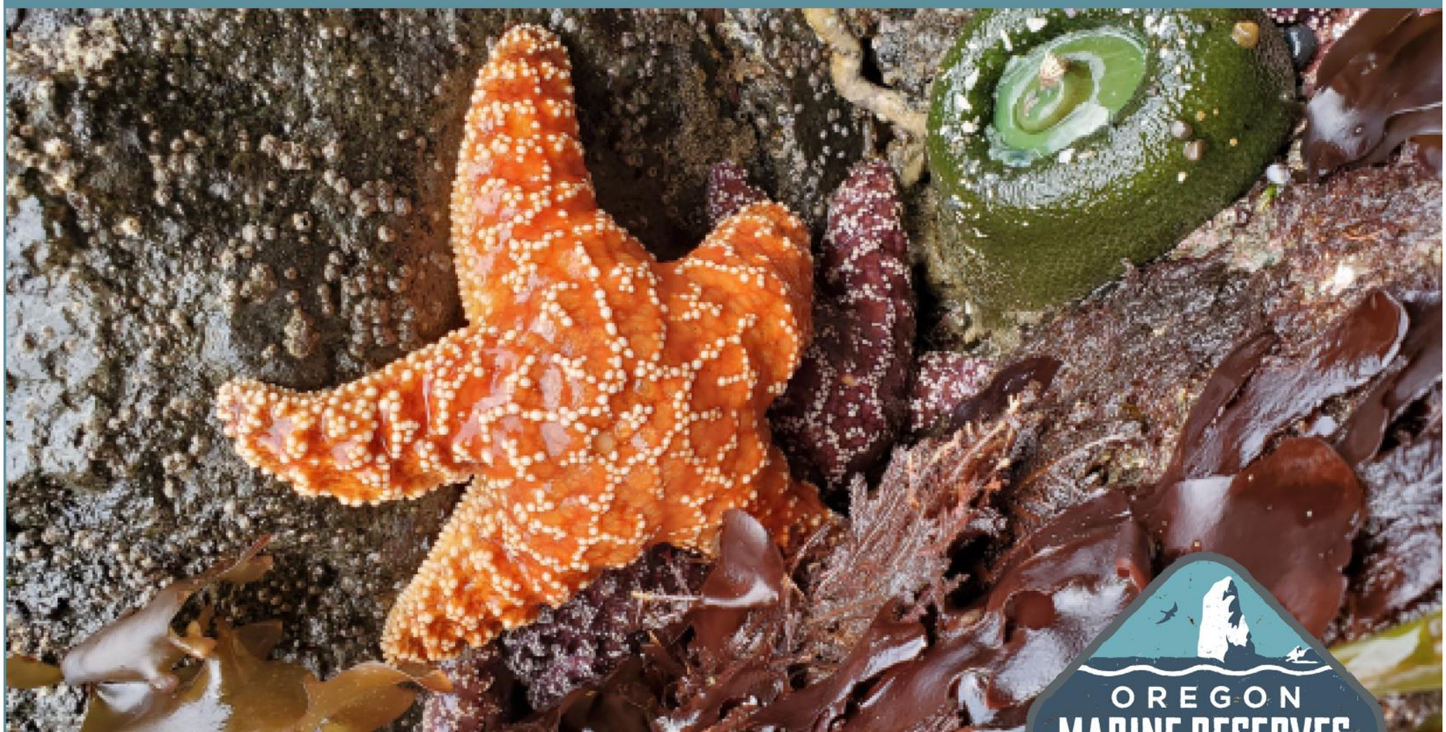
# Intertidal Sea Star Report



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# 1 Introduction

## 1.1 Project Goals and Background

In 2014, sea star wasting syndrome hit the Oregon Coast. It was the largest marine epidemic on record (Harvell et al. 2019, Gravem et al. 2021), and affected multiple Oregon sea star species (Hewson et al. 2014, Montecino et al. 2016). In response to this event, the ODFW Marine Reserves Program partnered with the Partnership for the Interdisciplinary Study of Coastal Oceans (PISCO) in 2015 to survey sea stars at intertidal sites in three Reserves. PISCO had sea star survey sites that they began surveying in 2000 in the Cape Perpetua Marine Reserve (Strawberry Hill) and two sites in non-Reserve areas that now serve as valuable Comparison Areas outside Reserves (Tokatee Klootchman near Cape Perpetua Marine Reserve; Fogarty Creek near Otter Rock Marine Reserve). To complement these surveys, the ODFW Marine Reserves program added sea star surveys using PISCO methods at Otter Rock and Cascade Head Marine Reserves in 2015. Adding surveys at Redfish Rocks and Cape Falcon Marine Reserves was considered but not pursued (see *Intertidal Methods* for more detail). The goal of these sea star surveys was to compare sea star communities among Reserves, to track the responses to and recovery of sea stars to sea star wasting disease (SSWD), and to track the settlement and growth of young sea stars at these sites.

## 1.2 Community Partnerships and Impact

Through our collaborative partnership, the ODFW Marine Reserves team and PISCO have been successfully monitoring sea star populations in all three Reserves with accessible habitat since 2015. Partnering with PISCO enabled the ODFW Marine Reserves team to build on the robust monitoring efforts in the Cape Perpetua Marine Reserve and two Comparison Areas. These sites provide the backbone of intertidal sea star monitoring and provide deeper context in which to evaluate the more recent data from the Otter Rock and Cascade Head Marine Reserves. In this time frame, we have counted and measured 12,562 sea stars in Marine Reserves and 15,797 in the two Comparison Areas. These included 26,133 *Pisaster ochraceus*, 2,062 *Leptasterias* spp., 160 *Henricia* spp., 3 *Evasterias troschelii*, and 1 *Ophiothrix fragilis* (surveys for the latter 3 species were done only since 2015 in 2 sites). ODFW Marine Reserves and PISCO completed 15 days in the field at Otter Rock, 10 days in the field at Cascade Head, and PISCO completed 40, 38, and 35 days at Cape Perpetua, Tokatee Klootchman, and Fogarty Creek, respectively, to collect these data.

As part of this work, the ODFW component of the sea star surveys has contributed to the training of several undergraduates, including 4 OSU Summer Undergraduate Research (SURE) students, 6 Sea Grant Summer Scholars, and one Oregon State University Marine Studies Initiative (MSI) Science Communication Internship. The

PISCO component of this work has also contributed to theses of multiple graduate students, the training of dozens of undergraduate volunteers, and has been the subject of multiple field courses taught by B. Menge. Much of this information was collected by these students. Further, these data have been presented in at least one publication (Menge et al. 2016) and several conference presentations. Finally, these sea star surveys were used as a community engagement tool during the 2019 BioBlitz coordinated by the Oregon Coast Aquarium. Over 15 volunteers were intensively trained to assist with data collection and included undergraduate students, graduate students, and Aquarium volunteers. The data collected are included in this report. This event allowed the public to see scientists in action, to participate in real data collection, and demonstrated how research is conducted in the intertidal areas.

## 1.3 Research Questions

For each Marine Reserve and Comparison Area, we addressed the following research questions:

**Population Densities**

- What is the relative abundance of species among Reserves over time?
- How did sea star wasting disease affect sea star populations?
- Have the sea star populations recovered from sea star wasting disease?

**Sea Star Health**

- What was the time course of SSWD in Oregon? Has sea star wasting disease abated?
- Were there certain size classes of sea stars that were more affected by wasting than others?

**Recruitment and Recovery**

- How have the sizes of sea stars varied annually?
- Has recruitment of sea stars contributed to recovery from SSWD?

# 2 Methods

## 2.1 Data Collection

All questions were addressed using sea star belt transect surveys that track sea star densities, health, and individual size annually at 5 sites (Fig. 1 in *Intertidal Methods*). Belt transect surveys for *P. ochraceus* were begun by the PISCO lab in 2000-2001

Cape Perpetua Reserve (PISCO Strawberry Hill site) and Comparison Areas Tokatee Klootchman (near Cape Perpetua) and Fogarty Creek (near Otter Rock). PISCO also surveyed *Leptasterias* spp. In 2015 and 2016. ODFW collaborated with PISCO to expand these surveys to Otter Rock and Cascade Head Marine Reserves in 2015 and additionally survey *Leptasterias* spp. *Henricia* spp., *Evasterias troschelii* and *Ophiothrix* spp. Transects were repeated yearly or twice yearly in spring and/or summer at each site (Table 1; For more detail, see *Intertidal Methods*).

Typically, five 5 x 2 m belt transects were surveyed at fixed locations parallel to and just below the lower edge of mussel beds 1-2 times each year in spring and summer (Table 1). In each transect we identified, counted, measured, weighed, and assessed SSWD symptoms for each sea star. Arm lengths were used to classify *P. ochraceus* as recruit, juvenile or adult (see *Intertidal Methods* for more detail).

*Table 1. The number of sea star belt transects performed at each site over time. P. ochraceus were surveyed in all transects. ^ indicates Leptasterias spp. were also surveyed, and * indicates Leptasterias spp., Henricia spp., Evasterias troschelii, and Ophiothrix spp. were also surveyed.*

| | Marine Reserve | Comparison Area | Marine Reserve | Comparison Area | Marine Reserve |
|---|---|---|---|---|---|
| | **Cape Perpetua** | **Tokatee Klootchman** | **Otter Rock** | **Fogarty Creek** | **Cascade Head** |
| 2000 | 2 | - | - | - | - |
| 2001 | 4 | 4 | - | 6 | - |
| 2002 | 5 | 6 | - | 5 | - |
| 2003 | 4 | 6 | - | 6 | - |
| 2004 | 3 | 6 | - | 6 | - |
| 2005 | 3 | 4 | - | 5 | - |
| 2006 | 4 | 5 | - | 5 | - |
| 2007 | 3 | 4 | - | 5 | - |
| 2008 | 1 | 2 | - | 5 | - |
| 2009 | 1 | 3 | - | 5 | - |
| 2010 | 5 | 5 | - | 5 | - |
| 2011 | 4 | 5 | - | 5 | - |
| 2012 | 3 | 5 | - | 5 | - |
| 2013 | 2 | 4 | - | 5 | - |
| 2014 | 5 | 5 | - | 5 | - |
| 2015 | 5^ | 9 | 5* | 7^ | 3* |
| 2016 | 4^ | 7^ | 4* | 6^ | 3* |
| 2017 | 3 | 4 | 3* | 7 | 4* |
| 2018 | 5 | 5 | 5* | 7 | 5* |
| 2019 | 5 | 5 | 6* | 6 | 5* |
| 2020 | 5 | 5 | 5* | 5 | 4* |

## 2.2 Data Analysis

## 2.2.1 Data Preparation

We used R, RStudio (v 1.2.5042) and the dplyr (v1.0.3) and tidyverse (v1.3.0) packages to prepare the data. We plotted all data using the ggplot2 R package (v 3.3.3). To create datasets to analyze population densities, we summed the number of seastars of each species measured in each transect and populated zero counts for transects without a given species of sea star as needed.

*Population Densities*

For population density analyses of *P. ochraceus* over time, we opted to analyze populations of only adult densities (>4 cm arm length, see Intertidal Methods for more) rather than total population density since we are interested in the long-term recovery of the population. High densities of very small *P. ochraceus* recruits occurred in 2014-2017, and 1) mortality of these young is very high, 2) SSWD was and is still occurring, 3) these young do not contribute to the ecological keystone role of P. ochraceus and 4) these young hinder analyses assessing the impact of SSWD on the adult population. We also trimmed the datasets down to only those transects that were reliably sampled in most sampling years to reduce the possibility that transect placement in anomalously high or low density areas could influence the results.

*Sea Star Health*

For sea star health we opted to analyze only *P. ochraceus* since 1) sample sizes were small for most other species, 2) not all other species were sampled consistently among sites and years, and 3) disease symptoms were not reliably recorded or observable in other species. For these analyses we included all sizes of animals and included all transects surveyed. For sea star health analyzes, we categorized animals simply as ‘healthy’ or ‘diseased’. The latter included symptoms including lesions, arm loss, deflation, lost grip, disintegration, and death (Menge et al. 2016). We removed any animals with regrowing arms from analyses since they may have been either recovering from disease or from another injury, so their disease status is undetermined. Since SSWD symptoms were only recorded starting in 2014, we used survey notes to assign animals with any arm loss, lesions, or other suspect health notes to the “diseased” category in these older data. When no notes were present, we assumed an animal was healthy. We used the percentage of individuals diseased in each transect as the response in each model, calculated as [total diseased / total seastars] * 100.

When testing whether certain size classes of sea stars that were more affected by wasting than others, we restricted the data to Cape Perpetua, Tokatee Klootchman, and Fogarty Creek in 2014 because we had both sufficient data to ask the question, and 2014 was when disease symptoms were at their peak. We investigated disease prevalence among size classes in Otter Rock and Cascade Head, but low sample size and covarying trends in disease prevalence and recruitment made this analysis uninformative.

*Recruitment and Recovery*

For sea star recruitment we opted to analyze only *P. ochraceus* since in other species sample sizes were low, effort was uneven, and recruits were rare. For these analyses we included all sizes of animals and included all transects surveyed.

## 2.2.2 Population Density Analyses

*Relative abundance of species over time*

To compare the relative abundance of species by Reserve, we focused only on data in 2015 and later since that was the time frame during which we surveyed all the sites. We did not statistically analyze the densities of sea star species between sites and years because many species were not sampled in every site or year. Instead, we described graphically and summarised in tables the relative abundance of various sea stars species among sites.

*Effects of SSWD on sea star populations*

To test how SSWD affected the densities of sea star populations, we focused our statistical analysis on *P. ochraceus* since it was the only species that had balanced designs among sites and years. For the other species, we graphically depict the trends in density over time. We tested the yearly variation in adult *P. ochraceus* population density from 2001-2019, which captures the effects of SSWD on the populations. These data were limited to three sites including Cape Perpetua, Fogarty Creek and Tokatee Klootchman. To perform the model, we categorized the years into disease phases. The *pre-outbreak* phase included all data before 2013. The *during* phase included 2014 only since that was the height of the outbreak (Menge et al. 2016). The *post-outbreak* phase spanned from 2015-2017, which was when the outbreak had dissipated but the disease was still occuring at low levels (Menge et al. 2016). The *recovery* phase spanned from 2018-2019, when the disease was rare and adult sea star populations began to show signs of recovery.  We analyzed the main and interacting effects of phase and site on *P. ochraceus* density. We used a mixed effects generalized linear model (glmer package v1.1-23), a poisson distribution, used count as the response variable, the log10 of the area of the transect as an offset variable to control for different surface areas covered among transects or sites, and included transect as a random variable nested within site to account for repeated measures over time. We used the lsmeans function and package (v 2.30-0)  to perform Tukey's post-hoc analyses. We tested the main and interacting effects of site and year on *P. ochraceus* density. By comparing pre-outbreak to post-outbreak densities, we could assess the severity of SSWD (% decline = 100* [(pre density - post density) / pre density]).

*Population Recovery after SSWD*

To test whether populations have recovered from SSWD, we analyzed the variation in ‘contemporary’ densities of *P. ochraceus* between 2015-2019, which span the years in which we had data for the three Reserves and the two Comparison Areas. In this model, we again used a mixed effects generalized linear model, a poisson distribution, used count as the response variable, the log10 of the area of the transect as an offset, transect nested within site as a random variable, and performed Tukey's post-hoc analyses. We tested the main and interacting effects of site and year on *P. ochraceus* density. This model focused on whether adult *P. ochraceus* populations have been recovering each year since the epidemic of SSWD, and whether that varied among sites.

## 2.2.3 Sea Star Health Analyses

*Time Course of SSWD & Abatement*

To test the time course of SSWD and ask whether the disease has abated, we assessed the severity of the disease outbreak annually in each Reserve and Comparison Area. We again focused on *P. ochraceus* since the datasets were more complete and diagnosing the disease in this species is more reliable than for other species. We performed two models on sea star health because the differing timelines of the data between sites made including all the sites in one model impossible. Sites in the first model were Cape Perpetua, Tokatee Klootchman, and Fogarty Creek and data spanned 2001-2019. So we compared all 4 SSWD phases (pre, during, post and recovery phases; see above for time frames). Sites in the second model were Otter Rock and Cascade Head and data spanned from 2016 to 2020. So we compared only the post-outbreak and recovery phases. We removed 2015 from all analyses because, while density was quantified, sea star health was not well-assessed at most sites. Both models were performed using the glm function in the lme4 package in R (v1.1-23). We specified a binomial distribution and tested the main and interacting effects of phase and site on the proportion seastars diseased.

*Size-dependent effects of SSWD*

To test whether disease symptoms varied among size classes, we used two-sample kolmogorov-smirnov tests for Cape Perpetua, Tokatee Klootchman, and Fogarty Creek to compare the counts of animals in 2014 (during the outbreak) that were healthy or diseased in each 1cm arm length bin using ks.test function in the dgof package (v1.2).

## 2.2.4 Recruitment and Recovery Analyses

*Annual Variation in Sizes*

To assess the annual variation in sea star sizes over time, we graphed histograms of the size structure of *P. ochraceus* populations among years and sites. We again focused on *P. ochraceus* because the datasets were more complete and size data more consistently assessed.

*Recruitment and Recovery of Sea Stars*

We focused on *P. ochraceus* for analyses of sea star recruitment and recovery since few recruits were recorded for the other species. To test whether recruitment had occurred and whether these young grew and contributed to recovery of larger sized animals, we compared the density of different sea star life stages over time. We first binned *P. ochraceus* sizes into stages as follows: adult (>4cm arm length), juvenile (1.5 - 4cm arm length) and recruit (<1.5 cm arm length). We again were required to run two models. The first model included Cape Perpetua, Tokatee Klootchman, and Fogarty Creek, data spanned 2000-2019, and all 4 SSWD phases were compared (see above for detail). The second model included Otter Rock and Cascade Head, and spanned 2016-2020 so analyzed only the post-outbreak and recovery phases. In each model, we used a mixed effects generalized linear model (glmer package v1.1-23), a poisson distribution, count as the response variable, the log10 of the area of the transect as an offset variable, and included transect as a random variable nested within site. We tested the main and interacting effects of site, life stage, and SSWD phase on the density of *P. ochraceus.* We used the lsmeans function and package (v 2.30-0) to perform Tukey's post-hoc analyses.

# 3 Population Densities

**Takeaway: Among Reserves, both *P. ochraceus* and *Leptasterias* spp. were extremely abundant at Cape Perpetua. Otter Rock had the most species (4 spp.) but the lowest overall densities of sea stars. Cascade Head was dominated by *P. ochraceus*. The SSWD outbreak caused dramatic declines in densities of *P. ochraceus* populations at all sites, but some sites have recovered or show signs of recovery.**

*Table 2. Summary of the densities of various species of sea stars among Marine Reserve and Comparison Areas between 2015-2020.*

| | Site | Species | N Transects | N Individuals | Mean Density m^2 | SE |
|---|---|---|---|---|---|---|
| **Marine Reserve** | **Cape Perpetua** | *Pisaster ochraceus* | 38 | 1610 | 4.243 | 0.814 |
| | | *Leptasterias spp.* | 10 | 413 | 4.130 | 1.085 |
| **Comparison Area** | **Tokatee Klootchman** | *Pisaster ochraceus* | 48 | 1432 | 2.983 | 0.504 |
| | | *Leptasterias spp.* | 1 | 6 | 0.600 | - |
| **Marine Reserve** | **Otter Rock** | *Pisaster ochraceus* | 51 | 177 | 0.354 | 0.063 |
| | | *Leptasterias spp.* | 50 | 205 | 0.418 | 0.113 |
| | | *Henricia spp.* | 50 | 159 | 0.316 | 0.042 |
| | | *Evasterias troschelii* | 50 | 3 | 0.006 | 0.006 |
| | | *Ophiothrix spp.* | 50 | 0 | 0.000 | - |
| **Comparison Area** | **Fogarty Creek** | *Pisaster ochraceus* | 56 | 865 | 1.221 | 0.119 |
| | | *Leptasterias spp.* | 6 | 429 | 7.150 | 1.957 |
| **Marine Reserve** | **Cascade Head** | *Pisaster ochraceus* | 31 | 628 | 2.026 | 0.313 |
| | | *Leptasterias spp.* | 29 | 199 | 0.686 | 0.359 |
| | | *Henricia spp.* | 29 | 1 | 0.003 | 0.003 |
| | | *Evasterias troschelii* | 29 | 0 | 0.000 | - |
| | | *Ophiothrix spp.* | 29 | 1 | 0.003 | 0.003 |

*Table 3. Summary of the densities of P. ochraceus sea stars among Marine Reserve and Comparison Areas and among phases of the sea star wasting disease outbreak: Pre-outbreak (2013 and earlier), during outbreak (2014), post-outbreak (2015-2017) and recovery (2018-2020). The % declines compare pre- and post-outbreak population densities.*

| | Site | Outbreak Phase | N Transects | N Individuals | Mean Density m^2 | SE | % Decline |
|---|---|---|---|---|---|---|---|
| **Marine Reserve** | **Cape Perpetua** | Pre | 72 | 4871 | 3.38 | 0.29 | 40.02 |
| | | During | 7 | 312 | 4.46 | 1.64 | |
| | | Post | 25 | 505 | 2.03 | 0.40 | |
| | | Recovery | 15 | 1290 | 7.98 | 1.56 | |
| **Comparison Area** | **Tokatee Klootchman** | Pre | 100 | 4598 | 2.30 | 0.13 | 41.21 |
| | | During | 9 | 200 | 2.22 | 0.89 | |
| | | Post | 31 | 419 | 1.35 | 0.20 | |
| | | Recovery | 17 | 1013 | 5.96 | 1.05 | |
| **Marine Reserve** | **Otter Rock** | Post | 21 | 91 | 0.43 | 0.11 | ND |
| | | Recovery | 30 | 86 | 0.30 | 0.08 | |
| **Comparison Area** | **Fogarty Creek** | Pre | 124 | 3949 | 1.59 | 0.10 | 53.82 |
| | | During | 10 | 246 | 2.46 | 0.67 | |
| | | Post | 34 | 262 | 0.74 | 0.12 | |
| | | Recovery | 22 | 603 | 1.97 | 0.13 | |
| **Marine Reserve** | **Cascade Head** | Post | 14 | 192 | 1.37 | 0.30 | ND |
| | | Recovery | 17 | 436 | 2.56 | 0.48 | |

*Table 4. Generalized linear model results testing trends in* P. ochraceus *populations over time. a) Results for the effects of sea star wasting disease phase and site on the density of P. ochraceus between 2001-2019 in Cape Perpetua and 2 Comparison Areas. b) Results for the effects of site and year on the density of P. ochraceus between 2015-2019 in the 3 Reserves and 2 Comparison Areas.*

**a) Cape Perpetua, Tokatee Klootchman, and Fogarty Creek 2001-2019**

| Factor | ChiSq | df | P |
|---|---|---|---|
| SSWD Phase | 1518.6 | 3 | < 0.001 |
| Site | 16.0 | 2 | < 0.001 |
| SSWD Phase*Site | 150.2 | 6 | < 0.001 |

**b) All sites 2015-2019**

| Factor | ChiSq | df | P |
|---|---|---|---|
| Year | 1730.0 | 4 | < 0.001 |
| Site | 112.1 | 4 | < 0.001 |
| Year*Site | 247.1 | 16 | < 0.001 |

## 3.1 Population Density in Cape Perpetua Marine Reserve

**Takeaway: *P. ochraceus* and *Leptasterias spp. are* generally very abundant at Cape Perpetua. The *P. ochraceus* population was strongly affected by SSWD, but has since recovered to above pre-outbreak densities.**

*Relative abundance of species over time*

In Cape Perpetua, adult *P. ochraceus* were extremely abundant (Fig. 1, Table 2). They were at higher densities than the other two Reserves (Table 2, Table 4a, $P < 0.012$ for pairwise site comparisons) and at similar to the Comparison Area at Tokatee Klootchman (Fig. 2, Table 4a, $P = 0.430$). *Leptasterias* spp. were also extremely abundant at Cape Perpetua (Fig. 1, Table 2). Pre-outbreak (2001- 2013), *P. ochraceus* density fluctuated, ranging from a low of 2.01 ± 0.87 $m^{-2}$ in 2002 to a high of 10.00 ± 0.00 $m^{-2}$ in 2009 (Mean ± SE, Fig. 1). Note that the apparent peak in 2008-2009 each had 1 transect completed, so the true magnitude of this peak is uncertain.

*Effects of SSWD and recovery of sea star populations after SSWD*

When SSWD occured, densities of *P. ochraceous* declined significantly (40.0% decline) and remained low in the post-outbreak period from 2015-2017 (Fig. 1, Table 3, Table 4a: pre vs. post $P < 0.001$). During this time, the densities were lower than any year since 2000. Densities have increased steadily each year since 2015, with a dramatic increase in the recovery phase (2018-2019) that surpassed even pre-outbreak levels (Fig. 1, Table 3, Table 4a; pre vs. recovery $P < 0.001$).

***<u>Tokatee Kootchman Comparison Area</u>***

*Relative abundance of species over time*

In Tokatee Klootchman Comparison Area, adult *P. ochraceus* were very abundant (Fig. 2, Table 2) and similar to densities in the nearby Cape Perpetua Marine Reserve (Table 2, Table 4a, $P = 0.430$). Densities were quite stable over time, ranging from 1.64 ± 0.72 $m^{-2}$ in 2002 to 4.00 ± 2.35 $m^{-2}$ in 2009 (Mean ± SE, Fig. 2). No other species were consistently surveyed at Tokatee Klootchman.

*Effects of SSWD and recovery of sea star populations after SSWD*

When SSWD occured at Tokatee Klootchman, densities declined significantly and reached lower densities than at any time in the past (41.2% decline, Fig. 2, Table 3, Table 4a, $P < 0.001$ for pre- to post-outbreak phases). However, densities have increased dramatically during the recovery phase to above pre-outbreak levels (Table 3, Table 4a, $P < 0.001$ for pre-outbreak to recovery phases). These trends mirror the timing and impact of SSWD in Cape Perpetua Marine Reserve.

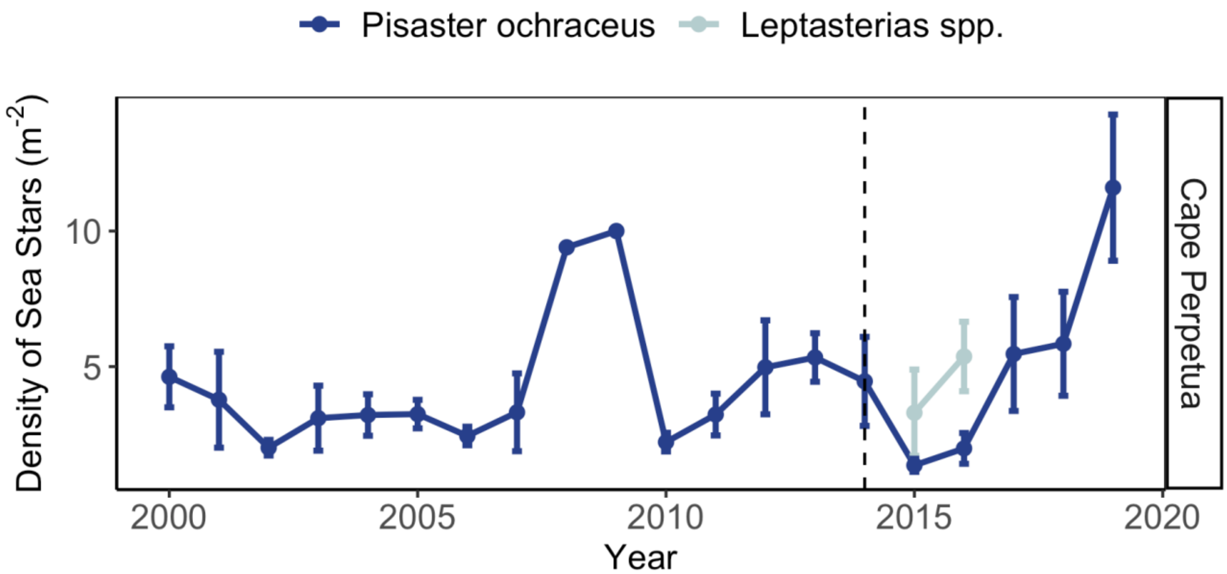


*Figure 1. The density (Mean ± SE) of sea stars Pisaster ochraceus (2000-2019) and Leptasterias spp. (2015-2016) at Cascade Head Marine Reserve. The dashed line in 2014 indicates the outbreak of sea star wasting disease.*

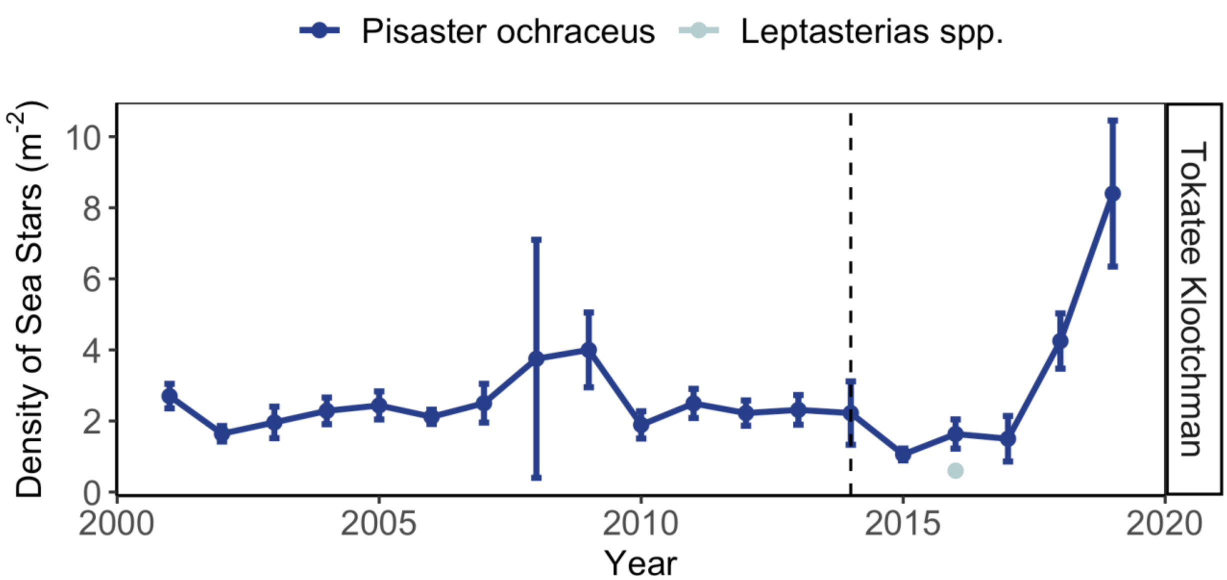


*Figure 2. The density (Mean ± SE) of sea stars Pisaster ochraceus (2000-2019) and Leptasterias spp. (016) at Tokatee Klootchman Comparison Area. The dashed line in 2014 indicates the outbreak of sea star wasting disease.*

## 3.2 Population Density in Otter Rock Marine Reserve

**Takeaway: Otter Rock has multiple species of sea stars but overall contains low population densities of *P. ochraceus*. *P. ochraceus* was likely affected by SSWD but does not appear to be recovering quickly.**

*Relative abundance of species over time*

Otter Rock Marine Reserve had a more diverse assemblage of sea stars than the other Reserve or Comparison Areas (Fig. 3, Table 2), with 3 species being consistently found (*P. ochraceus*, *Leptasterias* spp. and *Henricia* spp.). However, we note that the low intertidal was better surveyed and/or more accessible at this site than the others, so diversity may have also been similar at other sites. In recent years (2015-2020), *Leptasterias* spp. was the most abundant, followed by *P. ochraceus*, *Henricia* spp., and *E. troschelii*, while *Ophiothrix* spp. was not observed (Table 2). Densities of adult *P. ochraceus* were lower in Otter Rock than in any other Marine Reserve or Comparison Area (Fig. 3, Table 2, Table 4b, $P < 0.001$ for all site comparisons).

*Effects of SSWD and recovery of sea star populations after SSWD*

The lowest densities of *P. ochraceus* were recorded in 2015, just after SSWD (Fig. 3, Table 3, Table 4b). Though we have no pre-outbreak data, we assume that the disease caused declines at this site because of substantial declines at the Fogarty Creek Comparison Area (Fig. 4). Densities increased in 2017, but have since moderately declined again (Fig. 3, Table 3). However, there is no evidence that SSWD was responsible for these recent declines in 2019-2020 (see section 4.1.2 below). Based on these recent declines and the similar lack of substantial recovery at the Fogarty Creek Comparison Area (Fig. 4), it appears that *P. ochraceus* densities have not recovered from SSWD.

***<u>Fogarty Creek Comparison Area</u>***

*Relative abundance of species over time*

*Leptasterias* spp. abundances were higher at Fogarty Creek than any other site (Fig. 4, Table 2). Population densities of adult *P. ochraceus* are slightly higher than the nearby Otter Rock Marine Reserve, but lower than the other Reserves and Comparison Areas (Fig. 4, Table 2, Table 4b, $P < 0.001$ for all pairwise site comparisons). Densities were quite stable over time before SSWD, with a pre-outbreak range from $0.59 \pm 0.29$ m$^{-2}$ in 2001 to $2.79 \pm 2.56$ m$^{-2}$ in 2009 (Mean ± SE, Fig. 4).

*Effects of SSWD and recovery of sea star populations after SSWD*

Densities declined significantly due to SSWD at Fogarty Creek and were lowest in the post-outbreak phase (53.8% decline, Fig. 4, Table 3, Table 4a). Densities increased significantly each year from 2016-2018 ($P < 0.001$ for yearly comparisons), then began leveling off in 2018-2019 (Fig. 4, Table 4b). The population has not yet returned to pre-outbreak densities (Fig. 4, Table 3, Table 4a; P < 0.001 for pre vs. post and pre vs. recovery phases).

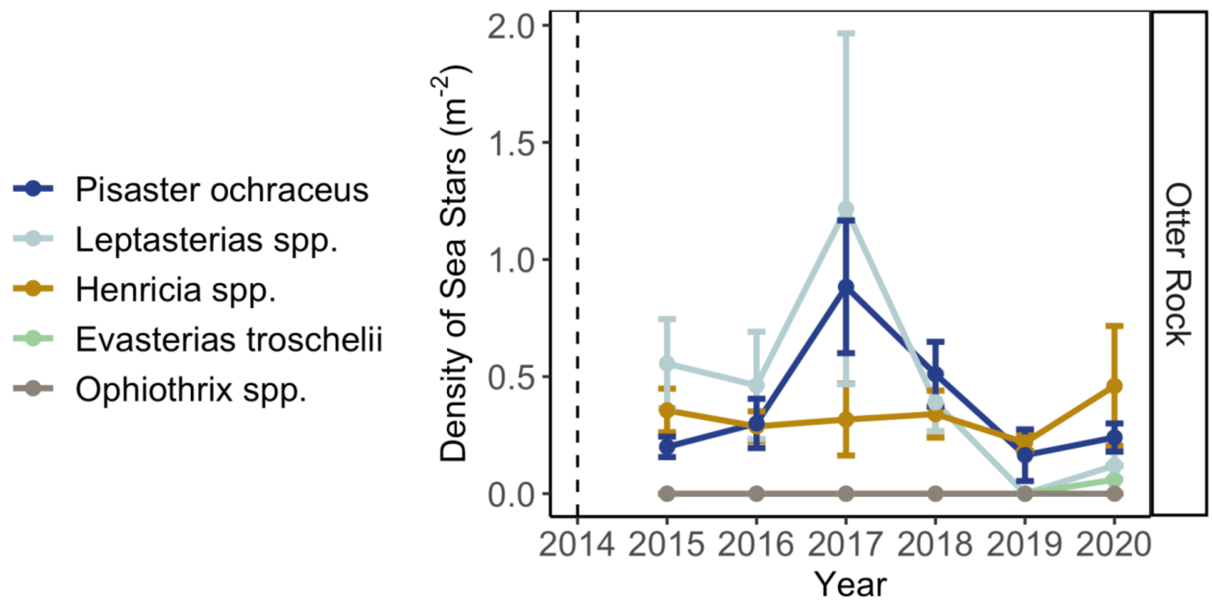


*Figure 3. The density (Mean ± SE) of 5 taxa of sea stars over time at Otter Rock Marine Reserve. The dashed line in 2014 indicates the outbreak of sea star wasting disease.*

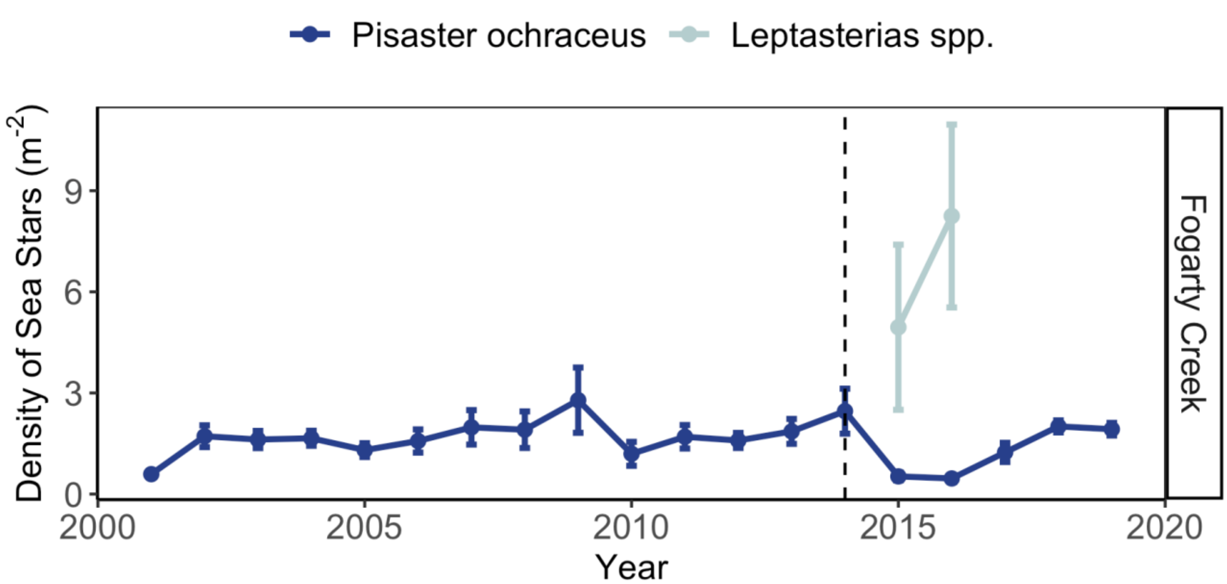

*Figure 4. The density (Mean ± SE) of 5 taxa of sea stars over time at Fogarty Creek Comparison Area. The dashed line in 2014 indicates the outbreak of sea star wasting disease.*

## 3.3 Population Density in Cascade Head Marine Reserve

**Takeaway: *P. ochraceus* is the most dominant sea star at Cascade Head and populations appear to be increasing since the SSWD outbreak.**

*Relative abundance of species over time*

Among species, *P. ochraceus* is the most dominant sea star at Cascade Head in recent years (Fig. 5, Table 2). It was more common at Cascade Head than at Otter Rock/Fogarty Creek, and less common than at Cape Perpetua/Tokatee Klootchman (Fig. 5, Table 2). *Leptasterias* spp. was fairly abundant in 2015 then rare thereafter, perhaps linked to declines due to SSWD, but high variability makes this relationship unclear (Fig. 5, Table 2). Both *Henricia* spp and *Ophiothrix* spp. were rare and *E. troschelii* were absent (Fig. 5, Table 2). However, these latter taxa may be more abundant in the very low to subtidal zones or in tidepools, which were not well sampled because they were inaccessible.

*Effects of SSWD and recovery of sea star populations after SSWD*

Adult *P. ochraceus* densities were lowest in the post-SSWD outbreak phase (Fig. 5, Table 3, Table 4b), similar to other Reserves and Comparison Areas. Though we have no pre-outbreak densities inside the Reserve, we expect that the population was affected similarly to other Reserve and Comparison Areas. Since SSWD, the population has increased significantly each year except 2018 and 2020 (Fig. 5, Table 3, Table 4b; $P < 0.02$ for all pairwise comparisons). So it appears that this population is exhibiting positive signs of recovery since SSWD.

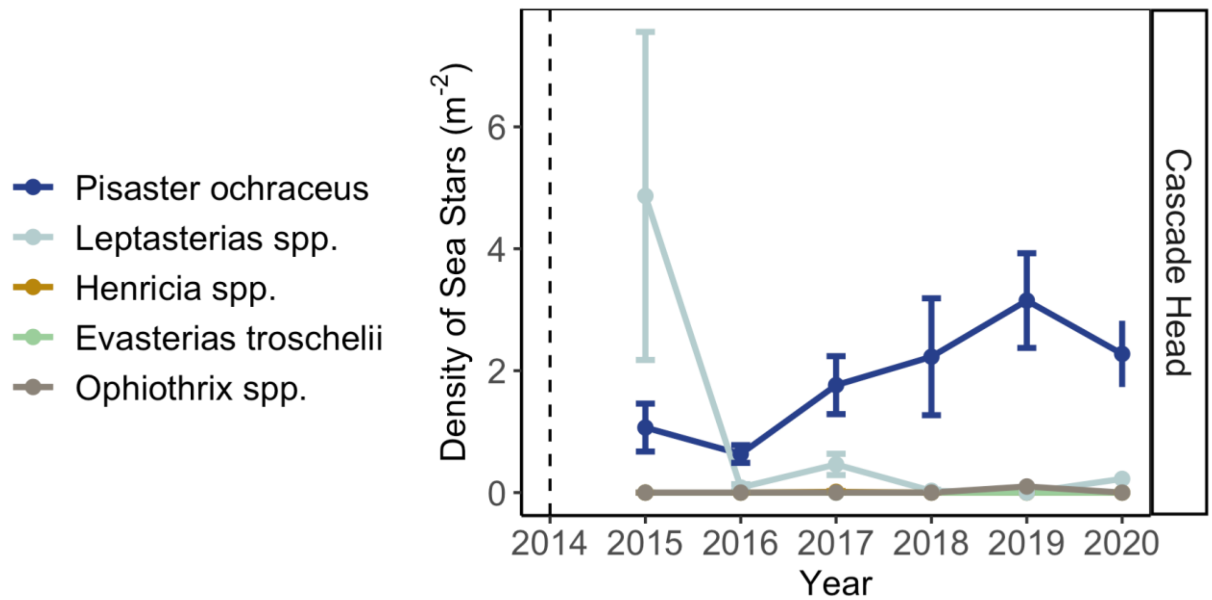


*Figure 5. The density (Mean ± SE) of 5 taxa of sea stars over time at Cascade Head Marine Reserve. The dashed line in 2014 indicates the outbreak of sea star wasting disease.*

# 4 Sea Star Health

## 4.1 Health of *P. ochraceus* Over Time

**Takeaway: Patterns in the health of *P. ochraceus* in and out of Oregon's Marine Reserves suggest that the sea star wasting disease outbreak was at its peak in 2014 and the disease continued to be prevalent through 2017. Though the outbreak has since subsided, the disease remains at low levels.**

*Table 5. Summary of the percent of* P. ochraceus *exhibiting symptoms of sea star wasting disease among Marine Reserve and Comparison Areas and outbreak phases. Outbreak phases include pre-outbreak (2013 and earlier), during outbreak (2014), post-outbreak (2015-2017) and recovery (2018-2020).*

| | Site | Outbreak Phase | N Transects | Mean % diseased | SE |
|---|---|---|---|---|---|
| Marine Reserve | Cape Perpetua | Pre | 42 | 0.35 | 0.21 |
| | | During | 5 | 63.03 | 16.06 |
| | | Post | 7 | 10.15 | 5.21 |
| | | Recovery | 12 | 4.18 | 1.58 |
| Comparison Area | Tokatee Klootchman | Pre | 59 | 0.64 | 0.18 |
| | | During | 5 | 27.29 | 9.20 |
| | | Post | 11 | 17.16 | 4.98 |
| | | Recovery | 10 | 3.80 | 0.52 |
| Marine Reserve | Otter Rock | Post | 7 | 14.04 | 4.36 |
| | | Recovery | 13 | 0.77 | 0.77 |
| Comparison Area | Fogarty Creek | Pre | 68 | 0.97 | 0.23 |
| | | During | 5 | 19.54 | 1.96 |
| | | Post | 16 | 9.28 | 2.67 |
| | | Recovery | 21 | 8.78 | 1.81 |
| Marine Reserve | Cascade Head | Post | 6 | 5.60 | 2.66 |
| | | Recovery | 14 | 0.14 | 0.14 |

*Table 6. Generalized linear model results testing trends in* P. ochraceus *health over time. a) Results for the effects of site and SSWD phase (pre, during, post, and recovery phases) on the percent of* P. ochraceus *diseased between 2001-2019 Cape Perpetua and 2 Comparison Areas. b) Results for the effects of site and sea star wasting disease phase (post-outbeak and recovery phases) on the percent of of* P. ochraceus *diseased in Otter Rock and Cascade Head in 2016-2020*

**a) Cape Perpetua, Tokatee Klootchman, and Fogarty Creek 2001-2019**

| Factor | ChiSq | df | P |
|---|---|---|---|
| SSWD Phase | 24.91 | 3 | < 0.001 |
| Site | 0.30 | 2 | 0.861 |
| SSWD Phase*Site | 2.70 | 6 | 0.845 |

**b) Otter Rock and Cascade Head 2016-2020**

| Factor | ChiSq | df | P |
|---|---|---|---|
| SSWD Phase | 2.25 | 1 | 0.134 |
| Site | 0.32 | 1 | 0.570 |
| SSWD Phase*Site | 0.01 | 1 | 0.925 |

## 4.1.1 Health in Cape Perpetua Marine Reserve

**Takeaway: SSWD severely affected *P. ochraceus* in Cape Perpetua in 2014. Though the outbreak has subsided, the disease lingers in the population. SSWD appears to have afflicted all sizes of *P. ochraceus* similarly.**

*Time Course of SSWD & Abatement*
At Cape Perpetua, there was an abrupt and dramatic increase in SSWD in 2014 (Fig. 6, Table 5, Table 6a). The disease declined in the post-outbreak phase, then further declined in the recovery phase, though no among-phase comparisons were significant (Fig. 6, Table 5, Table 6a, P > 0.113 for all pairwise comparisons). Overall, the disease affected Cape Perpetua more strongly than other sites (Table 5), but this was not significant (Table 6a).

*Size-dependent effects of SSWD*
We found no evidence that disease symptoms in *P. ochraceus* varied by size class at Cape Perpetua during the peak of the outbreak in 2014 (Fig. 8, P = 0.526). All size classes were similarly affected by the outbreak.

## Tokatee Klootchman Comparison Area

*Time Course of SSWD & Abatement*
Like Cape Perpetua, the percent of *P. ochraceus* exhibiting signs of SSWD was rare historically, but abruptly increased in 2014 at Tokatee Klootchman (Fig. 7, Table 5, Table 6a). The disease remained prevalent through the post-outbreak period (Fig. 7, Table 5). Since 2018, the disease has somewhat subsided but is still present (Fig. 7, Table 5). Overall, the time course and severity of disease was similar between Tokatee Klootchman and nearby Cape Perpetua Marine Reserve (Fig. 6).

*Size-dependent effects of SSWD*
Among size classes, the severity of the disease differed at Tokatee Klootchman (Fig. 8, $P < 0.001$). It appears that smaller sea stars were relatively less symptomatic of disease than adults. However, we suspect that this apparent trend may be due to smaller seastars succumbing faster to disease, making symptoms harder to capture in smaller size classes (Eisenlord et al. 2016).

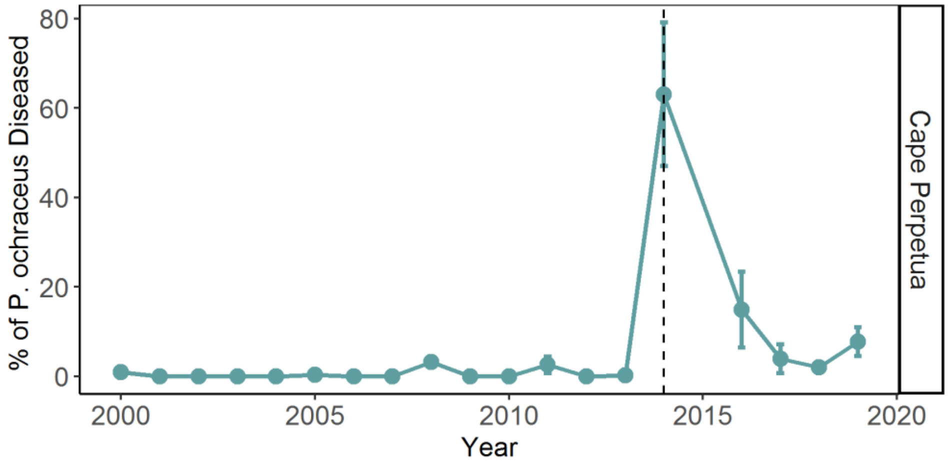


*Figure 6. The percentage (Mean ± SE) of* P. ochraceus *exhibiting symptoms of sea star wasting disease over time at Cape Perpetua Marine Reserve. The dashed line in 2014 indicates the outbreak of the disease.*

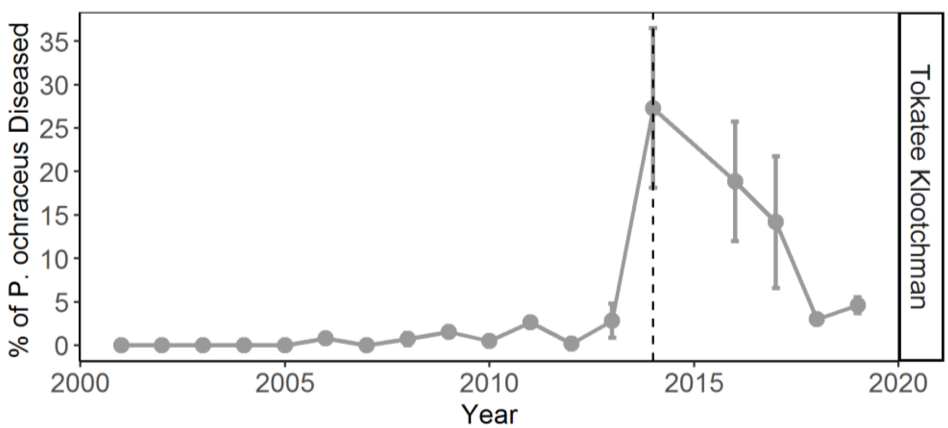


*Figure 7. The percentage (Mean ± SE) of* P. ochraceus *exhibiting symptoms of sea star wasting disease over time at Tokatee Klootchman Comparison Area. The dashed line in 2014 indicates the outbreak of the disease.*

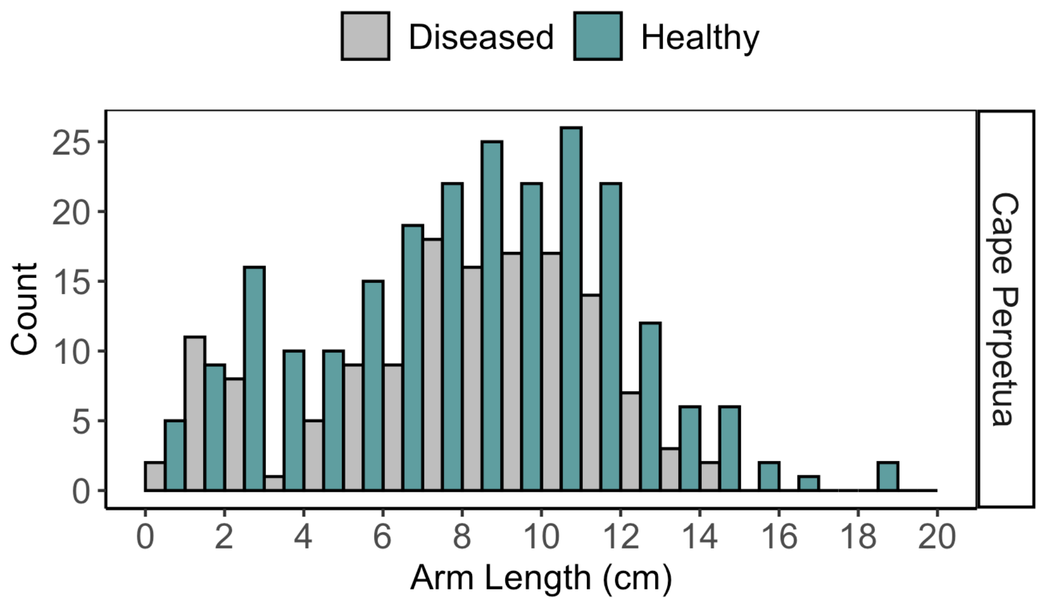


*Figure 8. The relative abundance of healthy and diseased* P. ochraceus *among size classes at Cape Perpetua Marine Reserve during the peak of the sea star wasting disease outbreak in 2014.*

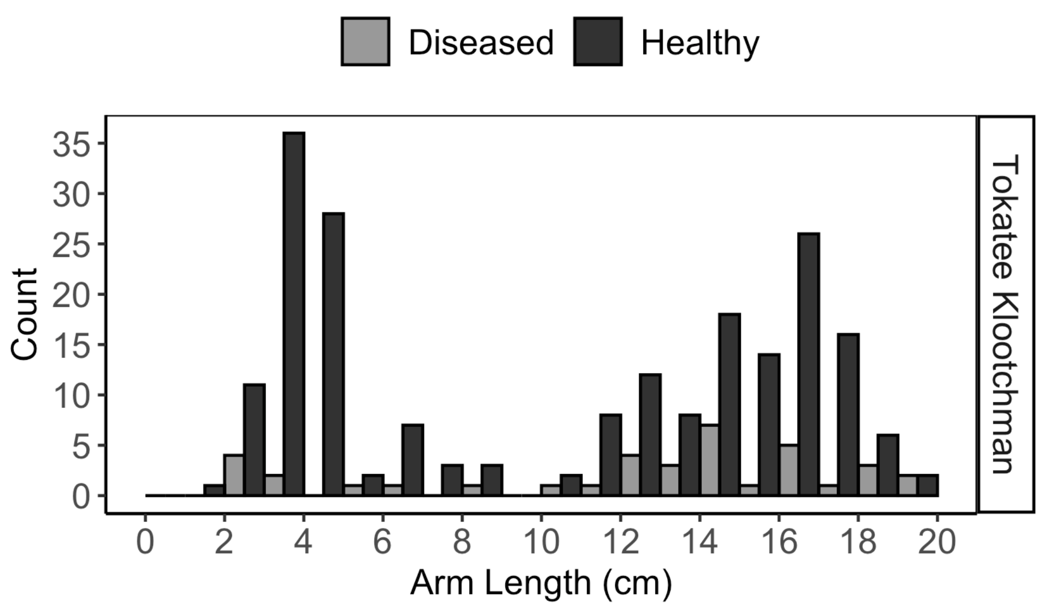


*Figure 9. The relative abundance of healthy and diseased Pisaster ochraceus among size classes at Tokatee Klootchman Comparison Area during the peak of the sea star wasting disease outbreak in 2014.*

## 4.1.2 Health in Otter Rock Marine Reserve

**Takeaway: SSWD was likely prevalent at Otter Rock during the outbreak, but it has since subsided.**

*Time Course of SSWD & Abatement*
At Otter Rock, there was a non-significant decline in the percent of *P. ochraceus* diseased between the post-outbreak and recovery phases (Fig. 10, Table 5, Table 6b). Unfortunately, we have no data during the height of the outbreak in 2014 and 2015, but the trend in infection shows that the disease was present at this site and has since subsided. Further, the peak in disease observed at nearby Fogarty Creek (Fig. 11) suggests that this site was affected by SSWD.

*Size-dependent effects of SSWD*
Low sample size and covarying trends in disease prevalence and recruitment made this analysis uninformative.

**<u>Fogarty Creek Comparison Area</u>**

*Time Course of SSWD & Abatement*
Like Cape Perpetua and Tokatee Klootchman, the percent of *P. ochraceus* exhibiting signs of SSWD was rare historically, then abruptly increased in 2014 (Fig. 11, Table 5), though no among-phase comparisons were significant (Table 6a, $P > 0.221$). The disease has somewhat subsided but remains present (Fig. 11, Table 5).

*Size-dependent effects of SSWD*
Among size classes, the severity of the disease differed at Fogarty Creek (Fig. 12, $P < 0.001$). Unlike Tokatee Klootchman, it appears that larger sea stars were relatively more healthy than smaller sea stars.

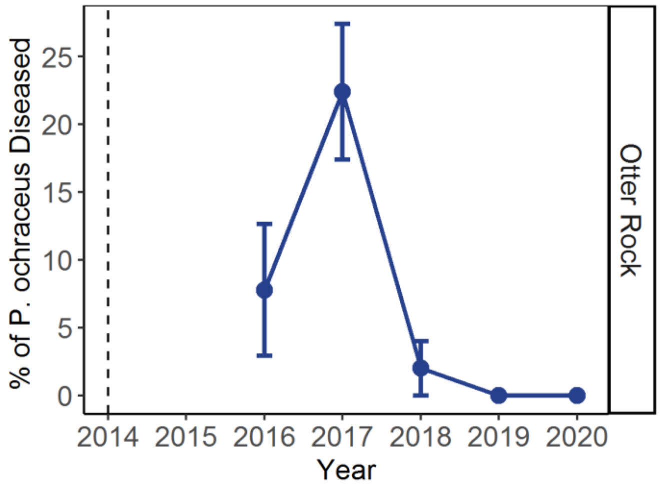


*Figure 10. The percentage (Mean ± SE) of P. ochraceus exhibiting symptoms of sea star wasting disease over time at Otter Rock Marine Reserve. The dashed line in 2014 indicates the outbreak of the disease.*

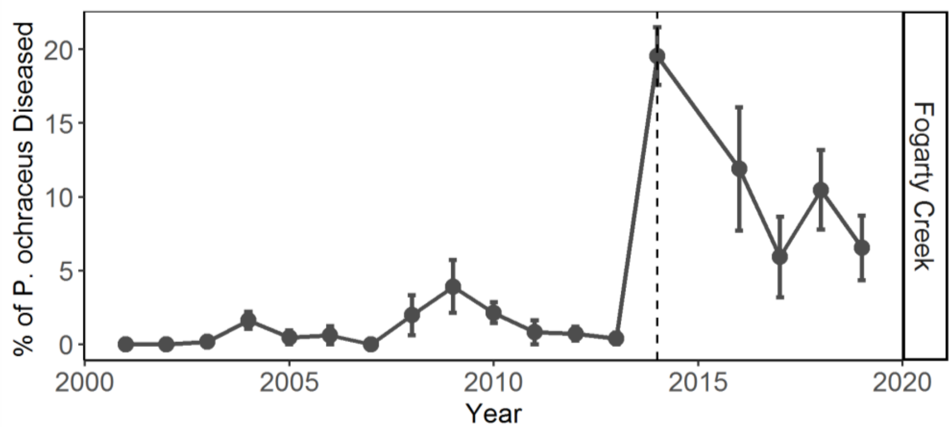


*Figure 11. The percentage (Mean ± SE) of P. ochraceus exhibiting symptoms of sea star wasting disease over time at Fogarty Creek Comparison Area. The dashed line in 2014 indicates the outbreak of the disease.*

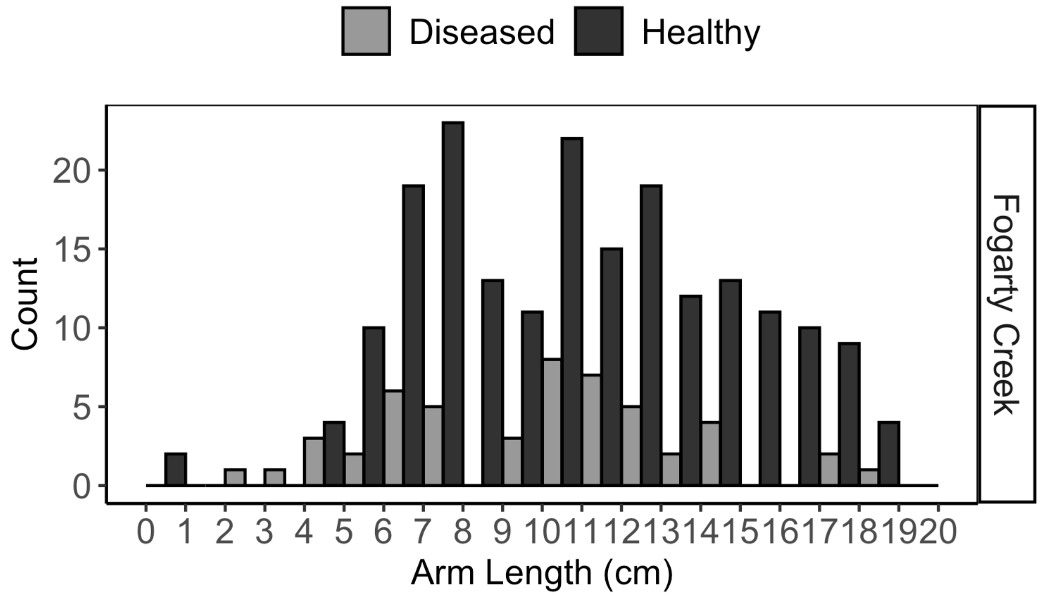


*Figure 12. The relative abundance of healthy and diseased Pisaster ochraceus among size classes at Fogarty Creek Comparison Area during the peak of the sea star wasting disease outbreak in 2014.*

## 4.1.3 Health in Cascade Head Marine Reserve

**Takeaway: SSWD was likely prevalent at Cascade Head during the outbreak, but it has since subsided.**

*Time Course of SSWD & Abatement*
At Cascade Head, there was a decline in the percent of *P. ochraceus* diseased between the post-outbreak and recovery phases (Fig. 13, Table 5). However, the decline was not significant due to high variability in the % diseased during the post-outbreak phase (Table 6b). Though we have no data during the peak of the outbreak in 2014 and 2015, Cascade Head exhibited a lower prevalence of infection in the post-outbreak and recovery phases than any other site and disease animals have been very rare since 2017 (Table 5). It is possible the outbreak was more mild at Cascade Head, but we are uncertain. Regardless, the outbreak has subsided at this site.

*Size-dependent effects of SSWD*
Low sample size and covarying trends in disease prevalence and recruitment made this analysis uninformative.

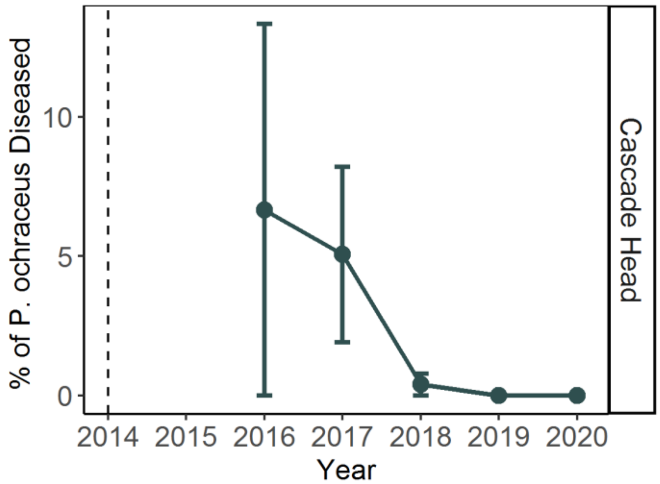


*Figure 13. The percentage (Mean ± SE) of Pisaster ochraceus exhibiting symptoms of sea star wasting disease over time at Cascade Head Marine Reserve. The dashed line in 2014 indicates the outbreak of the disease.*

# 5 Recruitment and Recovery

## 5.1 Recruitment and Recovery of *P. ochraceus* Over Time

**Takeaway: Most areas were historically dominated by adults, and young animals were rare. A substantial recruitment pulse of young *P. ochraceus* occurred in most places in the years following wasting disease. Since then, those animals have grown into juveniles and then adults, resulting in population increases. Adult densities (but not body sizes) have recovered at Cape Perpetua Marine Reserve, and Cascade Head Marine Reserve populations are growing. However, recruitment was not substantial at Otter Rock Marine Reserve, and this area does not appear to be recovering.**

*Table 7. Generalised linear model results testing the density of P. ochraceus in different life stages (adult, juvenile and recruit) over the phases of the sea star wasting disease outbreak (pre, during, post and recovery phase). a) Results for Otter Rock and Cascade Head in 2015-2020, spanning post and recovery phases only. b) Results Cape Perpetua and 2 Comparison Areas in 2000-2019, spanning all four SSWD phases.*

**a) Cape Perpetua, Tokatee Klootchman, and Fogarty Creek 2001-2019**

| Factor | ChiSq | df | P |
|---|---|---|---|
| Site | 28.2 | 2 | < 0.001 |
| SSWD Phase | 1866.1 | 3 | < 0.001 |
| Life Stage | 1968.8 | 2 | < 0.001 |
| Site * SSWD Phase | 867.6 | 6 | < 0.001 |
| Site * Life Stage | 166.3 | 4 | < 0.001 |
| SSWD Phase * Life Stage | 4926.5 | 6 | < 0.001 |
| Site * SSWD Phase * Life Stage | 545.7 | 12 | < 0.001 |

**b) Otter Rock and Cascade Head 2015-2020**

| Factor | ChiSq | df | P |
|---|---|---|---|
| Site | 170.1 | 1 | < 0.001 |
| SSWD Phase | 157.3 | 1 | < 0.001 |
| Life Stage | 220.0 | 2 | < 0.001 |
| Site * SSWD Phase | 23.6 | 1 | < 0.001 |
| Site * Life Stage | 75.7 | 2 | < 0.001 |
| SSWD Phase * Life Stage | 26.7 | 2 | < 0.001 |
| Site * SSWD Phase * Life Stage | 3.8 | 2 | 0.1493 |

## 5.1.1 Size Distribution in Cape Perpetua Marine Reserve

**Takeaway: At Cape Perpetua Marine Reserve, adult *P. ochraceus* were historically dominant and sizes were stable over time. After SSWD, an unprecedented pulse of *P. ochraceus* recruitment occurred, and these young have since grown rapidly into juveniles and adults. As the animals grow in body size this population is showing signs of making a full recovery.**

*Annual Variation in Sizes*
Cape Perpetua Marine Reserve historically had very high densities of *P. ochraceus* adults, but few juveniles or recruits (Fig. 14). Before SSWD, annual variation in sizes was remarkably stable.

*Recruitment and Recovery*
In 2015-2017, just after the outbreak of SSWD post-outbreak, there was an unprecedented increase in *P. ochraceus* recruits (Fig. 14, Table 7a, P < 0.001 for pre to post comparison). This pulse of recruits has tapered off (P < 0.001 for post to recovery comparison) but recruitment is still higher than it was historically (Fig. 14, Table 7a,P > 0.001 for pre to recovery comparison). Because of this pulse, the recruits have grown into juveniles, which are currently more abundant than anytime in the last 20 years (Fig. 14, Table 7a, P < 0.001 for all pairwise phase comparisons). However, we expect the juvenile densities to decline in the coming years since recruitment has been lower (Fig, 14). Notably, the juveniles increased in density as early as 2015 (Fig. 14), suggesting that they must have grown very fast at this highly-productive site (Menge et al. 2015) between 2014 and 2015. Consequently, adults are now more abundant than before SSWD (Fig. 14, Table 7a, P < 0.001 for pre to recovery comparison) but the adults are currently smaller than they were historically.

***<u>Tokatee Klootchman Comparison Area</u>***

*Annual Variation in Sizes*
Tokatee Klootchman, like its nearby Marine Reserve site at Cape Perpetua, was historically dominated by adult *P. ochraceus* and had apparently few historic recruitment pulses (Fig. 15).

*Recruitment and Recovery*
Similar to Cape Perpetua, Tokatee Klootchman Comparison Area also received a pulse of recruits (Fig. 15). However, the major recruit pulse was delayed by 2 years; they didn’t arrive in high numbers until 2017 to 2019. Indeed, recruit densities in the recovery period are higher than anytime previously (Fig. 15, Table 7a, P < 0.001 for recovery vs. all other phases). Like at Cape Perpetua, these recruits are growing quickly and juvenile and adult densities are also higher in the recovery period than anytime in the past (Fig. 15, Table 7a, P < 0.001 for both juveniles and adults for recovery vs. all other phases). Though the body size of these adults is still smaller than historically, this population is likely to fully recover from SSWD in the coming years.

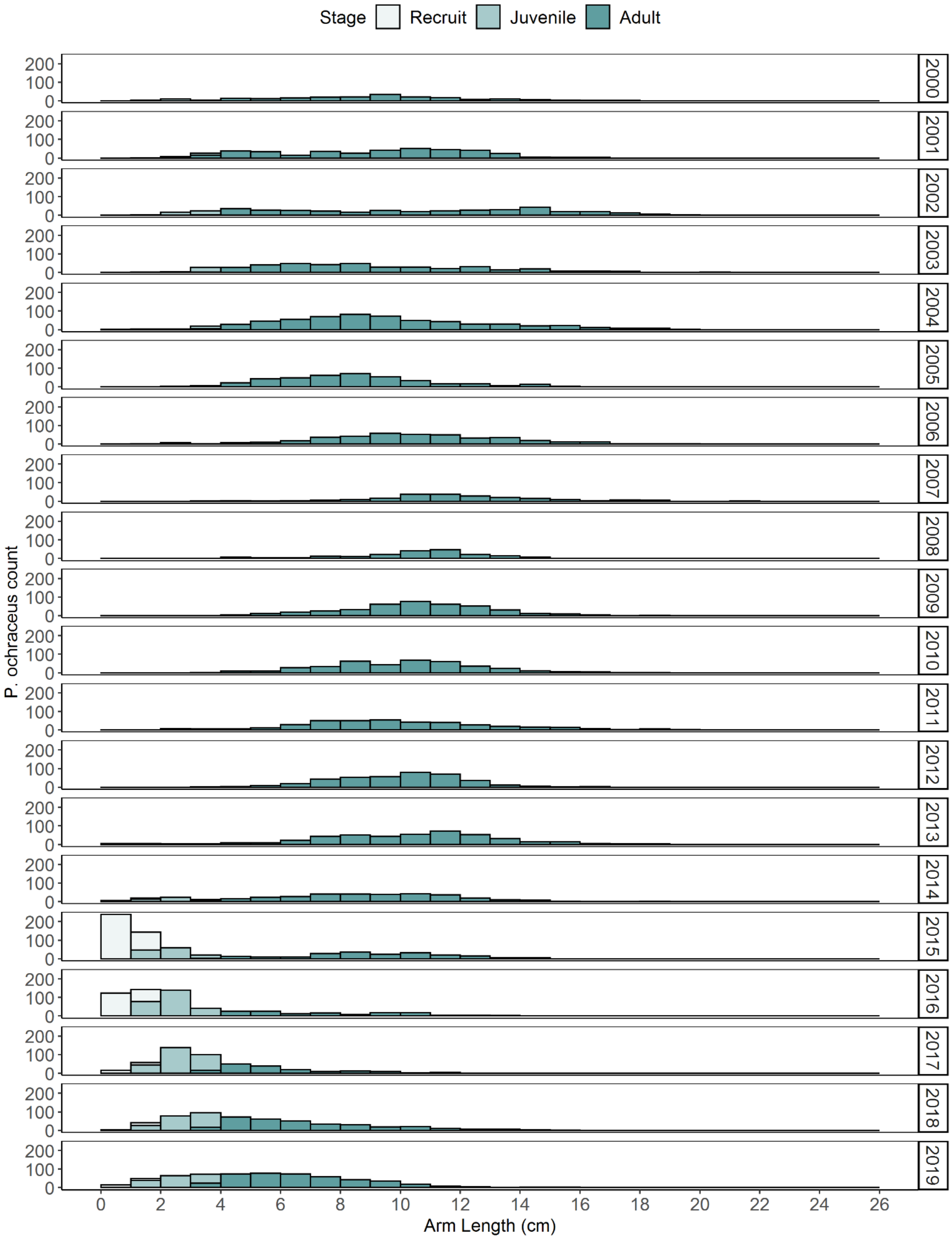


*Figure 14. The number of individuals of* P. ochraceus *in different life stages over time at Cape Perpetua Marine Reserve.*

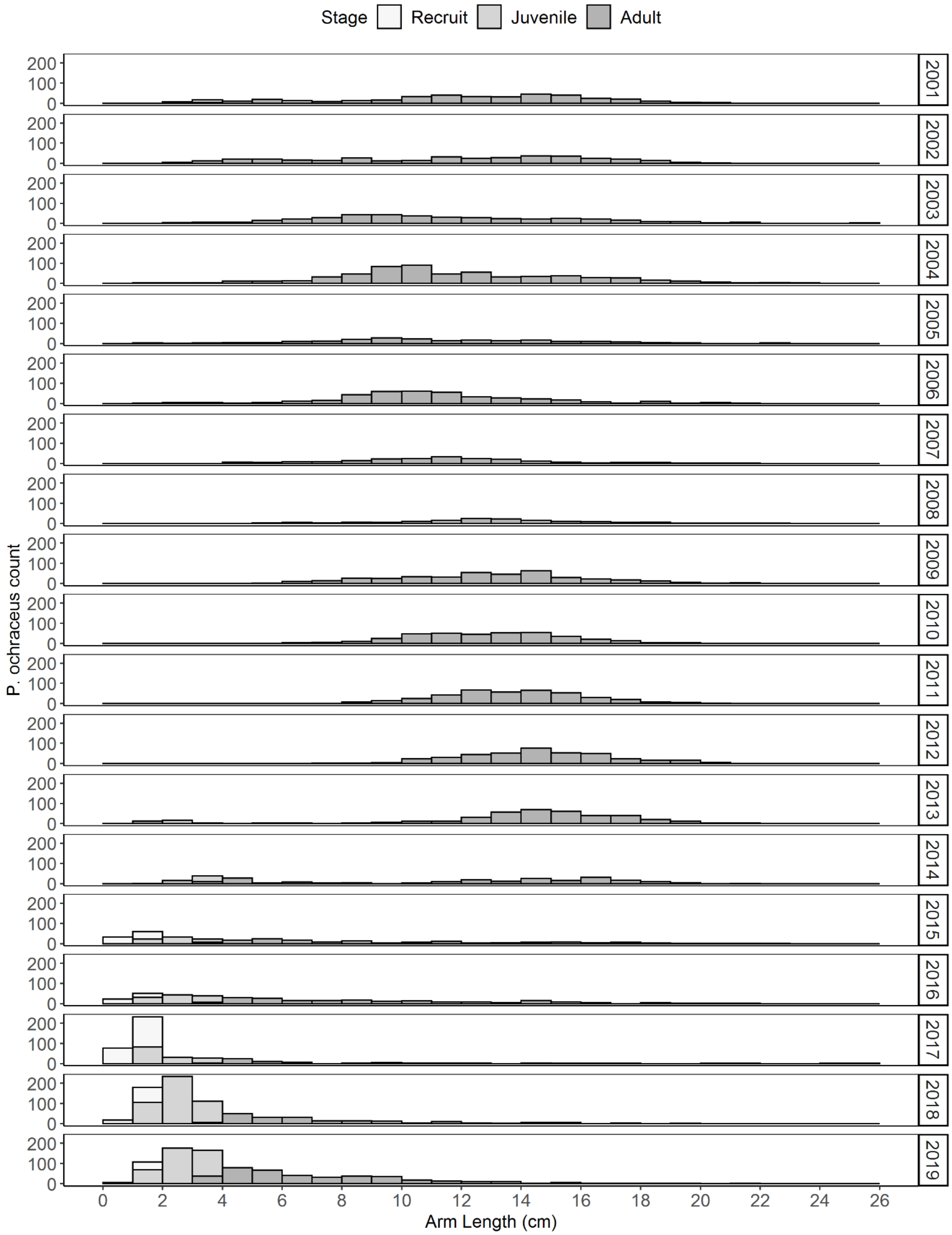


*Figure 15. The number of individuals of* P. ochraceus *in different life stages over time at Tokatee Klootchman Comparison Area.*

## 5.1.2 Size Distribution in Otter Rock Marine Reserve

**Takeaway: Though we have found modest numbers of recruits and juveniles at Otter Rock, the adult densities remain lower than its  Comparison Area at Fogarty Creek and other Marine Reserve sites. Since there is no data before 2015, it is unclear whether this site has simply not recovered from SSWD or if it has always had low densities of *P. ochraceus*.**

*Annual Variation in Sizes & Recruitment and Recovery*
At Otter Rock Marine Reserve since 2015, there were no detectable increases nor decreases in the densities of *P. ochraceus* at any life stage (Fig. 16, Table 7b, $P > 0.360$ for all pairwise comparisons) nor in the population as a whole ($P = 0.408$). The generally low densities at Otter Rock Marine Reserve may be the result of this lack of increase in recruits and  juveniles. However, recruits and juveniles have been found (Fig. 16) so it seems that there is at least some potential for population recovery into the future. The densities of *P. ochraceus* before SSWD are unknown, so it is unclear whether this site has yet to recover from SSWD or if it had historically low densities of *P. ochraceus*.

***<u>Fogarty Creek Comparison Area</u>***

*Annual Variation in Sizes*
Like other long-term sites, Fogarty Creek Comparison Area was historically dominated by adult sea stars (Fig. 17). However, there is evidence of a cohort that may have recruited in the 1990s since juveniles were common in 2001-2005 and the growth of those juveniles into adults is readily apparent over time (Fig. 17).

*Recruitment and Recovery*
Fogarty Creek Comparison Area also received a large pulse of recruits just after the SSWD outbreak in 2015-2017 (Fig. 17). The recruitment has tapered off in recent years, but is still higher than historical recruitment (Fig. 17, Table 7a, $P < 0.001$ for all pairwise comparisons). The initial pulse of recruits grew into juveniles post-outbreak (Fig. 17, Table 7a,  $P < 0.001$ for pre to post comparison). But in the recovery phase, juvenile density has declined ($P < 0.001$ for juvenile post to recovery comparison) as the juveniles have grown into adults ($P > 0.001$ for adult post to recovery comparison) and new recruits did not arrive to replenish the juvenile population (Fig. 17, Table 7a). Though this pulse of recruits have now become adults, the adult population is still smaller in number and body size than it was before SSWD ($P < 0.001$ for pre-outbreak to recovery comparison). Without new recruits, it is unlikely that the Fogarty Creek population will recover to pre-outbreak densities in the near future.

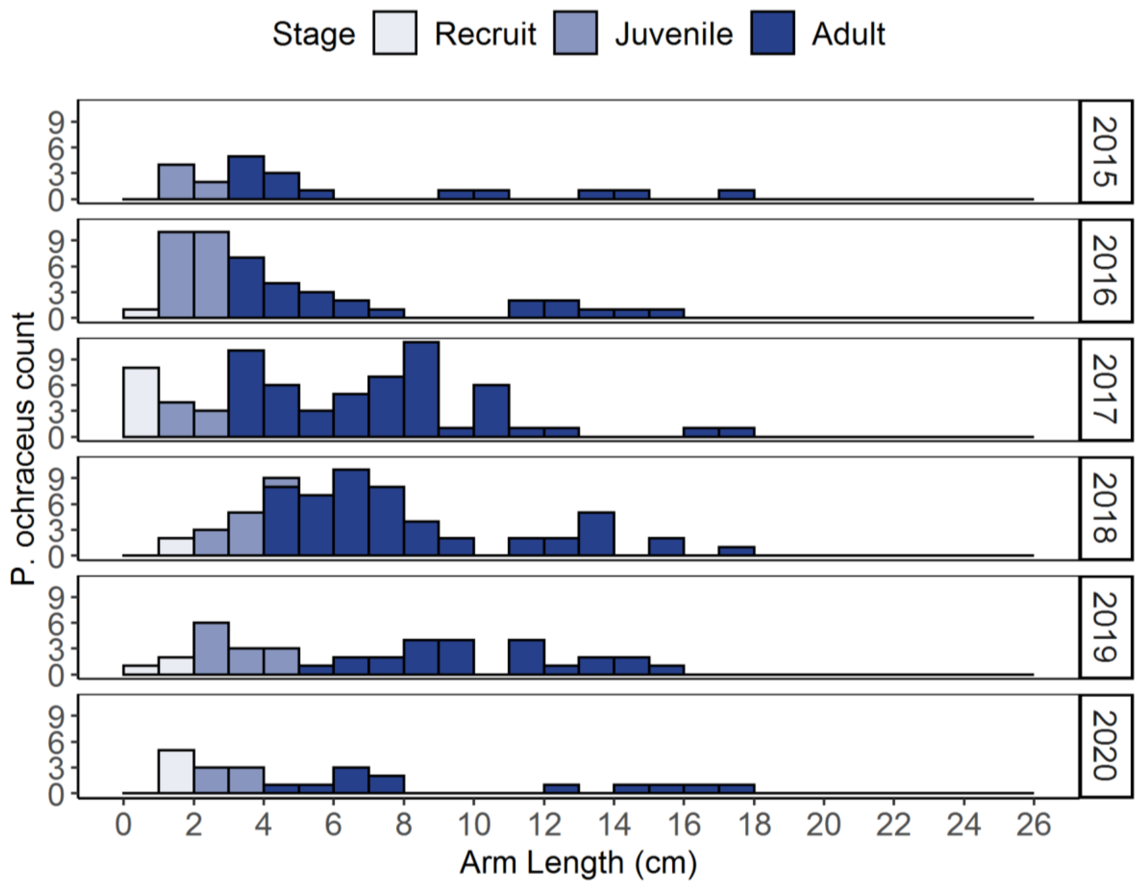


*Figure 16. The number of individuals of* P. ochraceus *in different life stages over time at Otter Rock Marine Reserve.*

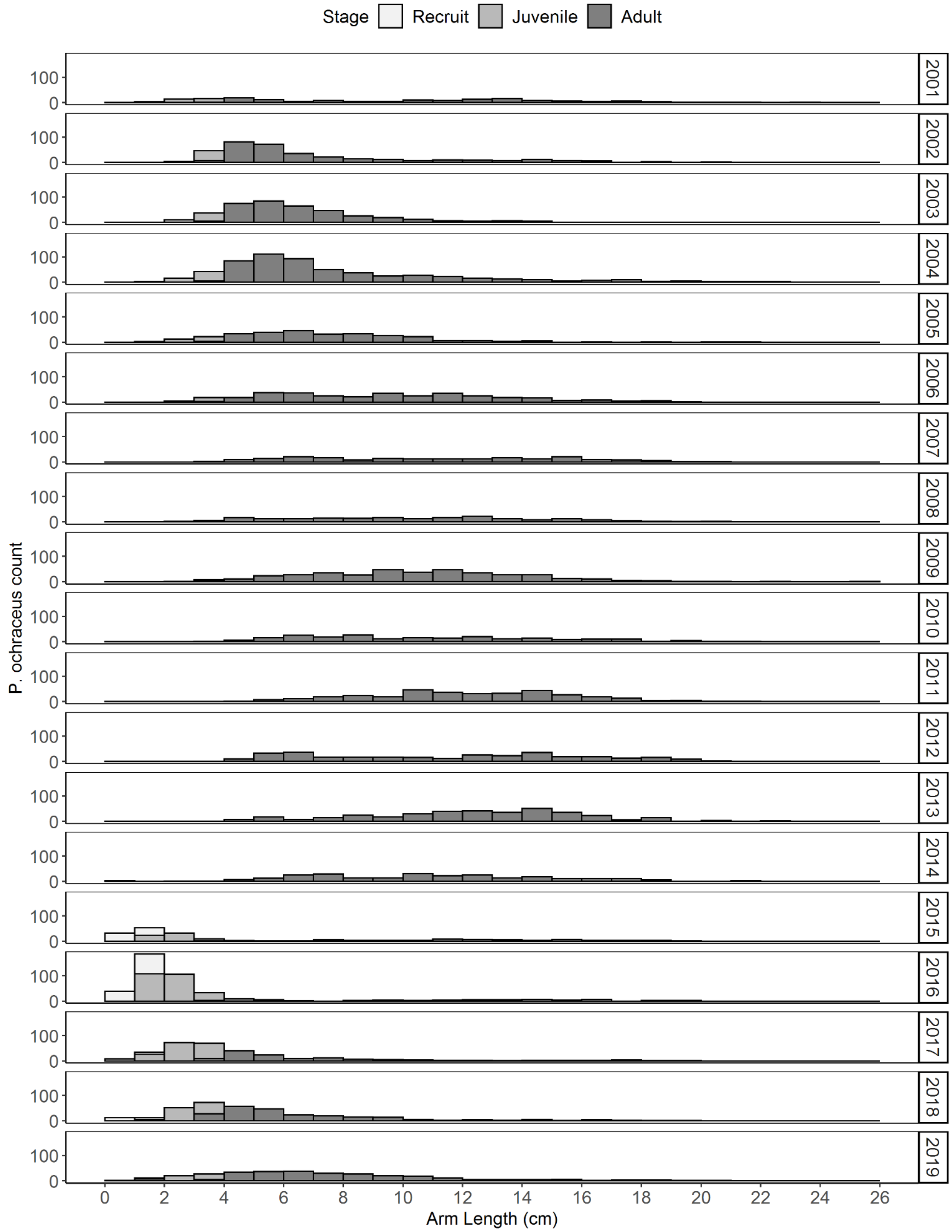


*Figure 17. The number of individuals of* P. ochraceus *in different life stages over time at Fogarty Creek Comparison Area.*

## 5.1.3 Size Distribution in Cascade Head Marine Reserve

**Takeaway: Continued recruitment of *P. ochraceus* from 2015-2020 has led to increased densities of both juveniles and adults. Though the densities before sea star wasting disease are unknown, this population appears to be increasing.**

*Annual Variation in Sizes & Recruitment and Recovery*
At Cascade Head Marine Reserve, there have been consistently high densities of recruits from the post-outbreak and continuing into the recovery period (Fig. 18, Table 7b, P = 0.157 for between-phase comparison). Consequently, the density of both juvenile and adult sea stars have increased during the recovery period as the recruits have grown (P < 0.001 for both pairwise comparisons). We lack data before 2015, so can not say whether this population has or will recover from SSWD, but the continued recruitment and increasing population indicates the population is healthy and increasing.

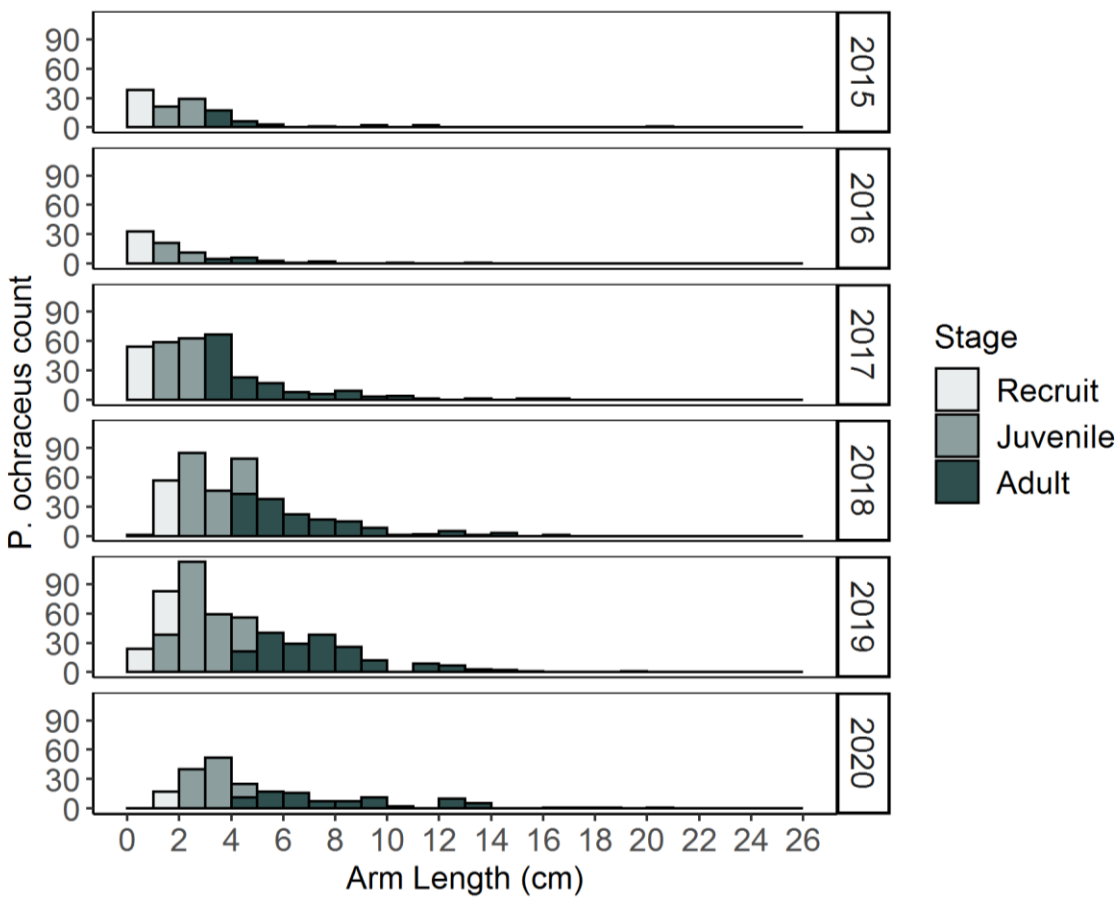

*Figure 18. The number of individuals of* P. ochraceus *in different life stages over time at Cascade Head Marine Reserve.*

# 6 Takeaways and Discussion

## 6.1 Summary of Findings

1) *How has the density of sea stars varied annually in each Reserve and Comparison Areas?*

In our analysis, we found that sea star densities vary substantially among species, among Reserves, and over time as sea star wasting disease swept through Oregon starting in 2014. Cape Perpetua has extremely high densities of *P. ochraceus* and very high densities of *Leptasterias* spp., and Tokatee Klootchman Comparison Area has similarly high densities of *P. ochraceus* (*Leptasterias* spp. not thoroughly assessed). Otter Rock Marine Reserve has both the highest diversity of sea stars (4 species observed with 3 being common) and the lowest density of the most dominant sea star *P. ochraceus*. Its Comparison Area, Fogarty Creek, has somewhat higher densities of *P. ochraceus*, much higher densities of Leptasterias spp. and lower densities of *Henricia spp.* The highest densities of *P. ochraceus* occurred at Cape Perpetua Marine Reserve and nearby Comparison Area Tokatee Klootchman, followed by Cascade Head Marine Reserve, Fogarty Creek Comparison Area and were lowest at Otter Rock Marine Reserve. Historically, densities of *P. ochraceus* at our long-term sites (Cape Perpetua Marine Reserve and Tokatee Klootchman and Fogarty Creek Comparison Areas was fairly stable over time before SSWD.

Though we have low sample sizes, there is no indication that sea star populations nor their response to SSWD differed systematically in Marine Reserves and associated Comparison Areas. The time series data from the PISCO long-term monitoring sites indicate that SSWD had strong effects on *P. ochraceus* populations and caused 40% declines in adults at the Cape Perpetua Marine Reserve, similar declines (41%) at its nearby Comparison Area Tokatee Klootchman, and 54% declines at Fogarty Creek (Comparison Area for Otter Rock Marine Reserve). These estimates of decline are slighter lower than was found at these same sites by Menge et al. 2016 (58-84%), but this may be attributable to different time frames used for pre- and post-outbreak. Menge et al (2016) compared % declines from spring 2014 to summer 2015, but in this report we compared % declines in pre-outbreak densities from 2000-2013 to post-outbreak densities in 2015-2017. While we can't assess the effects of SSWD directly at Otter Rock and Cascade Head Marine Reserves, the effects of SSWD (i.e. % decline) were likely similar to other sites in Oregon since the outbreak occurred state-wide (Menge et al. 2016). The declines in the Cape Perpetua Marine Reserve, its Comparison Area Tokatee Klootchman, and Fogarty Creek appear to be milder than the declines found in California, which typically ranged from 75% - 99% (Miner et al. 2018).

Data collected across the Marine Reserves and Comparison Areas since 2015 does allow us to understand trends in population densities for the post-wasting and recovery time periods. 2015-2016 was the low-point in adult population densities for all sites. Since then, all sites have shown increasing densities except for the Otter Rock Marine Reserve. The reason for the continued low densities at Otter Rock Marine Reserve is unclear. Densities at the Cape Perpetua Marine Reserve and its nearby Comparison Area Tokatee Klootchman have surpassed even historically high densities of *P. ochraceus*. These increases in density have been documented at many sites in Oregon, some sites in northern California, and have generally not occurred in Southern California (Menge et al. 2016, Miner et al. 2018).

2) *How has the health of sea stars varied annually in each Reserve and Comparison Areas?*

Our data indicate an abrupt and unprecedented surge in disease in Oregon starting in 2014, with 20-63% of individuals showing symptoms during that year at Cape Perpetua Marine Reserve, Tookatee Klootchman Comparison Area and Fogarty Creek (Comparison Area for Otter Rock Marine Reserve). The disease continued to be prevalent in all Reserves and Comparison Areas though 2017. The disease prevalence tended to be highest in the outbreak and post-outbreak periods at Cape Perpetua Marine Reserve, Tokatee Klootchman Comparison Area, Fogarty Creek Comparison Area, Otter Rock Marine Reserve, then Cascade Head Marine Reserve, but these differences were not statistically different. During the recovery period (since 2017) the disease seems to be absent or rare at the Otter Rock and Cascade Head Marine Reserves, but it is still present at the Cape Perpetua Marine Reserve and the two Comparison Areas.

Among the sites with data from the peak of the outbreak, we found mixed evidence for whether SSWD had size-dependent effects on sea stars. We found no difference in disease among sizes at Cape Perpetua Marine Reserve, evidence of relatively healthier juveniles in Tokatee Klootchman Comparison Area, and evidence of relatively healthier adults in Fogarty Creek Comparison Area (near Otter Rock Marine Reserve). Eisenlord et al. (2016) investigated this size-dependent effect of SSWD and found that “while larger ochre stars developed disease signs sooner than juveniles, diseased juveniles died more quickly than diseased adults”. These complex size-dependent expressions of disease symptoms make interpretation of our snapshot data on disease prevalence challenging to interpret. Thus, it is unclear whether SSWD differed in severity among size classes.

3) Has sea star recruitment contributed to population recovery since SSWD?

In two of the three Marine Reserves (Cascade Head & Cape Perpetua) , a substantial recruitment event for *P. ochraceus* occurred in the years following wasting disease. This was also observed at the Comparison Area for Cape Perpetua Marine Reserve and at the Comparison Area for Otter Rock. At Cape Perpetua Marine Reserve and its Comparison Area, this led to a surge in juveniles and then adults as the recruits grew. Currently the populations have exceeded pre-outbreak levels for density but body sizes are still smaller than before SSWD. Though we cannot state whether the Otter Rock and Cascade Head Marine Reserves have recovered from SSWD due to lack of pre-outbreak data, Cascade Head Marine Reserve populations are increasing for all life stages, indicating recovery. Conversely, the Otter Rock Marine Reserve populations have experienced little recruitment and population densities are not increasing. The densities at Fogarty Creek, the Comparison Area for the Otter Rock Marine Reserve, have recovered substantially, but will not likely reach pre-outbreak densities in the near future. Overall, it appears that populations at Cape Perpetua Marine Reserve and Tokatee Klootchman Comparison Area have recovered, that Cascade Head Marine Reserve is likely recovering, that Fogarty Creek Comparison Area has rebounded but not recovered, and that Otter Rock Marine Reserve has not recovered from SSWD.

## 6.2 Long-term data and the future of intertidal sea star monitoring in Oregon's Marine Reserves

Our ability to determine how sea star populations vary among Marine Reserves, their Comparison Areas, and over time has been greatly augmented by the collaboration between Oregon Marine Reserves and the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO). Many of the research questions explored in this report relied on the long-term monitoring efforts of the PISCO group at Oregon State University, led by B. Menge. These data provide valuable context with which to evaluate the smaller time-series at the Otter Rock and Cascade Head Marine Reserves. They also highlight the value of long-term datasets.

The SSWD epidemic highlights the ability of the ODFW Marine Reserves program to mobilize staff and monitoring efforts in response to emerging issues in Oregon's nearshore environment. In 2015, as researchers looked to understand the severity and scope of SSWD in Oregon, the Marine Reserves Program contributed with surveys in two Marine Reserves not previously monitored for sea stars, but also conducted surveys in other non-Marine Reserve sites in Yachats, Seal Rock and Newport. In the years since these first efforts, the Marine Reserves program has focused efforts to establish permanent transects at Otter Rock and Cascade Head Marine Reserves, and collaborated with PISCO to study the indirect effects of SSWD on the mussel bed and larger intertidal community. One of the objectives of Oregon's Marine Reserves is to serve as reference sites to better understand the effects of natural and human induced stressors. By building upon the long-term data at the Cape Perpetua Marine Reserve, establishing monitoring at Otter Rock and Cascade Head Marine Reserves, and collaborating to understand the indirect impacts of SSWD, the Marine Reserves in Oregon are expanding our understanding of the natural stressor of sea star wasting disease.

By collaborating with groups such as PISCO and their affiliated partner MARINe, (Multi-Agency Rocky Intertidal Network, e.g. Miner et al. 2018, also see Intertidal Biodiversity Appendix), the ODFW Marine Reserves program is contributing to understanding the impact of SSWD and change in intertidal communities west coast wide. PISCO has been collecting data in Cape Perpetua Reserve and many other sites on the Oregon coast for decades. Notably, the original placement of the Cape Perpetua Marine Reserve intentionally included the intertidal area to capture this wealth of long-term information, and it resulted in a detailed view of the largest marine epidemic ever recorded (Harvell et al. 2019, Gravem et al. 2021).Furthermore, building on the rich history of monitoring by PISCO at the Cape Perpetua Marine Reserve site, has also enabled this Marine Reserve to contribute substantially to state of the knowledge in marine science generally (see Oceanography special issue Vol 32(3) Sept 2019).

Looking forward, there is great value to continued intertidal sea star monitoring at Cape Perpetua Marine Reserve, Otter Rock and Cascade Head Marine Reserves. Long-term datasets such as those maintained by PISCO provide the backbone of intertidal sea star monitoring in Oregon's Marine Reserves. Continued collaboration and stronger connections between the ODFW Marine Reserves Program and PISCO would ensure continuity of these datasets. PISCO has funded all monitoring efforts at the Cape Perpetua Marine Reserve, in part because of the limited funding provided to the ODFW Marine Reserves Program. Additional funding for the ODFW Marine Reserves Program would help strengthen the collaborative nature of sea star monitoring at the Cape Perpetua Marine Reserve. Additional funding would also provide capacity to explore data across all Reserve sites related to additional natural stressors on intertidal communities such as climate warming and ocean acidification. Such capacity could also shed light on human stressors, such as intertidal harvest and recreational use on intertidal communities. The Otter Rock and Cascade Head Marine Reserves have the potential to provide unique linkages between intertidal and subtidal sea star populations; indeed we have yet to scratch the surface in our understanding of how subtidal *P. ochraceous* populations in Oregon have responded to SSWD. Additional ODFW Marine Reserve monitoring efforts on SCUBA and the Remotely Operated Vehicle (ROV) at these two Marine Reserves provide the opportunity for new knowledge to emerge about sea star populations, SSWD, and community change in Oregon's nearshore. Collaboration between the ODFW Marine Reserves Program and PISCO has resulted in multiple datasets that can be used to explore and reinforce our knowledge of intertidal sea stars, while building a bigger and better picture of intertidal community change over time.

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