A REPORT OF THE OREGON KELP ALLIANCE

## 2024 Oregon Kelp Forest

# STATUS REPORT

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# Executive Summary

Historically, kelp forests lined large sections of Oregon's coastlines particularly in the southern third of the state, from Cape Arago to Brookings. These productive ecosystems provide habitat for iconic species such as red sea urchins (*Mesocentrotus franciscanus*), abalone (*Haliotis* spp.), gray whales (*Eschrichtius robustus*), and multiple species of groundfish. Kelp forests also deliver a range of ecosystem services to coastal communities by supporting diverse fisheries, buffering coastlines from storms, creating recreational and cultural opportunities, transforming large amounts of carbon into organic material, and oxygenating and de-acidifying ocean waters locally. In response to the loss of many kelp forests along the West Coast of the US and concerns over declining kelp forests in Oregon, the Oregon Kelp Alliance (ORKA) initiated a suite of kelp forest surveys in 2023. The purpose of these surveys was to obtain a snapshot of the status of Oregon's kelp forests, which historically have been understudied relative to other West Coast systems. This report outlines several high-level trends and patterns observed in Oregon's canopy-forming kelp forests, based on data available to ORKA. Further, it identifies key needs for future research, monitoring, and conservation work.

Overall, we find that from 2010 to 2022, Oregon's kelp canopy cover has declined by 67–73% and we estimate that more than two-thirds of the state's kelp forest habitat no longer supports substantial kelp populations. Many areas are now dominated by urchin barrens. Since 2010, about 892 acres of bull kelp (*Nereocystis luetkeana*) forest have disappeared in Oregon. Preliminary estimates, based on the value of kelp forests in other systems, suggest that this loss costs the state approximately $23–$53 million each year. The loss of a majority of the Oregon's kelp forests in just over a decade has likely been driven in part by dramatic increases in purple sea urchin (*Strongylocentrotus purpuratus*) populations. Other drivers beyond sea urchin grazing, such as marine heat waves, have also likely contributed to kelp forest loss, but are not well understood in Oregon's context. Large increases in purple sea urchin populations, up to a 1000-fold increase in some places, are thought to have been driven by a combination of two factors: a recruitment boom sometime in the mid-2010s and the almost total loss of sunflower sea stars (*Pycnopodia helianthoides*), which are one of the few sea urchin predators in Oregon.

These losses are already having negative impacts on communities along Oregon's coast, including changes to gray whale foraging patterns, the closure of the red abalone (*Haliotis rufescens*) fishery, and shifts in the fishing grounds of red sea urchin divers. Despite the dramatic declines of kelp forests in some parts of the coast, Oregon's kelp forests also show signs of persistence and resilience. In 2023, extensive scuba and uncrewed aerial vehicle (UAV) survey work showed that the loss of kelp has been patchy in Oregon and identified several reefs that still support dense kelp populations. For instance, bull kelp forests around Cape Foulweather were unusually extensive in 2023, near maximums observed in the 1990s. Additionally, new sightings of sunflower sea stars raise new hope for the recovery of this species. This report raises key questions and expanded, systematic kelp forest monitoring will be critical to answering many of them. Restoration, protection, and research is urgently needed to revitalize Oregon's kelp forest ecosystems and the benefits they provide to Oregon's coastal communities.

# The Oregon Kelp Alliance

This report is produced by ORKA, a project of The Ocean Foundation, representing varied interests in kelp forest protection, restoration, and stewardship in Oregon. ORKA was founded in 2019 in response to reports by commercial sea urchin divers and others that Orford Reef, which historically accounted for about one half of Oregon's kelp forest canopy, was being transformed into a sea urchin barren. Ongoing monitoring focused on kelp forests in Oregon was relatively limited. In order to assess current kelp forest conditions, ORKA and its partners coordinated a 2023 survey effort to systematically target historic, canopy-forming, kelp forest habitat from Brookings to Pacific City. We combine these present-day data with several sources of ongoing kelp forest monitoring data to identify major trends in Oregon's kelp forests since 2010 and patterns in the current status of the state's kelp forests. While this effort documents several important changes in Oregon's kelp forest ecosystems, it also raises key questions that may be answered by critical future research, data collection, and monitoring. This report is written largely for a non-technical audience, with more additional information and technical details available in the extensive Appendix.

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**2024 KELP FOREST STATUS REPORT**

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# Definitions and Acronyms

## Definitions

**canopy-forming:** Kelp species, such as bull kelp (*Nereocystis luetkeana*) and giant kelp (*Macrocystis pyrifera*), that reach to the surface of the water when they are fully grown and thus are visible from shore or air

**scuba:** Integrated into common English language use as a word, "scuba" originated as an acronym that stands for "self-contained underwater breathing apparatus"

**subcanopy:** Kelp species that do not reach the surface of the water, cannot usually be seen from shore or air, and need to be monitored via underwater techniques like scuba or ROV

## Acronyms

**NOAA:** National Oceanic and Atmospheric Administration

**ORKA:** Oregon Kelp Alliance

**ODFW:** Oregon Department of Fish and Wildlife

**ROV:** Remotely Operated Vehicle—an underwater vehicle that is typically connected to a surface vessel via a communications/control tether.

**UAV:** Uncrewed aerial vehicles (commonly known as drones)

PHOTOGRAPH BY BRANDON COLE

# Introduction

Kelps are typically defined as large, brown seaweeds in the order Laminariales. Kelp forests are shallow (<30 m) marine ecosystems that form on rocky coastlines in the presence of kelps, usually in subpolar to temperate waters. They are widely distributed coastal ecosystems lining an estimated 24% of the world's coastlines.[1] Similar to trees in terrestrial forests, kelps are ecosystem engineers that provide extensive habitat and food, which attract a wide variety of other species.[2] Kelp forests also provide a wealth of ecosystem services that benefit human communities, including supporting diverse fisheries, buffering coastlines from storms and waves, creating opportunities for recreational and cultural activities, transforming large amounts of carbon into organic material, and oxygenating and de-acidifying ocean waters locally. The economic value of these benefits to human communities is estimated to be around $500 billion annually worldwide and $259 million annually in California alone.[3,4]

Kelp forests are highly dynamic but are experiencing a net decline globally due to the impacts of localized human activities, such as overfishing and water pollution, as well as the various impacts of global climate change.[5,6] Over the past decade, kelp forests have severely declined in several regions along the West Coast of North America, from Baja California to the Aleutian Islands.[7,8] The severity, spatial scale, and drivers of these declines vary from region to region. In Northern California, marine heat wave events, the vast expansion of kelp-grazing sea urchins, and the recent loss of a sea urchin predator to disease drove a widespread, synchronous collapse across several hundred miles of coastline.[9,10] Conversely, in Washington state, trends in kelp forest cover can vary over relatively small spatial scales (tens of kilometers) and losses are thought to be connected to long-term ocean warming, sedimentation, and nutrient pollution rather than to trophic dynamics.[11,12] Trophic dynamics, or feeding relationships within ecosystems, are often referred to as food chains or food webs. In any ecosystem, there are three basic trophic levels: producers, consumers, and decomposers. To maintain the health and function of an ecosystem, these relationships must be kept in balance. Regardless of the drivers, the loss of kelp forest ecosystems on the West Coast of North America has been accompanied by a host of negative societal impacts, including fisheries closures, shifting coastal livelihoods, loss of recreational opportunities, and the loss of cultural and food resources for Indigenous Nations.[9,13–15]

PHOTOGRAPH BY JUSTIN MYERS

# The Oregon Context

In what is today known as Oregon, kelp forest ecosystems have existed along the coastline since time immemorial. For much of Oregon's history, these productive ecosystems supported a suite of iconic species, including sea otters (*Enhydra lutris*), gray whales, red sea urchins, multiple species of abalone, and several species of groundfish such as rockfish, lingcod (*Ophiodon elongatus*), and cabezon (*Scorpaenichthys marmoratus*). Kelp forests are known to be particularly important habitat for juvenile fishes. Historically, Oregon's kelp forests provided rich nursery habitat for diverse fish species, including rockfish and likely salmon (*Oncorhynchus* spp.).[16–18] Recent work has also tied gray whales to kelp forests. The zooplankton communities these whales prey upon are found in increased concentrations in kelp forests.[19,20] From tiny fish to mighty marine mammals, kelp forests have been powerhouses of nearshore diversity and productivity along Oregon's wave-tossed shorelines for millennia.

Indigenous peoples in the region used kelps, and the species they house, for diverse purposes, including using bull kelp bulbs as containers for seal and sea lion oil, sea otter pelts as markers of status, and abalone shells for regalia, trade, and spiritual protection.[21–24] The impacts of colonization and genocide on the Indigenous peoples of Oregon have severed many traditional uses of the marine environment and eroded traditional stories and knowledge surrounding marine ecosystems. Despite this erosion, tribal members at many Oregon coastal Tribes, including the Confederated Tribes of the Siletz Indians, the Tolowa Dee-ni' Nation, the Confederated Tribes of the Coos, Lower Umpqua, and Siuslaw Indians, and the Coquille Indian Tribe continue some traditional uses of kelp forest ecosystems today and work for improved stewardship of kelp forest ecosystems.[21–23]

As colonization of the Oregon coast proceeded through the late 1800s, sea otters were extirpated by the global fur trade, removing a keystone top predator from the region's kelp forests.[25,26] Little data on kelp in Oregon exists in the historical record from the late 1800s through the 1980s, although Oregon-wide surveys were conducted in 1911 and 1954 to assess the extent of bull kelp.[27,28] Generally, these early surveys show a distribution of kelp forests along the Oregon coast that is similar to the distribution of kelp over the past several decades, but the infrequency of these historical surveys and differences in documenting methods and data make deeper insights difficult to gather from them.

More information on the state of Oregon's kelp forests became available in the 1980s and 1990s. NASA's Landsat 5 satellite came online in 1984 and fixed-wing airplane surveys commissioned by Oregon Department of Fish and Wildlife (ODFW) in 1990, 1996–1999, 2010, and 2022 documented the extent of canopy-forming bull kelp. By this time, Oregon's bull kelp forests were found primarily along rocky coastlines and offshore islands covering the southern third of the state from Cape Arago south to the border with California.[29–32] As is the case today, the northernmost stretch of large bull kelp forests existed along the coastline from Newport to Depoe Bay, with smaller, more isolated forests found northward in places such as Pacific City and Cape Lookout (figure 1). These surveys also began to document how bull kelp populations could vary substantially from year to year, as the annual life history of bull kelp allowed its populations to respond quickly to interannual changes in ocean conditions.[29–32]

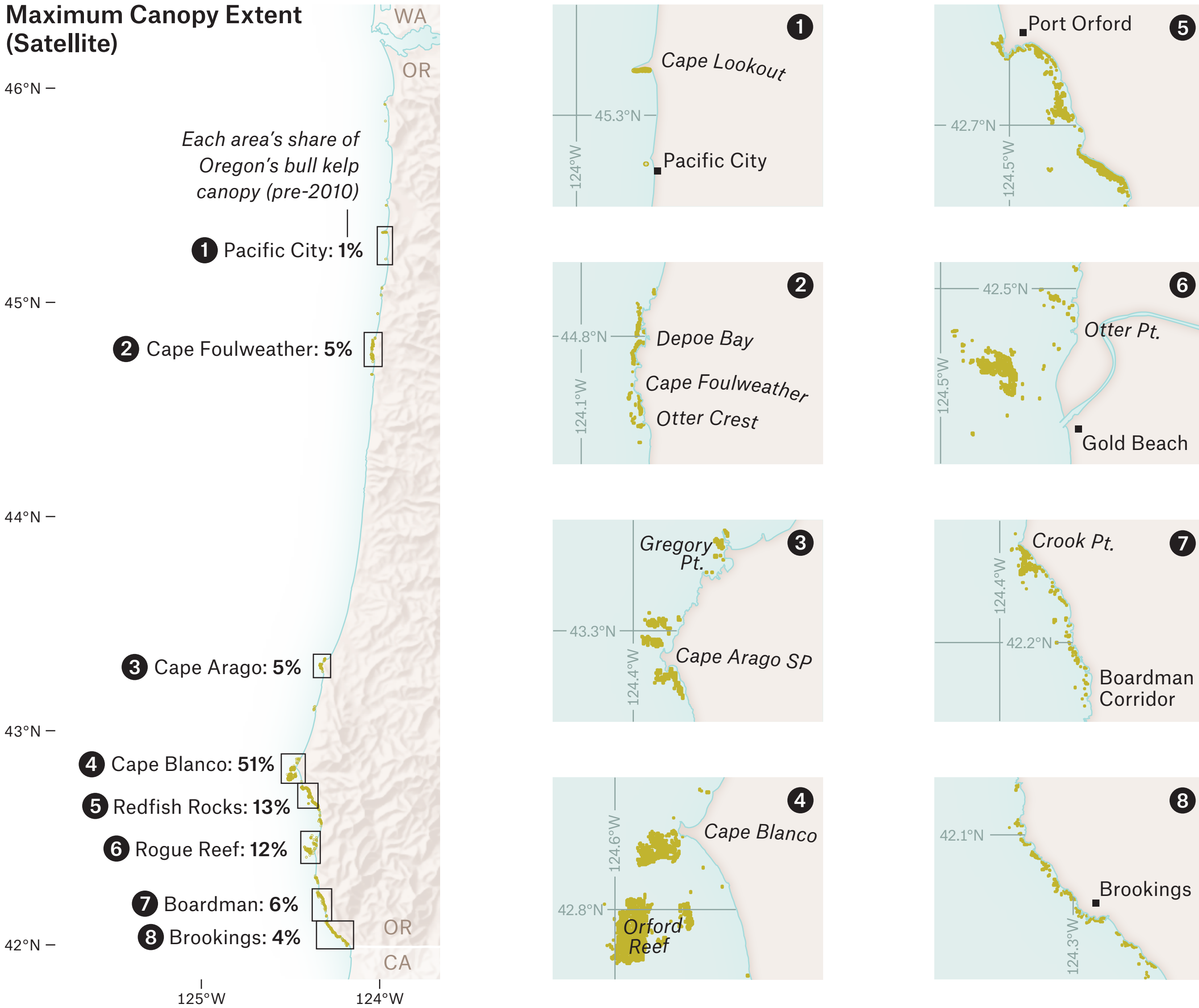


**Figure 1.** Maximum estimated extent of bull kelp canopy in Oregon from 1984–2023 as estimated by Landsat satellite data available through Kelpwatch. Note: On the whole Oregon map (left), the percentage underneath the name of each area indicates what percentage of Oregon's bull kelp canopy could be found in that area prior to 2010. Additionally, on this map, kelp forest cover appears larger than it really is in order to be seen at this zoomed out view of the whole state. The actual size of kelp forests is more representative in the zoomed-in panels (right).

Emerging industries spurred some of these new monitoring efforts. For example, public interest in kelp harvesting motivated ODFW's fixed-wing surveys of kelp forest extent.[33] The state banned the commercial harvest of bull kelp due to concerns about the highly variable biomass of the forests and, in 2006, listed bull kelp as a priority species in the Oregon Conservation Strategy.[33–35] Conversely, the red sea urchin commercial fishery in Oregon grew dramatically in the 1980s and the sport red abalone fishery restarted in 1996.[36,37] Both fisheries focused their efforts on kelp forests in southern Oregon. The red sea urchin fishery shrank substantially, after peaking in 1990 at 9 million pounds of landed red sea urchins per year and has since stabilized at roughly half a million pounds landed per year. Today, it is the third most valuable shellfish fishery in Oregon.[36]

Through the 2000s, there were few new developments regarding kelp forest ecology and monitoring in Oregon. By 2010, the implementation of Oregon's five Marine Reserves brought new, nearshore, scuba-based monitoring efforts that documented rocky reef biodiversity in and around several kelp forest areas, including Redfish Rocks and Cape Foulweather. Shortly thereafter, a perfect storm of interacting conditions negatively impacted kelp forest ecosystems across the entire West Coast of North America. From 2014–2016 this region concurrently experienced intense and sustained marine heat waves, sea star wasting disease, and dramatic increases in purple sea urchin populations.[10,38,39] Beginning in 2013, sea star wasting disease began decimating populations of sunflower sea stars, large predatory sea stars that can help control sea urchin populations through predation.[40–42] Around the same time, a historically severe marine heat wave caused extremely high nearshore ocean temperatures that persisted for years and that were likely beyond safe temperatures for kelps in many places, preventing successful growth and reproduction.[10,43,44] Finally, massive increases in purple sea urchin populations overgrazed standing kelp forests and prevented new kelp from establishing in the coming years.[10,39] Across hundreds of miles of Northern California coastline, researchers documented the collapse of bull kelp forests beginning around 2015. This collapse has persisted to the present.[9,10]

Evidence of similar changes in Oregon's kelp forests has been slowly accumulating since 2015. For instance, sunflower sea star populations were reduced by 99% in Oregon.[45–47] ODFW documented a 10,000% increase in purple sea urchin populations at long-term monitoring sites along Oregon's south coast.[48] Red sea urchin divers were forced to abandon prime historic fishing grounds such as Orford Reef due to a loss of kelp and poor quality red sea urchins resulting from limited food supply.[49] The small, largely recreational abalone fishery in Oregon was closed as abalone populations began to decline in response to food limitation.[50] Loss of kelp forest habitat in two sites near Port Orford has been connected to a decline in gray whale prey abundance and a subsequent decline in gray whale foraging at those sites.[20] While Oregon did not initially appear to be impacted as strongly as Northern California, satellite evidence did show loss of kelp forests at some places along the coast.[32]

Recent kelp forest declines have spurred a new focus on the restoration and stewardship of kelp forest ecosystems on the West Coast of North America. Kelp forest restoration work began in earnest in Central California, Northern California, Washington, and British Columbia using techniques designed to reduce sea urchin populations, increase the supply of reproductive kelp, and improve water quality.[14,51,52] In Oregon, ORKA formed in response to the concerns of red sea urchin divers as well as tourism operators, scientists, and fishermen, largely on Oregon's south coast, and then reaching along the entire Oregon coast, from Brookings to Cape Lookout. A push for sea otter reintroduction in Oregon and Northern California gained momentum, led in part by the Elakha Alliance.[53] Spurred in part by restoration and stewardship work, new methods of monitoring kelp forests have also emerged, including drones, new high-resolution satellites, and remotely operated vehicles.[54–56]

Given growing community concerns about the state of Oregon's kelp forests, in 2023 ORKA coordinated a kelp forest monitoring effort targeting historic, canopy-forming, kelp habitat spanning from Brookings to Pacific City. This effort aimed to provide new data on the status of Oregon's kelp forests. Here, we use these 2023 data as well as data from several ongoing kelp forest and nearshore monitoring programs to document some of the ways Oregon's kelp forests have changed over the past decade, the current status of many of these forests, and potential drivers of these changes. Given the limited and patchy monitoring of Oregon's kelp forests, we also provide recommendations for critical monitoring and data collection needed going forward to more thoroughly understand the state and drivers of Oregon's kelp forests and to support restoration and protection efforts.

# Brief Background on Kelp Forest Ecology

Kelps tend to have relatively short life spans, either as annuals or short-lived perennials (2–7 years) although some species can live for up to 25 years.[2] Different kelp species take different forms. Canopy-forming kelps, such as bull kelp and giant kelp (*Macrocystis pyrifera*), grow to the surface of the water and are often visible from land, whereas diverse subcanopy kelps exist below the surface of the water. Subcanopy kelp species usually take one or two forms, either as stipitate kelps with a tough, erect stipe holding the fronds off the seafloor or as prostrate kelps that lack a rigid stipe and lay closer to the seafloor. Regardless of the form, kelps have biphasic life cycles that alternate between microscopic, haploid gametophytes and the visible, diploid sporophytes that form kelp forests.[57]

Kelp forests are governed by a complex web of interactions between kelps, the environment, other organisms, and humans. Many of the drivers of kelp abundance fall into two categories, environmental and biotic. Environmental drivers that commonly shape kelp populations include temperature, light availability, nutrient concentrations, and storms. As photosynthesizers, kelps require adequate light levels to maintain their high levels of growth, which can be diminished by degraded water quality, such as when sediment becomes suspended in the water column via storms, construction, or runoff.[6] Nutrient supply is similarly crucial for kelps. Too few nutrients can limit kelp growth, particularly in warm waters, while too many nutrients can facilitate phytoplankton blooms that diminish light availability.[58–60] Kelps are also strongly influenced by temperature, and different kelp species and populations have varying ranges of temperatures where they can survive and thrive.[61,62] With climate change driving ocean warming, many kelp species are more regularly experiencing temperatures that surpass their optimum and maximum temperature thresholds, decreasing physiological performance and contributing to population decline.[62–64] While these are some of the best documented environmental drivers of kelp, many other environmental factors such as storms and pH can also influence kelps.[44,65]

Biotic forces also influence kelp abundance, as well as the interaction between biotic and environmental drivers. For instance, competition with other kelp species and sessile invertebrates for limited space on the rocky seafloor limits where and when new juvenile kelp can anchor themselves to the seafloor and begin growing.[66,67] Taller, canopy-forming kelp that reach to the surface of the water can shade out shorter, sub-canopy kelps.[62] Grazing invertebrates, particularly sea urchins, can quickly eliminate a kelp forest by grazing directly on kelp, particularly if they graze through the stipe and sever the kelp's anchor to the seafloor. Consequently, predators that prey on kelp grazers can also have strong impacts on kelp abundance. For instance, sea otters are known to promote healthy kelp forests via their predation of sea urchins.[39,68,69] It is also becoming increasingly clear that sunflower sea stars, large predatory sea stars, may also control sea urchin densities in kelp forest ecosystems.[39–41]

Under certain conditions, the rocky subtidal habitats that host kelp forests may oscillate between alternative stable states. Alternative stable states are discrete, non-transient states or phases that can occur within a single ecological system, in which different communities can exist. Transitions between alternative stable states are driven by perturbations in system feedbacks that, once they reach a threshold, force the ecosystem into a different state.[70,71] On the West Coast of North America, rocky reefs that support kelp forests can also support sea urchin barrens, an ecosystem dominated by sea urchins with few kelps and reduced biodiversity. In a productive kelp forest, sea urchins and other grazers prefer to feed passively, staying hidden in crevices and foraging on small bits of kelp debris floating down from the live kelps, which minimizes the impact of grazing. Grazers are also deterred from active grazing on live kelps by the back-and-forth whiplash motion of kelps in the waves, which can dislodge sea urchins from the reef. However, when the supply of kelp debris is reduced, often due to poor growing conditions, these invertebrates are more likely to emerge onto the open reef and begin grazing live kelps.[65,67]

Once sea urchins have overgrazed a kelp forest, the new state, an sea urchin barren supporting few or no kelps, tends to persist. This is because any juvenile kelps that settle on the seafloor are quickly consumed by the waiting sea urchins. Sea urchins can live decades longer than any kelp and are able to endure long periods without food. Crucially, the conditions needed to flip the system from one of these states to the other are often different from the conditions needed to flip the system back to its previous state, a concept known as hysteresis.[70–72] For example, while moderate densities of sea urchins can live in harmony in a kelp forest, once an sea urchin barren has been established, sea urchin densities must be reduced to very low levels before a kelp forest can re-establish.[6,72] The length of time a system stays in one state or another can vary between regions and contexts, states sometimes persist for decades and sometimes systems move between states every few years.[8,68,73,74]

# Data Used in this Report

To assess the status of kelp forests in Oregon, ORKA coordinated a series of surveys in 2023 aimed at quantifying current distributions of kelps and several key kelp forest species. These were focused primarily on a host of scuba surveys, although 21 UAV surveys of kelp forest extent were conducted as well. The scuba surveys were systematically distributed across Oregon's historic canopy-forming kelp habitat to create a coast-wide snapshot of the abundance of kelps, sea urchins, sea stars, and abalone. As of 2022, several forests had already been degraded and little kelp was present, so we used historical evidence of forests to target these sites.[29–31] ORKA worked with ODFW, Reef Check Oregon, the Galloway lab at the University of Oregon, and the Oregon Coast Aquarium to conduct these surveys. While scuba survey protocols varied somewhat between groups, all protocols estimated kelp, sea urchin, sea star and abalone density using standard 30 × 2 m swath transects. Target kelp species for all surveys include *Nereocystis luetkeana*, *Pterygophora californica*, *Pleurophycus gardneri*, and *Laminaria setchellii*. Beyond these ORKA coordinated surveys, we also utilized scuba surveys of the Cape Foulweather area coordinated by ODFW in Fall 2023. These surveys used methods similar to the scuba surveys coordinated by ORKA in 2023.

We also gathered data from several monitoring programs relevant to kelp forests that were initiated before ORKA's 2023 survey work, in order to increase the information available and to better assess the changing status of Oregon's kelp forests. We used data from five monitoring programs:

- **ODFW aerial bull kelp surveys:**[29,75] Plane-based aerial surveys of kelp canopy cover taken in late Fall of 2010 and 2022
- **Satellite-derived estimates of kelp canopy:**[76] Canopy extent data downloaded from the Kelpwatch online platform that estimates kelp canopy cover from Landsat satellite imagery
- **ODFW sea urchin fishery surveys:** Repeated scuba-based surveys of red and purple sea urchin densities at kelp forests, mostly in southern Oregon and collected primarily to aid in managing the red urchin fishery
- **ODFW marine reserves surveys:** [46] Scuba-based surveys of rocky reef habitat and ecosystems in marine reserves and nearby comparison sites
- **Reef Check community science surveys:** Scuba-based kelp forest ecosystem monitoring initiated in Macklyn Cove in 2017 and expanded to other sites in recent years

We did not use all data available from these data sources in this report. Rather we utilized data from sites (1) in key canopy-forming kelp forest habitat, and (2) that are well sampled over time (see Appendix for further details). To see a list of all the data sources and their respective survey types, spatial coverage, time frames, species surveyed, and number of surveys and transects, see **Appendix table 1**.

# Subtidal Kelp Forest Surveys using Scuba

For this report, we gathered scuba data from several ongoing monitoring programs into a cohesive database. We first defined boundaries of several sites along the coast that approximately correspond to a given rocky reef or kelp forest. We then grouped these sites into focal areas along the coast that roughly correspond to major headlands. We assigned every scuba survey to a site and area based on its geographic coordinates (**figure 2**).

While some of these surveys gathered data on a wide array of species, we focused our analyses on kelps and several species associated with kelp forests that are of particular ecological interest either because of their important role in their ecosystems or because of their economic or cultural value. We assigned species into categories or functional groups based on their ecological role in the system (**Appendix table 3**). Briefly, the functional groups (underlined) and ecological roles (bold) of target species were assigned as follows:

**Primary producers** including **canopy kelps** (bull kelp and occasionally giant kelp), **subcanopy kelps** (other smaller kelps), and **subcanopy vegetation** (red algae and surfgrass [*Phyllospadix* spp.])

**Grazers** including **purple sea urchins**, **red sea urchins**, and several **abalone**

**Predators** like **sunflower sea stars**, and **other large sea stars**

Because surveys from different data sources were taken using different protocols, spatial configurations, replication, and frequencies, we first standardized the data to calculate the density of each functional group at a given transect and date for a given data source. This typically included first calculating the count of each species at the transect level because transects were often subsampled for common species. We then summed counts for species or groups (**Appendix table 3**) to the functional group level (e.g., summed the different species of abalone). Finally, we divided this summed count by the area of the transect to calculate the density of each functional group in each transect.

# Remote and Aerial Data

We used two sources of long-term kelp canopy cover data derived from: (1) aerial surveys and (2) Landsat satellite imagery. Aerial kelp canopy surveys from 1996, 1997, 1998, 1999, 2010, and 2022 were obtained from ODFW-published records and datasets as well as unpublished datasets shared directly by ODFW.[29,75] Landsat-based estimates of kelp canopy cover were drawn from the Kelpwatch platform, which uses established methodologies to estimate kelp coverage by yearly quarter, from 1985 to the present.[32,76]

For these remote and aerial data, we focused on quantifying changes in kelp canopy cover between 2010 and 2022. We chose this timeframe because (1) we wanted to focus specifically on changes to Oregon's kelp forests over the past 15 years, and (2) both aerial and satellite data were available for these years. Because aerial data is of higher resolution than satellite data, and is therefore more accurate, we used aerial surveys wherever possible and satellite data for the areas that were not covered in aerial surveys. For further analysis and discussion of the strengths and weaknesses of satellite and aerial data in Oregon, we direct readers to a ODFW publication.[75]

We divided Oregon into nine kelp forest areas based on past aerial and satellite data, present-day kelp beds, and natural landmarks. We then assessed change by area for seven of these defined areas (**figure 2**). These areas include a Cape Lookout area stretching from Cape Lookout to just north of Cascade Head, a Cape Foulweather area from just south of Cascade Head to Waldport, a Cape Arago area stretching from Reedsport to Bandon, a Cape Blanco area stretching from just south of Bandon to just

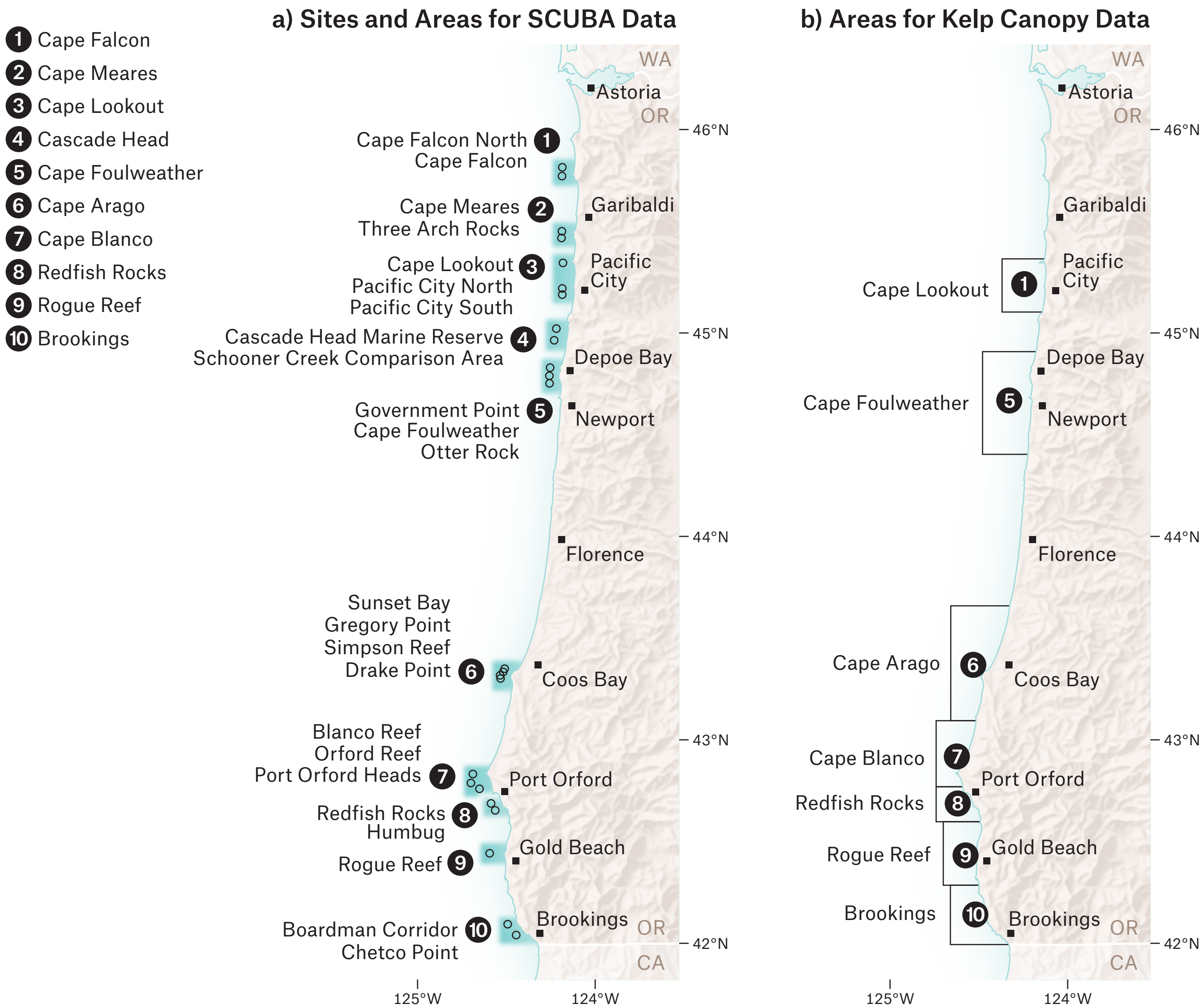


**Figure 2.** Map showing site (labels) and area designations (colors) for scuba surveys in Oregon. Sites approximately correspond to a given rocky reef or kelp forest and areas roughly correspond to major headlands. See **Appendix table 2** for coordinates. (left). Map showing area designations for aerial and satellite surveys. No box is present in the Cape Perpetua or northern area due to a lack of kelp. Some areas have been grouped slightly differently based on aerial/satellite data versus scuba data because the scale and extent of the two datasets are different (right).

north of Port Orford Heads, a Redfish Rocks area stretching from Port Orford Heads to the southern side of Sisters Rock, a Rogue Reef area stretching from south of Sisters Rock to Cape Sebastian, and a Brookings area stretching from Cape Sebastian to the California border. Two sections of the coastline, a North area stretching from Astoria to just north of Cape Lookout, and a Cape Perpetua area on the central coast stretching from Waldport to Reedsport, were not analyzed because canopy-forming kelp has rarely been detected there. Kelp cover is not evenly distributed across these areas and areas may encompass many miles of coastline without kelp habitat.

In 2023, ORKA conducted 21 UAV surveys across the state to assess the area of bull kelp canopy at nearshore sites. These surveys were conducted at locations that historically supported extensive canopy cover with a DJI Mavic 2 drone flying at an altitude of 300 ft with the camera at nadir. Survey images were stitched into an orthomosaic using Drone Deploy software. An initial classification of kelp canopy was conducted using the Kelp-o-matic image processing algorithm on Python and this classification was then corrected by hand in ArcGIS Pro.[77] Because these surveys were conducted from land rather than from boats, they capture nearshore kelp forests (within 1 km of shore), but do not include larger offshore reefs such as Orford Reef and Rogue Reef. Thus, the 21 completed UAV surveys are not a comprehensive look at all kelp canopy across the coast. They are a biased sample of 4–6 nearshore kelp forests across four different areas (Cape Foulweather, Cape Arago, Redfish Rocks, and Brookings).

## Temperature Data

We drew on two long-term temperature datasets maintained by NOAA's National Buoy Data Center to examine long-term exposure to stressful temperatures and changes in nearshore temperature in kelp forest habitat. Specifically, we drew on datasets from nearshore buoys at Port Orford (PORO3 buoy) and Charleston (CHAO3 buoy) which consist of near-surface (~3 ft depth), hourly temperature observations covering the 1990s to the present. Because the Charleston temperature station is located at the mouth of Coos Bay, we only used temperature data from periods when the tide level was ≥4.5 ft in order to filter out estuarine dominated periods. While these buoys are not measuring temperature directly within kelp forests, taken together these data help characterize nearshore temperature regimes within the state's core kelp forest habitat in southern Oregon.

# The Status of Oregon's Kelp Forests

## Changes in Kelp Forest Ecosystems Since 2010

ORKA's surveys, data collection, and analysis show evidence of declining kelp forest cover and increasing sea urchin populations since 2010. These changes are further detailed and discussed below.

### CHANGES IN CANOPY AREA FROM 2010 TO 2022

Historically, Oregon had extensive kelp forests lining the majority of the South Coast from Brookings up through Cape Arago as well as more northern kelp forests such as those at Depoe Bay and Pacific City.[27,28,30,32] Bull kelp, a canopy-forming kelp, has historically been a key species in Oregon's kelp forests. Assessing ebbs and flows in the extent of the bull kelp canopy reaching the ocean's surface is one way to quantify how kelp forests have changed over time. Kelp canopy data are limited in that they can only show changes in bull kelp and cannot provide information on the status of the diverse sub-canopy kelps that contribute to the composition of a kelp forest. However, because these data are derived from satellites, drones, and airplanes, they quickly capture information on kelp forest distribution along large parts of the coastline, which makes them useful in examining larger-scale patterns.

We assessed changes in kelp canopy cover by region between 2010 and 2022, using high-resolution aerial surveys where they are available and satellite-based estimates for regions not covered by aerial surveys (figure 3). The central Oregon coast was not historically included in ODFW aerial surveys. Therefore, we use satellite estimates for this area, even though satellite estimates are less accurate than aerial estimates.

Overall, aerial survey data estimates that from Cape Arago south to Brookings there was a 66.4% decrease in kelp forest canopy from 2010 to 2022, and satellite-derived data covering the entirety of Oregon's coastline estimated a similar decline of 73.5% from 2010 to 2022. Changes in kelp canopy during this time period are not consistent along the coast. Since 2010, we estimate that Oregon's kelp canopy

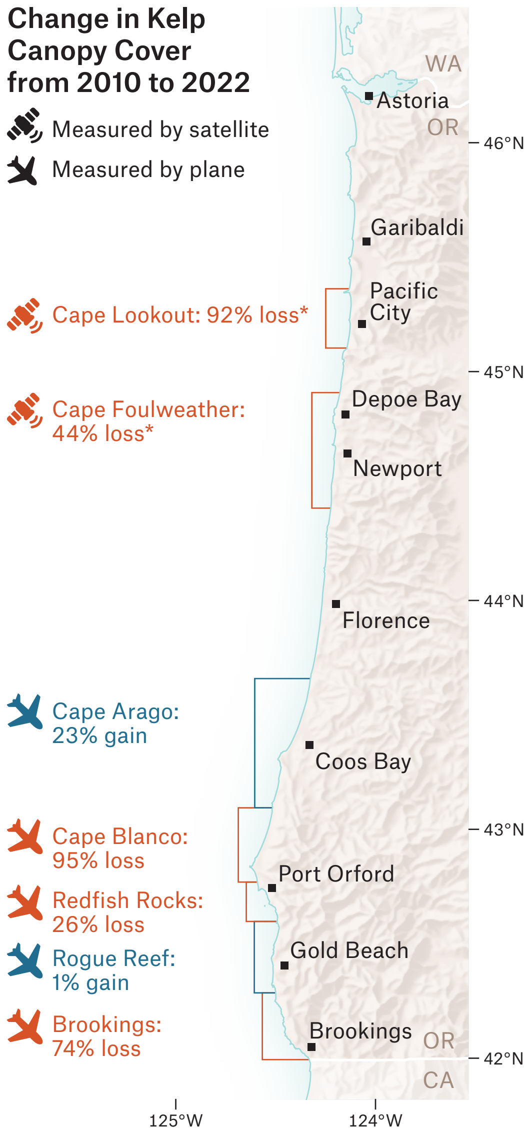


**Figure 3.** Map showing the percent change in bull kelp canopy cover from 2010–2022 for seven areas of the Oregon coast. From north to south, these areas are: Cape Lookout, Cape Foulweather, Newport, Cape Arago, Orford Reef, Redfish Rocks, and Brookings. The icon to the left of each estimate indicates whether the estimate was derived from ODFW aerial data (airplane) or Kelp Watch Landsat data (satellite). Asterisks next to the satellite-derived estimates indicate that these estimates are less accurate than aerially-derived estimates and have higher uncertainty associated with them.

area has declined in five of the seven areas analyzed: by 92% in the Cape Lookout area, 44% in the Cape Foulweather area, 95% in the Cape Blanco area, 26% in the Redfish Rocks area, and 74% in the Brookings area. Cape Arago and Rogue Reef are the only regions in Oregon to experience gains within the past decade at 23% and 1%, respectively. We note that while these numbers are one way to assess changes in kelp forest canopy over time, they represent merely a one-time snapshot of conditions. As an annual species that can quickly respond to varying ocean conditions, bull kelp populations are notoriously dynamic, and thus a one-time snapshot likely misses substantial interannual variability that is part of how these forests are changing over time.[29,30,32]

Aerial data from ODFW covering southern Oregon, from Brookings to Cape Arago, is some of the best information available on how the extent of kelp forests have changed in the past decade. From this data, we estimate that 892 acres of kelp forest has been lost in southern Oregon since 2010. Given that a recent study on the value of kelp forests estimated that an acre of bull kelp forest was worth US$159,000–$363,000/year, we estimate that this loss of kelp forest habitat costs the state about US$23–$53 million/year.[4] This estimate is a first approximation drawn from a global assessment and thus may not precisely estimate the value of kelp forests in Oregon. However, it is useful, given that the value of Oregon's kelp forests have never been estimated. Future investigation into the topic would yield more precise numbers for Oregon's context.

## CHANGES IN KELP FOREST COMMUNITIES FROM 2010 TO 2023

Relatively little scuba monitoring has focused on tracking kelp communities over time in Oregon. Therefore, limited evidence is available to assess how subtidal conditions have changed since 2010. One of the only repeated, kelp-forest-specific time series we are aware of has been conducted by Reef Check, a community science organization, at Macklyn Cove near Brookings. This monitoring began in 2017 as part of California's Marine Protected Area monitoring

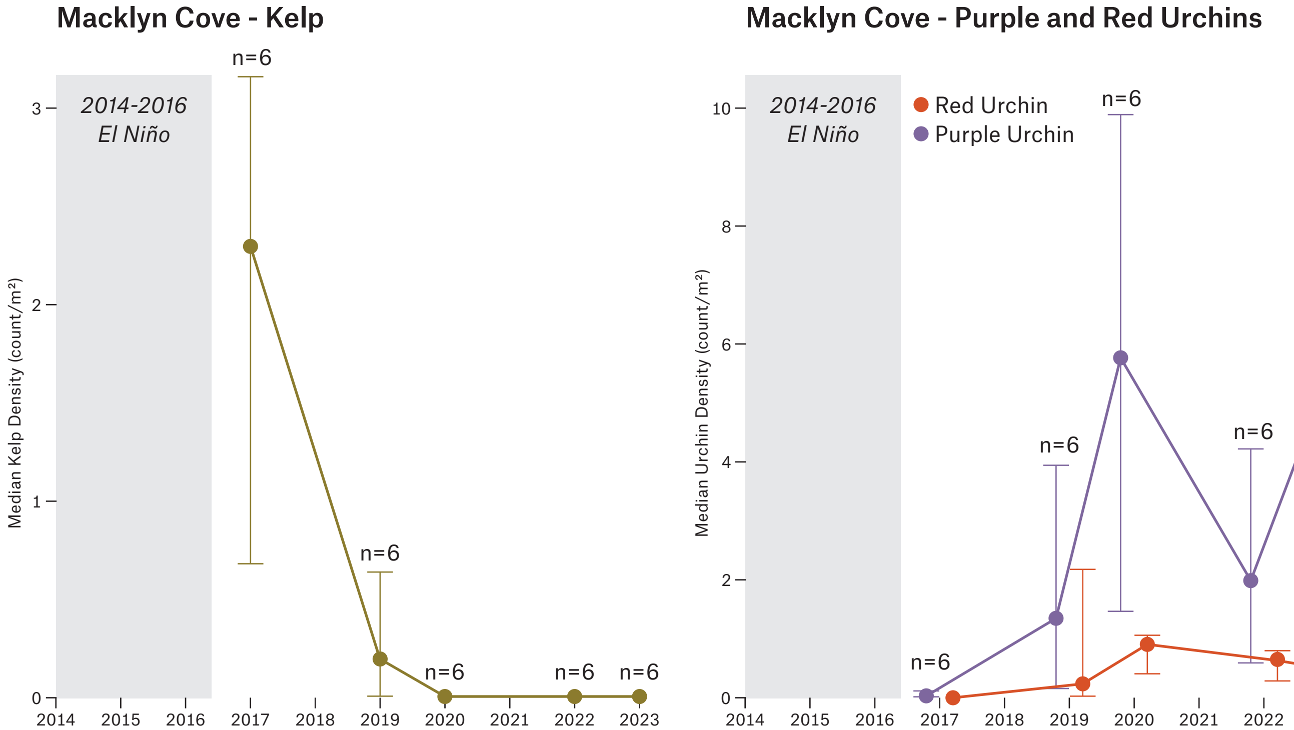


**Figure 4.** Time series of median total kelp, including *Nereocystis luetkeana*, *Pterygophora californica*, and *Laminaria setchellii* (left) and purple and red sea urchin density (right) at Macklyn Cove in Brookings, Oregon from Reef Check scuba surveys. Error bars represent 95% confidence intervals. The red outlined series of the figure highlights the 2014–2016 El Niño period. The small gray text above each chart point (e.g., n=6) indicates the number of surveys conducted in that year.

program, with Macklyn Cove set as a comparison site for Pyramid Point State Marine Conservation area across the Oregon-California border. At six transects surveyed annually in Macklyn Cove at depths from 17–25 ft, densities of three kelp species (*Nereocystis luetkeana*, *Pterygophora californica*, and *Laminaria setchellii*) were initially high when first surveyed in 2017, with a median density of 2.3 kelps/$m^2$. By 2019, kelp densities had plummeted to 0.19 kelps/$m^2$ and follow-up surveys in 2020, 2022, and 2023 found no kelp whatsoever at this site (**figure 4**, left).

Conversely, sea urchin densities showed an opposite pattern. Sea urchin densities were low in 2017 with a median of 0.05 purple sea urchins/$m^2$ and 0 red sea urchins/$m^2$. These median densities increased to 1.38 purple sea urchins/$m^2$ and 0.217 red sea urchins/$m^2$ by 2019 and have remained at elevated densities since then (**figure 4**, right). By 2023, median purple urchin density was at 4.89 sea urchins/$m^2$ and had increased about 98-fold compared to 2017. These data represent just a single cove, but this strong decline in kelp mirrors the dramatic loss documented in the Brookings area from aerial surveys across 2010-2022.

Outside of Macklyn Cove, ODFW has monitored purple and red sea urchin densities in kelp forest habitat for more than a decade to support fisheries management of the red sea urchin fishery. Kelp forests near Port Orford have been some of the most consistently monitored kelp forests due to the historical importance of this habitat to the red urchin fishery. In **figure 5**, we combined ODFW's urchin fishery survey data from three Port Orford area kelp forests, Orford Reef, Redfish Rocks, and Humbug Mountain, along with urchin survey data from ORKA's 2023 survey efforts to document changes in urchin densities at these sites from 2010–2023. Both data sources estimate sea urchin densities using 30 × 2 $m^2$ transects.

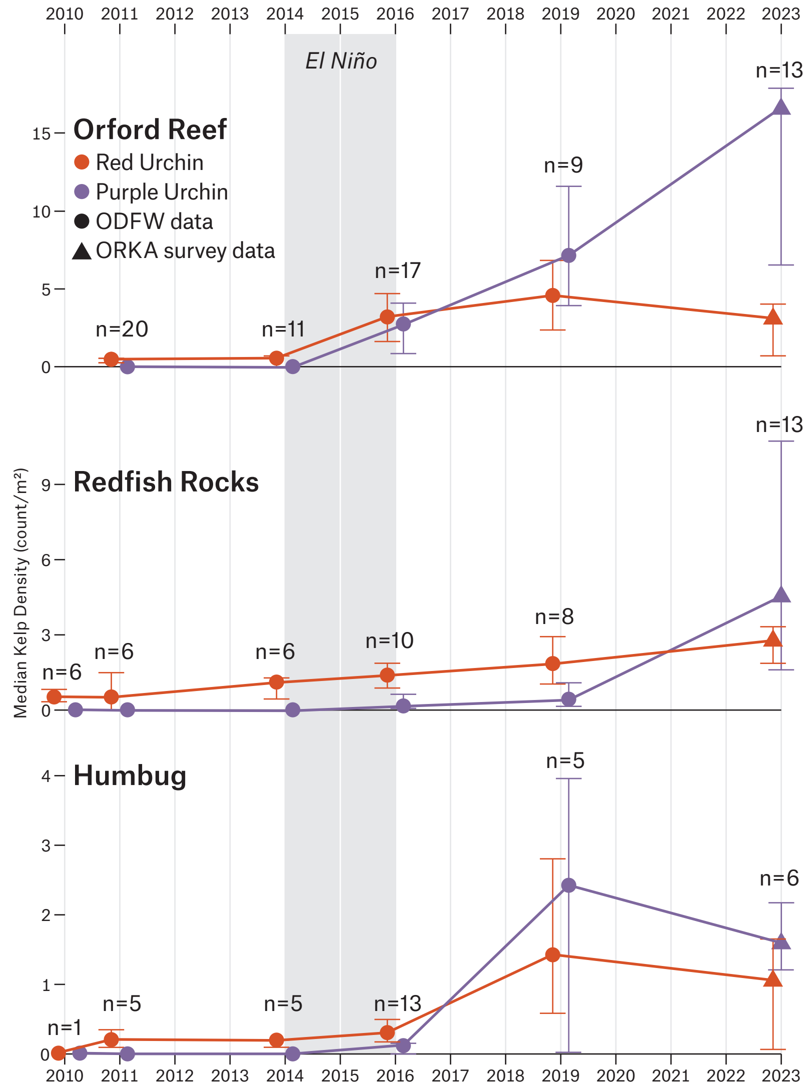


**Figure 5.** Time series of median purple and red sea urchin at three sites near Port Orford. Data for Orford Reef and Redfish Rocks was drawn from depths of 35–55 ft and for Humbug from depths of 25–45 ft. Error bars represent 95% confidence intervals. The red outlined series of the figure highlights the 2014–2016 El Niño period. The shape of each point indicates whether the data was drawn from ODFW or from ORKA surveys. The small gray text above each chart point (e.g., n=6) indicates the number of surveys conducted in that year.

Indeed, at all three sites, purple sea urchins were relatively uncommon prior to 2015 and were observed in only 16% of 123 surveys conducted from 2010 to 2014. At depths of 35–55 ft at Orford Reef, densities of purple sea urchins began to increase by 2016 and have continued increasing to the present day, where 2023 surveys showed a median purple sea urchin density of 16.7 urchins/m$^2$ compared to 0 urchins/m$^2$ in 2011. Red sea urchin densities are also increasing, from a median density of 0.43 urchins/m$^2$ in 2011 to 3.0 urchins/m$^2$ in 2023. At Redfish Rocks, at depths of 35–55 ft, purple sea urchins increased marginally from 2011–2019, but by 2023 had a median density of 4.5 urchins/m$^2$ compared to 0 urchins/m$^2$ in 2011. Red sea urchins have increased a similar amount at these depths at Redfish Rocks. At Humbug, at 25–45 ft depths, sea urchin densities rose up through 2019, peaking at median densities of 2.25 urchins/m$^2$ for purple sea urchins and 1.33 urchins/m$^2$ for red sea urchins. By 2023, median purple sea urchin densities had risen from 0 urchins/m$^2$ in 2011 to 1.5 urchins/m$^2$ in 2023 and red sea urchin densities were five times higher than in 2011. The ODFW Marine Reserves Synthesis also documented significant increases in purple and red sea urchin densities since 2010 at Redfish Rocks and Humbug (Orford Reef was not assessed).[46]

Overall, purple and red sea urchin densities rose significantly at Orford Reef, Redfish Rocks, Humbug, and Macklyn Cove (Appendix table 5 and Appendix table 6). Across these time series, mean purple

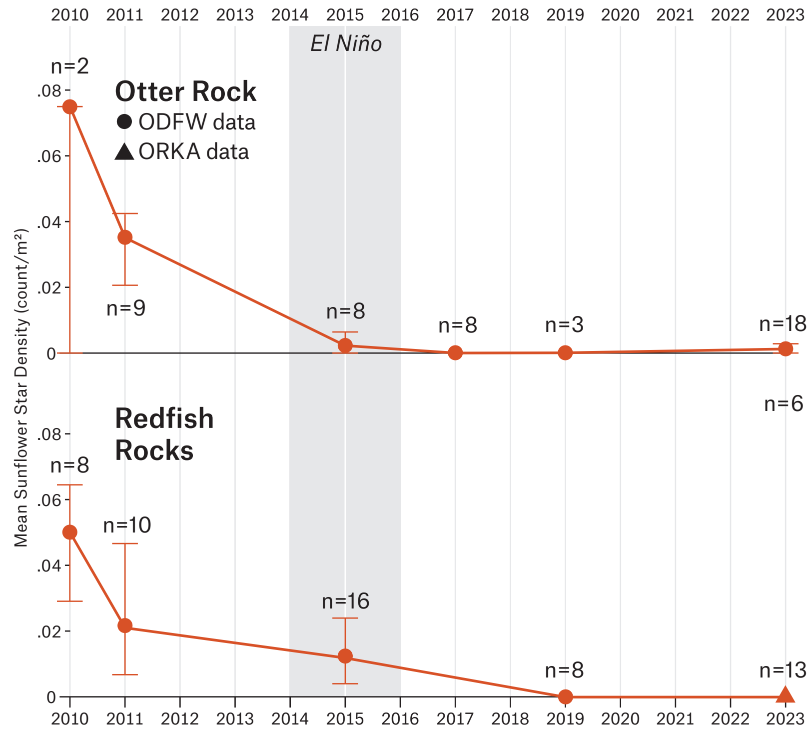


**Figure 6.** Time series of mean sunflower sea star density at two sites, Otter Rock near Depoe Bay and Redfish Rocks in Port Orford. Data for Otter Rock was drawn from depths of 15–35 ft and, for Redfish Rocks, from depths of 35–55 ft. Error bars represent 95% confidence intervals. The red outlined series of the figure highlights the 2014–2016 El Niño period. The shape of each point indicates whether the data was drawn from ODFW or ORKA surveys, and the small gray text above each chart point (e.g., n=6) indicates the number of surveys conducted in that year.

sea urchins have increased by 66–1000+ fold and red urchins by 3.5–85 fold. It is worth noting that although we have documented sea urchin increases in southern Oregon, these increases may not be consistent across all parts of Oregon's nearshore. For instance, the 2022 Marine Reserves Synthesis Report did not find an increase in sea urchin densities at the Otter Rock Marine Reserve.[46]

Although only representing a limited number of sites, these documented increases in both purple and red sea urchin densities mirror increases seen across much of the West Coast in the US and Canada.[10,39,41] It is hypothesized that these increases were driven in part by an increase in sea urchin recruitment sometime around 2015 as well as the loss of sunflower sea stars, an urchin predator, to sea star wasting disease.[9,10,40,41] While we are unaware of rigorous data on sea urchin recruitment covering the time period in question, available data does confirm that sunflower sea star densities plummeted from 2010 to 2023.

Using ODFW scuba surveys at Otter Rock and Redfish Rocks Marine Reserves, we show that, in 2010 and 2011, median sunflower sea star densities began around 0.035 stars/m$^2$ at Otter Rock at depths of 15ft–35 ft and 0.05 stars/m$^2$ at Redfish Rocks at depths of 35 ft–55 ft. Just a few years later, in 2016, no sunflower sea stars were found in eight different surveys at these depths at Otter Rock. Similarly, since 2019, no sunflower sea stars have been documented at these depths at Redfish Rocks in 21 surveys (**figure 6, Appendix table 7**).

Overall, these aerial and scuba time series suggest declines in kelp populations and increases in both purple and red sea urchins since 2010, in core kelp forest habitat. This shift seems to have begun during or shortly after 2014–2016, which coincides with evidence from other regions that the intense marine heatwaves, sea star wasting disease epidemic, and increases in purple sea urchin density associated with the 2014–2016 El Niño period drove changes to kelp forest systems.[9,10,39,41]

Without a kelp-forest-specific monitoring program, we are only able to clearly document changing kelp, sea urchin, and sea star communities over time at a few locations. This limits our capacity to understand whether the documented changes to kelp and urchin densities are consistent across the state or if changes vary from reef to reef. In the next section, we discuss what ORKA's 2023 survey efforts reveal about the current spatial variability in kelp forest conditions across the state.

# ORKA's Coordinated 2023 Survey Results

Both scuba surveys and UAV surveys in 2023 documented a mosaic of kelp forest conditions, ranging from a historically strong year for kelp on the central coast to urchin dominated reefs with minimal kelp across large swaths of the south coast.

## SPATIAL PATTERNS IN THE PRESENCE OF KELP AND PURPLE SEA URCHINS

The scuba surveys coordinated by ORKA and its partners in 2023 were a unique effort to document current kelp forest conditions. Kelp forests were surveyed at 70 different locations, over 14 sites, spanning from Brookings to Pacific City. Most surveys were conducted in the 20–50 ft depth range although surveys in some areas were skewed toward one end of this range, such as the Brookings areas where all dives were conducted at 17–25 ft. We also drew on 2023 ODFW scuba data from Cape Foulweather.

At six of the largest reefs in Oregon, 2023 surveys show that densities of kelps (i.e., summed density of *Nereocystis luetkeana*, *Pterygophora californica*, *Pleurophycus gardneri*, and *Laminaria setchellii*) varied widely between and within reefs (**figure 7**). Between reefs, the density of kelp was consistently near zero in Brookings, Redfish Rocks, and much of Cape Blanco. Conversely, kelp densities were higher on average at Cape Foulweather, Cape Arago, and Rogue Reef although densities varied from near zero to more than 5 kelps/m$^2$ over small spatial scales, <1 mile (**Appendix figure 2**). For instance, within Cape Arago, Drake Point has higher kelp densities, but Gregory Point and much of Simpson's Reef support little if any kelp.

In contrast to kelp, the highest densities of purple sea urchins were found in the Cape Blanco, Redfish Rocks, and Brookings areas. Purple sea urchin densities were generally, although not uniformly, lower at reefs that still supported kelp forests such as Cape Foulweather, Cape Arago, and Rogue Reef. Within reefs, higher purple sea urchin densities were often found in locations with low densities of kelps. For instance, while higher densities of kelp were found at Blanco Reef than Orford Reef, sea urchin densities often reached 15 urchins/m$^2$ at Orford Reef but never reached that density at Blanco Reef. However, some locations that lacked kelp also had low densities of purple sea urchins (less than 2 urchins/m$^2$), such as at Humbug Mountain in the Port Orford area and in the middle section of Cape Foulweather. Taken together, these surveys found extensive evidence of urchin barrens, reefs with no kelp, and high densities of purple sea urchins (>10 purple sea urchins/m$^2$), across much of Brookings, Redfish Rocks, and Cape Blanco, areas that used to be the heart of Oregon's kelp forest habitat. This was not the case at all reefs. Cape Foulweather, Cape Arago, and Rogue Reef supported patches of high kelp density (>2 kelp/m$^2$).

For the sake of space, we focus here on purple sea urchins rather than red sea urchins. Red sea urchin densities were much lower than those of purple sea urchins, rarely rising above 5 red sea urchins/m$^2$ in 2023 surveys (**Appendix figure 1**). In California, purple sea urchins are considered to be a more important driving force behind kelp declines than red sea urchins. However, further research is needed in Oregon to understand the relative roles these two species play in (1) initially denuding kelp forests, and (2) preventing juvenile kelps from recruiting to bare rock and re-establishing kelp populations after a decline.[9,10,39] While a better understanding of the role of red sea urchins is needed, depth may also play a role in the documented mosaic structure of kelp forest conditions. Anecdotal accounts from long-time divers indicate that, historically, purple sea urchins populations were found primarily in the intertidal and shallow subtidal zones and that their populations gave way at deeper depths to red sea urchins.[37,49] Future work should investigate whether purple sea urchins are expanding their depth range in Oregon,

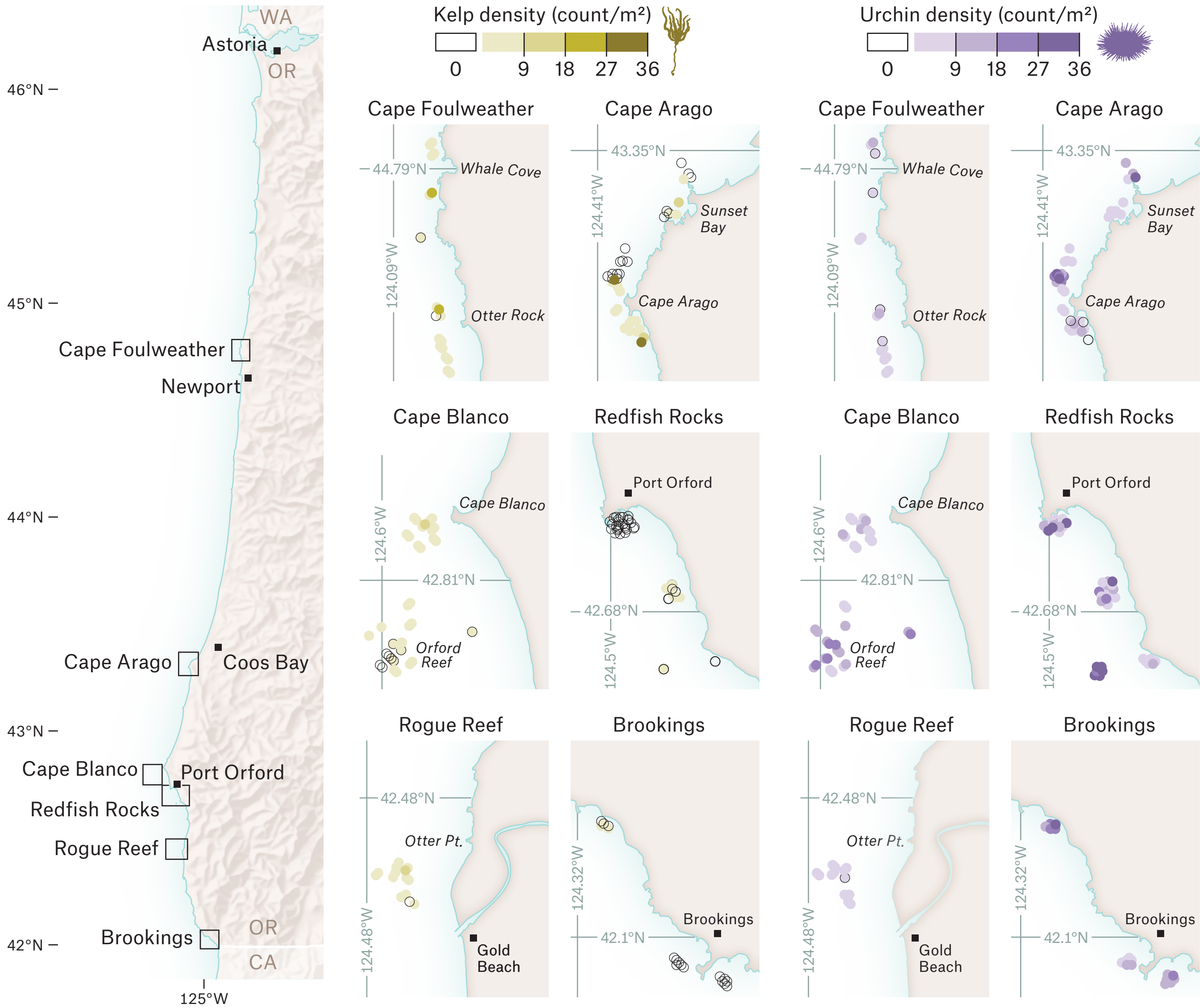


**Figure 7.** Estimates of kelp and purple sea urchin density from 2023 scuba surveys. Locations of each area surveyed are shown in the left panel and are highlighted in the inset maps shown in the center and right panels. The center panel shows kelp density, indicated by color, at each scuba transect conducted in 2023 at six major kelp forest areas. The right panel shows purple sea urchin density, indicated by color, at each scuba transect conducted in 2023 at six major kelp forest areas. Note: Surveys at Cape Foulweather occurred at depths of 15–50 ft and peaked around 35 ft depth, at Cape Arago surveys were conducted at depths of 10–45 ft and peaked around 25–30 ft, at Orford Reef surveys were conducted at depths of 15–45 ft and peaked from 30–40 ft, at Redfish Rocks surveys were conducted at depths of 15–55 ft and peaked around 25–35 ft, at Rogue Reef surveys were conducted at depths of 15–40 ft and peaked at 25–35 ft, and at Brookings surveys were conducted exclusively at depths of 17–25 ft. All sites, except for Cape Foulweather, draw on data collected during the 2023 ORKA survey efforts by ORKA partners Reef Check, the Oregon Coast Aquarium, and the Galloway lab at the University of Oregon. Cape Foulweather data was collected by ODFW.

how such an expansion may be impacting the depth range of red urchins, and whether sunflower sea stars or other urchin predators may have previously maintained this depth balance, as intertidal sea stars are documented to do with mussel beds.[78]

## 2023 UAV SURVEYS OF KELP FOREST EXTENT

In 2023, ORKA conducted 21 UAV surveys of nearshore areas that historically supported kelp canopy. These surveys did not evenly survey the entire coastline. Rather, they prioritized areas that were accessible from shore, and thus excluded important offshore reefs such as Rogue Reef and Orford Reef. However, even as a limited sample of kelp forest canopy, these surveys document some of the same patterns uncovered by the 2023 scuba surveys. For instance, just as scuba-based surveys documented minimal kelp in the Redfish Rocks and Brookings areas, UAV surveys documented very little nearshore kelp canopy in these areas (**figure 8, Appendix table 8**). Only one of the ten UAV-surveyed kelp forests, from Port Orford to Brookings, documented more than 2,000 $m^2$ of kelp canopy. Some surveys near Redfish Rocks and Brookings captured just a few individual bull kelps in places that previously had extensive canopy.[75]

In contrast to areas farther south, 2023 scuba survey data revealed that some kelp forests in the Cape Arago region had high densities of kelps. Similarly, six UAV surveys in the Cape Arago area documented kelp forests with 6,000–28,000 $m^2$ of kelp canopy. Even the smallest kelp forest surveyed at Arago had about three times more canopy than the largest forest farther south. These UAV surveys documented extensive bull kelp forests in the Cape Foulweather area of the central Oregon coast. Five drone flights in and around Cape Foulweather documented kelp forests ranging in size from 45,000–99,000 $m^2$ of bull kelp canopy, even with heavy waves obscuring portions of these kelp forests. While 2023 was the first year for UAV-based kelp surveys at Cape Foulweather, other lines of evidence suggests that 2023 may have been a historically good year for bull kelp canopy in the area. For instance, the footprint of kelp canopy extent captured by drones in 2023 is similar to the extent captured in 1990 aerial surveys (**Appendix figure 3**). Additionally, 2023 Landsat satellite estimates of canopy area, available on the Kelpwatch platform, recorded the second-highest canopy extent in the Cape Foulweather area of any year since 1985. Finally, a number of long-time local residents shared anecdotal accounts that the 2023 kelp canopy extent in the Cape Foulweather area was the largest in recent memory.[124,125]

Overall, UAV surveys confirm a key finding of scuba surveys—Oregon's kelp forests currently display a patchwork of conditions, ranging from denuded urchin barrens that support little, if any, kelp to dense forests with extensive canopy (**figure 8**).

## SIGHTINGS OF SUNFLOWER SEA STARS IN 2023

In addition to scientific surveys, a final key finding in 2023 was captured by community members in Oregon who provided a noticeable increase in reports of sunflower sea stars. Two community science platforms, iNaturalist and UC Santa Cruz's MARINe (SeaStarWasting.org), allow individuals to document sightings of various species of sea stars (see Appendix for more details). Using these platforms to summarize documented sightings in Oregon since 2015, we found that the number of sightings has been rare since 2017, with less than five sunflower sea stars recorded across Oregon in most years from 2015–2022 (**figure 9**).

However, in 2023, unique observations of sunflower sea stars jumped to more than 50. These sightings spanned the length of the coast from Port Orford in the south to Haystack Rock in Cannon Beach. Sometimes a single observation noted dozens of juvenile sunflower sea stars. Community science observations are not constant over time and some of this variability could be due to changes in the number of people contributing to these platforms. However, in addition to these community

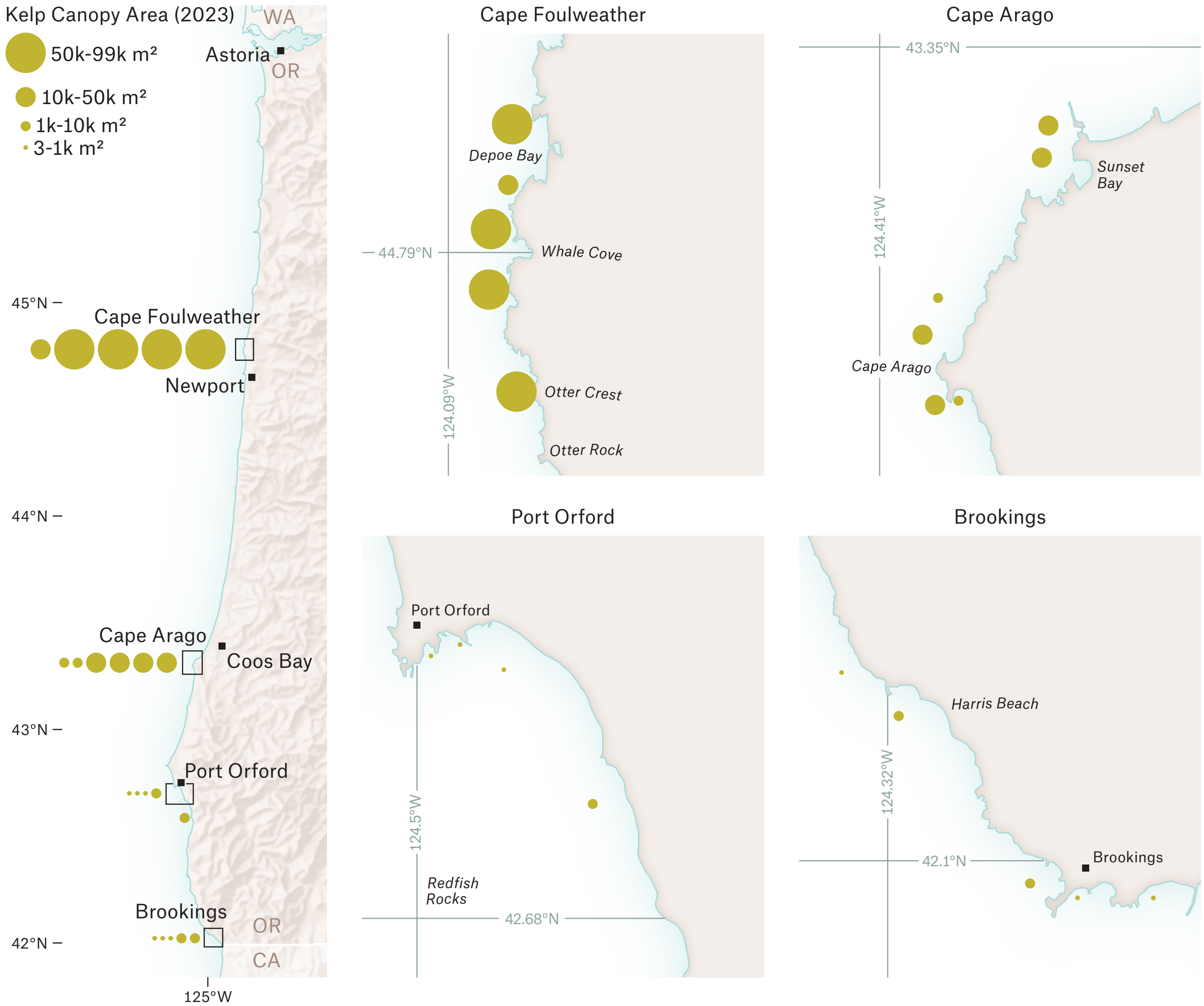


**Figure 8.** Estimates of kelp canopy area from 2023 UAV surveys. Note: In the left panel, bubbles representing estimated kelp canopy area extend outward from the coast to better visualize canopy extent. At this scale, the bubbles would overlap if placed at the actual kelp forest locations. The center and right panels show inset maps, at larger scale with more accurate forest locations. * Historically, much of Port Orford's kelp canopy area was located farther offshore than land-based drone surveys can capture.

observations, sunflower sea stars appeared on scientific surveys in 2023 for the first time in years. One set of ORKA-coordinated scientific surveys in 2023, documented a total of 61 sunflower sea stars on transects at Chief Kiwanda Rock in Pacific City. Most of the recorded sightings, by both community members and scientists, found small sea stars that are likely juveniles, although several larger adult sunflower sea stars were documented as well.

These opportunistic sightings of sunflower sea stars show that the species has not been fully extirpated in Oregon and raise hopes of some recovery of these sea urchin predators. While these sightings may be an indication of the start of population recovery in Oregon, we caution that densities are still extremely low. For instance, in 175 of 183 ORKA-coordinated surveys *no* sunflower sea stars were observed. Further, it remains to be seen whether these individuals are still affected by sea star wasting

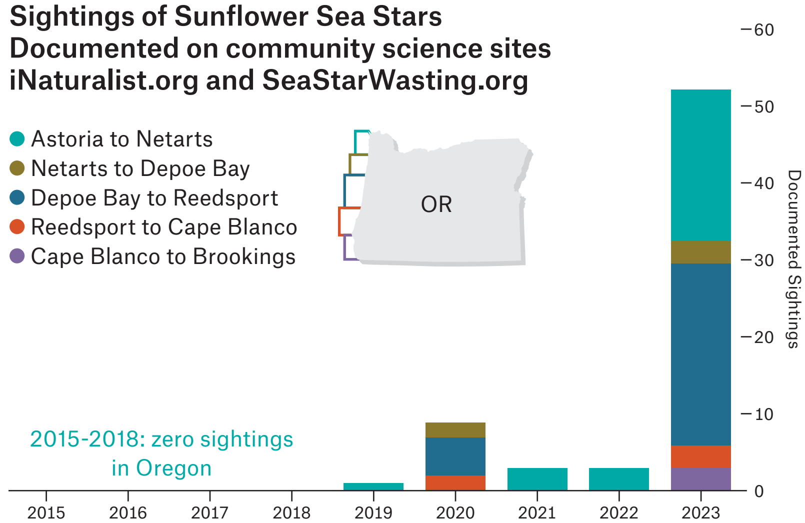


**Figure 9.** Community observations of sunflower sea stars on the iNaturalist and SeaStarWasting.org platforms showing the number of observations per year from 2015–2023. Color indicates where the observation took place, with the legend reading from north to south.

disease. Many of these sightings were of juvenile sunflower sea stars. In several other parts of the West Coast, juvenile sunflower sea stars have been regularly sighted but adults have remained elusive, leading to concerns about whether young sea stars are being killed by sea star wasting disease before reaching adulthood.[79] While these new observations of sunflower sea stars are a necessary component of population recovery, the species still faces many hurdles in re-establishing at densities that may be ecologically relevant to kelp forests in Oregon.

# Kelp Forest Status Along the Coast of Oregon

To help readers understand the relative status of various kelp forest areas in Oregon, we distilled the diverse data collected on them into a single qualitative metric of kelp forest status. To this end, we utilized three data metrics: (1) Percent change in canopy area from 2010–2022, (2) mean kelp density in 2023, and (3) mean purple sea urchin density in 2023. To assess historic change over time metric, we referenced 2010 and 2022 because both ODFW aerial canopy survey data and Kelpwatch satellite canopy survey data is available for these years. For this canopy change metric, we drew on the calculated percent change in canopy area shown in **figure 3**. Additionally, mean kelp density and purple sea urchin density in 2023 was used to represent current conditions because kelp density directly measures the presence of kelp populations and sea urchin grazing is an important driver of the state of kelp forests.[39,41,71,72]

For each metric, we assigned a score of 0 or 1 to each major kelp forest area, with 0 representing the poorest conditions and 1 healthier conditions. These metrics were generally chosen based on natural breaks in the range of each parameter. For percent change over the last decade, a kelp forest was assigned 0 points if its canopy area declined by 40% or more from 2010–2022 and 1 point if it declined by less than 40% or increased in area. For kelp density, a forest was assigned 1 point if it had a mean density of all kelp species of 1 kelp/m$^2$ or higher and 0 points if it had a mean density of 1 kelp/m$^2$ or lower. Finally, for mean purple sea urchin density, 1 point was assigned if it had a mean density of 8 purple sea urchins/m$^2$ or lower and 0 points if it had a mean density higher than 8 purple sea urchins/m$^2$. The points assigned to a kelp forest area across these three metrics were summed for a cumulative score. Forests with a total of 2–3 points were deemed to be of "less concern" and those with 0–1 total points categorized as of "higher concern." One area was categorized as "data limited—moderate concern" because no scuba surveys have been conducted in that area.

Overall, kelp forests that historically supported about 69%, or two-thirds, of Oregon's kelp canopy extent were categorized as of "higher concern," displaying a combination of high canopy loss over time, low current kelp density, and high current purple sea urchin density (figure 10). Most of the forests categorized as of "higher concern" are located in the southern part of the Oregon coast. Kelp forests that supported about 17% of Oregon's historic kelp forest area were categorized as of "less concern" and one kelp forest area representing about 6% of historic kelp forest area, the Boardman corridor, was categorized as "data limited—moderate concern." It is important to note that the category of "less concern" does not imply that an area supports healthy, intact, resilient kelp forests. A reef categorized as of "less concern" may still have degraded function and state and could be close to a tipping point where it would transition into a sea urchin barren or similar undesirable, alternate state. The metrics used here are meant to indicate the status of kelp forests relative to one another and are not meant to indicate the health or functionality of each forest on their own. Finally, we emphasize that this is not intended to be an objective or perfect metric of kelp forest condition, and future work could tie these thresholds and points to more biologically-relevant thresholds. However, we were satisfied with this metric because when thresholds were substantially changed, this resulted in very little change in the overall categories assigned to all forests (see Appendix tables 9–11).

## Processes Driving the Loss of Kelp Forests in Oregon

Globally, kelp forests are declining in the face of human-driven changes to coastal environments [5,6] The drivers of kelp forest loss vary strongly by region and include kelp overharvesting,[80–82] nutrient loading particularly along urbanized coastlines,[6,83,84] increases in kelp grazing,[72,85] loss of the predators of kelp grazers,[41,69,86–88] sedimentation and turbidity,[6,87,89] increases in temperature and frequency of marine heatwaves,[62,64,90–92] and invasive or range-expanding species.[93–95]

Usually, to attribute changes in kelp forest communities to particular drivers, long-term monitoring specific to kelp forests paired with targeted environmental monitoring or lab- and field-based experiments are needed. However, in Oregon, the aforementioned data limitations constrain our ability to assess which of these drivers are contributing to kelp loss. Two of the main hypotheses about what is driving of the loss of kelp forest ecosystems on the West Coast are: (1) increased grazing by sea urchins, and (2) warming ocean temperatures.[9,10,39,41,92] Using the data available to us at this time, we provide some high-level conclusions on the role these two drivers may be playing in Oregon as well as some possible hypotheses as to the role of other drivers.

### PURPLE SEA URCHINS

It has been widely documented that changes in the density or the feeding behavior of sea urchins can quickly decimate US West Coast kelp forests, often transforming them into urchin barrens.[10,39,86] Similar to what has been documented in Northern California, purple sea urchin densities have increased rapidly in a number of sites across southern Oregon. This increase is correlated to the loss of or lack of kelp in southern Oregon. For instance, at Macklyn Cove (figure 4), there is a significant negative relationship between declining kelp and increasing purple sea urchin density from 2017–2023 (Appendix figure 4). Furthermore, in 190 transects from the 2023 scuba surveys, higher densities of kelp (including *Nereocystis luetkeana*, *Pterygophora californica*, *Pleurophycus gardneri*, and *Laminaria setchellii*) were observed at areas with lower densities of purple sea urchins and vice versa (figure 11 and Appendix figure 5). Given the intense increase in purple sea urchin densities, estimated at 66–1000+ fold at four sites, it is very likely that purple sea urchin grazing has played a central role in documented kelp forest loss since 2010 (figure 11).

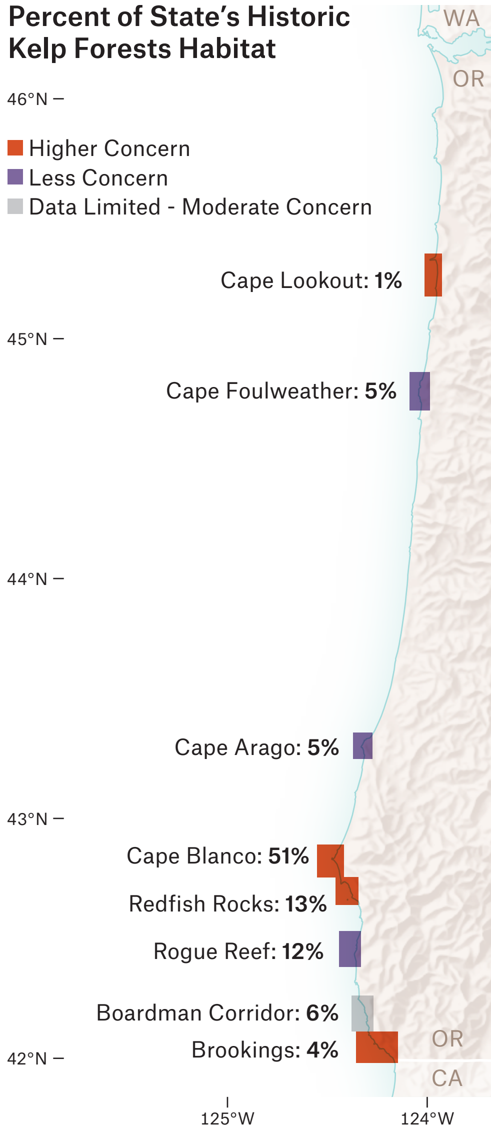


**Figure 10.** Status of Oregon's kelp forests categorized by level of concern. Note: Colors indicate the status as levels of concern, which are based on changes in canopy cover from 2010–2022, current kelp density, and current urchin density. Percentages to the left of the coast indicate the percentage of Oregon's canopy-forming kelp forests represented in each area.

| Area | Canopy Change Points | Kelp Points | Urchin Points | Total Points |
|---|---|---|---|---|
| Cape Lookout | 0 | 0 | 1 | 1 |
| Cape Foulweather | 0 | 1 | 1 | 2 |
| Cape Arago | 1 | 1 | 1 | 3 |
| Orford Reef | 0 | 0 | 0 | 0 |
| Redfish Rocks | 1 | 0 | 0 | 1 |
| Rogue Reef | 1 | 1 | 1 | 3 |
| Brookings | 0 | 0 | 0 | 0 |

However, this relationship is more complicated than it initially appears. At some sites surveyed in 2023, no kelp was found regardless of urchin density (Appendix figure 6). This may mean kelp loss in these areas was not related to sea urchin grazing. Or it may mean that, once kelp was lost to grazing sea urchins, large populations of sea urchins moved on to other areas and the remaining low densities of sea urchins were able to prevent the re-establishment of kelp—a phenomenon which has been documented extensively in kelp forest systems.[71,72] Conversely, sometimes kelp can be found at areas with very high densities of sea urchins, such as at a Cape Arago survey where, on one transect, kelp density was 2.8 kelps/$m^2$ despite purple sea urchin densities approaching 20 sea urchins/$m^2$. The exact nature of the relationship between purple sea urchins and kelps varies by surveyed area (Appendix figure 5). Thus, while purple sea urchins are likely a key part of Oregon's kelp forest declines, more investigation is needed to understand why some reefs can persist with high sea urchin densities while others may flip to sea urchin barrens under similar conditions. Potential factors that may play a role in the influence sea urchins exert on kelp forests include the productivity of a kelp forest, the interannual stability of kelp forest productivity, urchin feeding and movement behavior, and seafloor topography.[73,96]

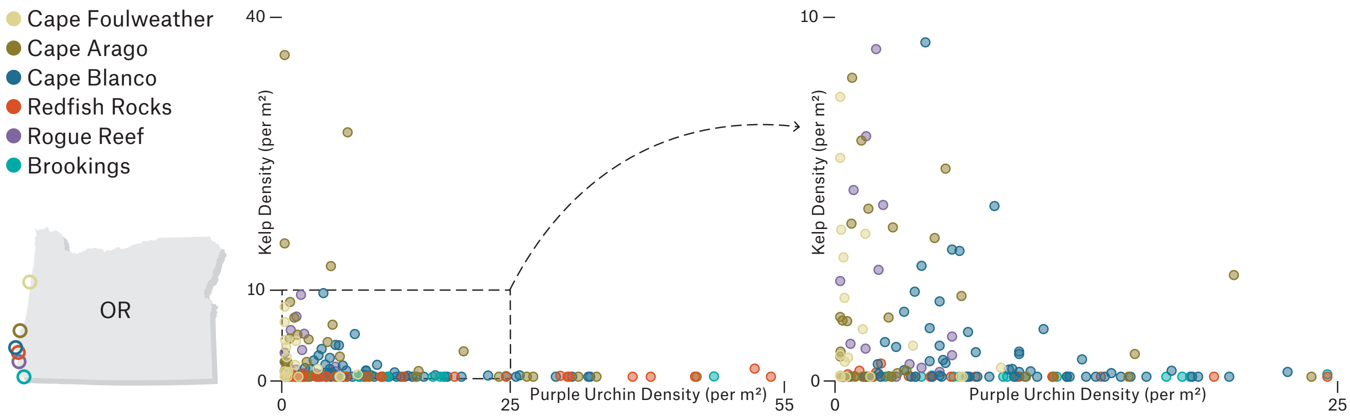


**Figure 11.** Purple sea urchin density versus summed kelp density on 170 transects from 2023 surveys. The graph at the right zooms in on the graph on the left to show the graph over a purple sea urchin density of 0–25 urchins/m². Color indicates the survey area. Data comes from ORKA's 2023 scuba survey work conducted by Reef Check, University of Oregon, and the Oregon Coast Aquarium, and ODFW 2023 scuba surveys in the Cape Foulweather area.

We focus largely on purple urchins in this report. The role red sea urchins play in driving kelp loss is less clear. Although red sea urchins tend to be found at much lower densities than purple sea urchins in Oregon currently, recent work in California has documented that even low densities of red sea urchins (<2 sea urchins/m$^2$) can prevent kelp from re-establishing at a deforested site.[97] While we assess the impacts of sea urchins on kelp here, it is still unknown exactly why sea urchin populations increased across many sites along the West Coast, and more work is needed to understand the drivers of sea urchin recruitment.

## TEMPERATURE

Recent studies from central California to Alaska have found that bull kelp performs well in temperatures from 10–14°C, exhibits decreased growth and reproductive success around 16–17°C, and experiences reproductive failure at temperatures from 18–20°C .[44,61,91,98–102] Interestingly, most of these papers found no evidence that bull kelp populations from different regions displayed local adaptation to temperature.[61,91,98,102] While less evidence is available on the thermal physiology of Oregon's subcanopy kelps than there is on bull kelp, several studies suggest they may have similar thermal limits.[61,103,104] Thus, it is reasonable to assume that Oregon bull kelp experiences adverse effects starting around 16°C and that sustained exposure to 18°C would have lethal consequences. Exactly how long water temperatures must stay at these temperatures to cause negative impacts to bull kelp is less understood.

Two long-term temperature time series at nearshore sites in Charleston and Port Orford offer insight into whether local water temperatures regularly reach stressful temperatures for bull kelp. These datasets show that nearshore surface temperatures rarely reached sub-lethal (16°C) or lethal thresholds (18°C) for bull kelp (figure 12). Over the last decade, of daily mean temperatures, only 0.6% from Charleston and 0.2% from Port Orford reached 16°C. Even during the record-breaking marine heat waves present from late 2013–2016, mean daily temperature reached 16°C only five times in Port Orford and eight times in Charleston, although maximum daily temperature reached this threshold more often (Appendix figure 7).

Surprisingly, over the last 30 years, we identified that water temperatures in Port Orford and Charleston both showed small but significant cooling trends rather than warming trends (Appendix table 12).[105] Additionally, neither Port Orford nor Charleston show significant increases over the past

30 years in either the number of days per year where the mean daily temperature reaches 16°C or the number of marine heat wave days per year (**Appendix figure 8** and **Appendix figure 9**).

These temperature time series do not show clear evidence that ocean temperatures regularly reach stressful thresholds for bull kelp or that ocean temperatures are getting warmer in core kelp habitat in Oregon. Interestingly, unlike recent work in British Columbia and Washington, local-scale differences in temperature do not clearly correlate with differences in kelp population status. Currently, Cape Arago has had better outcomes for kelp forests than Port Orford despite having relatively similar temperature regimes.[11,92] While these data are from surface waters near kelp forests rather than from subsurface waters within kelp forests, we would expect subsurface waters to be cooler than surface waters because they are less subject to surface heating from warm air temperatures. Future work should investigate temperatures taken at depths directly within kelp forest habitat to assess whether temperature regimes within these kelp forests differ from those measured by nearshore temperatures buoys.

Overall, while this brief look at nearshore temperatures in southern Oregon suggests that Oregon's kelp forests may not be subject to extensive temperature stress, further research is needed to understand how changing temperature regimes are influencing Oregon's kelp forests. For instance, kelps may be more sensitive to temperature stress during particular parts of their life cycles. Thus, future work could assess whether there are seasonal differences in long-term warming that could have an outsized impact on kelp.[44,61,99] Additionally, it is possible that kelp populations in Oregon are locally adapted to cooler temperatures compared to kelp populations in other parts of the West Coast. Investigation into whether local thermal thresholds for bull kelp and other kelp species are similar to those from other parts of the West Coast would be valuable in assessing the role temperature plays in Oregon's kelp forest changes.[91,92,98] Considering the overwhelming evidence that high temperatures are shaping the trajectories of kelp forests across much of the West Coast, investigating how temperature drives kelp forest dynamics and current patterns of loss across Oregon is a high priority for future research.[7,10,92]

## OTHER POSSIBLE DRIVERS

In other parts of the globe, particularly along urbanized coastlines, excess nutrient pollution leading to eutrophication is known to cause phytoplankton blooms. Such blooms reduce light availability and shift competitive advantages away from kelps and toward turf algae.[6] This is unlikely to be a major driver of kelp population loss in Oregon because (1) the Oregon coastline is sparsely populated and will therefore have relatively low sewage inputs into nearshore waters, (2) the central and southern Oregon coast largely lack major rivers that could deposit agricultural runoff, and (3) as a major upwelling system, Oregon's nearshore waters have historically been high in nutrients and Oregon's kelp forests likely evolved in the presence of high nutrient levels.[58,106] However, this has not been shown empirically and future investigation is needed.

Sedimentation and increased water turbidity can also reduce the light available to kelps and chip away at kelp forest stability.[6,89] In the Oregon context, increased erosion from coastal development, landslides, or coastal forestry could lead to increased turbidity. Although, at present, there is no evidence to suggest that this is playing a role in Oregon's kelp forests. Future work should investigate the effects of sedimentation and light levels in Oregon's kelp forests, particularly given evidence from intertidal kelp forests that dense phytoplankton blooms can reduce the light availability needed for intertidal kelps.[58]

Overharvesting is not likely to be impacting Oregon's kelp forests because no commercial harvest of kelps is allowed in the state and there is currently no evidence of high recreational harvest. Invasive species are also an unlikely driver. While invasive *Sargassum* species are present in Oregon, they are relatively uncommon along the coast. Few other invasive species have been documented in Oregon's

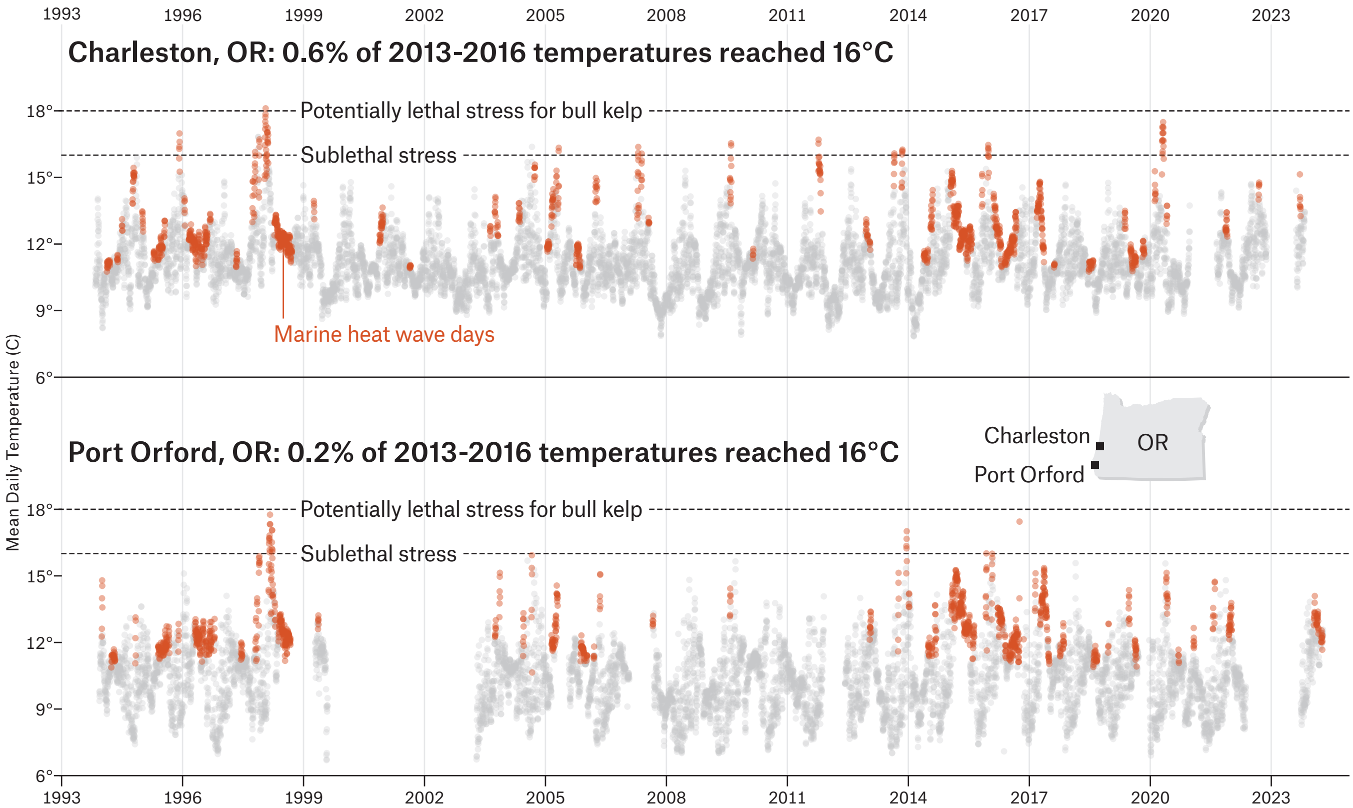


**Figure 12.** Mean daily temperature at the CHAO3 NOAA buoy in Charleston, OR (top) and the PORO3 NOAA buoy in Port Orford, OR (bottom). The orange dotted line at 16°C represents a putative threshold for sub-lethal stress on bull kelp and the dark red dotted line at 18°C represents a threshold for potentially lethal stress.

kelp forests. Overall, while increased grazing from purple sea urchins is the most likely cause of recent declines, few other potential drivers have been adequately explored.

# Expanded Monitoring to Support Kelp Forest Ecosystems

A systematic and long-term monitoring program is critical to better steward Oregon's kelp forest ecosystems. A targeted monitoring program will help identify early indicators of future ecosystem loss or recovery, pinpoint the drivers of kelp forest loss, select effective restoration strategies, and empower communities to better understand and become involved in stewarding local kelp forests. Future kelp forest monitoring in Oregon should not only monitor changes in kelp populations, but also changes in kelp forest communities and environmental conditions. In the sections below we identify key considerations and recommendations for implementing this targeted and expanded monitoring program to support kelp forest restoration, protection, and stewardship in the state.

It is important to consider "who" conducts kelp forest monitoring in Oregon, this matters as much as "where" and "how" it is conducted. Coastal Indigenous peoples have rights to their traditional lands and waters and should have the opportunity to collect, access, and analyze data on kelp forest monitoring as well as benefit from this monitoring work.[107] Oregon's coastal Tribes currently have limited capacity to engage in kelp forest monitoring and limited access to relevant kelp forest data, both of which inhibit Indigenous stewardship of kelp forest ecosystems. Additionally, community science programs, such as Reef Check, have already contributed greatly to kelp forest monitoring on the US West Coast. These programs enable community members to engage in monitoring, management, and stewardship.[108,109] Programs supporting community science and Indigenous science should be funded as part of kelp forest monitoring programs to enable improved stewardship of Oregon's kelp forest ecosystems into the future. Further, workforce development programs focused on training and equipping coastal residents to participate in kelp forest stewardship activities where they live should be supported as essential to the success of Oregon's kelp forest stewardship efforts.

## Ecosystem Monitoring

Scuba monitoring, aerial monitoring, ROV, and satellite monitoring are key tools currently used for monitoring kelp forest ecosystems in Oregon. Satellite and aerial approaches can only monitor changes in bull kelp canopy extent, whereas ROV and scuba surveys monitor the many kelp species that do not reach the surface of the water and the kelp forest animals that are often drivers of overall ecosystem status, such as sea urchins and sunflower sea stars.

Thus, our most urgent monitoring recommendation is to establish and fund semi-annual scuba monitoring at 10–15 core sites along the Oregon coast (**figure 13**). These core sites should include kelp forest habitat that spans a range of conditions, depths, and ecosystem statuses, including sea urchin barrens. Core sites should be established as fixed locations that allow the same location to be re-surveyed every year, such as by using accurate GPS drop points with set directions for transects. Monitoring these sites twice a year is recommended to (1) help capture early signs of change, and (2) ensure that core sites will be monitored at least annually even if one of the two semi-annual surveys has to be canceled due to weather, a common occurrence in Oregon.

Core site surveys should monitor the presence and densities of kelp, invertebrate, and fish populations and include surveys of seafloor cover using methods such as uniform point contact sampling. Additionally, monitoring kelp physiological processes—such as average biomass, growth rate, and reproductive success—can provide unique insights into the mechanisms of kelp loss and recovery.[110–113] At core sites, we recommend that a one-time survey of seafloor topography, known as rugosity, should be conducted. Seafloor topography can influence the composition and drivers of kelp forest ecosystems.[73,114] Whenever possible, core sites should include shallow (30 ft or less) and deep (>30 ft) surveys because conditions and trends likely vary across depth. Finally, in addition to in situ data collection, video ROV surveys can be utilized to maximize the amount of data that can be collected during Oregon's short, unpredictable diving season.

This semi-annual core site monitoring should leverage existing and ongoing scuba and ROV monitoring efforts in the state such as those conducted by Oregon Reef Check, the Oregon Coast Aquarium, ODFW, university scientists, and commercial divers. Funding these groups to conduct kelp forest monitoring will maximize successful data collection by leveraging local knowledge and existing capacity. New scuba and ROV monitoring efforts should work with existing institutions and operations to ensure coordination of monitoring efforts, comparable survey protocols, and data management pipelines that allow for integration of various datasets. Crucially, the data taken for these surveys should be made readily and easily accessible to the public to empower local communities in stewarding their kelp forests and to play a role in enhancing future research and science.

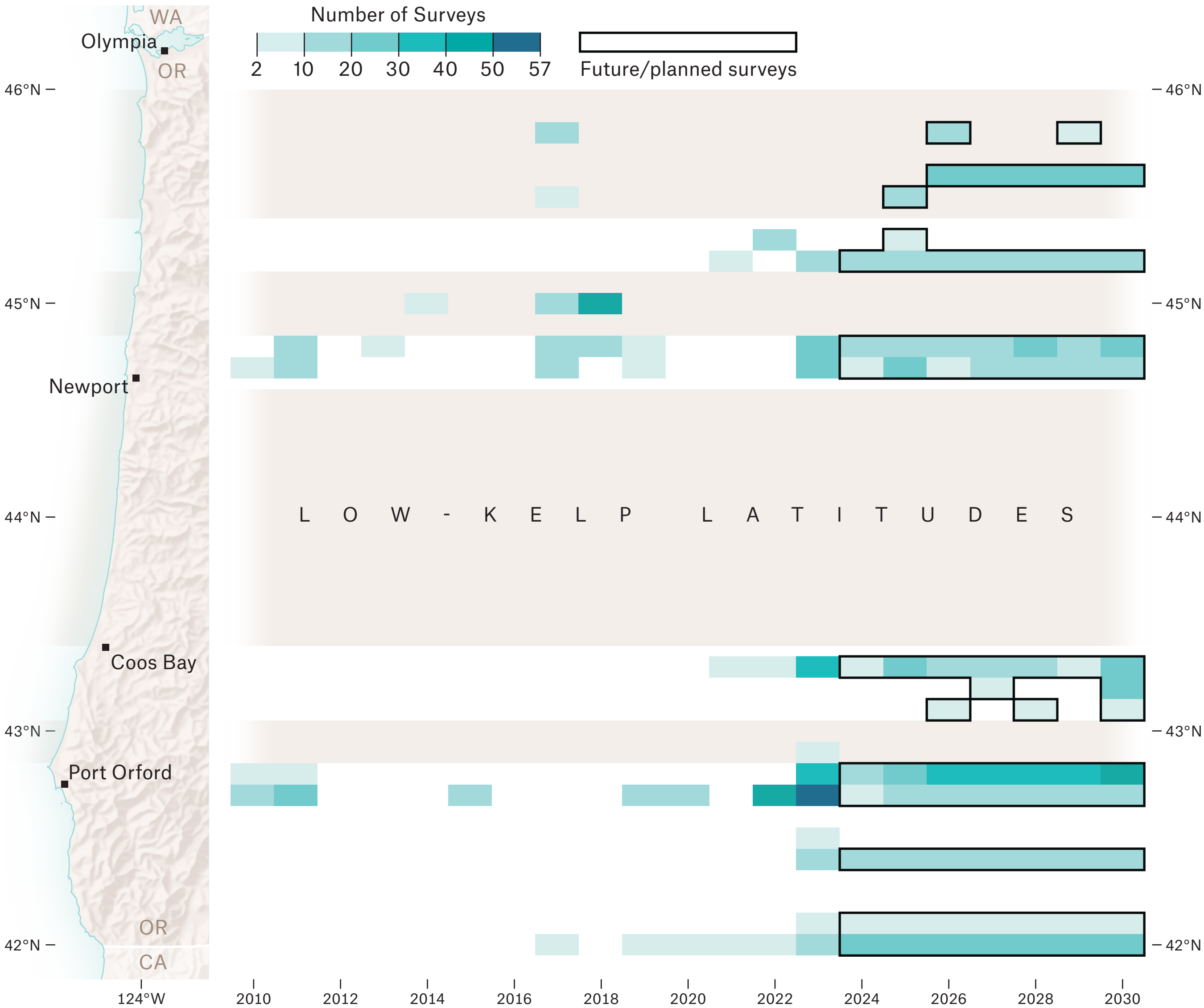


**Figure 13.** Heatmaps showing how data available for this report from scuba-based monitoring varied across Oregon over 2010-2023 (left) and what data availability could look like over the next decade if a targeted kelp forest monitoring program was implemented (right).

Aerial and satellite data can help monitor larger-scale changes in forest size over time compared to monitoring using scuba-based survey data. For instance, Landsat satellite data extends back to the 1980s and has been invaluable for understanding long-term changes in kelp forests.[32,76,90] However, the coarse scale of older satellite data (30 m) means these data provide only rough estimates of forest size that are affected by artifacts such as nearshore rocks and non-kelp vegetation. These data also miss small patches of kelp, potentially reducing the amount of detectable kelp. New satellite datasets, such as the private Planet satellite network, are of much higher resolution (3 m). Researchers at UCLA and Woods Hole Oceanographic Institution are working to develop tools for quantifying kelp canopy from Planet data.[54] We recommend that Oregon support these ongoing advances in kelp forest satellite sensing via financial support and partnerships that will increase the speed with which these improved satellite tools can be applied locally.

Aerial monitoring techniques include both fixed-wing airplane surveys and UAV surveys.[115] Both fixed-wing airplane and UAV surveys should be used for ongoing kelp forest monitoring in Oregon as they have somewhat different strengths and limitations.[115] Aerial surveys quickly capture high-resolution information that cover vast stretches of coastline in a single day, provide an unparalleled snapshot of kelp conditions across the coast, and capture remote, offshore, and nearshore kelp forests. While UAV surveys can only capture 2–3 individual sites a day, they are very useful for monitoring restoration sites. They can be deployed more regularly to monitor short-term changes, and they are of sufficient resolution to monitor fine-scale restoration work. UAV techniques also provide opportunities for workforce development and the opportunity to include coastal residents in local kelp forest stewardship.

For aerial monitoring, we recommend that (1) fixed-wing airplane surveys be flown annually from Cape Foulweather to the California border, and (2) UAV surveys be performed once or more times a year, targeting a subset of nearshore and restoration sites. To maximize the value of aerial surveys, we recommend identifying ways to more readily and easily share the resulting data with the public. Additionally, the process of going from raw aerial imagery to estimates of kelp canopy area can be time-consuming and complex. The use of artificial intelligence tools to assist in analyzing these data should also be explored. Groups producing these data, such as ODFW and ORKA, should consider documenting and sharing these data-processing pipelines to increase coordination across datasets. Finally, in addition to conducting ecological monitoring with techniques already in use in Oregon, monitoring can be supplemented by adopting methods utilized in other regions (such as kayak surveys) or incorporating emerging technologies (such as remotely operated vehicles or diver-propulsion, vehicle-based surveys).

## Environmental Monitoring

In addition to ecosystem monitoring, environmental monitoring is a second critical component of any targeted kelp forest monitoring program. Currently, little of Oregon's ocean monitoring infrastructure overlaps with kelp forest habitat.[116] Buoys and sensors that are even a few kilometers offshore do not adequately capture the conditions experienced by kelp forests because nearshore oceanography is very dynamic, patchy, and influenced by land-based processes.[117,118] A few sources of nearshore data exist, such as the NOAA water temperature stations highlighted in this report, and the seasonal temperature and dissolved oxygen monitoring associated with the Oregon Marine Reserves. However, we have found that, overall, our current understanding of the role of environmental drivers and climate change in ongoing kelp forest loss is limited by the lack of relevant temperature, light, nutrient, salinity, dissolved oxygen, and pH data. Without understanding the drivers of change, we lack the crucial insight needed to identify effective restoration and protection strategies.

Thus, we recommend that environmental monitoring of temperature, salinity, and light availability within the shallow, nearshore, rocky reefs of kelp forests be included in long-term monitoring. Measurements of nutrient concentrations may also be of value. Although, in general, Oregon waters are thought to be nutrient rich and high nutrient concentrations are not expected to limit kelp growth.[32,58] Sets of these sensors distributed across 4–5 of the previously proposed core monitoring sites and spanning the Oregon coast would greatly increase our capacity for linking environmental conditions to kelp forest outcomes. Sensors should be placed in areas that are expected to have diverging environmental conditions. For example, salinity sensors can be located in kelp forests at the mouth of rivers as well as in kelp forests away from significant freshwater input. Sensors ideally should take multiple measurements a day and monitor year round because brief but extreme environmental conditions can have strong effects on biological outcomes.[119–121] Additionally, while dissolved oxygen and pH are not generally considered to have strong impacts on kelps, they can have strong impacts on key members of the kelp forest ecosystem such as sea urchins.[122,123] Thus, monitoring these parameters would aid our understanding of drivers of change in key kelp forest species. Overall, regular monitoring of the environment in kelp forests, alongside simultaneous monitoring of kelp forest ecology metrics such as composition and health, will enable a much more targeted assessment of what factors drive kelp forest change.

## Critical Areas of Future Investigation

While we present crucial information here regarding the current status of Oregon's kelp forests, important questions remain. To meaningfully steward Oregon's kelp forest ecosystems in the future, we highlight just a few of the critical questions that need to be investigated in the coming years.

- How do temperature changes and marine heat waves impact kelps and kelp forest communities in Oregon?
- What other environmental variables, such as light availability and salinity, impact kelps, sea urchins, and sea stars in Oregon?
- What role are red sea urchins playing, compared to purple sea urchins, in kelp forest loss and recovery?
- Are the recent sightings of sunflower sea stars in Oregon evidence of recovering populations? If so, how much will the population need to recover in order to play an ecologically functional role in kelp forests?
- What sites are most desirable for restoration work? What sites are most desirable for protection work? Which criteria should we use to make these decisions?

# Conclusions

Overall, this report finds that Oregon kelp forests have declined substantially since 2010. Between 2010 and 2022, aerial surveys documented that, across the south coast of Oregon, only a third of previous kelp forest canopy remains—a loss of nearly 900 acres. Additionally, ORKA's 2023 kelp forest monitoring work demonstrates that an estimated 69% of historical kelp forest habitat no longer supports robust kelp populations. Dramatic increases in purple sea urchin populations are the most likely driver of these losses, although a suite of changes to the marine environment, driven by climate change, have likely contributed as well—particularly marine heatwaves. Based on synthesis data,[4] this loss of kelp forest habitat costs the state a first-order estimated range of $23–53 million per year in lost benefits to fisheries, local economies, and coastal residents, particularly on Oregon's south coast. Kelp forest declines have already begun negatively affecting the red sea urchin and red abalone fisheries, and the findings in this report raise concern about the future of several species dependent on kelp forests, such as abalone and nearshore rockfish.

Despite considerable reduction in canopy-forming kelp habitat in some areas, the results of 2023 kelp forest survey work show that kelp forest conditions vary across the state. Although large swaths of the kelp forest habitat on the southern Oregon coast now support little-to-no kelp, areas such as Rogue Reef, Cape Arago, and Cape Foulweather have, in general, higher densities of kelp and lower densities of purple sea urchins. Despite this worrying shift in kelp forest ecosystems across some parts of Oregon, this report also documents surprising signs of resilience, such as initial signs of recovery in sunflower sea stars and an historically strong year for kelp forests across the Cape Foulweather area.

This report documents high-level trends and patterns in Oregon's kelp forest ecosystems and raises many questions, demonstrating that there is high uncertainty about a number of essential aspects of

Oregon's kelp forests. Investment in kelp forest restoration, enhancement, protection, monitoring, research, and community-based stewardship is critical to leveraging the positive signs of resiliency documented here to ensure the flourishing of kelp forests in the future. The companion document to this report, the *2024 Oregon Kelp Forest Stewardship Action Plan*, will lay out areas of opportunity for restoration, enhancement, protection, and stewardship work and will be available to the public early in 2025. While the future of Oregon's kelp forests may look different than the past, we hope that this *2024 Oregon Kelp Forest Status Report* can help contribute to a future Oregon where humans can continue to steward and enjoy kelp forest ecosystems, as they have done for millennia.

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# Appendix

PHOTOGRAPH BY BRANDON COLE

# Extended Methods and Analysis

## INTRODUCTION

### A Map of Maximum Historical Canopy Extent

To create figure 1, we downloaded all available Oregon kelp cover data from the first quarter of 1985 through the third quarter of 2023 from the Kelpwatch platform, which estimates canopy cover from Landsat satellite imagery using a standardized methodology.[1] To minimize the chance of including occasional detached floating canopy or other random, one-time processes, the Kelpwatch platform only includes 30 m × 30 m pixels if kelp was detected in them by the Landsat algorithm in at least 1% of all cloud-free Landsat images for that pixel. We then plotted all pixels that Kelpwatch identified to show the maximum extent of kelp canopy in Oregon. This may include some marginal habitat that has historically supported kelp canopy, but the maps shown in figure 1 largely match with other sources of kelp canopy data such as ODFW aerial kelp canopy maps.[2–4]

## DATA USED IN THIS REPORT

### Area and Site Designations

The "areas" and "sites" identified in figure 2 were decided in consultation with ORKA's Scientific and Technical Advisory Committee at a workshop in February 2023. The "area" level designations largely align with large breaks (10 s of km) in historic kelp habitat, often driven by breaks in rocky reef habitat. Additionally, these "area" designations largely follow the way ODFW broke down Oregon's kelp forest habitat in their 2010 aerial survey report.[2] Sites correspond to finer-scale locations, usually broken down to a single contiguous reef on the scale of 1–5 km. Because this is a statewide report, we chose to assess changes in kelp forests at an area scale to create a manageable number of regions to assess, communicate around, and visualize for a statewide audience. As readers can see, substantial intra-area variability exists in 2023 kelp and urchin densities (figure 7). Those smaller-scale levels of variability should be considered in future research and when planning restoration and protection work. Additionally, we did use "sites" when showing subtidal data in response to feedback from our Scientific and Technical Advisory Committee.

### ORKA's 2023 Coordinated Surveys

In 2023, ORKA coordinated a series of surveys specific to kelp forests with three partners, Reef Check, the Oregon Coast Aquarium, and the Galloway lab at the University of Oregon. As the timeline to conduct these surveys was relatively short (less than a year from the time funds were available to the end of the dive season), we focused on leveraging standing methods and expertise to conduct these surveys.

For protocols, Reef Check used their pre-existing kelp forest monitoring protocols that feature six sets of four 30 m × 2 m transects a characterize kelp abundance, invertebrate abundance, fish abundance, and benthos characteristics at any given site. For more information on Reef Check monitoring and protocols see their Kelp Forest Monitoring website (https://www.reefcheck.org/kelp-forest-program/). The Aquarium and Galloway lab used a slightly different set of protocols developed by the Galloway lab and known as a "macroswath" survey. These surveys are meant to focus more narrowly on four taxa relevant to kelp forests (kelps, sea urchins, large sea stars, and abalone) in order to shorten survey time so that more sites can be surveyed. Macroswath surveys also include stereo-video records of surveyed transects. While these surveys use only a subset of the species list that Reef Check does, they both estimate the density of four key kelp species (*Nereocystis luetkeana, Pterygophora californica, Pleurophycus gardneri*, and *Laminaria setchellii*), two sea urchin species (*Strongylocentrotus purpuratus* and *Mesocentrotus franciscanus*), three species of large sea star (*Pycnopodia helianthoides, Solaster dawsonii,* and *Solaster stimpsonii*), and three species of abalone (*Haliotis rufescens, Haliotis kamtschakana,* and *Haliotis walallensis*) along 30 m × 2 m transects.

Survey locations for these dive teams were coordinated by ORKA. We started by focusing our survey efforts on areas where kelp canopy was documented from past aerial and satellite surveys. We worked to ensure that a wide geographic range of Oregon's kelp forests would be surveyed, sending teams from Brookings to Pacific City. When possible, we directed scuba teams to sites of previous subtidal survey work conducted by ODFW, although often the precise locations of previous survey work was not available to us until after the conclusion of the field season. In general, we guided teams toward conducting surveys in 20–50 ft of water to focus on the depth range of historic kelp forest habitat. Because of the limited dive time available during Oregon field seasons, we focused on increasing the geographic scope of our survey work instead of consistently sampling from distinct depth bins at each location. Overall, with ORKA support, our partners were able to conduct 170 unique transects over 24 boat days.

## Other Data Sources

Below (**Appendix table 1**), we outline the data sources we drew upon for this report (in addition to ORKA's 2023 coordinated surveys). Because this report was meant to be a relatively concise overview of kelp forest status in Oregon, we did not use all data available from each data source. Rather, we drew on sets of surveys that were particularly meaningful for this report, usually because of repeat effort or because they were in a key part of Oregon's kelp forest habitat. We also note which data we used from each data source and why the data were used (**Appendix table 2** and **Appendix table 3**).

**ODFW aerial bull kelp surveys:** [28,29,31] These were airplane-based aerial surveys of kelp canopy cover taken in late Fall 2010 and late Fall 2022. We label these as bull kelp surveys because bull kelp is the primary canopy-forming kelp in Oregon, although these surveys may also extend over small patches of giant kelp (*Macrocystis pyrifera*) that are present at Cape Arago. While aerial surveys are available from the 1990s, they used a different methodology than later surveys, which makes direct comparisons difficult. Since we were using these aerial surveys to look at change over time, we focused on the 2010 and 2022 surveys because they used more comparable methods and captured recent changes in canopy cover. However, for those interested, ODFW has published a number of reports assessing the findings of these earlier surveys that are publicly available.[2–4]

**ODFW sea urchin fishery surveys**: These were time series of scuba-based surveys of red and purple sea urchin densities at kelp forests. They focused mostly on Southern Oregon and were collected primarily to aid in managing the red urchin fishery. These surveys work with commercial red sea urchin divers to conduct estimates of red and purple sea urchins, large sea stars, and abalone along quadrats or transects. These surveys are usually conducted in summer and at a set of index sites that were historically areas of red sea urchin harvest. For further details please see ODFW Sea Urchin Surveys.[5]

In this report we drew only on red and purple sea urchin data from these surveys and only from 2010 onward, in order to match the time span covered by the 2010 and 2022 aerial surveys. While surveys were conducted at a number of sites near Depoe Bay, Cape Arago, Port Orford, and Brookings over this time, we focused our analysis on surveys conducted at three sites near Port Orford (Orford Reef, Redfish Rocks, and Humbug Mountain) because these sites were surveyed more often during this time period than other sites. Therefore, they were more useful for time series analysis (4–5 sets of annual surveys in these locations versus 1–3 annual surveys in others).

**ODFW Marine Reserves surveys**: These were scuba-based surveys of rocky reef habitat in marine reserves and nearby comparison sites. The Oregon Marine Reserves Program has conducted scuba-based surveys along with several other kinds of monitoring at reserves and nearby comparison sites since 2010. We focused on scuba data taken at Otter Rock Marine Reserve and its comparison sites and Redfish Rocks Marine Reserve and its comparison sites because the three other reserves do not include canopy-forming kelp habitat. We were unable to use time series of kelp density data from the Oregon Marine Reserves because the methodology for kelp surveys has changed over time and thus the Reserves program considers it unreliable for tracking changing kelp densities.[6] However, we did include Fall 2023 kelp densities from the Otter Rock Marine Reserve and comparison areas in the maps and analyses underlying **figure 7** and **figure 11** since these surveys use protocols similar to those of ORKA's 2023 survey partners.

We also used data on sunflower sea star observations from Marine Reserves scuba surveys to document the loss of sunflower sea stars since 2014 in Oregon (**figure 6**). While these surveys also record purple and red sea urchin densities, we did not utilize these for time series of sea urchin density data over time (**figure 5**) because we received feedback from ODFW to avoid mixing different datasets into a single analysis. We felt that the sea urchin fishery surveys data more comprehensively surveyed data in key kelp habitat over the time period in question. Thus, we focused on using it to document urchin changes over time instead of using Marine Reserves data. The Marine Reserves program takes other forms of nearshore data beyond what was used in this report, including oceanographic data at eight sites along the state's coastline. For more information see the Oregon Marine Reserves website (https://oregonmarinereserves.com/) and the 2022 Oregon Marine Reserves Synthesis Report.[7]

**Reef Check community science surveys**: Reef Check has been conducting community science kelp forest ecosystem surveys since 2017 at Macklyn Cove and since 2020 at several other sites in Oregon. Reef Check uses modified PISCO protocols that revolve around a series of four 30 m × 2 m transects that characterize kelp abundance, invertebrate abundance, fish abundance, and benthos characteristics. For more information on Reef Check monitoring and protocols see their Kelp Forest Monitoring website (https://www.reefcheck.org/kelp-forest-program/).

For our report, we highlight the monitoring Reef Check has conducted in Macklyn Cove since that monitoring has been ongoing since 2017 as well as the 2023 work they conducted in coordination with ORKA for this report. While about 6–10 other sites have been surveyed multiple times by Reef Check since 2020, these sites received few years of monitoring and often after kelp had crashed at these locations and thus were less useful in showing how subtidal kelp cover has changed over time. In figure 4, we draw only from surveys taken in June–October because kelp densities shifted seasonally and may not be as abundant in spring or late Fall.

**Appendix table 1.** List of data sets used in this report, including the source, the type of data included, the frequency, time frame, spatial coverage, and species surveyed. The total number of surveys among sites and years by each data contributor is also listed, with the number of transects in parentheses. An asterisk indicates that instead of a true transect, we summed counts in a series of quadrats in a given site.

| Dataset Source | Data Type | Frequency | Years covered | Spatial Coverage | Species Surveyed | Number of Surveys (and Transects) |
|---|---|---|---|---|---|---|
| ORKA nearshore drone surveys | Drone surveys | Annual | 2021–present | Several nearshore kelp forests | Canopy forming kelp, particularly *Nereocystis leutkeana* | 5–20/year |
| ODFW Aerial Kelp Surveys | Airplane-based surveys | Irregular | 1990 –2022 | Primarily Port Orford south but sometimes up through Depoe Bay | Canopy forming kelp, particularly *Nereocystis leutkeana* | 6 |
| Kelpwatch Landsat satellite data | Satellite-based, 4-band imagery | Every 816 days | 1984–present | Entire coast | Canopy forming kelp, particularly *Nereocystis leutkeana* | 156 quarterly averages |
| Oregon Coast Aquarium Macroswath surveys | Scuba surveys | Standalone | 2023 | Historic kelp forest habitat at Cape Arago, Cape Blanco, and Rogue Reefs | Kelps, sea urchins, abalone, sea stars, some sessile invertebrates | 3 (50) |
| University of Oregon Macroswath surveys | Scuba surveys | Standalone | 2022–2023 | Historic kelp forest habitat from Gregory Point to Redfish Rocks | Kelps, sea urchins, abalone, sea stars, some sessile invertebrates | 10 (37) |
| ODFW fishery independent sea urchin surveys | Scuba surveys | Irregular | 1993–present | Rocky reef habitat from Government Point to Chetco Point including reserves | Red and purple sea urchins primarily<br>Abalone are also surveyed but this data has not been released for this report.<br>Some other habitats and species were surveyed depending on the year and area. | 89 (645*) |
| ODFW Marine Reserves monitoring | Scuba surveys | Sites revisited every 2–3 years | 2010–present | Oregon's five Marine Reserves and nearby comparison sites from Cape Falcon North to Humbug | All functional groups | 60 (778) |
| Reef Check community science surveys | Scuba surveys | Annual | 2017–present | Historic kelp forest habitat from Cape Lookout to Chetco Point | All functional groups | 51 (480) |

**Appendix table 2.** List of site and area groupings used in this report listed from north to south, with nearby ports included. Sites approximately correspond to a given rocky reef or kelp forest and areas roughly correspond to major headlands.

| Site | Area | Nearby Port | Site Latitude | Site Longitude |
|---|---|---|---|---|
| Cape Falcon North | Cape Falcon | Garibaldi | 45.805 | -123.984 |
| Cape Falcon | Cape Falcon | Garibaldi | 45.762 | -123.986 |
| Cape Meares | Cape Meares | Garibaldi | 45.492 | -123.987 |
| Three Arch Rocks | Cape Meares | Garibaldi | 45.459 | -123.990 |
| Cape Lookout | Cape Lookout | Pacific City | 45.337 | -123.980 |
| Pacific City North | Cape Lookout | Pacific City | 45.213 | -123.985 |
| Pacific City South | Cape Lookout | Pacific City | 45.212 | -123.985 |
| Cascade Head Marine Reserve | Cascade Head | Pacific City/Depoe Bay | 45.015 | -124.026 |
| Schooner Creek Comparison Area | Cascade Head | Pacific City/Depoe Bay | 44.958 | -124.041 |
| Government Point | Cape Foulweather | Depoe Bay | 44.824 | -124.069 |
| Cape Foulweather | Cape Foulweather | Depoe Bay | 44.784 | -124.074 |
| Otter Rock | Cape Foulweather | Depoe Bay | 44.747 | -124.073 |
| Gregory Point | Cape Arago | Coos Bay | 43.343 | -124.377 |
| Sunset Bay | Cape Arago | Coos Bay | 43.333 | -124.383 |
| Simpson Reef | Cape Arago | Coos Bay | 43.316 | -124.404 |
| Drake Point | Cape Arago | Coos Bay | 43.301 | -124.401 |
| Blanco Reef | Cape Blanco | Port Orford | 42.832 | -124.582 |
| Orford Reef | Cape Blanco | Port Orford | 42.788 | -124.595 |
| Port Orford Heads | Cape Blanco | Port Orford | 42.736 | -124.508 |
| Redfish Rocks | Redfish Rocks | Port Orford | 42.702 | -124.469 |
| Humbug | Redfish Rocks | Port Orford | 42.668 | -124.441 |
| Rogue Reef | Rogue Reef | Gold Beach | 42.444 | -124.468 |
| Boardman Corridor | Brookings | Brookings | 42.097 | -124.347 |
| Chetco Point | Brookings | Brookings | 42.044 | -124.291 |

**Appendix table 3.** List of species or clades surveyed during scuba-based surveys by at least one data contributor (**Appendix table 1**). Species and clades were often surveyed to a finer taxonomic level but were often lumped to functional group levels below for analyses (thin borders). Broad taxa are included for reference. We classified species into four major ecological roles (bold borders), including producers, grazers, passive or filter feeders, and predators.

| Species or Group | Common Name | Functional Group | Taxon | Ecological Role |
|---|---|---|---|---|
| *Nereocystis luetkeana* | Bull kelp | Canopy kelp | Kelp | Producer |
| *Macrocystis pyrifera* | Giant kelp | Canopy kelp | Kelp | Producer |
| *Pterygophora californica* | Old growth kelp, winged kelp | Canopy kelp | Kelp | Producer |
| *Egregia menzisii* | Feather Boa kelp | Subcanopy kelp | Kelp | Producer |
| *Pleurophycus gardneri* | Ribbed Kelp | Subcanopy kelp | Kelp | Producer |
| *Laminaria setchellii* | Split kelp, torn kelp, torn blade kelp | Subcanopy kelp | Kelp | Producer |
| *Sargassum muticum* | Sargassum | Subcanopy kelp | Brown alga | Producer |
| Other brown alga | Other brown alga | Subcanopy kelp | Brown alga | Producer |
| Red alga | Red alga | Subcanopy vegetation | Red alga | Producer |
| Surfgrass | Surfgrass | Subcanopy vegetation | Surf grass | Producer |
| *Strongylocentrotus purpuratus* | Purple sea urchin | Purple sea urchin | Sea urchin | Grazer |
| *Mesocentrotus franciscanus* | Red sea urchin | Red sea urchin | Sea urchin | Grazer |
| *Haliotis walallensis* | Flat abalone | Abalone | Abalone | Grazer |
| *Haliotis kamtschatkana* | Pinto abalone | Abalone | Abalone | Grazer |
| *Haliotis rufescens* | Red abalone | Abalone | Abalone | Grazer |
| Anemone | Anemone | Other sessile invertebrate | Anemone | Passive or filter feeder |
| Barnacle | Barnacle | Other sessile invertebrate | Barnacle | Passive or filter feeder |
| Bivalve | Bivalve | Other sessile invertebrate | Bivalve | Passive or filter feeder |
| *Cryptochiton stelleri* | Gumboot chiton | Other sessile invertebrate | Other invertebrate | Passive or filter feeder |
| Other echinoderms | Other echinoderms | Other sessile invertebrate | Other echinoderms | Passive or filter feeder |
| Other invertebrates | Other invertebrate | Other sessile invertebrate | Other invertebrate | Passive or filter feeder |
| *Pycnopodia helianthoides* | Sunflower sea star | Sunflower sea star | Sea star | Predator |
| *Solaster dawsoni* | Dawson's star | Other predatory sea star | Sea star | Predator |
| *Pisaster ochraceus* | Ochre star | Other predatory sea star | Sea star | Predator |
| *Solaster stimpsoni* | Stimpson's star | Other predatory sea star | Sea star | Predator |
| Other fish | Other fish | Predatory fish | Fish | Predator |
| Rockfish | Rockfish | Predatory fish | Fish | Predator |

### Estimating Change in Kelp Canopy from 2010–2022

Satellite and aerial surveys have different strengths for estimating kelp canopy cover over time. Landsat satellite records extend back to 1984, are taken every 8–16 days, and have used very consistent methodology over this time period. Thus, Landsat satellite data offers one of the most consistent, longest running time series of kelp canopy cover available at larger spatial scales. However, Landsat imagery is taken at a coarse resolution for measuring kelp forest extent (30 $m^2$) and cannot accurately measure kelp close to the shoreline, kelp close to exposed rocks, or small patches of kelp.[1,8]

Conversely ODFW aerial survey data is much higher resolution and can delineate smaller patches of kelp up to a meter below the water's surface and in nearshore areas.[2,4] However, because these surveys are expensive and time consuming, they are available much less often than satellite imagery, often on the order of once a decade. Additionally, the methodology of taking aerial imagery and converting it to polygons representing kelp beds has changed over time as new tools have emerged. Thus, the kelp extent derived in different years was taken at varying resolutions, making the datasets less comparable.[9]

Recent investigation into the differences in kelp canopy estimates in Oregon between these two methodologies show that the two can yield surprisingly different estimates.[4] Landsat-based estimates of kelp cover appear to deeply underestimate canopy cover at the present time, particularly for small beds or for kelp slightly below the surface. Because data from aerial surveys are much more accurate, we drew on ODFW aerial survey data whenever possible, relying only on Landsat-based Kelpwatch data in regions where no other information is available.

To create estimates of kelp canopy change from aerial imagery, all analyses were conducted in RStudio using raster, tidyverse, ncdf4, sp, sf, scales, and lubridate packages. ODFW provided fixed-wing aerial survey data in the form of polygon shapefiles delineating kelp canopy that was derived from the original photographs. We used the sf package in RStudio to split these shapefiles into each of the five southern regions (**figure 2**). We then calculated the area of kelp coverage for each region using the area feature included in the original shapefiles.

To create an estimate of canopy change from Kelpwatch data, we downloaded all available quarterly data covering Oregon from the platform. We filtered the data to boundaries of each specified region (**figure 2**) and then summed the quarter 3 estimates of canopy cover from 2010 and 2022 across all pixels covering that region. We used quarter 3 estimates because late summer and early fall is generally when bull kelp canopy extent is at its fullest.

We used the 2010 and 2022 estimates of area for each region to calculate the percent change shown on **figure 3**. For each region, only satellite or aerial data was used for 2010 and 2022 estimates. We did not use satellite estimates for one year and aerial for another.

### Change Over Time in Kelp, Sea Urchins, and Sea Stars from Scuba Surveys

#### MACKLYN COVE TIME SERIES

In **figure 4**, we show changes in kelp, purple sea urchin, and red sea urchin density at Macklyn Cove in Brookings, OR from 2017–2023 using Reef Check community science data. Six transects at Macklyn Cove have been surveyed in 2017, 2019, 2020, 2021, 2022, and 2023. We limited our scope to surveys conducted from June–October, when kelp is most abundant. Thus, the surveys from 2021, which were conducted in late November, were excluded. We used a one-sided wilcox test to test the significant difference between kelp and urchin densities from 2017, 2019, and 2013 and used generalized additive models fit with Tweedie distributions with a log link to estimate trends over time (**Appendix table 4**). In general, we used medians and non-parametric statistics as the data was not normally distributed. The 95% confidence intervals displayed on **figure 4** were calculated in R using the np.boot function in the nptest package that calculates intervals using nonparametric bootstrap resampling with R = 9999.

**Appendix table 4:** Statistical tests and outputs used to assess changes in kelp and sea urchin densities from 2017–2023 from Reef Check data at Macklyn Cove, Brookings.

| Description | Statistical Test | Output | P-value |
|---|---|---|---|
| Was 2017 median kelp density the same as 2019 median kelp density? | One-sided wilcox test | Significantly lower median density in 2019 than 2017 | p-value = 0.006 |
| Was 2017 median kelp density the same as 2023 median kelp density? | One-sided wilcox test | Significantly lower median density in 2023 than 2017 | p-value = 0.001 |
| Was 2017 purple sea urchin median density the same as 2019 median density? | One-sided wilcox test | Significantly higher median density in 2019 than 2017 | p-value = 0.02 |
| Was 2017 purple sea urchin median density the same as 2023 median density? | One-sided wilcox test | Significantly higher median density in 2023 than 2017 | P-value = 0.002 |
| Was 2017 red sea urchin median density the same as 2019 median density? | One-sided wilcox test | Significantly higher median density in 2019 than 2017 | p-value = 0.01 |
| Was 2017 red sea urchin median density the same as 2019 median density? | One-sided wilcox test | Significantly higher median density in 2023 than 2017 | p-value = 0.001 |
| Was there a significant trend in kelp densities from 2017–2023? | GAM using a Tweedie distribution with a log link | Significant year coefficient = -1.33 | P-value = 5.87e-07 |
| Was there a significant trend in purple urchin densities from 2017–2023? | GAM using a Tweedie distribution with a log link | Significant year coefficient = 0.28 | P-value = 0.0054 |
| Was there a significant trend in red urchins densities from 2017 –2023? | GAM using a Tweedie distribution with a log link | Insignificant year coefficient = 0.13 | P-value = 0.194 |

### SEA URCHIN TIME SERIES

We used ODFW urchin survey data from Orford Reef, Redfish Rocks, and Humbug Mountain to estimate changes in urchin densities over time in some Oregon kelp forests. While ODFW surveyed other locations in this time period, we focused on these sites as they were the only sites sampled after 2015. At each site, we only used surveys from a 20-foot depth range particular to each site in order to minimize the influence of differing depth distributions between years. The exact range varies somewhat between sites due to local topography and depth of the rocky habitat (35–55 ft at Orford and Redfish Rocks and 25–45 ft at Humbug). We only include years with at least five surveys at that site to ensure an adequate sample size. We used one-sided wilcox tests to estimate differences between specific years and used generalized additive models fit with Tweedie distributions with a log link to estimate trends over time (**Appendix table 5 and Appendix table 6**). In general, we used medians and non-parametric statistics as the data was not normally distributed. However, when estimating fold changes (e.g., a 66-fold increase) in sea urchin densities over time, we often used mean statistics because pre-2015 median values often had zeroes which would result in an infinite fold change. The 95% confidence intervals displayed on **figure 5** were calculated in R using the npboot function in the nptest package that calculates intervals using nonparametric bootstrap resampling with R = 9999.

**Appendix table 5:** Statistical tests and outputs used to assess changes in purple sea urchin densities from 2010–2023 at Orford Reef, Redfish Rocks, and Humbug.

| Description | Species | Statistical Test | Output | P-value |
|---|---|---|---|---|
| Was 2011 median purple sea urchin density the same as 2019 density at Orford Reef? | Purple sea urchin | One-sided wilcox test | Significantly higher median density in 2019 than 2011 | p-value = 6.6e-07 |
| Was 2011 median purple sea urchin density the same as 2023 density at Orford Reef? | Purple sea urchin | One-sided wilcox test | Significantly higher median density in 2023 than 2011 | p-value = 9.4e-08 |
| Was there a significant trend in purple urchin densities from 2011–2023 at Orford Reef? | Purple sea urchin | GAM using a Tweedie distribution with a log link | Significant year coefficient = 0.35 | p-value = 2e-16 |
| Was 2011 median purple sea urchin density the same as 2019 density at Redfish Rocks? | Purple sea urchin | One-sided wilcox test | Significantly higher median density in 2019 than 2011 | p-value = 0.002 |
| Was 2011 median purple sea urchin density the same as 2023 density at Redfish Rocks? | Purple sea urchin | One-sided wilcox test | Significantly higher median density in 2023 than 2011 | p-value = 0.0003 |
| Was there a significant trend in purple urchin densities from 2011–2023 at Redfish Rocks? | Purple sea urchin | GAM using a Tweedie distribution with a log link | Significant year coefficient = 0.57 | p-value = 4.1e-14 |
| Was 2011 median purple sea urchin density the same as 2019 density at Humbug Mountain? | Purple sea urchin | One-sided wilcox test | Significantly higher median density in 2019 than 2011 | p-value = 0.004 |
| Was 2011 median purple sea urchin density the same as 2023 density at Humbug Mountain? | Purple sea urchin | One-sided wilcox test | Significantly higher median density in 2023 than 2011 | p-value = 0.0008 |
| Was there a significant trend in purple urchin densities from 2011–2023 at Humbug Mountain? | Purple sea urchin | GAM using a Tweedie distribution with a log link | Significant year coefficient = 0.42 | p-value = 1.1e-06 |

**Appendix table 6:** Statistical tests and outputs used to assess changes in red sea urchin densities from 2010–2023 at Orford Reef, Redfish Rocks, and Humbug.

| Description | Species | Statistical Test | Output | P-value |
|---|---|---|---|---|
| Was 2011 median red sea urchin density the same as 2019 density at Orford Reef? | Red sea urchin | One-sided wilcox test | Significantly higher median density in 2019 than 2011 | p-value = 1.2e-05 |
| Was 2011 median red sea urchin density the same as 2023 density at Orford Reef? | Red sea urchin | One-sided wilcox test | Significantly higher median density in 2023 than 2011 | p-value = 0.00039 |
| Was there a significant trend in red sea urchin densities from 2011–2023 at Orford Reef? | Red sea urchin | GAM using a Tweedie distribution with a log link | Significant year coefficient = 0.16 | p-value = 5.0e-08 |
| Was 2011 median red sea urchin density the same as 2019 density at Redfish Rocks? | Red sea urchin | One-sided wilcox test | Significantly higher median density in 2019 than 2011 | p-value = 0.022 |
| Was 2011 median red sea urchin density the same as 2023 density at Redfish Rocks? | Red sea urchin | One-sided wilcox test | Significantly higher median density in 2023 than 2011 | p-value = 0.0037 |
| Was there a significant trend in red urchin densities from 2011–2023 at Redfish Rocks? | Red sea urchin | GAM using a Tweedie distribution with a log link | Significant year coefficient = 0.11 | p-value = 1.82e-07 |
| Was 2011 median red sea urchin density the same as 2019 density at Humbug Mountain? | Red sea urchin | One-sided wilcox test | Significantly higher median density in 2019 than 2011 | p-value = 0.0060 |
| Was 2011 median red sea urchin density the same as 2023 density at Humbug Mountain? | Red sea urchin | One-sided wilcox test | Significantly higher median density in 2023 than 2011 | p-value = 0.04 |
| Was there a significant trend in red urchin densities from 2011–2023 at Humbug Mountain? | Red sea urchin | GAM using a Tweedie distribution with a log link | Significant year coefficient = 0.17 | p-value = 3.7e-05 |

### SUNFLOWER SEA STAR TIME SERIES

We used ODFW Marine Reserve scuba survey data to illustrate changes in sunflower sea star densities over time in some Oregon kelp forests. While ODFW surveyed other locations in this time period, we focused on these sites because they had the highest number of years sampled in a common depth range. At each site, we only used surveys from a 20-ft depth range particular to each site in order to minimize the influence of differing depth distributions between years. The exact range varies somewhat between sites due to local topography and depth of the rocky habitat (15–35 ft at Otter Rock and 35–55 ft at Redfish Rocks). Additionally, we only include years with at least five surveys at that site to ensure an adequate sample size. We used generalized additive models fit with Tweedie distributions with a log link to estimate trends over time (**Appendix table 7**). While the data is not normally distributed, we used displayed mean density over time in **figure 6** because the high number of zeros present in estimates of median density made calculating confidence intervals difficult. The 95% confidence intervals displayed on **figure 6** were calculated in R using the npboot function in the nptest package that calculates intervals using nonparametric bootstrap resampling with R = 9999.

**Appendix table 7:** Statistical tests and outputs used to assess changes in sunflower sea star densities from 2011–2023 at two sites monitored by the ODFW Marine Reserves Program.

| Description | Species | Statistical Test | Output | P-value |
|---|---|---|---|---|
| Was there a significant trend in red sea urchin densities from 2011–2023 at Otter Rock? | Sunflower sea star | GAM using a Tweedie distribution with a log link | Significant year coefficient = -0.49 | p-value = 0.00012 |
| Was there a significant trend in red sea urchin densities from 2011–2023 at Redfish Rocks? | Sunflower sea star | GAM using a Tweedie distribution with a log link | Significant year coefficient = -0.34 | p-value = 0.00073 |
| Percent change in the density of Sunflower Sea Stars from 2011–2023 at Otter Rock | Sunflower sea star | One-sided Wilcoxon test | 97.3% decline (2011 density = 0.035/m2 and 2023 density = 0.00093/m2) | p-value = 7.2e-06 |
| Percent change in the density of Sunflower Sea Stars from 2010–2023 at Redfish Rocks | Sunflower sea star | One-sided Wilcoxon test | 100% decline (2010 density = 0.05/m2 and 2023 density = 0/m2) | p-value = 0.0083 |

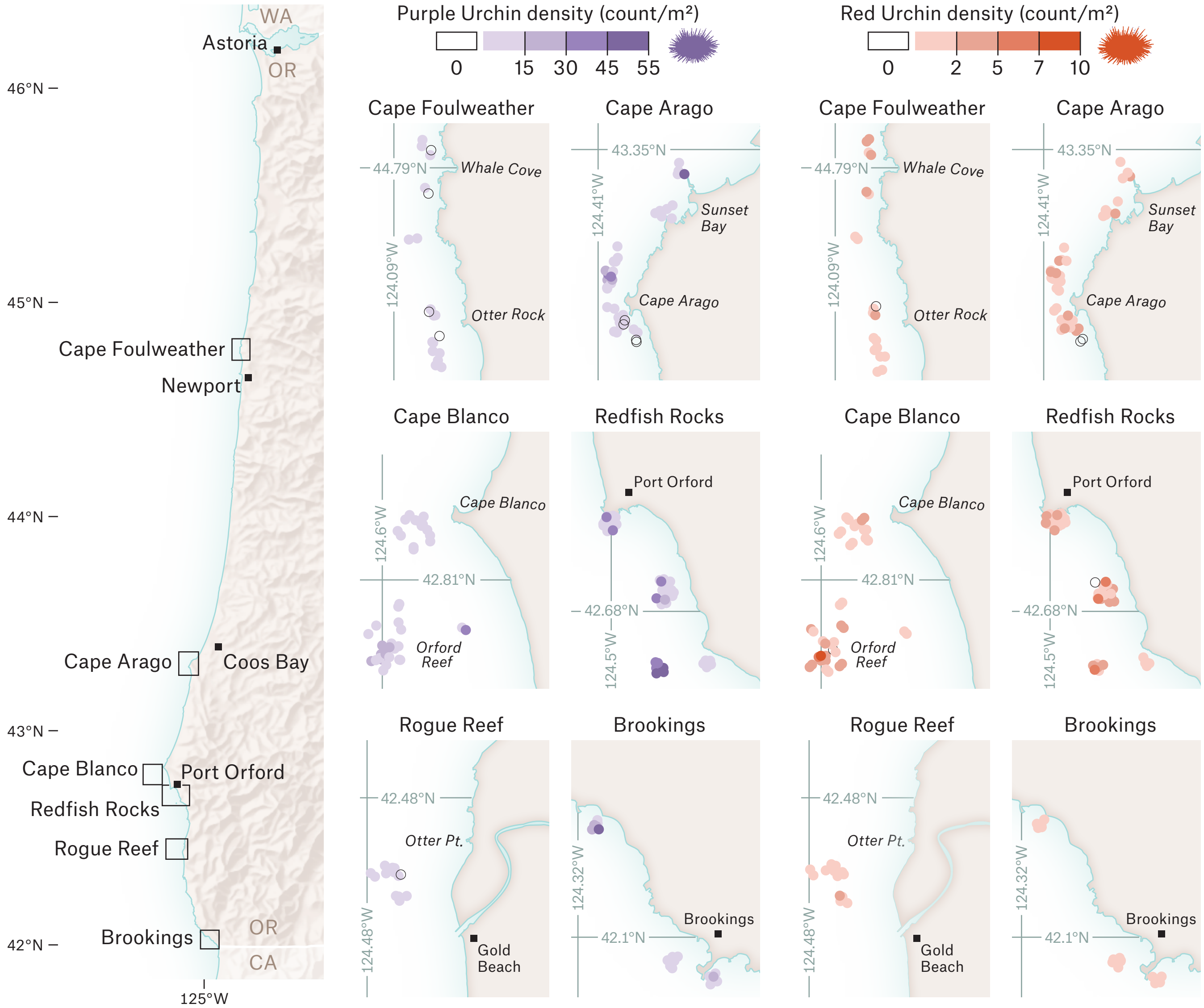
### SPATIAL PATTERNS IN THE PRESENCE OF KELP AND PURPLE SEA URCHINS

Below (**Appendix figure 1**) we show a map similar to **figure 7** except this version shows the densities of purple sea urchins and red sea urchins, so viewers can compare differences in the densities of the two species. The scales between the two are quite different as red sea urchin densities rarely exceed 5 urchins/$m^2$ whereas purple urchins were regularly found in densities up to 15 urchins/$m^2$ (**Appendix figure 2**).

## 2023 UAV Surveys of Kelp Forest Extent

In 2023, ORKA conducted 21 UAV surveys across the state to assess the area of bull kelp canopy at nearshore sites. Survey images were stitched into an orthomosaic using Drone Deploy software. An initial classification of kelp canopy was conducted using the Kelp-o-matic image processing algorithm on Python and this classification was then corrected by hand in ArcGIS Pro.[10] First, the rasters outputted by the Kelp-o-matic algorithm were transformed into shapefile multipolygons. We then removed polygons from the Kelp-o-matic output shapefile that had an areas less than 1 $m^2$, because these small patches were more likely to be misclassifications than larger patches and removing them eliminated substantial sources of error without having a large effect on the total area estimated. After that step, we began hand correcting the multipolygons. Because of how time-intensive hand classification can be, we were unable to create perfect classifications. Instead, we used several rules to guide our classification work that we felt removed substantial sources of error. These include:

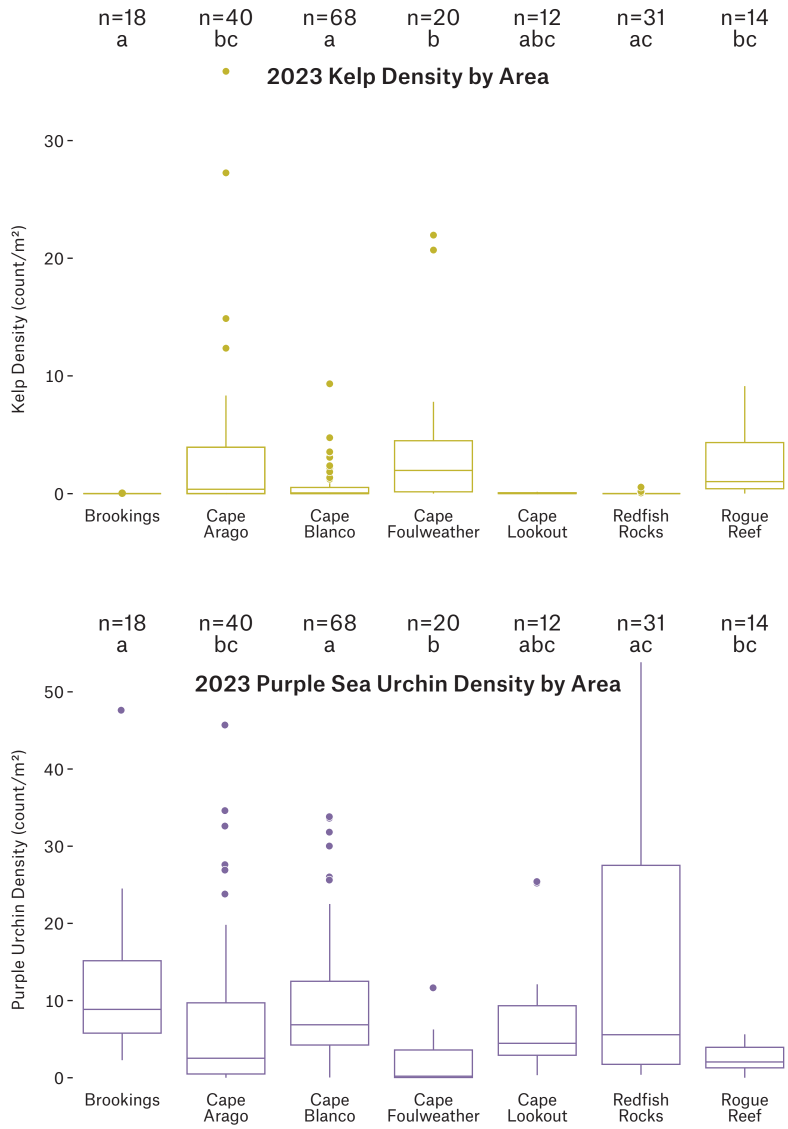
- Removing any misclassifications, including non-canopy forming kelp captured in the intertidal such as *Egregia*
- Ensuring that any patches of kelp including three contiguous kelps or more that the Kelp-o-matic algorithm missed were classified as kelp.




**Appendix figure 1:** Purple sea urchin density, indicated by color, at each scuba transect conducted in 2023 at six major kelp forest areas (left). Red sea urchin density indicated by color, at each scuba transect conducted in 2023 in six major kelp forest areas (right). Surveys occurred in the 15–50 ft range and peaked at a depth of around 35 ft at Cape Foulweather, in the 10–45 ft range and peaked at a depth of around 25–30 ft at Cape Arago, in the 15–45 ft range and peaked at depths from 30–40 ft at Orford Reef, in the 15–55 ft range and peaked at depths of around 25–35 ft at Redfish Rocks, in the 15–40 ft range and peaked at depths from 25–35 ft at Rogue Reef, and in the 17–25 ft range exclusively at Brookings. All sites except for Cape Foulweather draw on data collected during the 2023 ORKA survey efforts by ORKA partners Reef Check, the Oregon Coast Aquarium, and the Galloway lab at the University of Oregon. Cape Foulweather data was collected by ODFW.

Patches smaller than three kelps were generally not classified as in many scenes, it would be too time-intensive to correctly classify every individual kelp.

One problem we encountered, particularly in the Cape Foulweather area, was waves. Waves could obscure even thick canopy with foam and surf. In general, we avoided trying to delineate kelp canopy within wavy areas as we could not be sure where the kelp patch started and stopped. In Appendix table 8, where we list out the sites and estimate canopy area, we also note about how much of the scene was obscured by waves so readers are aware that some scenes could be substantial underestimates. Additionally, we generally put a time cap on hand classification of each scene in order to manage our times. Most scenes could be hand classified well in about 1–1.5 hours, but some larger or complex scenes took up to 3 hours. Overall, while UAV-based estimates of canopy area are very useful,



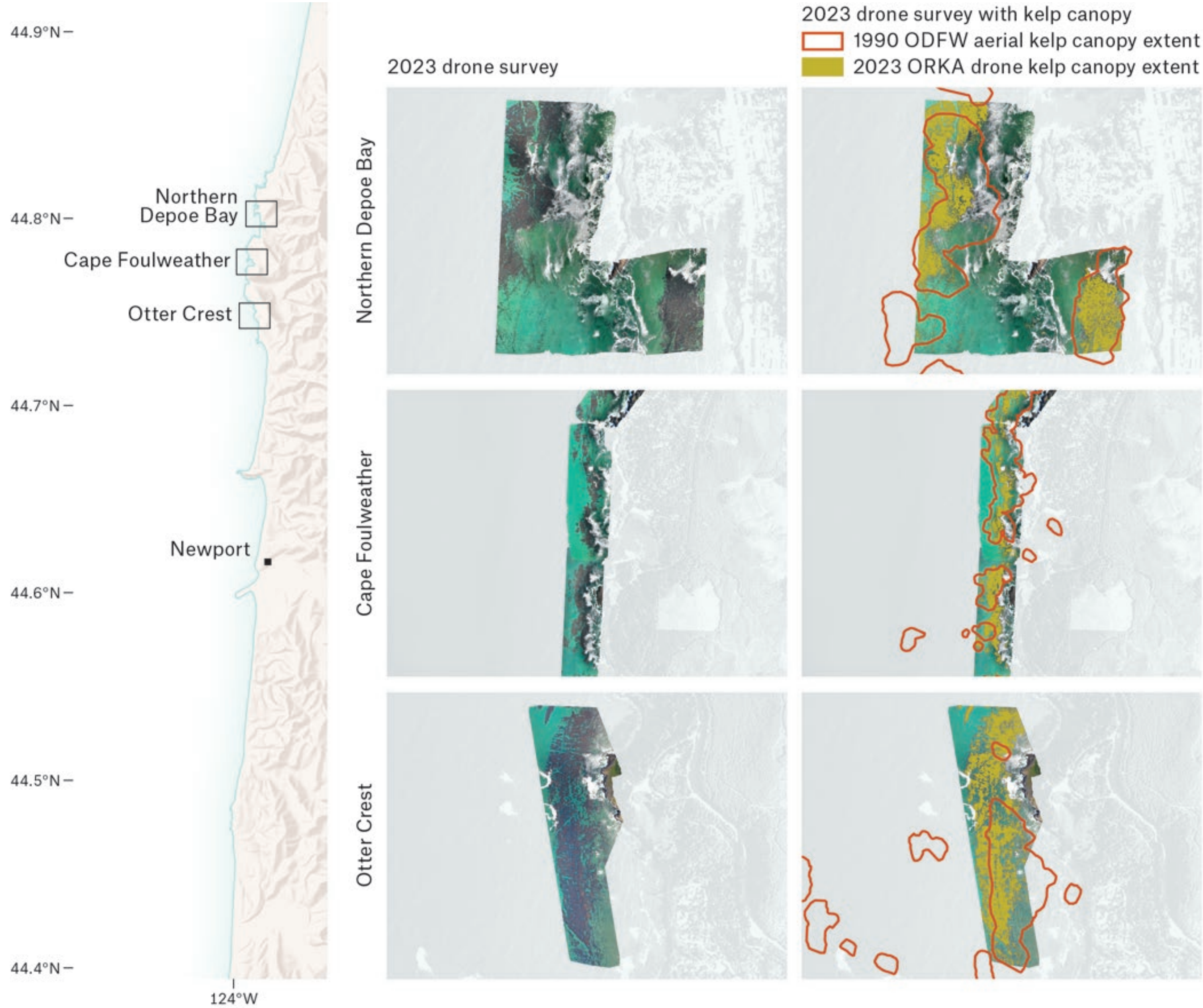

**Appendix figure 2:** Box and whisker plots of 2023 kelp densities (top) and purple sea urchin densities (bottom) across various kelp forest areas. Gray numbers at the top of each column indicate the number of surveys conducted in each area. Black letters at the top of each column indicate the statistically significant groupings according to a Kruskal Wallis test followed by a Dunn post hoc test with a Bonferroni correction. All sites except for Cape Foulweather draw on data collected during the 2023 ORKA survey efforts by ORKA partners Reef Check, the Oregon Coast Aquarium, and the Galloway lab at the University of Oregon. 2023 Cape Foulweather data was collected by ODFW.

they do contain noteworthy sources of error. In the future, we would like to better quantify what this error is and how it varies across different kinds of scenes (e.g., waves, mixed kelp species, intertidal areas).

As noted in the report, we were surprised at the extent of kelp canopy estimated from UAV surveys in the Cape Foulweather area in the central Oregon coast. In order to compare 2023 canopy extent to historic extent, we overlaid outlines of kelp canopy beds identified from 1990 ODFW aerial surveys, which had the largest kelp canopy extent of the seven aerial surveys conducted by ODFW since 1990: 1990, 1996, 1997, 1998 1999, 2010, and 2022 (Appendix figure 3). The surveys completed in 1990 were conducted at a lower resolution than 2023 drone surveys and the methodology for outlining beds likely drew rough polygons around forests rather than designating exact area of kelp.[9] Thus, the 1990 surveys are likely to overestimate kelp bed area in comparison to UAV surveys. With these caveats in mind, 2023 UAV estimates of kelp canopy area have similar footprints to the 1990 surveys. While the canopy footprints do not align precisely, where one 2023 bed may have somewhat less canopy cover than 1990 (e.g., Cape Foulweather) in another scene, the 2023 bed extends beyond the 1990 outlines (Otter Crest). Thus, while a precise quantitative comparison of 1990 versus 2023 kelp canopy area is not possible, due to methodological differences in the surveys, it does appear that 2023 bull kelp forests near and south of Depoe Bay had a similar extent to 1990.

### Sunflower Sea Star Sighting Time Series

To produce figure 9, we compiled a data set of all documented community sightings since 2015 in order to




**Appendix figure 3:** Three orthomosaics of kelp forest canopy area derived from ORKA 2023 UAV surveys in the Depoe Bay Area (left). In pink, kelp canopy identified from these 2023 orthomosaics is overlaid with bright green outlines of kelp canopy from 1990 ODFW aerial surveys (right). A site map of the three scenes shown above (bottom).

get an assessment of their presence within the kelp forest ecosystems. We used sightings from websites that offer the public an opportunity to document their sightings, such as iNaturalist (https://www.inaturalist.org/) and UC Santa Cruz's MARINe (https://marine.ucsc.edu/data-products/sea-star-wasting/). We drew all records of sightings of the sunflower sea star from these online platforms within the borders of Oregon since 2015 and integrated them into a single dataset mirroring the one we created for 2023 ORKA survey data.

### Kelp Forest Status Across Oregon

To assess how sensitive the kelp forest categories shown in figure 10 were to changes in the thresholds used to assign points, we conducted a robustness analysis. For a conservative assessment, we changed thresholds to make it harder for a forest to be classified as "high concern" and for a liberal assessment, we changed thresholds to make it easier for a forest to be classified as "high concern" (Appendix table 9).

**Appendix table 8:** UAV kelp canopy cover surveys at 21 sites across the Oregon coast from 2023.

| Site | Area | Latitude | Longitude | Date | Estimated Canopy Area (m2) | Estimated % of Total Kelp Area Obscured by Waves |
|---|---|---|---|---|---|---|
| Outer Pirate Cove | Cape Foulweather | 44.81454 | -124.068 | September 5th, 2023 | 52095.8 | 25% |
| Cape Foulweather North | Cape Foulweather | 44.80189 | -124.072 | September 5th, 2023 | 45744.7 | 35% |
| Cape Foulweather South | Cape Foulweather | 44.79251 | -124.074 | September 5th, 2023 | 50641.2 | 25% |
| Rocky Creek | Cape Foulweather | 44.78128 | -124.075 | September 6th, 2023 | 63301.9 | 25% |
| Otter Crest | Cape Foulweather | 44.76042 | -124.069 | September 6th, 2023 | 99072 | 15% |
| Gregory Point | Cape Arago | 43.34094 | -124.378 | September 17th, 2023 | 10606.7 | 15% |
| Sunset Bay | Cape Arago | 43.33642 | -124.379 | September 17th, 2023 | 16013 | 4% |
| Simpson's Reef North | Cape Arago | 43.31665 | -124.399 | August 30th, 2023 | 9516.5 | 1% |
| Simpson's Reef | Cape Arago | 43.31147 | -124.402 | August 29th, 2023 | 28524.7 | 3% |
| South Cove | Cape Arago | 43.30161 | -124.4 | August 29th, 2023 | 21980.8 | 8% |
| South Cove East | Cape Arago | 43.30247 | -124.396 | August 29th, 2023 | 6047.5 | 1% |
| Port Orford Dockside | Cape Blanco | 42.73885 | -124.501 | August 25th, 2023 | 446.3 | 10% |
| Mill Rocks | Redfish Rocks | 42.73392 | -124.485 | September 21st, 2023 | 938.8 | 2% |
| Rocky Point | Redfish Rocks | 42.71154 | -124.465 | August 24th, 2023 | 9537.8 | 1% |
| Sister's Rock | Sister's Rock | 42.59166 | -124.402 | August 24th, 2023 | 1769.7 | 3% |
| Harris Beach North | Brookings | 42.06739 | -124.318 | September 20th, 2023 | 109.1 | 5% |
| Harris Beach | Brookings | 42.06304 | -124.31 | September 20th, 2023 | 1425.4 | 3% |
| Macklyn Cove | Brookings | 42.04627 | -124.292 | September 18th, 2023 | 2248 | 5% |
| Chetco Cove | Brookings | 42.04484 | -124.286 | September 18th, 2023 | 328.1 | 5% |
| Brookings Harbor | Brookings | 42.04485 | -124.276 | September 18th, 2023 | 393.9 | 10% |

**Appendix table 9:** Thresholds used to assign points for assessing kelp forest status across three scenarios including the thresholds used for **figure 10** in the main body of the report, a more conservative set of thresholds, and a more liberal set of thresholds.

| Assessment | Canopy Change Points | Kelp Points | Purple Sea Urchin Points |
|---|---|---|---|
| Main body of report: Figure 9 | Loss of ≥ 40% ~ 0 points<br>Loss of < 40% ~ 1 point | Mean density < 1 kelp/m² ~ 0 points<br>Mean density ≥ 1 kelp/m² ~ 1 point | Mean density ≥ 8 urchins/m² ~ 0 points<br>Mean density < 8 urchins/m² ~ 1 point |
| Appendix: Conservative set of thresholds | Loss of ≥ 60% ~ 0 points<br>Loss of < 60% ~ 1 point | Mean density < 0.5 kelp/m² ~ 0 points<br>Mean density ≥ 0.5 kelp/m² ~ 1 point | Mean density ≥ 10 urchins/m² ~ 0 points<br>Mean density < 10 urchins/m² ~ 1 point |
| Appendix: Liberal set of thresholds | Loss of ≥ 20% ~ 0 points<br>Loss of < 20% ~ 1 point | Mean density < 1.5 kelp/m² ~ 0 points<br>Mean density ≥ 1.5 kelp/m² ~ 1 point | Mean density ≥ 6 urchins/m² ~ 0 points<br>Mean density < 6 urchins/m² ~ 1 point |

Interestingly, through all three sets of thresholds, we found that only a single kelp forest area was assigned a different status between surveys (**Appendix table 10 and Appendix table 11**). In the conservative assessment, Orford Reef/Cape Blanco changed from "High concern" to "Less concern." This is because kelp and sea urchin densities no longer crossed the threshold for 0 points in the conservation assessment. For both of these thresholds, Orford Reef just barely meets them in the conservative analysis with an estimated mean sea urchin density = 9.55 urchins/m$^2$ and an estimated mean kelp density = 0.63 kelp/m$^2$.

When paired with observations of kelp density and purple sea urchin density in **figure 11**, this likely reflects divisions between the state of kelp forests at Orford Reef and the nearby smaller reef of Cape Blanco. While Cape Blanco still has areas with high kelp densities and low urchins, very few surveys at Orford reef found any kelp whatsoever and sea urchin densities were consistently high. This reflects that a patchwork of kelp forest conditions may be found within a single designated area. Future work could include defining kelp forest state at the site level or other smaller-scale levels that would help reveal the complex mosaic of conditions within Oregon's kelp forests.

**Appendix table 10:** Categorization of kelp forest areas into higher concern and lower concern bins using liberal thresholds, where all thresholds are adjusted to make it easier for a forest to fall into high concern categories. Blue numbers represent higher classifications indicative of healthier kelp forests and red numbers lower classifications indicative of less healthy kelp forests.

| Area | Canopy Change Points | Kelp Points | Urchin Points | Total Points |
|---|---|---|---|---|
| Cape Lookout | 0 | 0 | 0 | 0 |
| Cape Foulweather | 0 | 1 | 1 | 2 |
| Cape Arago | 1 | 1 | 0 | 2 |
| Orford Reef | 0 | 0 | 0 | 0 |
| Redfish Rocks | 0 | 0 | 0 | 0 |
| Rogue Reef | 1 | 1 | 1 | 3 |
| Brookings | 0 | 0 | 0 | 0 |

**Appendix table 11:** Categorization of kelp forest areas into higher concern and lower concern bins using conservative thresholds, where all thresholds are adjusted to make it more difficult for a forest to fall into high concern categories. Blue numbers represent higher classifications indicative of healthier kelp forests and red numbers lower classifications indicative of less healthy kelp forests.

| Area | Canopy Change Points | Kelp Points | Urchin Points | Total Points |
|---|---|---|---|---|
| Cape Lookout | 0 | 0 | 1 | 1 |
| Cape Foulweather | 1 | 1 | 1 | 3 |
| Cape Arago | 1 | 1 | 1 | 3 |
| Orford Reef | 0 | 1 | 1 | 2 |
| Redfish Rocks | 1 | 0 | 0 | 1 |
| Rogue Reef | 1 | 1 | 1 | 3 |
| Brookings | 0 | 0 | 0 | 0 |

## PROCESSES DRIVING THE LOSS OF KELP FORESTS IN OREGON

### Urchin/Kelp Relationship

To assess whether there was a statistically significant relationship between kelp density and purple urchin density at Macklyn Cove from 2017–2023, we fitted a generalized additive model assessing of the form:

**Kelp Density = Coefficient * Urchin Density**

using a Tweedie distribution with a log link function. The Kelp Density term is a sum of all kelps (usually including *N. luetkeana, P. californica, P. gardneri,* and *L. setchellii*) seen on a transect divided by transect area. Even with the small sample size, the model was significant (p-value = 0.036, **Appendix figure 4**) and calculated a coefficient = -0.35.

To assess whether there was a statistically significant relationship between kelp density and purple urchin density at all sites in 2023, we fitted a generalized additive model of the form:

**Kelp Density = Coefficient * Urchin Density**

using a Tweedie distribution and a log link function. The Kelp Density term is a sum of all kelps (usually including *N. luetkeana, P. californica, P. gardneri,* and *L. setchellii*) seen on a transect divided by transect area. The model was statistically significant (p-val = 2.95 e-05) and estimated a coefficient = -0.082 (**Appendix figure 5**).

Additionally, we also added an interaction between urchin density and Area into the gam listed above to observe the effect that various locations had on this relationship:

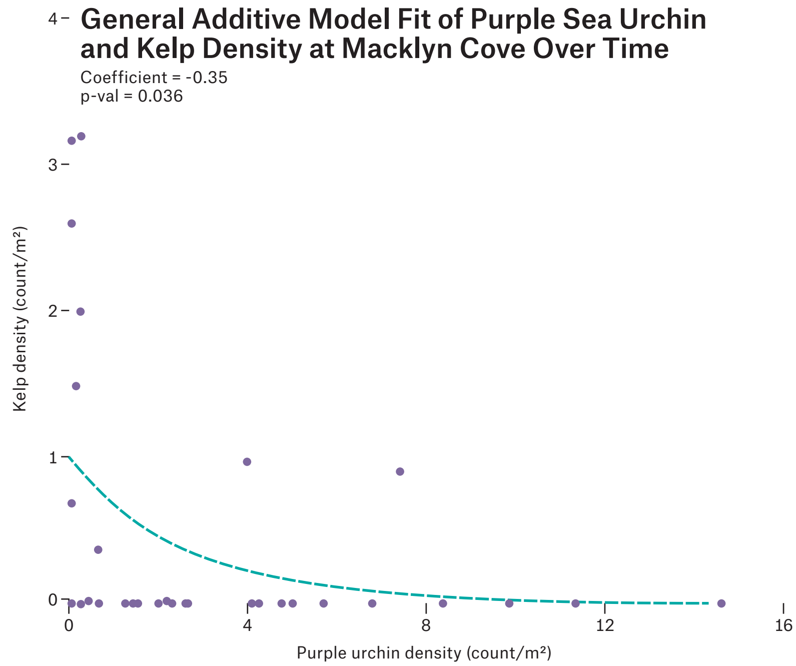
**Kelp Density = Coefficient * Urchin Density + Coefficient * Area + (Urchin Density * Area)**

When adding terms for site, Urchin Density term was no longer significant. Instead, urchin density was only significant when interacting with specific sites, specifically Cape Arago (interaction p-val = 0.03), Cape Blanco (interaction p-value = 0.01), and Rogue Reef (interaction p-values = 0.05). This makes sense considering that at several sites (**Appendix figure 6**), such as Brookings and Redfish Rocks, where purple sea urchin density was not significantly related to kelp density, no kelp was found regardless of urchin density.

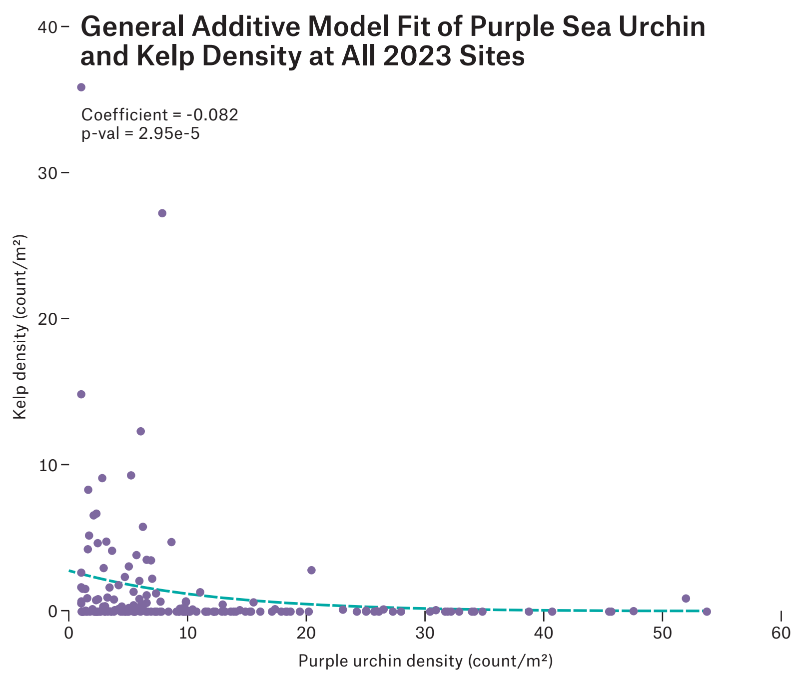
### Kelp Temperature Thresholds

In addition to assessing patterns in daily mean temperature from the Charleston and Port Orford nearshore NOAA buoys, we also looked at daily maximum temperature (**Appendix figure 7**). Predictably, daily maximum temperature did reach the sublethal threshold of 16°C more often than daily mean temperature did, for a total of 0.55% of daily maximum observations at the PORO3 buoy in Port Orford and 1.5% of daily max observations at the CHAO3 buoy in Charleston. For the entirety of the time series, daily maximum temperature at the Port Orford buoy only reached the lethal 18°C threshold twice and at the Charleston buoy only once, although several other days were close.

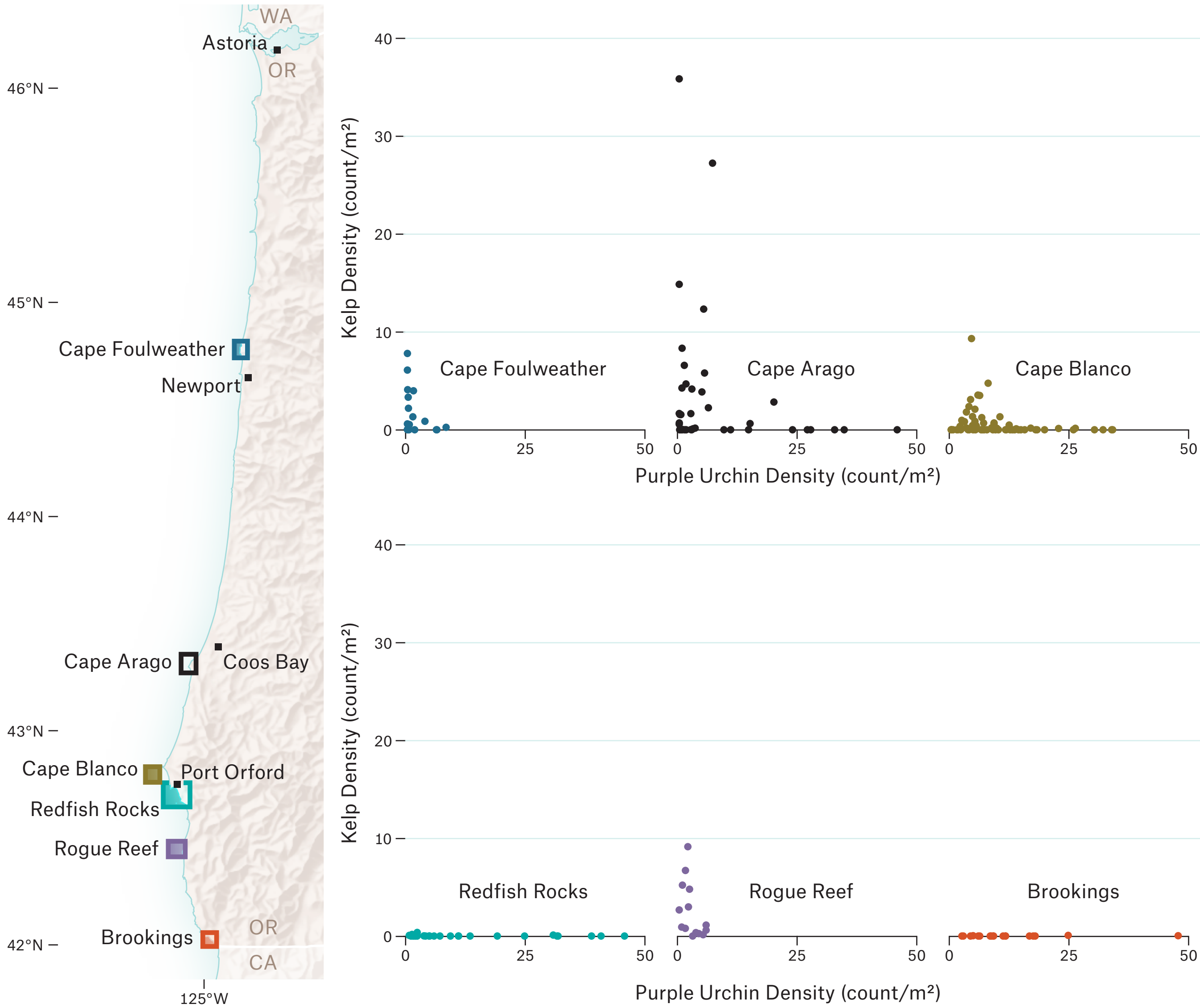
We chose to primarily analyze the mean daily temperature in the main body of the report because more of the literature we cite investigates the impacts of high temperatures on kelps over days to weeks. It is less clear how brief exposure (on the order of hours) to higher temperatures affects the individual and population outcomes for kelps.




**Appendix figure 4:** Purple sea urchin density versus. total kelp density for Macklyn Cove Reef Check surveys from 2017–2023 (gray points) and a generalized additive model fit to these data (red dotted line). The estimated Urchin Density coefficient from that model and its associated p-value is printed in the top right corner.




**Appendix figure 5:** Purple sea urchin density versus total kelp density for 170 scuba surveys taken across Oregon in 2023 (gray points) and a generalized additive model fit to these data (red dotted line). The estimated Urchin Density coefficient from that model and its associated p-value is printed in the top right corner. Data shown here was collected during the 2023 ORKA survey efforts by ORKA partners Reef Check, the Oregon Coast Aquarium, and the Galloway lab at the University of Oregon, except for a subset of surveys collected at Cape Foulweather by ODFW.

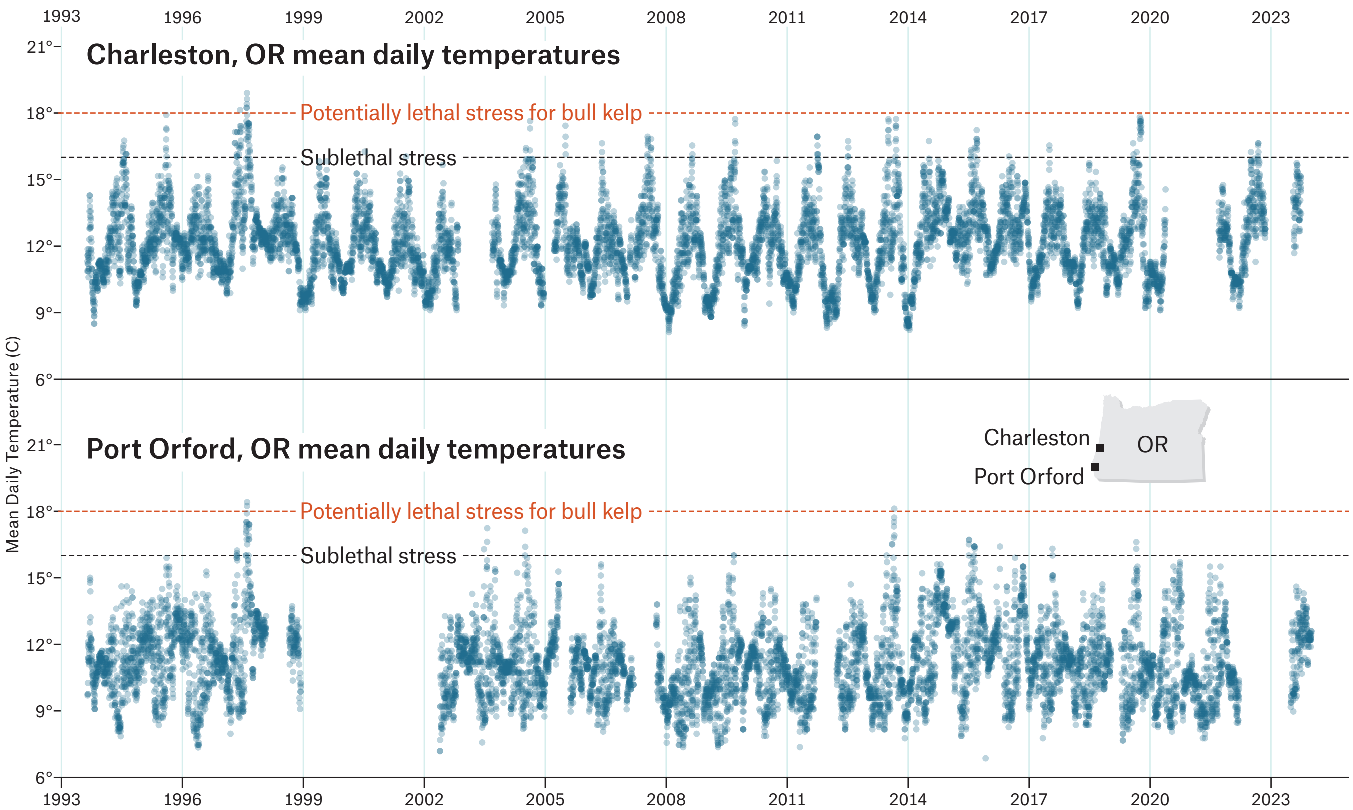



**Appendix figure 6**: Purple sea urchin density versus total kelp density 2023 scuba surveys split by the area in which they were taken. Data shown here was collected during the 2023 ORKA survey efforts by ORKA partners Reef Check, the Oregon Coast Aquarium, and the Galloway lab at the University of Oregon, except for a subset of surveys collected at Cape Foulweather by ODFW.

Ocean warming trends have been linked to kelp forest declines or collapses in a number of regions of the globe.[11,12] To assess the extent to which kelp forests in Oregon were exposed to warming temperatures, we used a seasonal Mann Kendall test to assess whether a significant monotonic trend existed in mean daily temperatures spanning 1993–2023 at Charleston and Port Orford (**Appendix table 12**). Both datasets showed small, significant cooling trends.

**Appendix table 12:** Estimated trend in daily mean temperature for three long-term temperature time series derived from seasonal Mann Kendall tests.

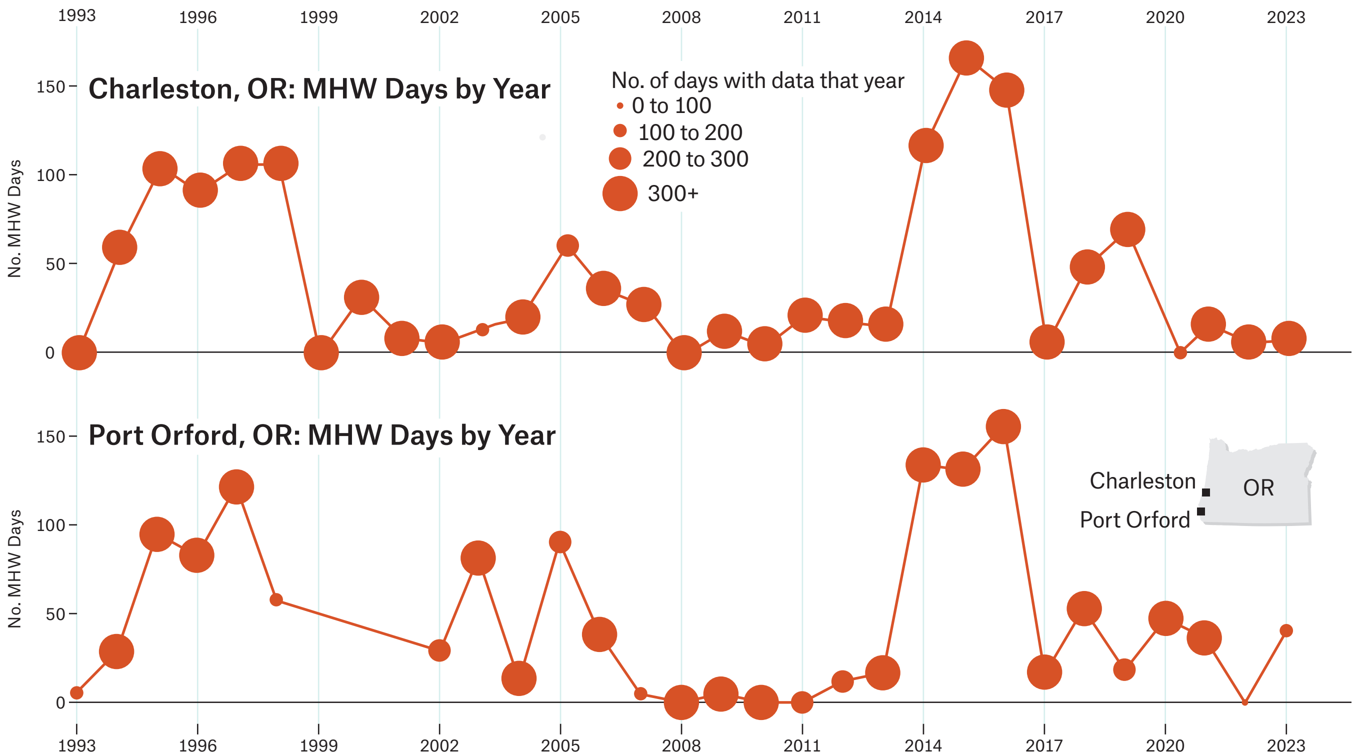
| Dataset | Trend | P-value | Confidence Interval |
|---|---|---|---|
| Charleston, OR | -0.004 deg/year | 0.004 | -0.007 to -0.001 |
| Port Orford, OR | -0.004 deg/year | 0.02 | -0.007 to -0.0005 |



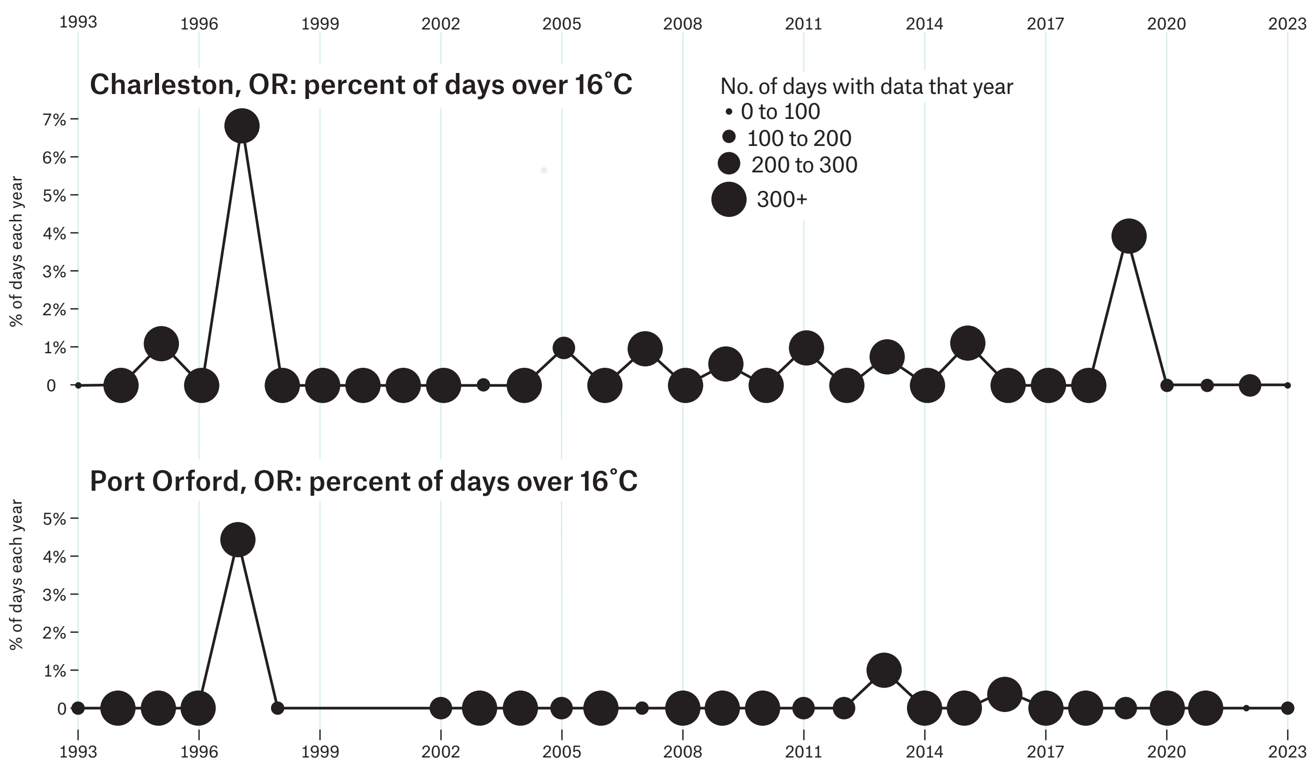

**Appendix figure 7:** Daily maximum temperature at the CHAO3 NOAA buoy in Charleston, OR and the PORO3 NOAA buoy in Port Orford, OR from 1993–2023. The orange dotted line represents a putative threshold for sublethal stress for bull kelp and the red dotted line a threshold for potentially lethal temperatures.

In addition to trends in temperature, other metrics of temperature may impact kelp outcomes. For instance, if extreme temperatures rather than mean temperatures are driving kelp resilience to climate change, then a trend in the number of marine heatwave days or in the number of days that reach 16°C may be more indicative of stress than a trend in mean temperature. Thus, we calculated the number of marine heat wave days per year for each dataset using the definition found in Hobday et al. (2016) for heat waves (Appendix figure 8) as well as the number of days per year where the mean temperature reached 16°C or higher (Appendix figure 9).[13] Linear regressions estimating the trend in the number of marine heatwave days and the number of 16°C day over time for each site did not identify any significant trends for either metric.

While these initial graphs and analyses are a useful first approximation of exposure to temperature stress in nearshore southern Oregon, additional research is needed to more precisely quantify how kelp forests in Oregon are affected by changing temperature regimes and marine heat waves. This first approximation does not provide clear evidence that kelps in Oregon's kelp forests are currently exposed to extensive heat stress but further investigations assessing the temperature at depth with different kelps forests, the impact of short-term exposure to high temperatures, and local adaptation in various species thermal thresholds may reveal different results.




**Appendix figure 8:** The number of marine heatwave days per year from 1993–2023 at nearshore NOAA stations in Charleston (top), Port Orford (bottom). The size of each point indicates the number of days each year where temperature was measured.




**Appendix figure 9**: The number of days per year where mean daily temperature reached 16°C or higher from 1993–2023 at nearshore NOAA stations in Charleston (top) and Port Orford (bottom).

## Recommended Further Reading

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