduction:

- Outplanting captively-reared individuals into areas in which the species has been extirpated (i.e., disappeared within its historical range).
- Translocating individuals from higher density areas to areas in which the species has been extirpated.

Reinforcement:

- Outplanting individuals reared in captivity into areas with reduced densities to bolster population numbers and densities to facilitate reproductive success and recovery, either by enhancing density above an identified threshold needed for populations to naturally maintain or grow, or to enhance genetic diversity or introduce genetic material needed for disease resistance or climate change resilience.
- Translocating individuals from higher density areas into lower density areas.
- Translocating individuals from populations with genetic traits identified for resistance or resilience into populations that lack these genetic traits, regardless of population density.

Rescue:

- The capture of wild individuals to protect against disease, temperature extremes, or other forecasted catastrophic events to be maintained healthy in captivity during these "impact events," and either outplanted to their collection site once the event has subsided or translocated into areas where the event is not occurring or is of lesser degree. This has been applied to other imperiled species (e.g., black abalone; Bell and Raimondi 2020) and may prove important for the maintenance of imperiled populations of sunflower sea stars.

Translocation or outplanting of captively-reared individuals can be effective tools for species recovery but need rigorous justification (IUCN/SSC 2013). Outplanting captive-reared individuals has a benefit over transplanting of requiring minimum removal of individuals from other populations, which may be impacted to some degree by sunflower sea star removal. When considering translocation or outplanting, the population level benefits (not just benefits to outplanted individuals) must outweigh impacts to the focal and non-focal species (IUCN/SSC 2013). Thoughtful consideration should be given to factors and risks for any potential outplanting effort (Box 5.1). Comprehensive risk assessments help to identify high risk or high uncertainties, and areas and circumstances to avoid (IUCN/SSC 2013; OIE/IUCN 2014).

Determining approaches to outplanting captively reared sunflower sea stars has been identified by the Pycnopodia Recovery Working Group as a high priority; however, the Pycnopodia Recovery Working Group has also raised concerns about disease, genetic, and ecological risk in outplanting.

Given successes in captively rearing sunflower sea stars, juvenile sea stars may be ready for experiments to determine best approaches for outplanting as soon as the spring of 2023. Determining approaches to outplanting captively reared sunflower sea stars has been identified by the Pycnopodia Recovery Working Group as a high priority; however, the Pycnopodia Recovery Working Group has also raised concerns about disease, genetic, and ecological risk in outplanting. There are many areas in need of exploration and discussion on this topic. The following questions and actions should be addressed to best inform sunflower sea stars outplanting efforts.

Box 5.1: Thinking Through Outplanting

Factors to consider in outplanting efforts:

- Spatial genetic structure;
- Local adaptations;
- Existing densities of the focal species in receiving areas;
- How translocated individuals benefit or impact receiving populations;
- Ensuring outplanting does not impact genetic population structure and diversity;
- Local community structure that may benefit outplanting success, including predator-prey dynamics, and interspecific competitive interactions;
- Potential impacts to other sensitive species in receiving areas.

Risks of outplanting efforts:

- Disease risk to both focal species and other sea stars;
- Impacts to focal species;
- Impacts to ecosystem interactions and function in source and destination areas;
- Effects on ecosystem services and human benefits.

ACTIONS NEEDED to support Objective 5

ACTION 5.1 ▪ Assess disease risks with sunflower sea star reintroduction and determine best practices.

ACTION 5.2 ▪ Investigate outplanting techniques and approaches to maximize outplanting success and efficiency and establish best practices.

ACTION 5.3 ▪ Determine outplanting goals, Objectives, and action plans based on local, regional, and range-wide population estimates and trajectories to inform when and where outplanting or transplanting should be conducted.

ACTION 5.4 ▪ Establish robust monitoring protocols in advance of any translocation project and ensure monitoring is conducted for a pre-determined appropriate duration.

ACTION 5.1

Assess disease risks with sunflower sea star reintroduction and determine best practices.

The Pycnopodia Recovery Working Group has identified concerns with disease risk of translocation and outplanting of sunflower sea stars. When disease is an identified risk, the IUCN recommends a Disease Risk Assessment be conducted prior to outplanting or transplanting efforts (IUCN/SSC 2013, OIE/IUCN 2014). A wildlife Disease Risk Assessment provides an open, transparent process with the following main components: hazard identification, risk assessment, risk management, and risk communication (OIE/IUCN 2014). To explore uncertainties, identify key concerns and areas of confidence, consider important immediate next steps, and propose best paths forward; members of the Pycnopodia Recovery Working Group have suggested holding an in-person or virtual roundtable discussion workshop. Participants should come from a range of fields, including epidemiology, disease ecology, biosecurity, sunflower sea star and SSWD genetics and genomics, and individuals involved in the captive rearing and transplanting of sunflower sea stars and other wildlife species of disease concern. This workshop is an immediate priority, as outcomes will inform and guide critical near-term actions for sunflower sea star recovery. Parties involved with other species recovery involving disease (e.g., white, pinto, and black abalones) should be invited to share methods of disease mitigation (e.g., screening for disease prior to moving from captive rearing to wild and careful consideration of when animals should be outplanted) and other lessons learned. Concerns about disease risk and potential mitigation actions should be discussed as soon as possible to facilitate continued momentum in exploring outplanting techniques as outlined in Action 5.2., and outcomes and assumptions of this roundtable discussion should be clearly articulated to the community of practice working on sunflower sea star research and recovery via the Pycnopodia Recovery Working Group and other outlets.

ACTION 5.2

Investigate outplanting techniques and approaches to maximize outplanting success and efficiency and establish best practices.

The Pycnopodia Recovery Working Group has identified the desire to explore methods of outplanting captively-reared sunflower sea stars using controlled experiments as soon as possible. This should be done to establish protocols and a precedent for effective outplanting. One key area to be addressed in advance of experimental outplanting is disease risk as outlined in Action 5.1. Goals of outplanting experiments are to test outplanting logistics and methods in order to be prepared when the opportunity or requirement of outplanting comes to maintain or enhance populations of sunflower sea stars. While information from captive rearing may inform the optimal stage for outplanting from a production perspective, we lack an understanding about basic life history such as size or life stage-based survival in the wild (Objective 2), which would further inform decisions as to best size or life stage to outplant. Field experimentation is needed to address the many questions, including ecological considerations, disease risk mitigation, and basic logistics of outplanting captively-reared sunflower sea stars into the wild.

ACTION 5.3

Determine outplanting goals, objectives, and action plans based on local, regional, and range-wide population estimates and trajectories to inform when and where outplanting or transplanting should be conducted.

Outplanting goals will draw directly from plans developed in Action 1.3 and inform production needs of captive rearing efforts (Action 4.1). Here we further highlight the need to determine appropriate numbers of stars and frequency of outplanting to meet these goals. Genetic structure as informed by research outlined in Action 2.3 to direct plans outlined in Action 1.3 will also be important to guide and inform appropriate outplanting to meet recovery goals. Lessons learned from conservation genomics emphasize the importance of harnessing adaptive loci, while preserving adaptive potential, and without compromising the natural selective process of wild survivors through outbreeding depression (Hohenlohe et al. 2019). The use of genotyping to inform outplanting could facilitate the selection for individuals with greater resistance to SSWD or temperature stress. This may also simultaneously help avoid a severe genetic bottleneck, which may occur through natural recolonization events of previously denuded sections of coast or if reintroduction used standard selective breeding to establish disease resistance (Leberg & Firmin 2008). Work in this area has begun, but there is more to be done to investigate and understand the genomics and population genetics of sunflower sea stars to inform conservation efforts, including outplanting (Actions 1.1, 2.3, 3.3, 3.4). Further, an assessment of what density and size structure of sunflower sea stars can provide ecological services, such as stabilizing community structure through predation, is needed to inform a goal of returning densities of sunflower sea stars, such that they may re-assume their role in their ecological community (Objective 1).

Work in this area has begun, but there is more to be done to investigate and understand the genomics and population genetics of sunflower sea stars to inform conservation efforts, including outplanting

KEY QUESTIONS in need of further research

- What size or life stage is most appropriate for outplanting? There is a need to balance production ease, cost, and survival in the laboratory relative to expected survival in the field, as well as ecological interactions, including the potential for juvenile sunflower sea stars feeding on juvenile purple sea urchins (Strongylocentrotus purpuratus; Miller 1995; Hodin et al. 2021).

- What habitat type and area should sunflower sea stars be outplanted, including depth, substrate, and biological community structure? As previously noted, little is known about the juvenile life history and how habitat and other species affect survival. Habitat suitability modeling off Oregon may provide guidance for a portion of the range (Hemery et al. 2016), but how distribution varies with habitat attributes over the remainder of the range is poorly known. More research on this is needed.

- What numbers and densities of outplants are needed to provide population influence? How frequently and for how long should these numbers be outplanted?

- Are there habitat modifications necessary to improve survival of outplants? (For example, in abalone, fouling may cause once-suitable abalone habitat to no longer be suitable for either outplanting or translocating.)

- Is site preparation needed to enhance survival of outplanted sunflower sea stars, e.g., removal of predators or addition of facilitative structure or organisms? Can we determine what physical and biological parameters are conducive, or not, for successful outplanting and subsequent survival, and can we develop a series of benchmarks that can guide site selection and outplanting efforts?

- What are the most appropriate logistics of outplanting? Must this be done carefully with high human effort, which is constrained by SCUBA limitations? Or can individuals of a given life stage be released onto a reef from the side of a boat? Or do they need to be piped into a given habitat? What are the sensitivities of individuals of the outplanted life stage, and how does the method of outplanting affect survival?

ACTION 5.4

Establish robust monitoring protocols in advance of any translocation project and ensure monitoring is conducted for a pre-determined appropriate duration.

Monitoring is needed to inform how outplanting efforts are affecting population recovery at local, regional, and global levels (Actions 1.1 and 2.1), and whether the introductions of new sunflower sea stars are having unintended ecological consequences. Monitoring may require interstate or international collaboration to inform outcomes of recovery efforts and how they affect populations and communities. Monitoring should also account for disease dynamics (Objectives 1, 2, 3, and 6) and subsequent influence of recovering sunflower sea star densities on ecological communities and conditions (Objectives 1,2, and 3). Monitoring will best inform appropriate outplanting and management decisions when intentionally and pro-actively used in an adaptive management framework (Walters 1986). Monitoring could be coordinated with existing ecological monitoring programs that also include evaluation of sunflower sea stars, such as efforts by state and federal agencies, several American Indian tribes and indigenous First Nations, various academic institutions, and a host of non-profit and/or citizen science programs, including Reef Environmental Education Foundation (REEF), Ocean Wise, and Reef Check Foundation.

OBJECTIVE 6

Identify and Address Permitting and Biosecurity Challenges

To understand the current biosecurity and permitting frameworks among jurisdictions, this Objective of the Roadmap was informed by a questionnaire sent to each of the federal and state agencies throughout the range of sunflower sea stars. Below we highlight major challenges identified to permitting and advancing sunflower sea star research and conservation actions, provide a high-level overview of permitting within and between jurisdictions, and then outline actions that will facilitate a more collaborative and productive process between permitters and permittees and inter-jurisdictional collaboration.

The natural range of sunflower sea stars spans three countries, four US states, and the native and sovereign lands of several American Indian tribes and indigenous First Nations. While the global population has declined by over ninety-four percent, declines vary among regions associated with each of these different jurisdictions (Gravem et al. 2021; Hamilton et al. 2021). Consequently, the sequencing and prioritization of recovery actions will also vary among the different regional authorities. However, recovery actions will—and have—required collaboration among these distinct regions and jurisdictions. For example, one region may require broodstock, embryos, larvae, or juveniles from a different region and jurisdiction in order to pursue captive rearing and/or transplanting individuals for population recovery or enhancement. Each jurisdiction will have its own permitting process for these interventions. Further, any permitting processes are likely to become more involved if sunflower sea stars are federally listed by the US National Marine Fisheries Service (NMFS) or under the Canadian Species at Risk Act (SARA) as an at-risk species. Permitting seeks to ensure that proposed actions do more benefit than harm to focal and non-focal species. Major challenges of permitting proposed conservation actions for sunflower sea stars include the potential for disease transmission and threats to biosecurity, and the lack of information about fundamental biology and ecological interactions. Permitting entities must act using best available information, and in the absence of ample science to guide decision-making, the precautionary principle will likely lead to inaction.

Major Challenges Identified

The major challenge commonly identified among jurisdictions is the potential for disease transmission and how to mitigate against transmission events, highlighting a prioritized need for research in this area (Objective 3). First, there is concern of continued or new disease outbreaks and how this may affect natural populations and recovery. Concern has also been raised of disease being spread or facilitated by conservation interventions, including moving animals for captive rearing (Objective 4), outplanting (Objective 5), or transplanting of adults. While each geography has experience in addressing potential disease transmission or harm to wild populations of focal and other species, all experiences are with other invertebrate or fish species (Box 6.0). Finally, there are long-standing challenges of applying conservation actions in the underwater environment (Glidden et al. 2022).

Box 6.0: Analogs to consider for lessons learned to be applied to sunflower sea star recovery actions

- Pinto abalone (*Haliotis kamtschatkana*)—successes in Washington and Canada
- Red abalone (*H. rufescens*)—unsuccessful in Oregon, successful in Baja California
- Black (*H. cracherodii*) and white abalone (H. sorenseni)—successes in California and Baja California
- Olympia oysters (*Ostrea lurida*)—successes in Oregon
- Fishes, particularly Pacific salmon species in US and Canada and totoaba (*Totoaba macdonaldi*) in Mexico

The novel multi-host nature of the SSWD system will require thoughtful assessment and planning of recovery actions. The lack of understanding of basic epidemiology, including causative agent(s), triggers of outbreaks, and how SSWD effects vary among the different host species, life stages, and environmental conditions (Objective 3) challenges our understanding of how conservation interventions may affect disease dynamics. Conservation actions such as transplanting or outplanting need to consider risks relative to benefits (Objective 5; IUCN/SSC 2013); however, it is currently difficult or impossible to assess spatio-temporal components of disease, making it challenging to identify appropriate outplanting sites or consequences of outplanting or transplanting actions. This further highlights the critical importance of research to answer key epidemiological questions (Objective 3). A related challenge is the lack of genetic information for the species, highlighting the need for research in this area (Actions 1.1, 2.3). A better understanding of genetic variation in thermal tolerance, disease resistance, local adaptation, and population structure is needed to inform outplanting and recovery actions (Objective 5). Another challenge identified is the relationship of water temperature to disease dynamics, as well as basic thermal tolerances for the species (Objective 3). This will be particularly important in the southern edge of the species range and as ocean water temperatures rise with climate change.

We also highlight the further need for basic biological information for sunflower sea stars (Objective 2). We still lack understanding of survival and growth rates among life stages, age at reproductive maturity, longevity, reproductive life span, and generation times (Objective 2). We still do not fully understand natural causes of mortality among life stages (Objectives 1, 2, and 4). New research is needed to help identify these sources of natural mortality and disentangle them from disease-related mortality. Understanding these natural processes, including influences to mortality, will inform how actions requiring permits may be affected by or influence mortality and population-level responses.

Monitoring (Objective 2) will be needed throughout any recovery actions and strategies to determine whether recovery actions are meaningful and effective over the short- and long-term (Objective 1). Determining whether environmental conditions have changed enough that species range would be expected to change (e.g., loss of sunflower sea stars in southern end of range) would be important to decide if transplants or outplants would be warranted and/or expected to survive in those locations.

Garnering public support for recovery of a species that is rarely encountered and not exploited will be a challenge (Objective 7). This will be especially true if trawl and trap-based fisheries (especially recreational and commercial shrimp and crab fisheries) are directly impacted by recovery actions. There also appears to be regional variability in public perceptions of just how imperiled the species is, based on regional encounter rates.

Permitting

In Canada and the US, permits are required (state permits in the US) for captive rearing, outplanting, transplanting, relocating, and field or laboratory research involving handling, collecting or relocating sunflower sea stars. In Mexico, permits are required for transplanting, outplanting, and moving sunflower sea stars. In the US, importing animals from another state or federal jurisdiction requires permits, and as noted above, would likely require the animals to be certified disease free, or maintained in quarantine conditions. For example, in California, a health certificate verifying that the source of animals has been disease free for a minimum of two consecutive years is required prior to the importation or outplanting of live animals. Likewise, Oregon and Washington also require certifications of animal health prior to imports of marine invertebrates into state waters. The importing of animals into Canada would need to go through a federal-provincial introduction and transfers committee for permitting and approvals. Permits for these activities typically take one to several months to secure and are valid for one to five years.

Within the US, a federal Endangered Species Act (ESA) listing would require additional permitting beyond state permitting, involve more scrutiny, and require more time to assess and approve. If an ESA listing occurs, federal permit issuance would likely take three to five months; the federal permit would be required before state permits could be issued; federal permits could be valid for one to five years, and annual reports would be required. In California, if a species becomes ESA listed after state permits are issued, work must cease until federal permits are obtained. The level of listing (threatened or endangered) would affect what kinds of actions are permissible and also the overall, and regional, quantity of take allowed. Any requested actions having high levels of lethality would be carefully scrutinized, as would any action that permanently removed individuals from the wild (i.e., take for captive rearing or transplanting). Similarly, in Canada, if federally listed through the Canadian Species at Risk Act, more permitting would be required and more time would be added to the process of obtaining work authorization.

The following actions have been identified to help streamline the permitting process for both permitters and permittees:

ACTIONS NEEDED to support Objective 6

ACTION 6.1 ■ Communication and collaboration early and often between permittee and permitter.

ACTION 6.2 ■ Refer to an established and justified need.

ACTION 6.3 ■ Address key questions and uncertainties.

ACTION 6.4 ■ Facilitate and maintain interstate and international coordination.

ACTION 6.1

Communication and collaboration early and often between permittee and permitter.

Early, clear, transparent communication with state permitting departments and, ideally, direct communication with the individual person issuing the permit allows a collaborative process to address any challenges, and typically facilitates a smooth, expedient application process.

ACTION 6.2

Refer to an established and justified need.

A clearly documented need for the action either in agency-level documentation or an existing and vetted recovery document will help justify the action and need for a permit.

ACTION 6.3

Address key questions and uncertainties.

Having clear, supported answers or manners of addressing concerns regarding the permitted action will be necessary. To this end, research into the major challenges identified above and throughout this Roadmap will help with future state and federal permitting processes. In some cases, revisions or changes to existing policies, regulations, or permitting requirements may be needed in advance of a permit request to address the specific issues associated with sunflower sea stars.

ACTION 6.4

Facilitate and maintain interstate and international coordination.

The multi-jurisdictional nature of population declines and potential need for cross-border recovery actions highlights the need for building multi-agency teams that also include external partners from academia, NGOs, and stakeholders to network, inform, plan, and collaborate on recovery actions.

Areas in need of research and action to facilitate permitting research and recovery actions

- Gather genetic information about population-level variances, if any, in key physiological traits to inform the potential need for region-specific management (Action 2.3).
- Identify the agent(s) of SSWD and the triggers that result in outbreaks. Demonstrate disease tolerance in specific populations, such that captive rearing and outplanting can be defended (Objective 3).
- Establish agreed upon protocols for captive rearing, disease mitigation measures, quarantine, identifying disease and non-disease traits and symptoms, proper handling methods, and methods for outplanting and transplanting (Objectives 3, 4 and 5).
- Maintain and enhance international communication and collaboration among Canada, the US, Mexico, American Indian tribes, indigenous First Nations, as well as among US states towards research and recovery.
- When moving or transporting animals, quarantine individuals in a closed-loop system for a fixed period of time to ensure interactions with wild populations are not possible.
- Treat effluent water (e.g., with UV light) from facilities with captive sunflower sea stars to ensure any disease is not released into the wild.

OBJECTIVE 7

Develop and Implement Public Outreach and Communications

In 2019, a small, international group of scientists and conservationists convened to discuss the dramatic declines of sunflower sea stars and to develop a series of immediate, no regret actions that should be taken for the recovery of the species. This meeting catalyzed the first sunflower sea star captive rearing program beginning in 2019 and continuing today (Hodin et al. 2021), an IUCN global population assessment resulting in the red listing of Critically Endangered (Gravem et al. 2021), and dedicated research in sunflower sea star SSWD epidemiology (Gehman et al. in prep). This group has grown into the Pycnopodia Recovery Working Group, a thriving community of practice over seventy-five members strong with representation across 42 distinct organizations throughout the entire range of the sunflower sea star. The Pycnopodia Recovery Working Group was instrumental in facilitating the aggregation of a novel range-wide dataset comprising nearly 50,000 scientific surveys to inform range-wide and regional assessments of SSWD-related declines (Gravem et al. 2021; Hamilton et al. 2021). The Pycnopodia Recovery Working Group convenes three times a year to share lessons learned from throughout the species' range, identify areas in need of attention, facilitate collaboration, and catalyze action. Indeed, the Pycnopodia Recovery Working Group was instrumental in shaping and developing this Roadmap and will be instrumental in communicating and coordinating the implementation of actions identified in this Roadmap to accelerate recovery of the species.

The Pycnopodia Recovery Working Group highlights the importance of open, clear, and consistent communication and the ability of a consortium of state, tribal, indigenous, and federal representatives to affect change. As with most conservation actions, recovering this imperiled species may require influencing human behaviors associated with the proximate and ultimate causes of the species decline. For sunflower sea stars, declines were driven by a disease event, but further work is needed to assess other threats that may impact depleted populations (Action 1.2). Changing human behavior requires engaging directly with people and communicating widely. Below we highlight areas and manners of engagement to aid in coordinated efforts of monitoring, enhancing, and maintaining populations of sunflower sea stars, and to accelerate recovery.

To advance the actions described in this Objective, two working groups should be created and one range-wide network:

- Communications and Public Relations Sub-Working Group (*Action 7.1*)
- Outreach and Engagement Sub-Working Group (*Action 7.2*)
- Range-wide network of outreach and engagement partners (*Action 7.3*)

ACTIONS NEEDED to support Objective 7

ACTION 7.1 ■ Establish relevant working groups to lead development and execution of plans to enhance awareness of sunflower sea stars, threats to their populations, and recovery actions to key audiences.

ACTION 7.2 ■ Develop and implement outreach and engagement strategies focused on specific audiences, including developing relevant materials and participating in events hosted by partner organizations and reinvigorating existing community science programs.

ACTION 7.3 ■ Establish and coordinate a range-wide network of outreach and engagement partners beyond the working groups to leverage existing expertise, platforms, and expand outreach efforts.

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ACTION 7.1

Establish relevant working groups to lead development and execution of plans to enhance awareness of sunflower sea stars, threats to their populations, and recovery actions to key audiences.

Once created, the Communications and Public Relations Sub-Working Group should take the lead on making the Pycnopodia Recovery Working Group recognized and publicly accessible to increase awareness and support of all of its work. This will ensure the work within this Objective continues to progress, specifically that any plans or strategies developed move into implementation. It will require the creation of a website, which will serve as the foundation and central place for sharing information, progress, publications, and resources. To support development of the website, the Communications and Public Relations Sub-Working Group will need to develop a communications and messaging strategy plan, including a frequently asked questions document. To do so, they should work in close coordination with partners and experts across the Pycnopodia Recovery Working Group to ensure accuracy and scientific integrity of key messages. This will require a lead, support capacity, and funding.

The communications and messaging strategy should communicate recovery milestones and a recommended schedule for awareness campaigns. To prepare for the initial launch of the website, and follow-on campaigns, the sub-working group will need to create a press kit, including the key messages, information about relevant partners, and select media. Pycnopodia Recovery Working Group members are encouraged to gather and share media assets (e.g., photos, videos), especially those associated with key recovery milestones. If funding allows, the sub-working group will guide the development of short videos (two to three minutes) as a part of awareness campaigns.

ACTION 7.2

Develop and implement outreach and engagement strategies using relevant materials to engage specific audiences and reinvigorate existing community science programs.

The Outreach and Engagement Sub-Working Group could take the lead on developing an outreach strategy. The primary audiences that are likely to rise to the top during this planning process are fishing communities, divers and coastal communities, and decision-makers (e.g., elected officials, resource managers).

Both commercial and recreational fishers may often encounter sunflower sea stars when recovering crab and shrimp pots—the sunflower sea stars latch onto and enter the pots to feed on the bait and trapped prey inside. There is an opportunity to develop an outreach strategy and associated materials to raise awareness of the importance of sunflower sea stars to healthy marine ecosystems and how fishers can safely remove sunflower sea stars from pots without damaging the animals.

Divers and coastal communities also have the opportunity to see and interact with sunflower sea stars—and this should increase as recovery progresses. The two key pathways for engaging community action in sunflower sea star recovery include participating in community science activities and awareness campaigns. To reach these communities, the Outreach and Engagement Sub-Working Group should develop a list of dive shops and operators to whom working group members could present, as well as coastal community events where working group members could help spread awareness and appreciation for conservation and recovery activities. The Pycnopodia Recovery Working Group should also connect with and present through existing coastwide networks, such as the California Marine Protected Areas (MPA) Collaborative Network, Multi-agency Rocky Intertidal Network (MARINe), Reef Check Foundation, REEF, and others. This outreach will feed into the creation of a range-wide network of outreach and engagement partners (*Action 7.3*). Outreach should focus on how these stakeholders may get involved through support and citizen science, including recording observations of sunflower sea star occurrence and disease state to the MARINe Sea Star Wasting Syndrome Observation Reporting website (seastarwasting.org).

Decision-makers are another key audience to ensure they are not only aware of the species, threats, and recovery efforts underway, but have the information needed to support and enhance these efforts through allocation of resources, policy changes, supporting scientifically justified species or habitat protections, and making appropriate state and federal listing decisions. The Pycnopodia Recovery Working Group can take advantage of existing events, both regional (e.g., California Ocean Day, Washington Environmental Lobby Day) and national (e.g., Capitol Hill Ocean Week), and develop region-specific collateral to deliver to elected and other government officials.

Standardized outreach materials for such presentations and events (e.g., posters, banners, overview slide decks) should be created and shared to ensure a coherent and consistent message is communicated, although tailored to the regional and local audiences. Branding guidelines and formatting templates should be coordinated with the Communications and Public Relations Sub-Working Group. Strong and thoughtful outreach is an important step toward engaging people in activities to support recovery.

As outlined in Objectives 1-3, there is a need to gather additional baseline data, track recovery, and monitor ongoing disease outbreaks. Citizen science can be important to enhancing data on occurrence and disease trends (Action 2.1; e.g., the MARINe Sea Star Wasting Syndrome Observation Reporting website). Successful community science programs find ways to meaningfully link data collected to conservation action, which could include analyzing and sharing data with decision makers, ensuring that volunteers are informed of such efforts, and recognized for their contributions.

Opportunities may also arise throughout the recovery process for mobilizing audiences as a means of increasing awareness, engagement, and capacity for time-bound actions. An example of this could be to generate support for resourcing and policy decisions that can support species recovery. Increasing public awareness and participation could help better inform decisions and even streamline the process by avoiding delays due to uninformed or late-informed public response. Coordination between the Pycnopodia Recovery Working Group and a consortium of state, tribal, indigenous, and federal representatives will ensure efforts and outcomes are aligned and more effective. Public engagement can be enhanced through a network of avenues as described further in Activity 7.3.

ACTION 7.3

Establish and coordinate a range-wide network of outreach and engagement partners beyond the working groups to leverage existing expertise, platforms, and expand outreach efforts.

The Pycnopodia Recovery Working Group already includes a diverse array of partners across the West Coast of North America, many of which have not only outreach and engagement expertise on staff but also have strong platforms—virtual and in-person—and extensive audiences. For example, the Seattle Aquarium connects with almost a million people a year in-person and has a virtual following of greater than 200,000. By leveraging existing platforms, the Pycnopodia Recovery Working Group has the potential to reach millions of people across the species range and beyond. The Pycnopodia Recovery Working Group should specifically work to strengthen and expand collaboration with organizations that have in-person platforms (e.g., aquariums, marine field stations, science centers) and a large reach. In addition to visitors to their facilities, many of these organizations also have field programs that bring naturalists to the coast for public engagement opportunities, which could also be leveraged to incorporate sunflower sea star recovery messaging. Regional monitoring and community networks also exist and could serve as important pathways for sharing updates, mobilizing support, and soliciting public feedback (e.g., California MPA Collaborative Network, MaRINE).

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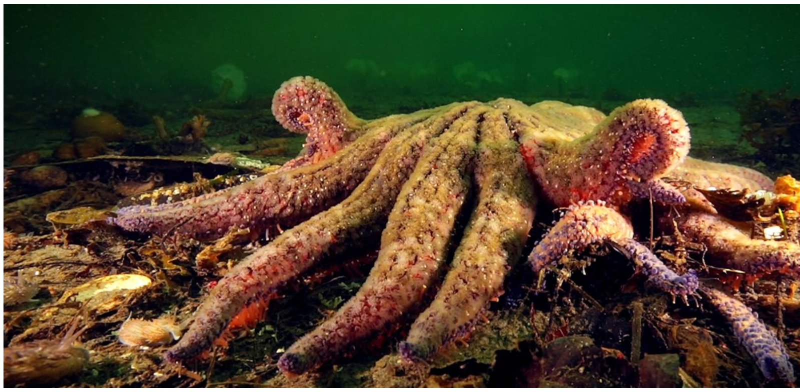

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