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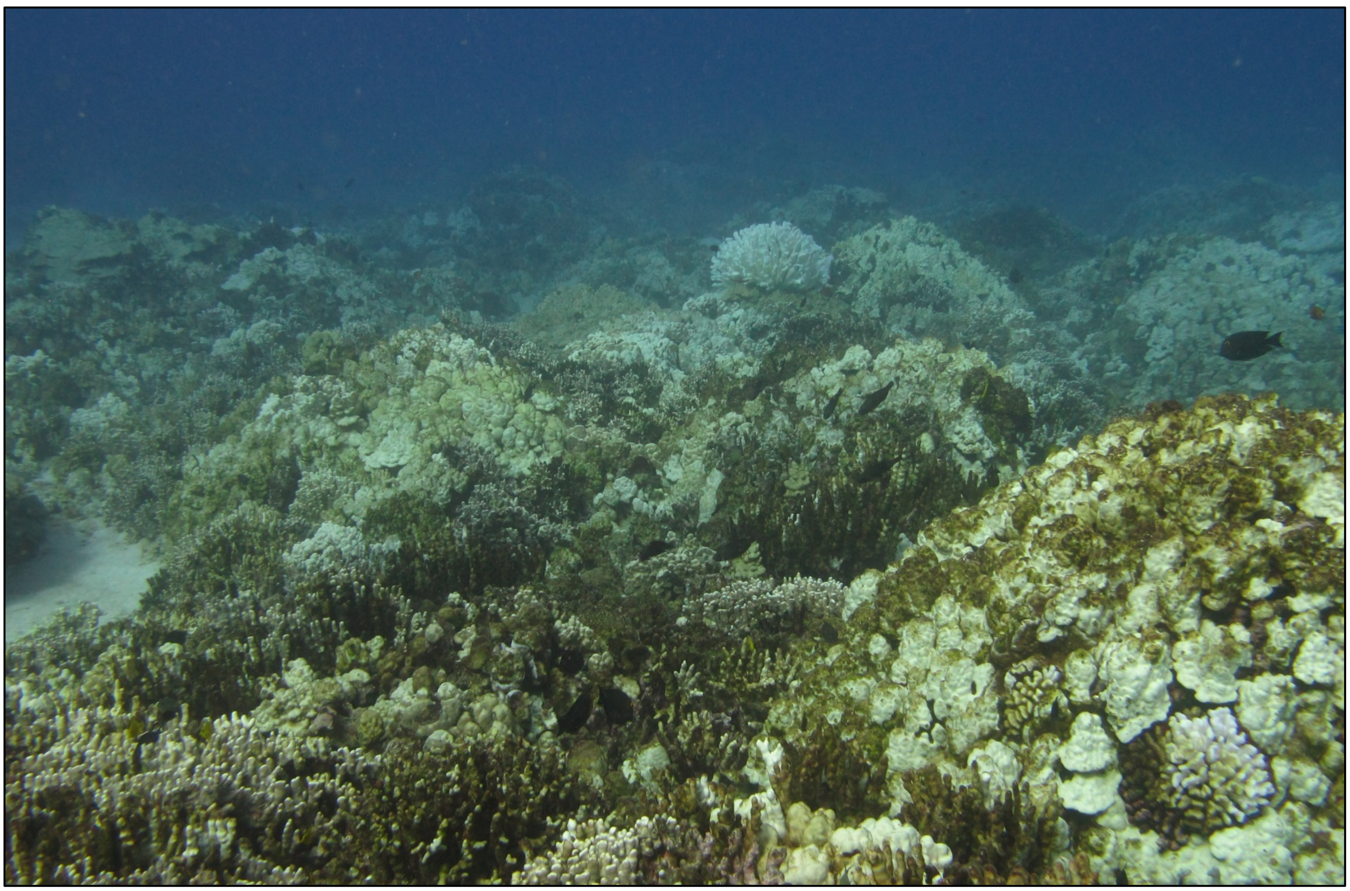
Coral Bleaching, Mortality and Benthic Community Assemblages on the Reefs within the Pacific Island Network National Parks

Natural Resource Report NPS/PACN/NRR—2021/2322



ON THE COVER
Bleached reef at Kaloko-Honokōhau National Historical Park in October 2015
Photo by Amanda L. McCutcheon

Coral Bleaching, Mortality and Benthic Community Assemblages on the Reefs within the Pacific Island Network National Parks

Natural Resource Report NPS/PACN/NRR—2021/2322

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Abstract

The 2014–2017 global-scale coral bleaching event caused extensive coral injury and mortality. Since 2006, the National Park Service Pacific Island Inventory and Monitoring Network has monitored benthic marine communities annually at reef sites within four parks: Kaloko-Honokōhau National Historical Park (KAHO) on Hawai‘i Island, Hawai‘i; Kalaupapa National Historical Park (KALA) on Moloka‘i Island, Hawai‘i; the National Park of American Samoa (NPSA) on Tutuila Island in the U.S. territory of American Samoa; and War in the Pacific National Historical Park (WAPA) in the U.S. territory of Guam. Photo quadrats were taken annually along 15 fixed transects (25 m length) in each park on hard-bottom substrate between 10- and 20-m depth. Benthic cover and coral health were analyzed using standard point-count image analyses to determine percent substrate type and incidence of coral bleaching. Trends in benthic cover, bleaching, and mortality were assessed across the time-series and in relation to temperature data. Results indicated that KAHO was the most impacted by coral bleaching with 77% bleached coral cover in 2015, a 63% reduction in coral cover from 2014 to 2016, and significant post-bleaching mortality of the most abundant coral taxa (*Porites lobata*, *Porites compressa*, *Pocillopora meandrina*, and *Montipora capitata*). At KALA, coral cover significantly declined (8% in 2006 to 4% in 2019), but 2014–2016 image analysis suggested this was not bleaching related. At NPSA, coral cover significantly increased (24% in 2007 to 33% in 2019) and bleached cover was greatest in 2017 (8%) with no significant mortality detected. At WAPA, time of survey did not coincide with peak bleaching conditions, but coral cover remained stable from 2008 to 2019 (Asan 22%, Agat 3%), indicating no significant mortality within our observed depths of 10- to 20-m. Bleaching assessment was limited by the sampling frame and time of survey of the monitoring program. To strengthen our ability to detect and assess future coral bleaching and other disturbance events, we recommend adjusting annual benthic monitoring for heat stress events when feasible, adding shallow reef transects, and implementing regular manta tow surveys to detect and document large-scale disturbances. In light of forecasted increases in the frequency of coral bleaching events, we recommend proactive visitor management strategies, identification and mitigation of point source pollution events, and continued evaluation of heat-tolerant coral species to improve reef resiliency to future bleaching events.

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List of Acronyms

COTs	Crown-of-thorns seastars
DAR	Hawaiʻi Department of Aquatic Resources
DHW	Degree Heating Weeks
GCBE	Global-scale Coral Bleaching Event
GCRRT	Guam Coral Reef Response Team
KAHO	Kaloko-Honokōhau National Historical Park
KALA	Kalaupapa National Historical Park
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NPSA	National Park of America Samoa
PACN	Pacific Island Inventory and Monitoring Network
SST	Sea Surface Temperature
TNC	The Nature Conservancy
WAPA	War in the Pacific National Historical Park

Introduction

Coral bleaching events are one of the greatest threats to the world's coral reefs. Three global-scale coral bleaching events (GCBEs) have been recorded. The first, occurred in 1998–1999. It resulted from an extremely strong El Niño and caused extensive mortality on reefs in the Indian Ocean, Southeast Asia and the far western Pacific (Wilkinson 2000). The second GCBE, in 2010, which resulted from a milder El Niño, was not as well-documented, but caused widespread mortality in several regions (Eakin et al. 2019, Heron et al. 2016a). The third GCBE, in 2014–2017 was longer and more widespread than the previous GCBEs and caused extensive coral injury and mortality throughout the world (Eakin et al. 2016, Eakin et al. 2017, Eakin et al. 2019). The 2014–2017 GCBE was triggered by dramatically elevated ocean temperatures that resulted from complex climate phenomena, including El Niño, the Pacific Decadal Oscillation, and an unusually large region of warm sea surface temperature (SST) in the northern Pacific Ocean referred to as "the Blob" (Bond et al. 2015, Couch et al. 2017, Eakin et al. 2019, Gove et al. 2019). Many areas like the Hawaiian Islands, the Great Barrier Reef, and American Samoa suffered the worst bleaching event on record (Kramer et al. 2016, Couch et al. 2017, Eakin et al. 2017, GBRMPA 2017, Eakin et al. 2019). Smaller-scale/regional bleaching events occur more commonly and can be devastating locally (Oliver et al. 2009, Hernon et al. 2016a). Thermal stress is considered the primary cause for coral bleaching, but water quality, disease, and solar irradiance can also play a role (Brown 1997, Anthony et al. 2009). Coral bleaching events have worsened, and there is scientific consensus that they will become more frequent and severe due to increased thermal stress related to climate and environmental change (Heron et al. 2016a, van Hooidonk et al. 2016).

Coral bleaching is the whitening of corals due to loss or degradation of their symbiotic algae (zooxanthellae). The symbiotic algae provide up to 90% of a coral's energy requirements, so prolonged or frequent coral bleaching can lead to mortality (Hoegh-Guldberg 1999, Anthony et al. 2009). The susceptibility of corals to thermal stress can vary between genera, species, and between and within colonies of the same species. Corals follow a generalized hierarchy of susceptibility to bleaching, where branching corals (e.g. *Acropora* spp. and *Pocillopora* spp.) are usually more susceptible to bleaching than massive and encrusting forms (e.g. *Porites* spp.) (Marshall and Baird 2000, Loya et al. 2001, McClanahan 2004). Bleaching patterns observed in the same species can vary by spatial scales ranging from meters to thousands of kilometers (van Woesik 2000, Lenihan et al. 2008, Penin et al. 2013), and light exposure can cause the upward surfaces to bleach more severely than shaded portions of the same colony (Coelho et al. 2017). Some corals have been shown to acclimate or adapt to surrounding sea temperatures (van Woesik 2000, Lenihan et al. 2008, Morikawa and Palumbi 2019). External factors (weather, currents, upwelling, etc.) can make coral bleaching events highly variable (Marshall and Baird 2000, van Woesik 2000, Loya et al. 2001, Coles and Brown 2003, McClanahan 2004, Lenihan et al. 2008).

To quantify thermal stress, the National Oceanographic and Atmospheric Administration (NOAA) has developed a Degree Heating Week (DHW) index that provides a unit of measure for the cumulative stress over consecutive weeks when SSTs are in excess of 1°C of the expected summer maximum (Eakin et al. 2009). Coral bleaching HotSpots are areas of the ocean (as measured by satellite with resolution of 50 km) that have exceeded the maximum monthly mean SST by at least 1°C. Significant coral bleaching is expected within HotSpots when DHW reaches 4°C-weeks (Alert Level 1) and mass coral bleaching is expected when DHW reaches 8°C-weeks (Alert Level 2) (Table 1, Eakin et al. 2009, Kayanne 2016, NOAA 2020). According to this index, more than 50% of the world's coral reefs experienced two, if not three years of bleaching during the 2014–2017 GCBE (Eakin et al. 2017, Eakin et al. 2019).

Table 1. Summary of NOAA Coral Reef Watch Satellite Bleaching Alert System. Thresholds are color-coded by stress level. Bleaching heat stress levels based on the values of the daily 50 km Coral Bleaching HotSpot and Degree Heating Week (DHW) products (Table from NOAA 2020).

Stress Level	Definition	Potential Bleaching Intensity
No Stress	HotSpot < = 0	No Bleaching
Bleaching Watch	0 < HotSpot < 1	–
Bleaching Warning	1 < = HotSpot and 0 < DHW < 4	Possible Bleaching
Bleaching Alert Level 1	1 < = HotSpot and 4 < = DHW < 8	Significant Bleaching Likely
Bleaching Alert Level 2	1 < = HotSpot and 8 < = DHW	Severe Bleaching and Significant Mortality Likely

Among the areas that experienced heat stress during the 2014–2017 GCBE are four U.S. national parks in the Pacific Ocean that include coral reefs and marine areas within their boundaries (NOAA 2020, Figure 1). These four parks are Kaloko-Honokōhau National Historical Park (KAHO) on Hawai‘i Island, Hawai‘i; Kalaupapa National Historical Park (KALA) on Moloka‘i Island, Hawai‘i; the National Park of American Samoa (NPSA) in the U.S. territory of American Samoa, and War in the Pacific National Historical Park (WAPA) in the U.S. territory of Guam. Marine areas surrounding Hawai‘i Island reached Alert Level 2 in October 2015 and October 2019, Moloka‘i reached Alert Level 1 in October 2014 and October 2019 and Alert Level 2 in September 2015, American Samoa reached Alert Level 1 in April 2016 and April 2019 and Alert Level 2 in February 2017, and Guam reached Alert Level 1 in September 2016 and Alert Level 2 in October 2013 and October 2017 (Figure 2, NOAA 2020).

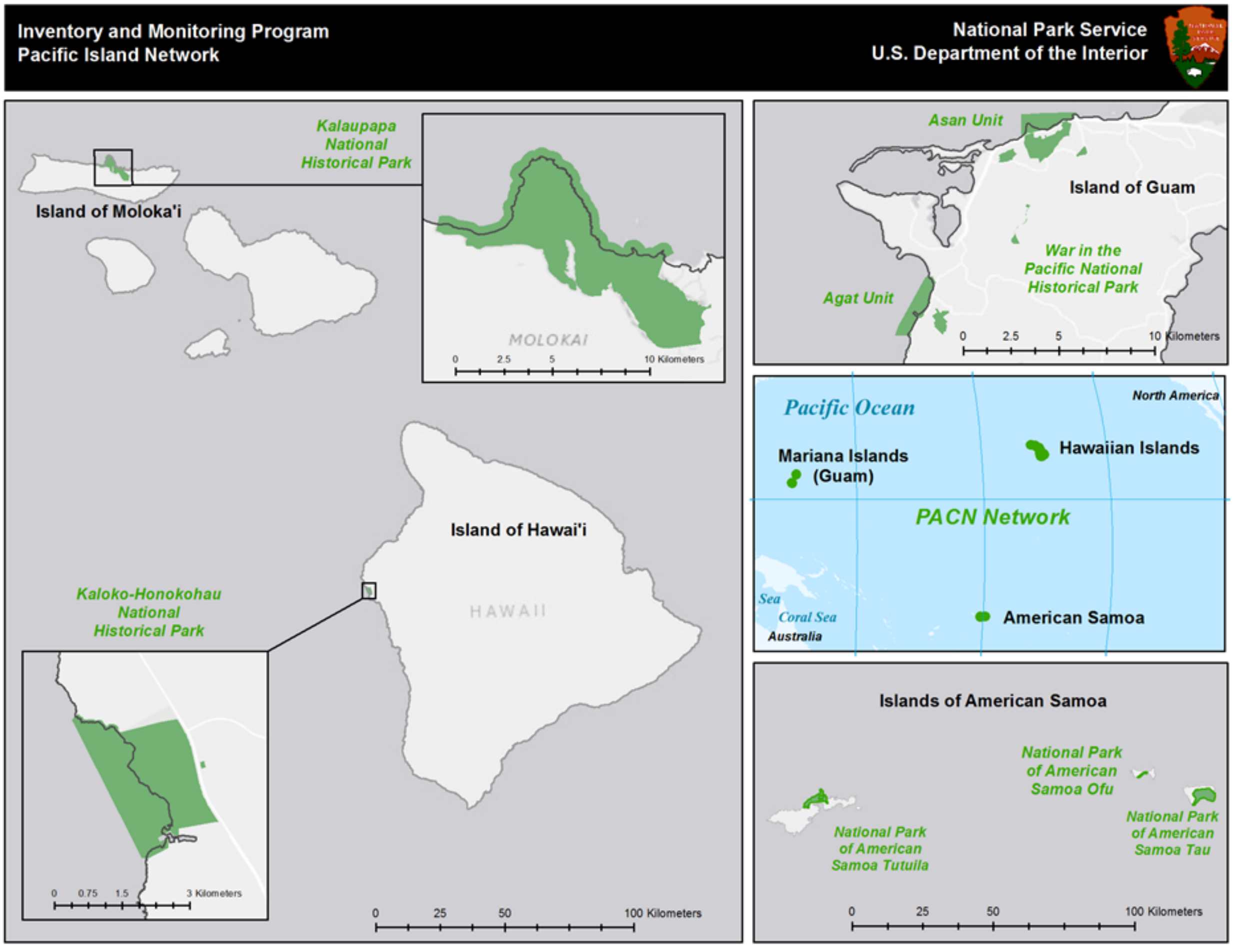

Figure 1. Location of the four U.S. National Parks in the Pacific Ocean containing coral reefs within their boundaries. The four parks: Kaloko-Honokōhau National Historical Park; Kalaupapa National Historical Park; National Park of American Samoa; and War in the Pacific National Historical Park are part of the Pacific Island Inventory and Monitoring Network (PACN).

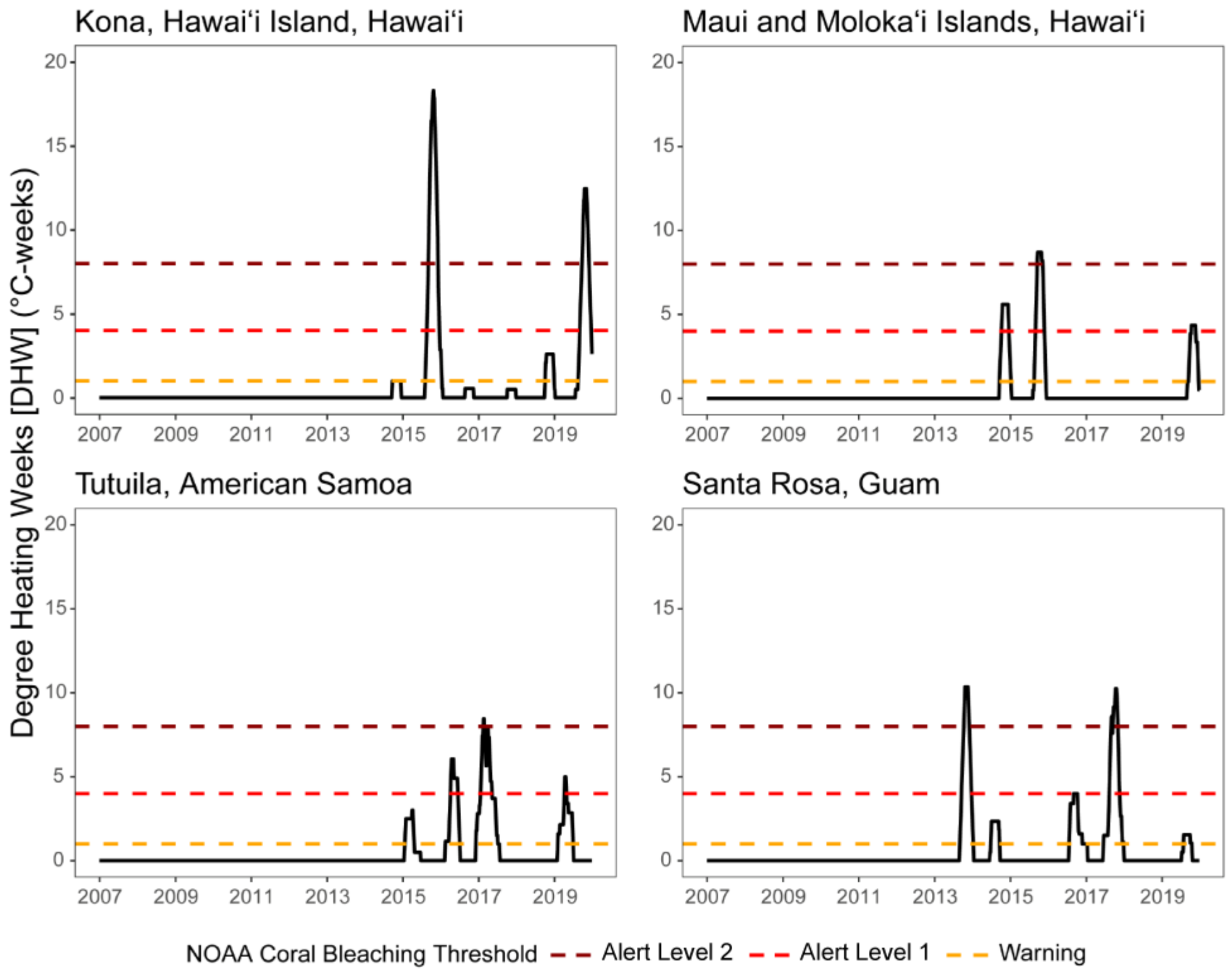

Figure 2. Degree Heating Weeks (50 km resolution) from 2007–2019 (NOAA 2020). Coral bleaching threshold values are indicated by dashed lines.

As expected with coral bleaching watch values at alert levels 1 and 2, significant bleaching occurred in these three regions (the main Hawaiian Islands, American Samoa, and Guam) during the 2014–2017 GCBE. In the main Hawaiian Islands, significant bleaching was reported in Oahu, Maui, and Kauai in 2014 (Barh et al. 2015, University of Hawai‘i 2017). The main Hawaiian Islands experienced peak temperatures in 2015, and unprecedented bleaching was observed to cause significant mortality across the main Hawaiian Islands that year (Eakin et al. 2016, Kramer et al. 2016, Maynard et al. 2016, TNC 2017, University of Hawai‘i 2017). Particularly hard hit was the west coast of Hawai‘i Island, where KAHO is located. Studies by the State of Hawai‘i Department of Aquatic Resources (DAR), the Nature Conservancy (TNC), and NOAA showed greater than 50% bleaching prevalence across the reefs of west Hawai‘i Island in October 2015, resulting in loss of about half of the live coral cover (Kramer et al. 2016, Maynard et al. 2016, TNC 2017). Significant bleaching-related mortality was also reported on Maui and the south shore of Moloka‘i in 2015 (University of Hawai‘i 2017, DLNR 2019). KALA is located on the north shore of Moloka‘i (Figure 1), where no significant bleaching was reported, but surveys are limited. The main Hawaiian

Islands suffered a significant bleaching event again in 2019, but the event was not as severe as 2015 (DLNR 2019), and at the time of this report mortality has not yet been assessed.

In American Samoa, where NPSA is located, shallow backreefs on the island of Tutuila are known to bleach annually and recover with little mortality (Fenner et al. 2008). Some backreef areas on the island of Ofu are exposed to great thermal variability with frequent temperatures above bleaching thresholds of most reefs, which has created a unique population of corals that have high tolerance to heat stress (Barshis et al. 2018, Morikawa and Palumbi 2019). The reef slopes, which do not experience the same degree of daily and seasonal temperature fluctuations, are susceptible to mortality from severe bleaching (Morikawa and Palumbi 2019). Severe bleaching has been reported in American Samoa in 1994, 2002, 2003 (Fenner et al. 2008, Fenner 2019), and in association with the 2014–2017 GCBE, in late 2014/early 2015 and early 2017 (Lawrence 2017, Eakin et al. 2017, Sudek and Lawrence 2016, Fenner 2019, Morikawa and Palumbi 2019). In 2015, mass bleaching was reported in reef flat areas and backreef pools of Tutuila, resulting in high mortality of staghorn *Acropora* corals in some areas, with low (1–10%) bleaching numbers on reefs slopes. In 2017, extensive bleaching was reported on reef flats and reef slopes to a depth of 130 ft (40 m) in Tutuila and in the historically bleaching-resistant backreef pools of Ofu (Lawrence 2017).

In Guam, where WAPA is located, widespread bleaching on shallow reefs was reported every year from 2013 to 2017 (Heron et al. 2016b, Eakin et al. 2017, Burdick and Raymundo 2018, Raymundo et al. 2019). Record heat stress struck the reefs in 2013 causing significant coral bleaching and mortality on the shallow seaward slopes (Burdick and Raymundo 2018, Raymundo et al. 2019). Heat stress paired with extreme low tides caused by the strong El Niño event in 2014 through 2015 ravaged stands of branching *Acropora* on Guam's shallow reef flats, including a site within WAPA's Asan unit (Raymundo et al. 2017, Raymundo et al. 2019). Bleaching was less severe in 2016, but that small pause was countered by the worst year on record in terms of heat stress and coral bleaching in 2017 (Burdick and Raymundo 2018, Raymundo et al. 2019).

Since 2006, the coral reefs within these parks (KAHO, KALA, NPSA and WAPA) have been monitored by the National Park Service (NPS) Pacific Island Inventory and Monitoring Network (PACN) of the National Park Service. PACN implements protocols to provide spatial and temporal data and to monitor "vital signs", which are indicators of physical, chemical, and biological elements and ecosystem processes selected to represent the overall health or condition of natural resources within parks. Three protocols are implemented on select coral reef locations within the four parks: the benthic marine community protocol (Brown et al. 2011b), the marine fish protocol (Brown et al. 2011a), and the water quality protocol (Jones et al. 2011). We use the monitoring data from the benthic marine protocol collected in KAHO, KALA, NPSA and WAPA to examine changes in the benthic community assemblages over time, especially in relation to the 2014–2017 GCBE, and to provide opportunistic assessment of the extent and severity of bleaching when surveys coincided with heat stress events. A summary of the coral reefs within the four park units of KAHO, KALA, NPSA and WAPA is provided in Table 2. The location of the fixed transects used for benthic monitoring and for this report are noted. Certified data used in this report are available online (PACN et al. 2021).

In this report, our primary objectives are to summarize and assess trends in benthic assemblage (percent benthic cover) and coral bleaching time-series data collected by PACN at the 15 fixed transects in each of the four parks. Further, an in-depth analysis of the 2015 bleaching event at KAHO, which was the most severe bleaching and mortality event recorded for the four parks, is presented. We examine timeframe (month and year) of our sampling in light of thermal data (SST and DHW) derived from NOAA (2020). We discuss changes over time for duration of our surveys for major taxonomic groups (i.e. scleractinian coral, turf algae, coralline algae, etc.) as well as park-specific taxa of interest in relation to coral bleaching events recorded by PACN and others.

Table 2. Summary information for four U.S. National Parks in the Pacific describing spatial extent of marine area, location of PACN monitoring transects, coral reef habitat, dominant benthic cover types and most abundant coral taxa. Park abbreviations are as follows, KAHO = Kaloko-Honokōhau National Historical Park, KALA = Kalaupapa National Historical Park, NPSA = National Park of American Samoa, WAPA = War in the Pacific National Historical Park. Table adapted from Brown et al. (2016).

Park	Marine boundary area, features and location of PACN transects	Coral reef habitat description	Dominant benthic cover types and most abundant coral taxa within PACN transects (PACN et al. 2021)
KAHO	• 2.4 km^2 • All 30 transects (15 fixed, 15 temporary) are measured annually within one park unit	• Coral reefs comprised of a basalt boulder habitat with aggregated reef structure interspersed. • 26 coral species • 137 fish species • Herbivorous urchins, green sea turtles abundant	• Turf algae and scleractinian coral are dominant benthic cover types. • Scleractinian coral: *Porites lobata*, *Porites compressa*, *Pocillopora meandrina* and *Montipora capitata* • *Sacrothelia edmonsoni*, an octocoral was abundant prior to 2015 in select park areas.
KALA	• 8.1 km^2 • Quarter mile offshore of coastline around Kalaupapa pennisula • All 30 transects (15 fixed, 15 temporary) are measured annually within one park unit	• Coral reefs comprised of basalt boulder habitat with isolated coral colonies • 25 coral species • 200 fish species	• Turf algae is the dominant benthic cover type. • Scleractinian coral: *Pocillopora meandrina* and *Porites lobata*
NPSA	• 18.2 km^2 • Quarter mile offshore and three separate islands (coral reefs in park units on Ta'u, Tutuila, and Ofu) • All 30 transects (15 fixed, 15 temporary) are measured annually within the Tutuila unit	• Coral reefs comprised of aggregated coral reef areas • 250 coral species • 900 fish species • fringing reefs in the Ofu unit are a unique shallow microhabitat	• Turf algae, scleractinian coral and crustose coralline algae are dominant benthic cover types. • Scleractinian coral: *Montipora* spp., *Porites rus, Porites* spp., *Acropora* spp., *Pavona varians*

Table 2 (continued). Summary information for four U.S. National Parks in the Pacific describing spatial extent of marine area, location of PACN monitoring transects, coral reef habitat, dominant benthic cover types and most abundant coral taxa. Park abbreviations are as follows, KAHO = Kaloko-Honokōhau National Historical Park, KALA = Kalaupapa National Historical Park, NPSA = National Park of American Samoa, WAPA = War in the Pacific National Historical Park. Table adapted from Brown et al. (2016).

Park	Marine boundary area, features and location of PACN transects	Coral reef habitat description	Dominant benthic cover types and most abundant coral taxa within PACN transects (PACN et al. 2021)
WAPA	• 4.0 km^2 • Coral reefs in Asan and Agat marine units • 30 transects are measured annually and split between Asan (7 fixed, 8 temporary) and Agat (8 fixed, 7 temporary) units	• Aggregated coral reef areas and hard substrate • Most of Guam's > 300 coral species • Most of Guam's > 1000 fish species	• In Asan, turf algae is the dominant benthic cover type. • In Agat, turf algae and macroalgae (primarily *Padina* spp.) are the dominant benthic cover types. • Scleractinian coral: massive *Porites* spp. (Asan and Agat), *Porites rus* (Asan)

Methods

Sampling Locations and Dates

At each park, 30 transects (25 m/82 ft in length) are sampled annually. Survey dates vary due to weather conditions and staff availability and often do not coincide with peak SST (discussed in detail in the Results and Discussion sections for each park). A split panel design is used that includes 15 transects that are fixed (permanent) and sampled annually, and 15 transects that are temporary and sampled only once. The sampling frame from which all fixed and temporary locations are generated is the hardbottom substrate areas of the forereef slope between 10 and 20 m (33 and 66 ft) depth within the park's legislated boundary plus adjacent coastal areas that are closely associated with the park area (Brown et al. 2011b). The PACN marine fish protocol (Brown et al. 2011a) is sampled during the same timeframe, on the same 30 transects, annually. Here we use only benthic data from the 15 fixed (permanent) transects from the beginning of PACN monitoring at each park (2006 to 2009) through 2019 (Figure 3). Temporary transects were not used because much of the photo analysis for bleaching was *post hoc* and time-intensive, and the fixed transects are more appropriate to assess trend over time on this relatively short timescale.

Transects are located in the field using a handheld GPS unit. During the initial survey year, fixed transects were marked with a rebar pin at the beginning and end to aide with locating the fixed site and maintaining consistency year to year.

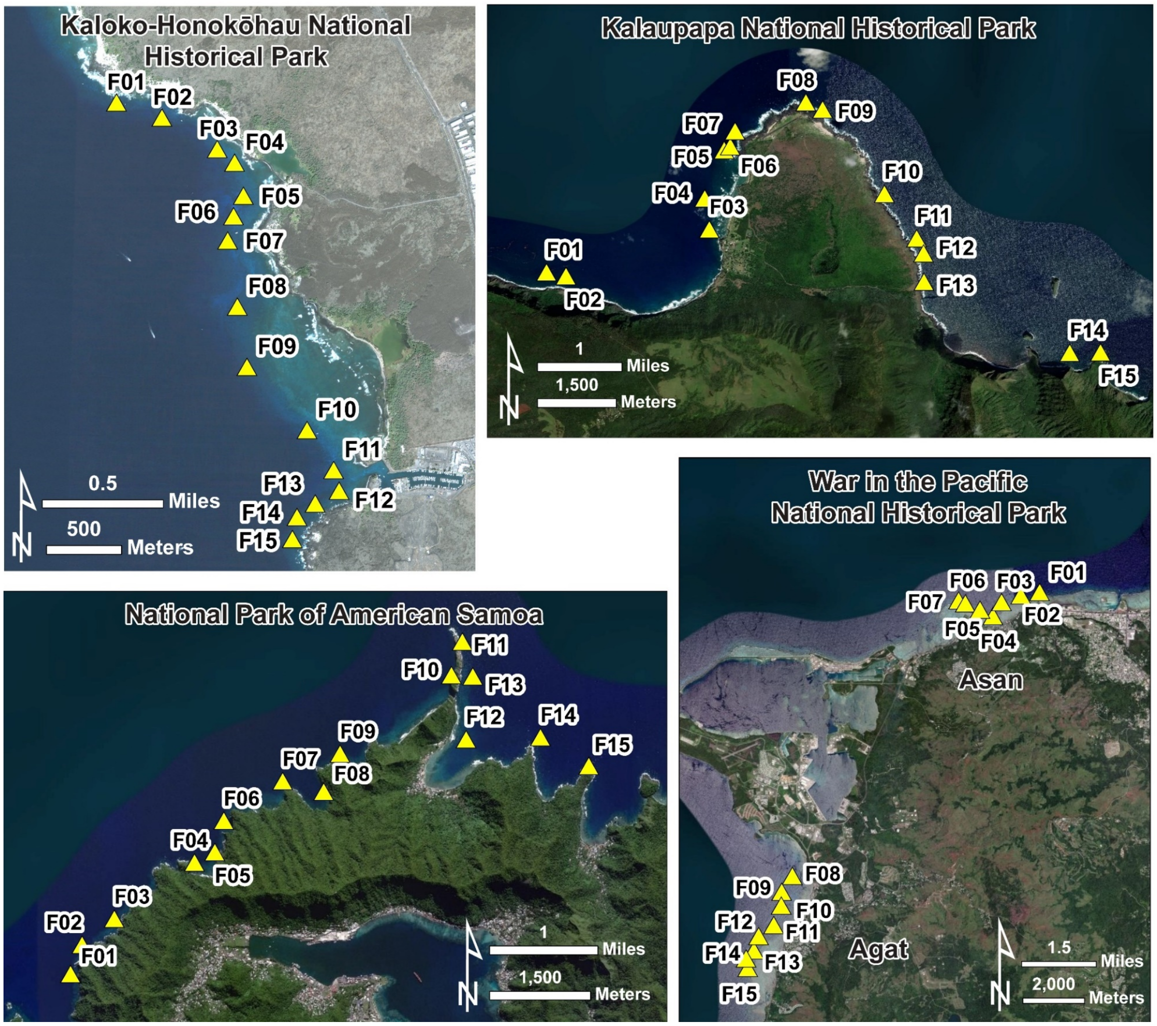

Figure 3. Pacific Island Inventory and Monitoring Network fixed (permanent) transect names and locations at Kaloko-Honokōhau National Historical Park, Kalaupapa National Historical Park, National Park of American Samoa, and War in the Pacific National Historical Park. There are 15 fixed transects at each park, designated F01 through F15. At War in the Pacific National Historical Park, the transects are split between two marine units, F01 through F07 are in Asan and F08 through F15 are in Agat.

Survey Methods

Upon arrival at each site a transect tape is secured either to the start pin for fixed transects or to the substrate for temporary transects. Twenty-five meters (82 ft) of tape is then laid out along the depth contour (typically, parallel to the shoreline). Images are taken at one-meter intervals along each 25 m long transect, beginning at 0 m for a total of 26 images per transect.

Benthic images are taken perpendicular to the substrate with a digital camera mounted to a monopod, designed to keep the camera approximately 0.5 m (1.6 ft) above the substrate. Cameras are white balanced *in situ* at the start of each transect. Camera model and field of view captured varies by park, but efforts are made to avoid overlapping images.

Image Analysis

Images are analyzed using PhotoGrid software. Fifty randomly generated points are overlaid onto each image. The substrate under each point is identified to the lowest possible taxonomic level or substrate type. Additionally, a designation of "Yes" or "No" is given to each image to indicate whether bleaching and/or disease is present on coral captured anywhere in the entire image (regardless of generated point location). This designation is used to rapidly assess the transects for bleaching and disease and provide a trigger for further analysis. It does not provide a means to distinguish between the occurrence of bleaching and disease, it merely indicates that one or both are observed in the image.

In response to the 2014–2017 GCBE, image analysis was adapted to include a quantitative (point-by-point) assessment of bleached cover and which species of coral exhibited bleaching. For each of the 50 randomly generated points that overlays a coral, further classification is given to indicate whether that point on the coral is bleached (Yes, No, or Unknown). The new method was adopted into routine image analysis at KAHO in 2016, at WAPA in 2017, at KALA in 2019, and at NPSA in 2020. For years prior to implementation, the transect images were revisited *post hoc* to conduct the point-by-point bleaching assessment only when greater than 30% of the images for a sampling event (all 15 fixed transects) were found to contain bleaching and/or disease via the rapid assessment and in a few special cases when management implications warranted (Table 3). This 30% threshold was chosen after evaluation of the KAHO data, where percent bleached cover was significantly correlated with the percentage of images containing bleaching and/or disease ($r = 0.89$, $t(7) = 5.37$, $p = 0.001$) and 30% images containing bleaching and/or disease corresponded with approximately 10–15% bleached cover. We recognize that *post hoc* assessment of the images is not the preferred method, but it was the only way to get data on bleaching prior to adding bleaching assessment to the routine benthic image analyses. Moving forward, field notes will be taken describing bleaching by species *in situ* and all images will be assessed point-by-point for bleaching at all parks during the routine photo analysis that occurs soon after field data collection. Further analysis of coral diseases observed in the images has not been assessed to date and is not addressed in this report.

Table 3. Summary of annual survey information, bleaching image analyses performed, and statistical analyses performed for each park: Kaloko-Honokōhau National Historical Park (KAHO), Kalaupapa National Historical Park (KALA), National Park of American Samoa (NPSA), and War in the Pacific National Historical Park (WAPA). Taxa of interest are coral taxa that represent greater than 1% of the benthic cover at each park location. For WAPA the Asan and Agat marine units are considered separately.

	Annual Survey Information			**Bleaching Image Analyses Performed**		**Statistical Analyses Performed**	
Park	**Years of Survey**	**Number of Transects**	**Taxa of Interest (≥ 1% benthic cover)**	**% images with bleaching and/or disease**	**% bleached cover (as a percent of total coral cover, point-by-point) – *post hoc* or routine, with rationale**	**T-test between years, paired by site**	**Trend assessed by General Linear Mixed Model by year, site as random factor**
KAHO	2008–2010, 2014–2019	15	*Porites lobata, Porites compressa, Pocillopora meandrina, Montipora capitata, Sarcothelia edmonsoni**	All years	2008–2014 – *post hoc* due to management interest 2015 – *post hoc* due to severe bleaching 2016–2019 – added to routine analysis	2014/2016 – before/after recorded severe bleaching	2016–2019 – after bleaching/ mortality
KALA	2006–2019	15	*Pocillopora meandrina, Porites lobata*	All years	2019 – added to routine analysis, bleaching and/or disease was also in > 30% of images	2014/2016 – before/after local bleaching	2006–2019
NPSA	2007–2019	15	*Montipora* spp., *Porites rus, Porites* spp., *Acropora* spp., *Pavona varians*	All years	2014, 2015, 2017–2019 – *post hoc* due to bleaching and/or disease in > 30% of images, added to routine monitoring in 2020	2014/2018 – before/after local bleaching events	2007–2019
WAPA Asan	2008–2011, 2014–2019	2011 – 5 All other years – 7	*Porites rus,* massive *Porites* spp.	All years	2017–2019 – added to routine monitoring	2010/2018 – before/after local bleaching events	2008–2019
WAPA Agat	2008–2011, 2014–2019	2011 – 7 All other years – 8	massive *Porites* spp.	All years	2017–2019 – added to routine monitoring	2010/2018 – before/after local bleaching events	2008–2019

* *Sarcothelia edmonsoni* is an octocoral. All other taxa of interest are scleractinian corals.

Percent cover for each major taxonomic group (scleractinian coral, coralline algae, turf algae, macroalgae, other invertebrates, and sand/substrate) were calculated by dividing the number of points identified for each group by the total number of points per transect and multiplying by 100%. Any point that overlaid a fish or other non-benthic objects, such as the transect line, were removed from the dataset prior to calculating percentages. Average values were calculated for each park and year. Within WAPA, the Asan and Agat units were considered separately for the cover analysis because the benthic composition is very different between the two areas and normality for statistical tests could not be achieved when the two were combined. Percent cover was also calculated for each taxa of interest. Taxa of interest at all parks included coral taxa that covered about 1% or greater of the benthic habitat in the PACN survey data (Table 3). Within KAHO, taxa of interest are the scleractinian corals *Porites lobata*, *Porites compressa*, *Pocillipora meandrina*, and *Montipora capitata* and the octocoral *Sarcothelia edmonsoni*. Within KALA the taxa of interest are *P. meandrina* and *P. lobata*. For NPSA, species of the genera *Montipora, Acropora,* and *Porites* (except *Porites rus*) were grouped for this analysis because a diversity of species in each genus was present in low numbers and identification to species level was not always possible. The resulting taxa of interest are *Montipora* spp., *P. rus*, *Porites* spp., *Acropora* spp., and *Pavona varians*. Within WAPA, taxa of interest are massive *Porites* spp., which includes *P. lobata* and *Porites lutea,* for both Asan and Agat and *P. rus* for the Asan unit only.

The proportion of images containing bleaching and/or disease were calculated for each transect by dividing the number of images for which the observer indicated "Yes" for the presence of bleaching and/or disease by the total number of images analyzed and multiplying by 100. This value was calculated for all transects every year and was used as a rapid assessment of the data only; it is not a quantitative assessment of bleaching or disease prevalence.

Percent bleached cover (as a percent of total coral cover) was calculated for each fixed transect for all sampling events where the additional point-by-point bleaching analysis was conducted (Table 3). Percent bleached cover was calculated by the dividing the number of points that were bleached coral by the total number of points that fell on coral per transect and multiplying by 100.

For each of the major taxonomic groups, percent change in cover (loss or gain) related to the 2015 bleaching event at KAHO were calculated by subtracting the percent cover observed in 2016 from the percent cover observed in 2014 by transect, dividing the resulting value by the percent cover observed in 2014, and multiplying by 100. Significant mortality due to bleaching was not detected in any other park so similar calculations were not warranted.

Statistical Analysis

Trends over time for cover of the major taxonomic groups were assessed using a general linear mixed model for all available years in KALA, NPSA, and WAPA (Table 3, Starcevich et al. 2013). A trend analysis was not performed for the KAHO data from 2008 to 2019 because the 2015 bleaching event resulted in extensive coral mortality and interrupted the long-term dataset. Instead, trend was evaluated for the 2016 to 2019 timeframe to assess potential effects of bleaching or recovery to date. Data for the major taxonomic groups were logit transformed to meet the assumption of normality. Analysis of the logit transformed cover data was preformed using the *lmer* function from the *lmerTest* package in R (Kuznetsova et al. 2017, R Core Team 2020). Site was included as a random factor in the model to account for the random site effects.

Significance of cover gain or loss for major taxonomic groups and taxa of interest before and after the major bleaching/thermal stress events specific to each park were assessed using paired t-tests (Table 3). Data were compared between the survey year before and after each event using the *t.test* function in the *stats* package in R (R Core Team 2020). Due to zeros in the dataset, data for taxa of interest were arcsine squareroot transformed to meet the assumption of normality.

Results and Discussion

Kaloko-Honokōhau National Historical Park (KAHO)

Benthic cover and coral bleaching were surveyed annually at 15 fixed transects at KAHO 2008–2010 and 2014–2019. Surveys were generally conducted in October, immediately after or during the warmest month of the year for most survey years, so it can be expected that all substantial bleaching that occurred was recorded (Table 4). Prior to 2015, very little coral bleaching was recorded. In October 2015, 77% bleached cover was recorded, corresponding with the GCBE and NOAA's Alert Level 2 bleaching warning (Figure 2, Table 4). In October 2019, 11% bleached cover was recorded, again corresponding with NOAA's Alert Level 2 warning (Figure 2, Table 4). These results corroborate other major bleaching assessments conducted along the west coast of Hawai‘i Island. Hawai‘i DAR, TNC, and NOAA reported greater than 50% bleaching prevalence in 2015 (Kramer et al. 2016, Maynard et al. 2016, TNC 2017). The Hawai‘i DAR also reported bleaching along the west coast in 2019, with lower percentages compared to 2015 (DLNR 2019).

Table 4. Sampling timeframe, temperature data and observed bleaching at Kaloko-Honokōhau National Historical Park. No transects were surveyed 2011–2013. Information is for fixed transects (n = 15) by year (2008–2019) with a comparison of the month(s) that surveys were conducted to warmest reported month, average weekly sea surface temperature (SST) for that month, and maximum degree heating week (DHW) value recorded for the year as derived from NOAA (2020). The percent of images where bleaching and/or disease were present (one value per transect derived from presence/absence score by photo) is reported. The percent bleached coral cover (as a percent of total coral cover) is reported for all years surveyed as determined by analysis of each random point within photos that fell on coral.

Time Frame		Temperature Data (Kona, Hawai‘i [NOAA 2020])			Observations	
Year	Month(s) Surveys Conducted	Warmest Month	Average Weekly SST (°C)	Max DHW (°C-week)	Images with bleaching and/or disease (%)	Bleached Coral Cover (%)
2008	Oct	Jul	26.2	0	5.9	0.3
2009	Nov	Oct	26.8	0	3.3	0.1
2010	Oct	Oct	26.3	0	7.5	0.3
2011	*No Surveys*	Sep	26.6	0	*N.D.*	*N.D.*
2012	*No Surveys*	Oct	26.3	0	*N.D.*	*N.D.*
2013	*No Surveys*	Sep	26.8	0	*N.D.*	*N.D.*
2014	Nov	Oct	27.6	1.0 (Sep–Dec)	12.5	0.3
2015	Oct	Sep	29.1	18.3 (Oct)	93.6	76.9
2016	Oct–Nov	Aug	28.0	2.9 (Jan)	20.0	2.5
2017	Sep–Oct	Sep	27.8	0.5 (Oct–Dec)	19.7	0.9
2018	Oct	Oct	28.2	2.6 (Oct–Dec)	14.3	1.2
2019	Oct	Sep	28.5	12.5 (Oct–Nov)	59.4	10.5

No surveys were conducted 2011–2013. N.D. = No data.

In 2015, the percent bleached cover varied from 55% to 91% by transect (Figure 4), with no distinct spatial pattern. Maynard et al. (2016) reported in their surveys along the west coast of Hawaiʻi Island that 38 to 99% of corals were bleached by site with an average of 60% bleached at deeper sites (11.6 to 12.8 m/38 to 42 ft) in October 2015. Seventy percent of the corals were bleached at their site "Honokōhau", which was located within KAHO. The nearest PACN transect was F10, where PACN surveys found 81% bleached cover. Across KAHO in 2019, percent bleached cover varied from 3% to 24% by transect with the transects on the south side the park generally having higher percentages than the rest of the area (Figure 5). The potential for southern sites to be more vulnerable to bleaching will be examined as more data is collected, as this area is subjected to greater nutrient outflows from the Honokōhau Harbor (Raikow et al. 2021).

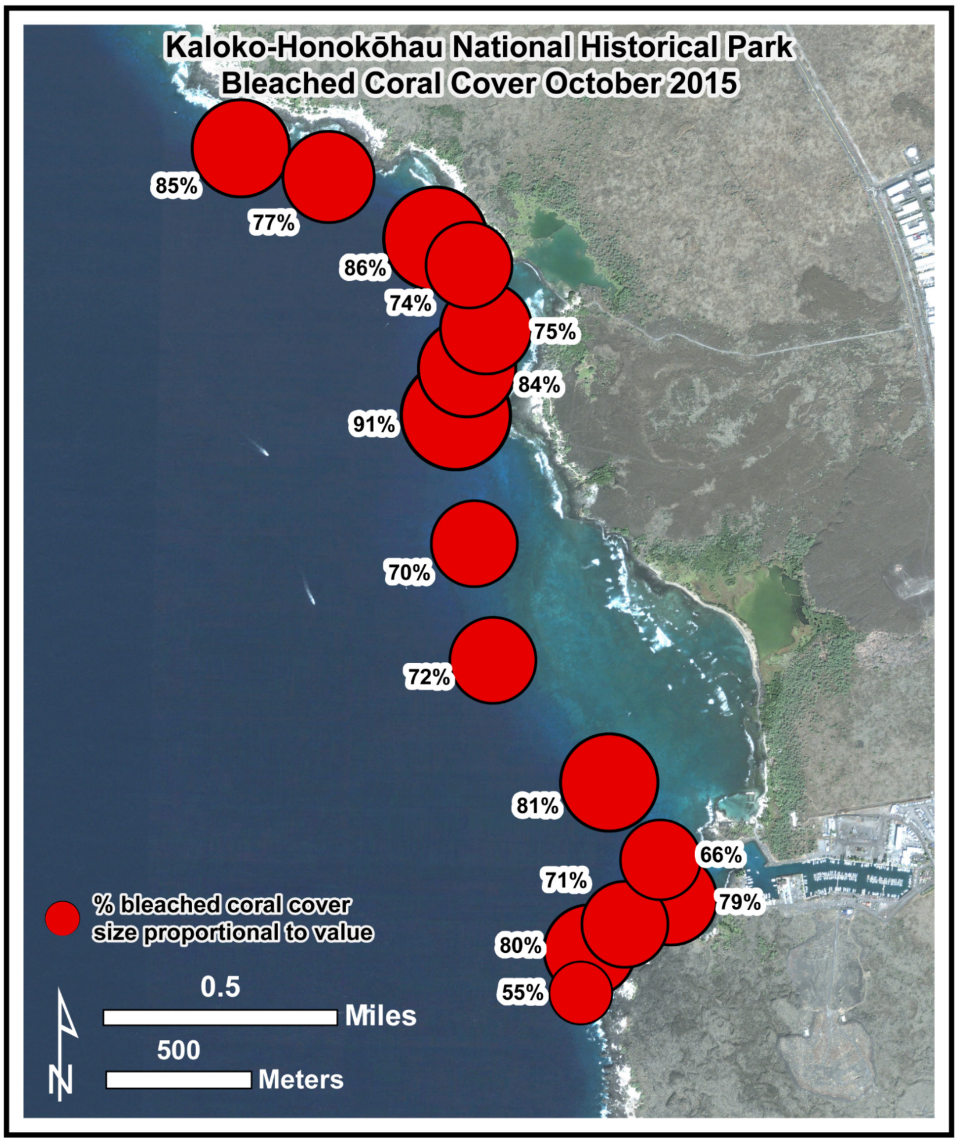

Figure 4. Percent bleached cover in October 2015 at the 15 fixed transects at Kaloko-Honokōhau National Historical Park. Bubble size is proportional to percentage.

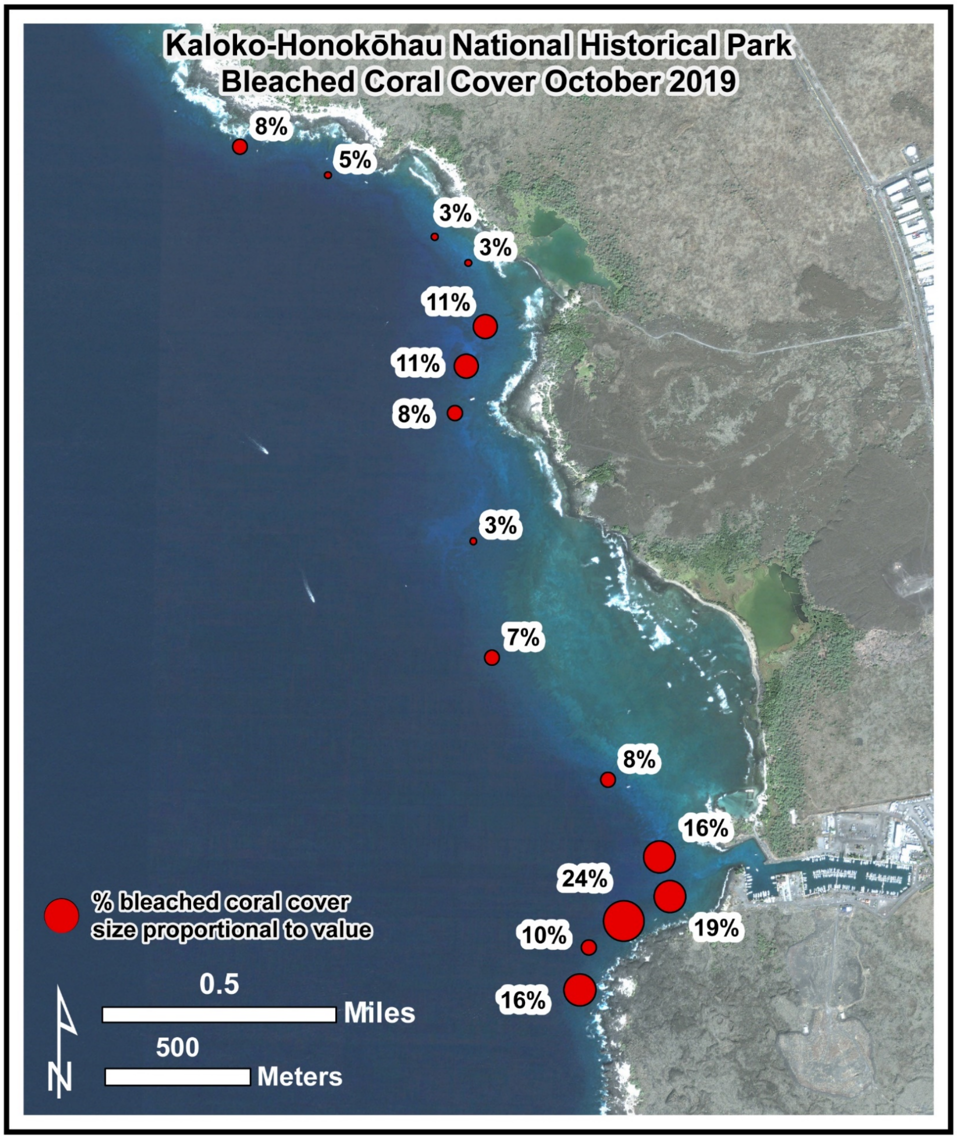

Figure 5. Percent bleached cover in October 2019 at the 15 fixed transects at Kaloko-Honokōhau National Historical Park. Bubble size is proportional to percentage.

Of the four most abundant coral species (*P. lobata*, *P. compressa*, *P. meandrina*, and *M. capitata*) along the KAHO transects, *M. capitata* was most frequently observed as bleached throughout the years surveyed (Table 5). In 2015, the percent bleached cover for all four species was high; 77% of *P. lobata*, 75% of *P. compressa*, 99% of *P. meandrina*, and 69% of *M. capitata* were bleached (Table 5). Corals of the genus *Porites* are generally considered to have low bleaching susceptibility (Sheppard et al. 2014, Maynard et al. 2017), so the high prevalence of bleaching in *P. lobata* and *P. compressa* in 2015 is very alarming and demonstrates that these extreme temperature events can impact any species. In 2019, bleaching was observed again in all four species. Percent bleached cover for *P. lobata* and *P. compressa* was 7% and 19% respectively, which is considerably lower than their observed percent bleaching values in 2015 when they experienced greater thermal stress. Substantial bleaching was observed again in 2019 in both *M. capitata* (69% bleached cover) and for

P. meandrina (75% bleached cover). These relatively high values demonstrate that both species are highly susceptible to bleaching and is concerning for the future of these species in light of forecasted increase in frequency and severity of bleaching events (NOAA National Marine Fisheries 2018, Heron et al. 2016a, van Hooidonk et al. 2016). Coral mortality is discussed below.

Table 5. Percent bleached cover (as a percent of total coral cover) for the four most abundant coral taxa (*Porites lobata*, *Porites compressa*, *Pocillopora meandrina*, and *Montipora capitata*) on fixed transects at Kaloko-Honokōhau National Historical Park 2008–2019 (n = 15). No random points fell on *P. meandrina* in 2016–2017 due to high mortality in 2015. No transects were surveyed 2011–2013.

Year	Bleached Cover by Species (%)			
	Montipora capitata	***Pocillopora meandrina***	***Porites compressa***	***Porites lobata***
2008	12.0	1.4	0.0	0.0
2009	0.0	0.9	0.1	0.0
2010	8.0	4.1	0.0	0.0
2014	5.3	4.0	0.0	0.0
2015	68.8	99.4	75.1	76.8
2016	20.0	No points	2.8	2.2
2017	22.2	No points	1.0	0.7
2018	45.5	50.0	2.1	0.5
2019	69.2	75.0	19.3	6.6

Changes in benthic cover were detected in relation to the 2015 bleaching event at KAHO (Figures 6–8). It is clear from all reports documenting bleaching along the west coast of Hawaiʻi Island that the 2015 bleaching event was devastating, causing about 50% mortality or more (Marynard et al. 2016, Kramer et al. 2016, TNC 2017). The observed reduction in live coral cover between 2014 and 2016 was 63% on PACN fixed transects. This result was statistically significant ($t(14) = 10.3$, $p < 0.001$), with cover reduced from 33% (95% CI = 27.7–35.5%) to 12% (95% CI = 10.3–13.7%) across the fixed transects. Coral cover loss ranged from 39% to 78% by transect, with no apparent depth or spatial pattern (Figures 7 and 8). Hawaiʻi DAR reported 50% cover loss across the west coast with six of their 26 sites having cover loss in excess of 60% (Kramer et al. 2016).

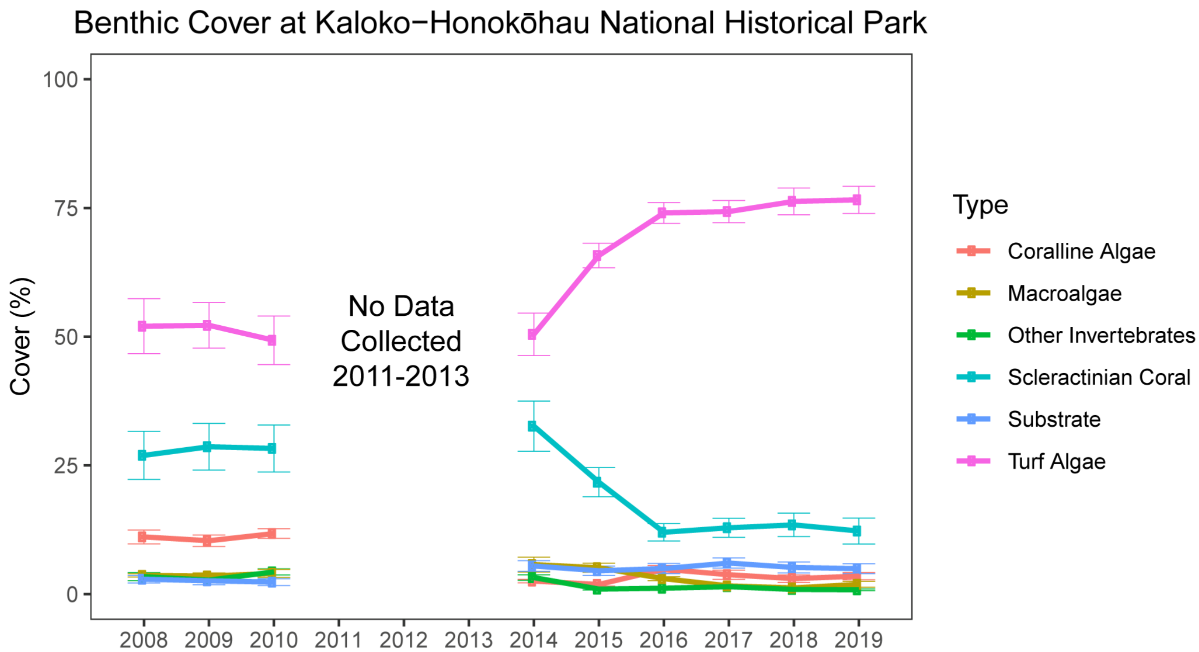

Figure 6. Mean percent benthic cover by type on fixed transects (n = 15) by year at Kaloko-Honokōhau National Historical Park 2008–2019. No transects were surveyed 2011–2013. Error bars are the 95% confidence interval centered on the mean. Mean percent scleractinian coral cover was significantly reduced from 2014 to 2016 ($t(14) = 10.3$, $p < 0.001$) but remained stable from 2016 through 2019 ($t(44) = -1.60$, $p = 0.117$).

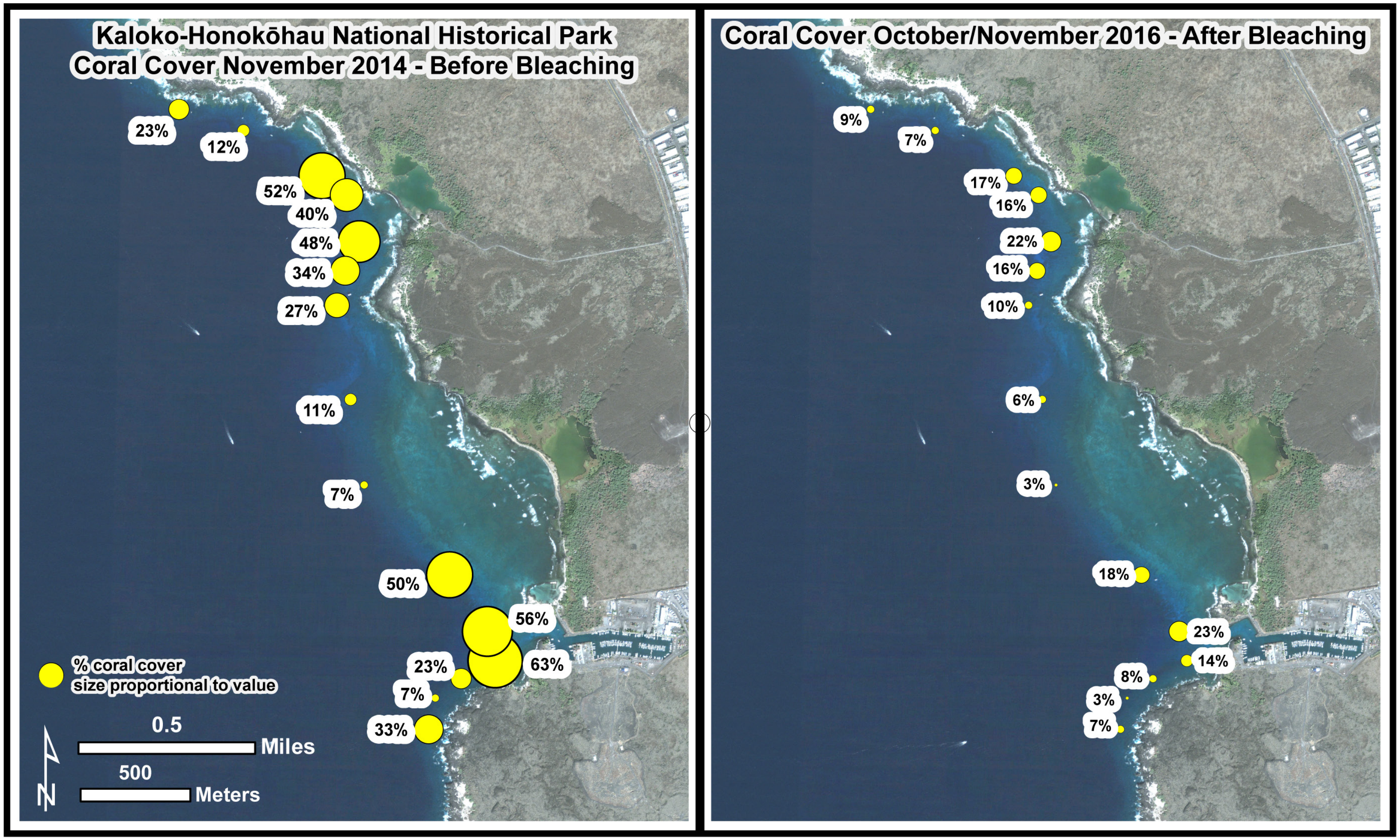

Figure 7. Percent live coral cover by transect for the 15 fixed transects at Kaloko-Honokōhau National Historical Park in 2014 (left panel) prior to the 2015 bleaching event, and in 2016 (right panel). Bubble size is proportional to percentage. A significant reduction in percent live coral cover is observed between 2014 and 2016 ($t(14) = 10.3$, $p < 0.001$).

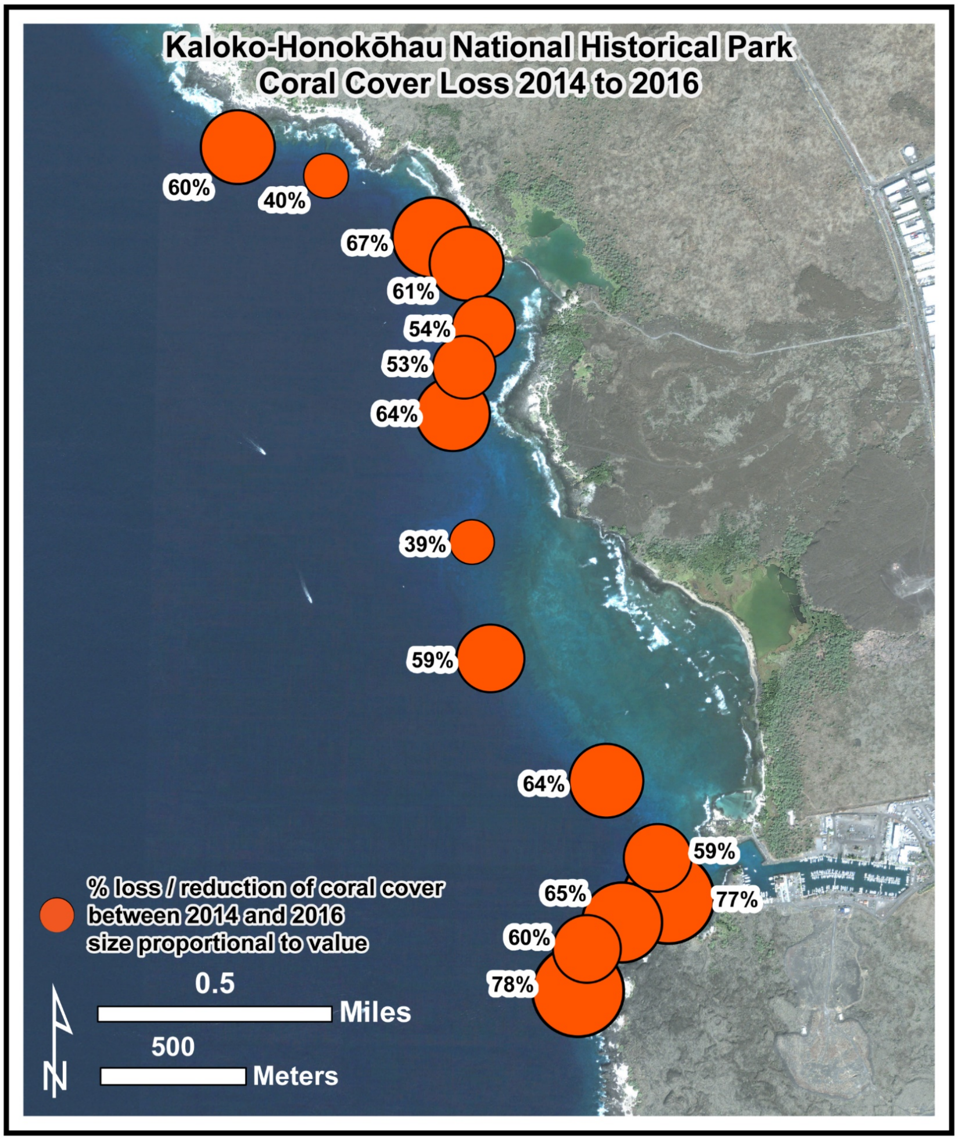

Figure 8. Percent live coral cover loss by transect for the 15 fixed transects at Kaloko-Honokōhau National Historical Park between 2014 and 2016. Bubble size is proportional to percentage. A significant reduction in percent live coral cover is observed between 2014 and 2016 ($t(14) = 10.3$, $p < 0.001$).

Coral cover was relatively stable between 2016 and 2019 (Figure 6, $t(44) = -1.60$, $p = 0.117$), indicating that further decline related to the 2015 bleaching event did not occur and any elevated temperatures 2016–2018 were not severe enough to result in significant mortality. However, heat stress like that observed on the reefs of KAHO in 2015 can lead to reduced coral growth and calcification lasting for years after the event (Cantin and Lough 2014) and increased susceptibility to disease (Brandt and McManus 2009, Brodnicke et al. 2019). Reef resiliency along the west coast of Hawaiʻi Island was examined by Maynard et al. (2016). A resiliency score based on numerous ecological factors was calculated for each of 20 sites and compared to each other. Their site Honokōhau, which lies within the park boundaries, had the fourth lowest resiliency score for the shallow reef (5–7 m/16–23 ft). Factors that contributed to this low score included relatively higher incidence of coral disease, lower coral cover and coral diversity, and lower coral recruitment compared to the average of all sites. The deeper reef site (12–15 m/39–49 ft) fared better, receiving a medium-high resiliency score, but still ranked among the worst for incidence of coral disease and coral recruitment. Neither coral disease nor coral recruitment have been studied quantitatively park-wide. The percentage of images that contained bleaching and/or disease in our assessment was much greater than bleached corals accounted for, indicating that there is coral disease present throughout the park (Table 4) and further investigation is warranted. A long-term recruitment study by DAR includes the same site used by Maynard et al. (2016), "Honokōhau", and that has been monitored annually since 2004. At that site the average recruitment rate (2004–2018) was 22 recruits per meter squared per year, which is below the average for their sites along the west coast of Hawai'i Island and also low compared to other studies around the world (Martin and Walsh 2018). Continued monitoring by PACN will increase understanding of whether coral communities in KAHO will recover or shift to substantially lower cover estimates overall. Any cover changes related to the 2019 coral bleaching will be evaluated after the next annual surveys are completed.

Percent cover loss by species between 2014 and 2016 was 65% for *P. lobata* ($t(14) = 7.65$, $p < 0.001$), 49% for *P. compressa* ($t(14) = 2.67$, $p = 0.018$), 100% for *P. meandrina* ($t(14) = 4.29$, $p < 0.001$), and 84% for *M. capitata* ($t(14) = 3.99$, $p = 0.001$). Cover loss for all four species was most pronounced at the sites that had the highest cover (Figures 9–12). DAR reported similar ranges in cover loss for *P. lobata* and *P. compressa* and nearly complete loss of *P. meandrina* and *Porites evermanni* (Kramer et al. 2016). Between 2016 and 2019, cover was relatively stable for the four most abundant species (no statistically significant changes, Figures 9–12).

Recovery of these species will likely be variable. Long-term recovery is highly complex, and as this is the first severe bleaching event recorded along west Hawai'i Island, it is difficult to predict whether full recovery will be possible. Often bleaching-tolerant species such as *P. lobata* are the short-term winners following a bleaching event, while long-term success is dependent on growth rate and recruitment as well as tolerance to any additional thermal events and confounding threats/factors (van Woesik et al. 2011, Schoepf et al. 2015, Pratchett et al. 2020). *P. lobata* is a slow-growing mound coral (linear extension rate ~1 cm/year, Lough and Barnes 2000, Forsman et al. 2006) and it could take decades for this species to recover from the substantial cover loss seen in 2015. *Porites compressa* is a branching coral with a similarly slow growth rate (Forsman et al. 2006, Chen et al. 2018), but a unique ability to reproduce through asexual fragmentation (in addition to broadcast spawning) that has allowed it to recolonize degraded areas in the absence of larval recruitment (Hunter 1993, Chen et al. 2018). One study in Oahu showed that *P. compressa* recovered surprisingly well from severe bleaching in 2015 (Matsuda et al. 2020). Although changes from 2016 to 2019 at KAHO were not statistically significant, *P. compressa* cover did increase at most sites over this period, suggesting the species may be recovering. *M. capitata* takes on an encrusting growth form at KAHO, though at other locations it can form branching colonies. Literature suggests *M. capitata* has a linear extension rate about 2–3 cm/yr (Kolinski 2007, Barnhill et al. 2020). In the absence of repeat bleaching, this species has the potential to recover quicker than the *Porites* corals, however, there is evidence that consecutive years of bleaching could be detrimental to the species as it may not metabolically recover from a bleaching event within a year (Barnhill et al. 2020, Matsuda et al. 2020). *P. meandrina* is a branching coral with a linear extension rate about 2 cm/yr (Kolinski 2007). After being nearly completely wiped out by the 2015 bleaching event, live *P. meandrina* was not observed on the fixed or temporary transects at KAHO in 2016 or 2017. A few colonies were observed near the transects in 2017 (Authors pers. obs.) and some small colonies were observed in the transect images in 2018 and 2019, indicating the species is beginning to recover. The faster extension rate of *P. meandrina* compared to the *Porites* corals, suggests that it may be able to recover more quickly; however, as demonstrated by the nearly complete loss during the severe bleaching in 2015, it is highly susceptible to bleaching-related mortality, and any future bleaching events could prevent the long-term recovery of this species (van Woesik et al. 2011).

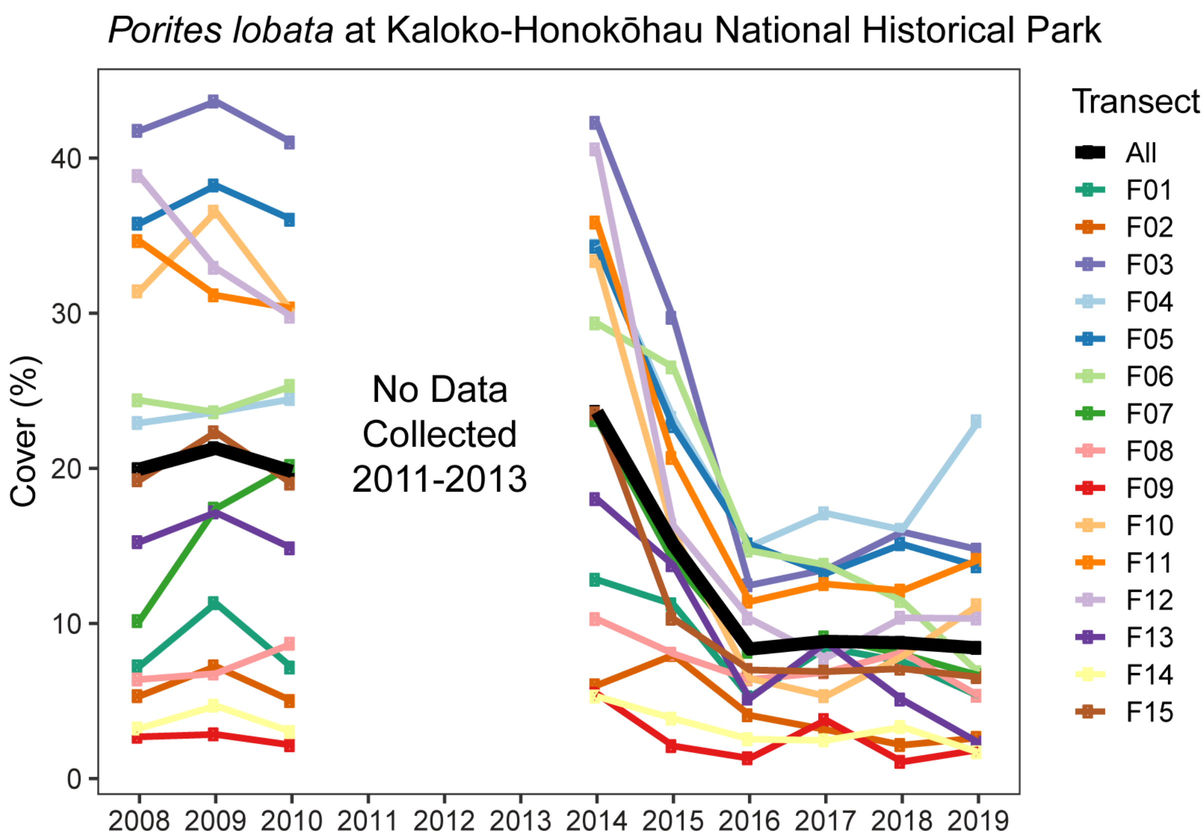

Figure 9. Percent cover of *Porites lobata* at the fixed transects (n = 15, where individual transects are color-coded F01 through F15) at Kaloko-Honokōhau National Historical Park 2008–2019. Black line represents mean percent cover calculated from all 15 transects for each year. No transects were surveyed 2011–2013. Significant loss of *P. lobata* cover is recorded between 2014 and 2016 ($t(14) = 7.65$, $p < 0.001$), and no significant change was recorded from 2016 to 2019 ($t(44) = -0.48$, $p = 0.634$).

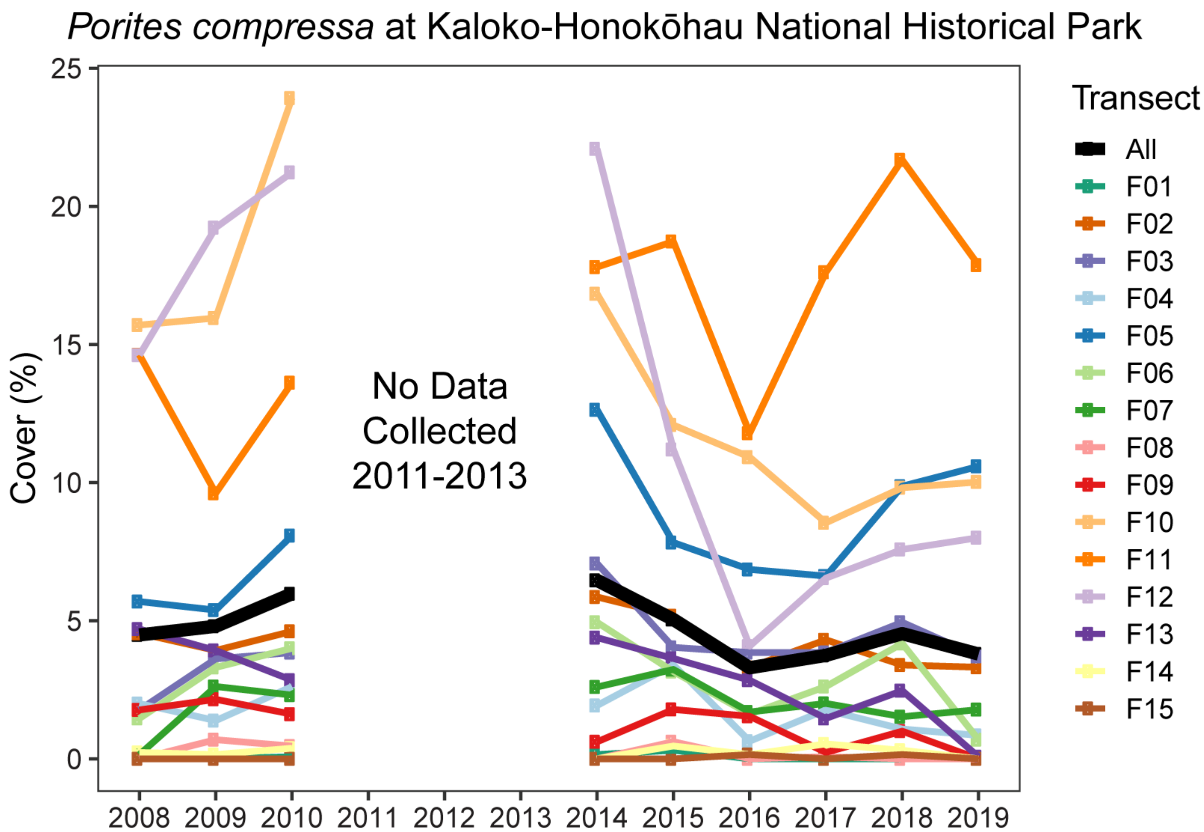

Figure 10. Percent cover of *Porites compressa* at the fixed transects (n = 15, where individual transects are color-coded F01 through F15) at Kaloko-Honokōhau National Historical Park 2008–2019. Black line represents mean percent cover calculated from all 15 transects for each year. No transects were surveyed 2011–2013. Significant loss of *P. compressa* cover is recorded between 2014 and 2016 ($t(14) = 2.67$, $p = 0.018$), and no significant change was recorded from 2016 to 2019 ($t(44) = -0.38$, $p = 0.708$).

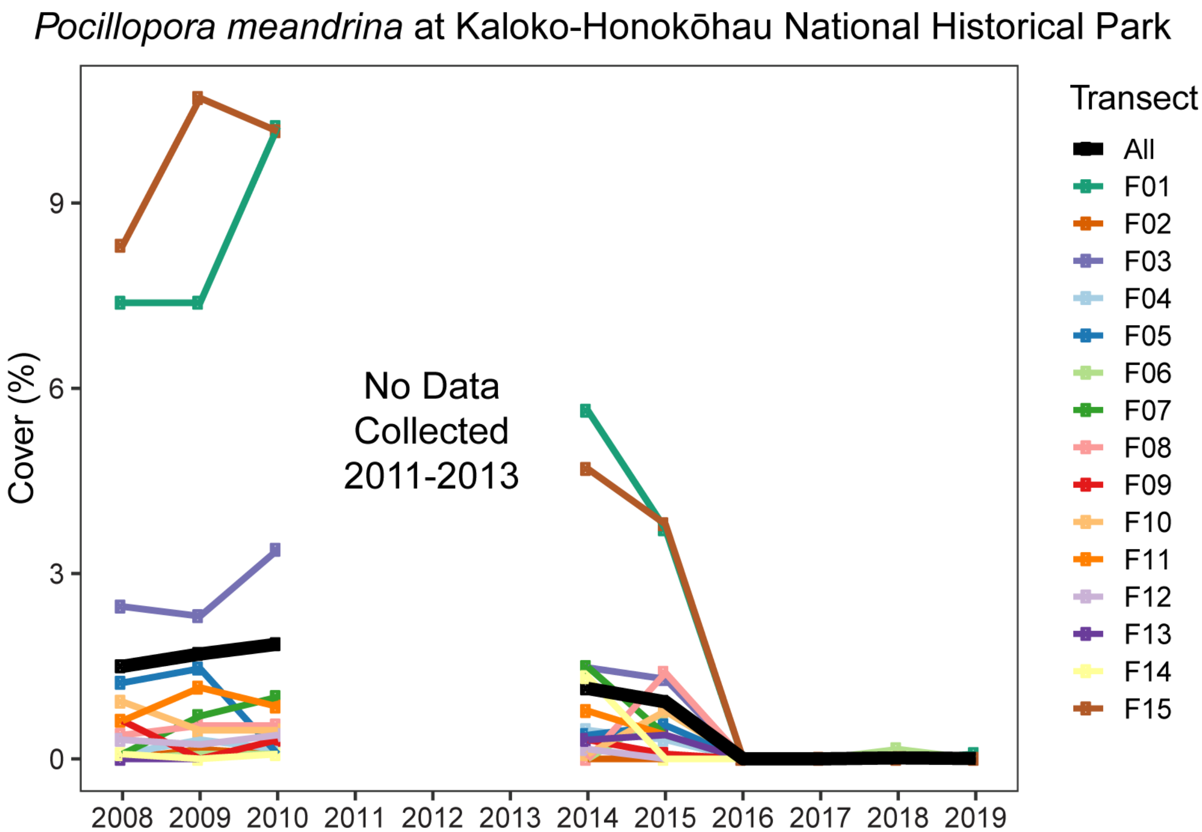

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Figure 11. Percent cover of *Pocillopora meandrina* at the fixed transects (n = 15, where individual transects are color-coded F01 through F15) at Kaloko-Honokōhau National Historical Park 2008–2019. Black line represents mean percent cover calculated from all 15 transects for each year. No transects were surveyed 2011–2013. Nearly complete loss of *P. meandrina* cover is recorded between 2014 and 2016 ($t(14) = 4.29$, $p < 0.001$). Recorded values of *P. meandrina* for the years 2016–2017 is 0% for all transects.

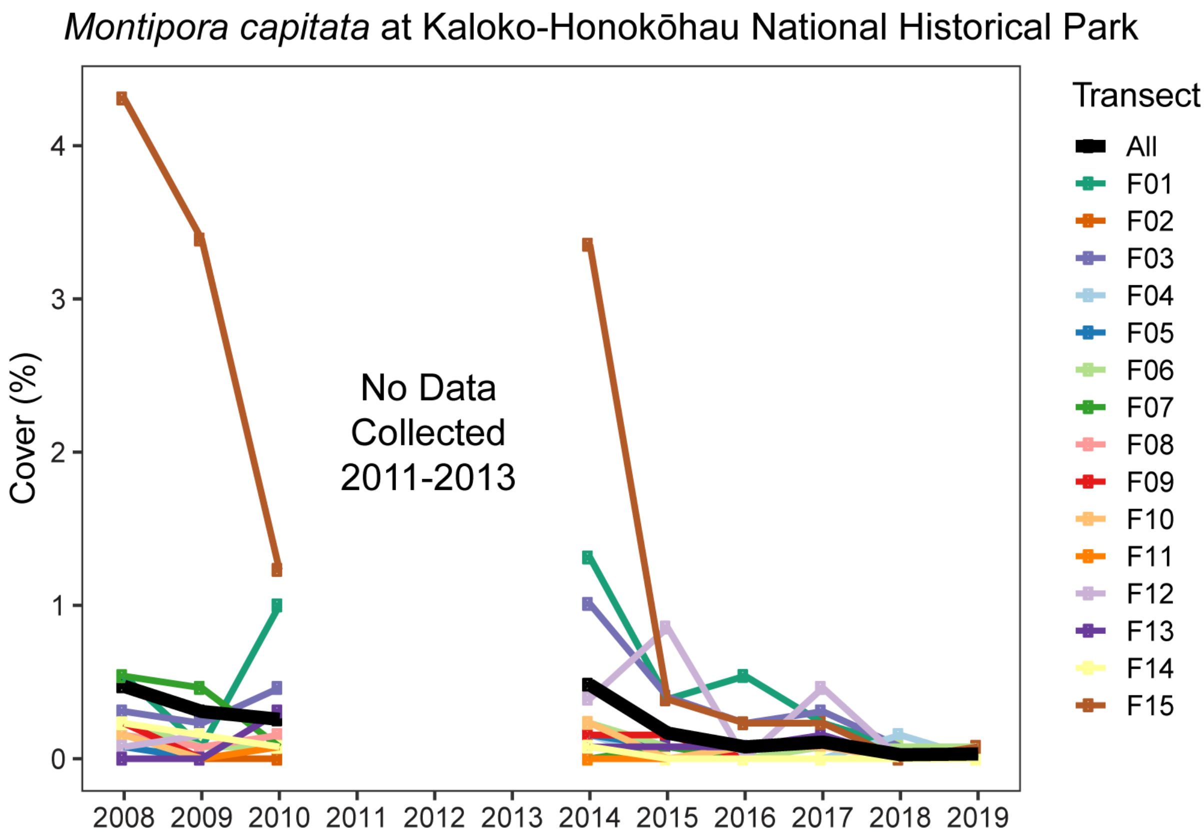

Figure 12. Percent cover of *Montipora capitata* at the fixed transects (n = 15, where individual transects are color-coded F01 through F15) at Kaloko-Honokōhau National Historical Park 2008–2019. Black line represents mean percent cover calculated from all 15 transects for each year. No transects were surveyed 2011–2013. Significant loss of *M. capitata* cover is recorded between 2014 and 2016 ($t(14) = 3.99$, $p = 0.001$), and no significant change was recorded from 2016 to 2019 ($t(44) = -1.38$, $p = 0.174$).

Live coral lost in 2015 was primarily replaced by turf algae across KAHO. A significant increase in percent cover of turf algae at fixed transects was observed from 50% (95% CI = 46.3–54.6%) in 2014 to 74% (95% CI = 72.0–76.1%) in 2016 corresponding to the loss of coral (Figures 6 and 13, $t(14) = -6.79$, $p < 0.001$). An increase in percent cover of coralline algae was also observed at some transects (Figure 14). An increase in cover by coralline algae was particularly noticeable at F10 and F11 (Figures 14 and 15). The overall change in coralline algae was small (2.3%, 95% CI = 1.1–3.5%), but significant ($t(14) = -3.53$, $p = 0.003$). Bioerosion of the coral colonies that died because of the bleaching event was also apparent at many sites (Figure 15).

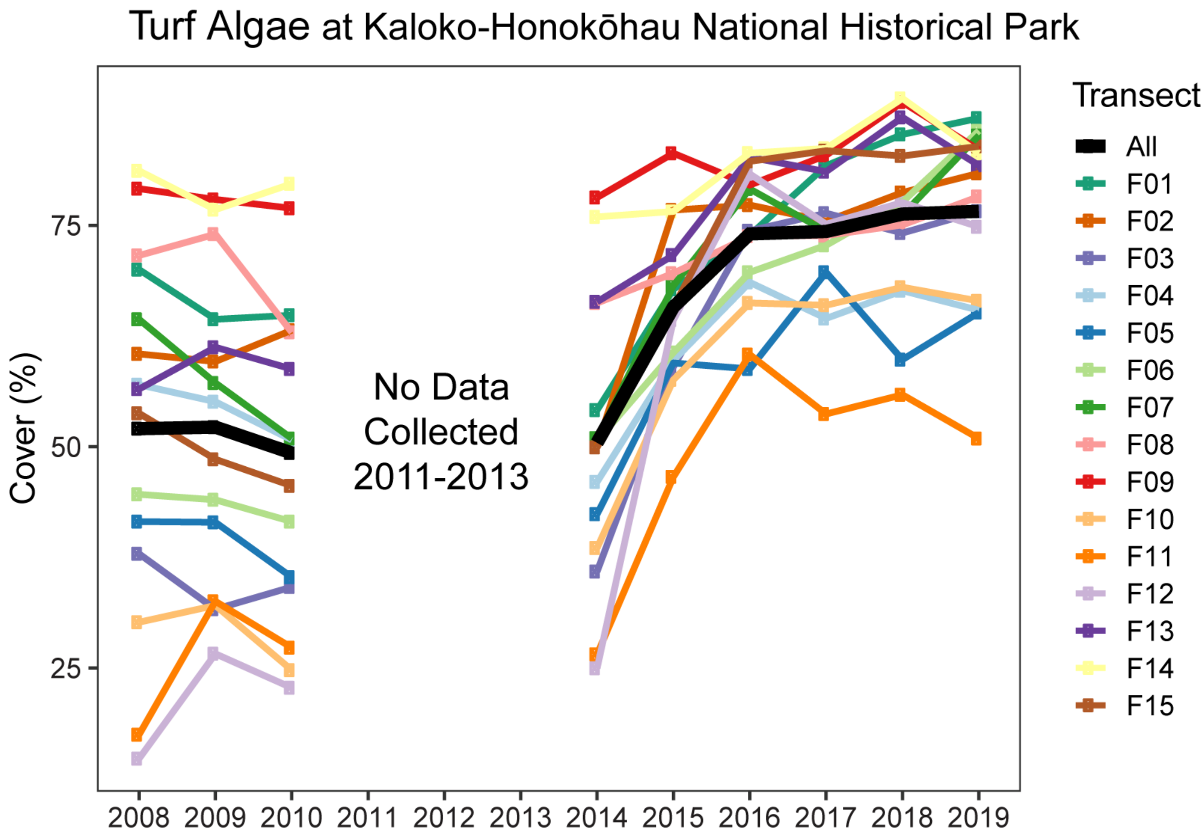

Figure 13. Percent cover of turf algae at the fixed transects (n = 15, where individual transects are color-coded F01 through F15) at Kaloko-Honokōhau National Historical Park 2008–2019. Black line represents mean percent cover calculated from all 15 transects for each year. No transects were surveyed 2011–2013. Turf algae cover increased significantly from 2014 to 2016 ($t(14) = -6.79$, $p < 0.001$).

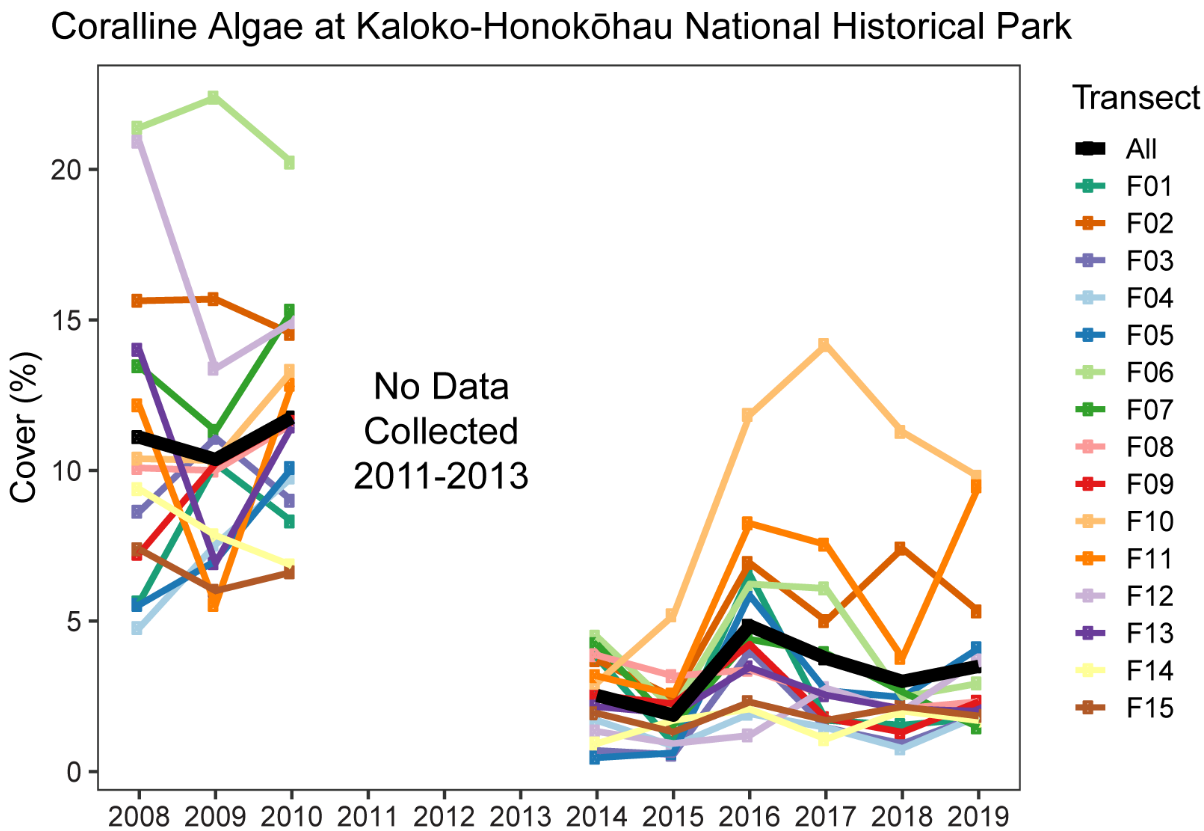

Figure 14. Percent cover of coralline algae at the fixed transects (n = 15, where individual transects are color-coded F01 through F15) at Kaloko-Honokōhau National Historical Park 2008–2019. Black line represents mean percent cover calculated from all 15 transects for each year. No transects were surveyed 2011–2013. Following the 2015 bleaching and coral mortality event an increase in cover by coralline algae is noticeable at F10 and F11. The overall change in coralline algae is significant ($t(14) = -3.53$, $p = 0.003$) between 2014 and 2016.

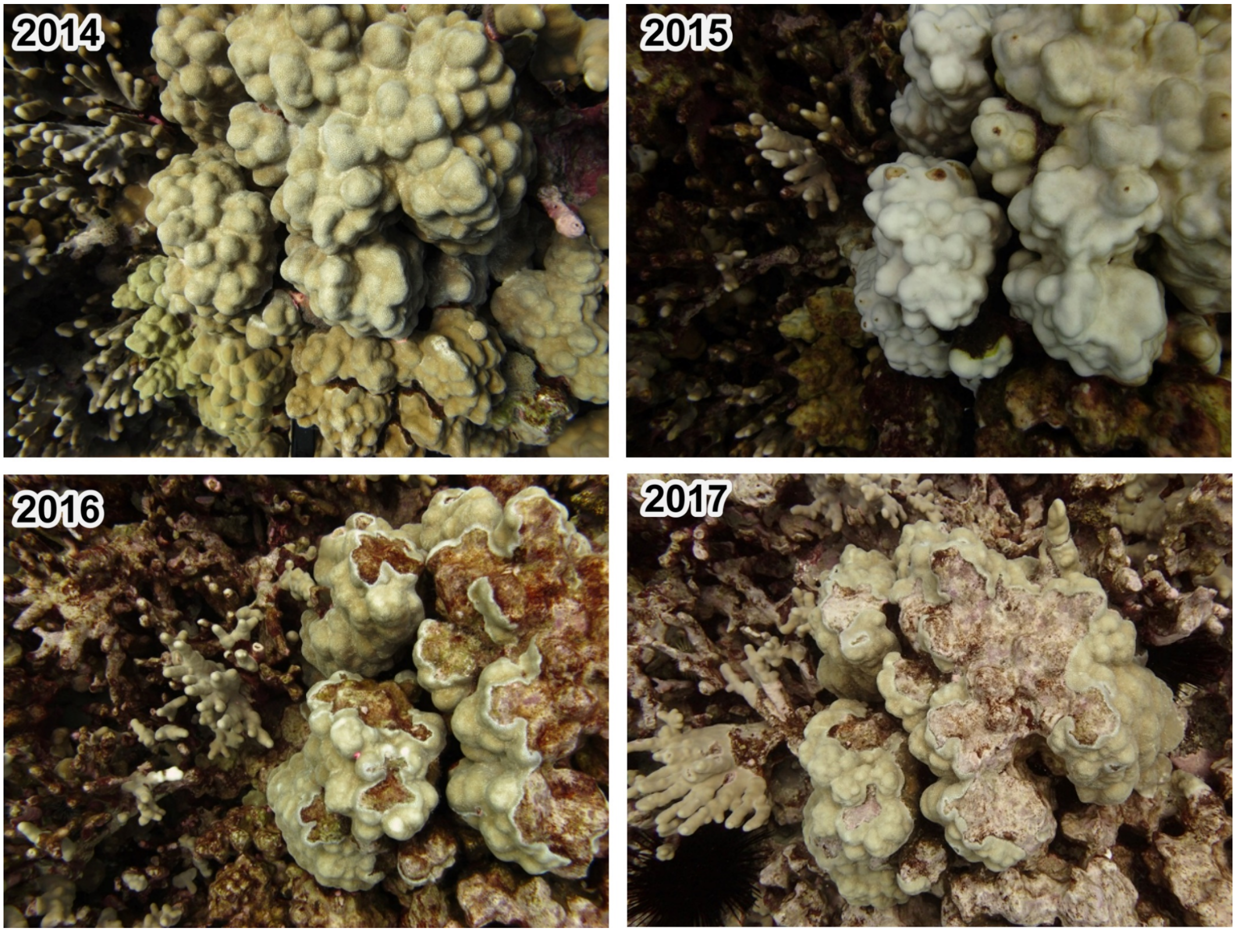

Figure 15. Benthic transect images at the start of transect F11 at Kaloko-Honokōhau National Historical Park in 2014, 2015, 2016, and 2017. Bleaching and coral mortality is evident in 2015, coral mortality and bioerosion is evident in 2016, and further bioerosion and an increase in coralline algae cover is evident in 2017.

Change in cover of macroalgae was not significant (Figure 6, $t(14) = 1.28$, $p = 0.220$). Replacement by turf algae and coralline algae with little change in macroalgae cover is an encouraging sign. Macroalgae often outcompete coral recruits, whereas coralline algae provide suitable habitat and cues for recruitment (McCook et al. 2001, Kuffner et al. 2006). Past bleaching events have resulted in phase shifts in certain reefs around the globe from coral-dominated to macroalgal-dominated reefs. Low herbivore numbers (overfishing/overharvesting), water quality issues, and poor coral recruitment and survivorship have driven these shifts (Hughes et al. 2007, Ledlie et al. 2007, Norstrom et al. 2009). Past surveys have shown that herbivorous sea urchins are abundant at KAHO (Marrack et al. 2014, Weijerman et al. 2014), and along with other herbivores such as green sea turtles and fish, they play an important role in controlling macroalgal growth (Wabnitz et al. 2010). These herbivores likely helped prevent or possibly slowed a potential phase shift from occurring on the park reefs following the 2015 mass bleaching event. Continued monitoring of the benthic assemblages will provide insight to the reef's trajectory.

In addition to the decline of scleractinian coral, PACN surveys revealed nearly complete loss of the blue octocoral, *S. edmondsoni,* at KAHO, corresponding with the 2015 bleaching event (Figure 16). Overall *S. edmondsoni* cover was 2.3% (CI 95% = 1.8–2.9) on the transects in 2014 and was not observed in the benthic images in 2015 to 2019 (0% cover). A couple patches were observed in 2017 outside the transect images at F12, the site nearest to the Honokōhau Harbor (A. McCutcheon, pers. obs.). Although it has not been documented in a report to date, widespread loss of *S. edmonsoni* has been seen throughout the park (S.C. Beavers, personal communication, May 21, 2019) and along the west coast of Hawaiʻi (K.L. Kramer, personal communication, February 27, 2018). There are some conflicting reports about the origin and taxonomy of the octocoral, but it is assumed to be native (Walsh et al. 2010). High cover of the octocoral had been recorded near Honokōhau Harbor and Kailua Bay compared to other west Hawaiʻi Island reefs and it was suggested that the distribution may have been related to anthropogenic influence (Walsh et al. 2010, Weijerman et al. 2014). PACN water quality monitoring consistently finds elevated nutrient levels in the vicinity of Honokōhau Harbor compared to other areas in the park (Raikow et al. 2017, Raikow et al. 2021). The near complete loss of the octocoral during the 2015 bleaching event, suggests that the species has low tolerance to heat stress. Annual PACN surveys will allow us to track the long-term outcome for this species on KAHO's reef slope.

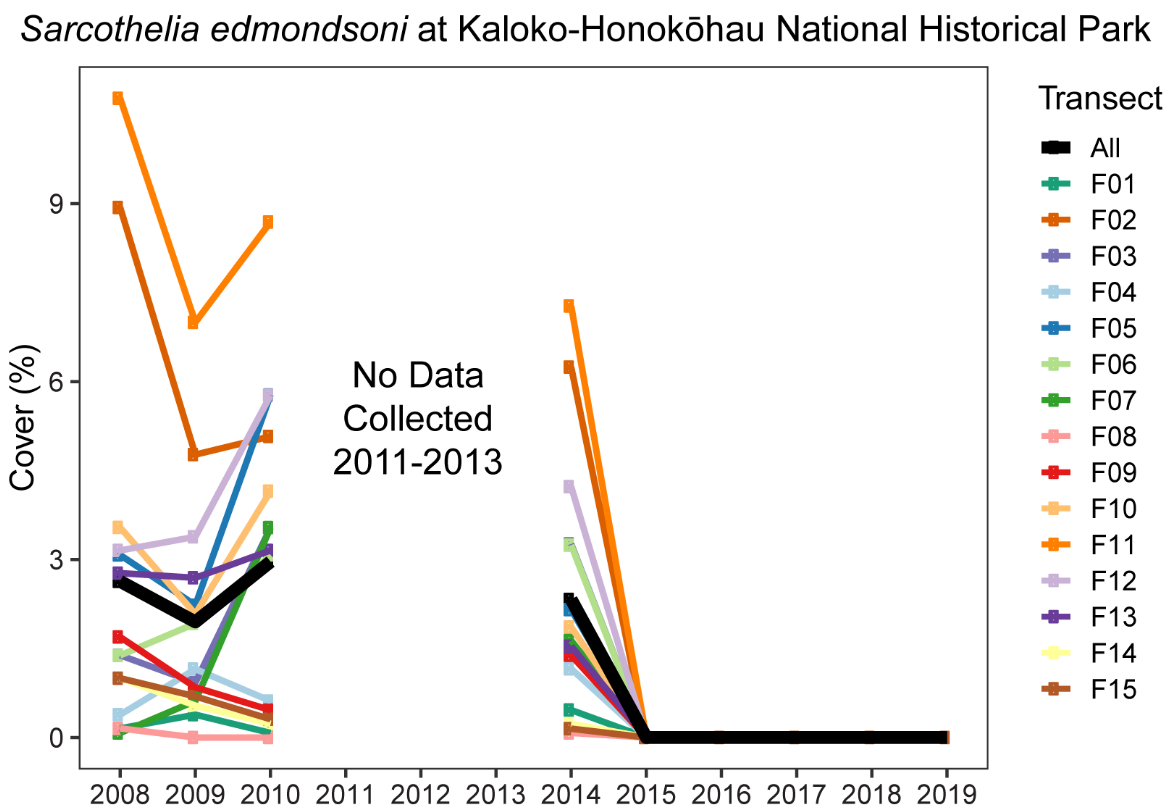

Figure 16. Percent cover of *Sarcothelia edmondsoni* at the fixed transects (n = 15, where individual transects are color-coded F01 through F15) at Kaloko-Honokōhau National Historical Park 2008–2019. Black line represents mean percent cover calculated from all 15 transects for each year. No transects were surveyed 2011–2013. Percent cover is 0% for all transects 2015–2019.

Kalaupapa National Historical Park (KALA)

Benthic cover was surveyed annually in KALA at 15 fixed transects from 2006–2019. Surveys occurred about a month prior to the warmest month and before maximum DHW values were reached most years (Table 6). These surveys may not have recorded the full extent of coral bleaching that occurred, but the surveys can indicate if any significant mortality events occurred. Data on coral bleaching were collected only as the presence or absence of bleaching and/or disease (one score per photo) from 2006 to 2018. The *post hoc* point-by-point bleaching analysis was not warranted because the percentage of images containing bleaching and/or disease was less than 30% (Table 6). In 2019, a bleaching event was detected at KALA; the proportion of images containing bleaching and/or disease was 40% and percent bleached cover was 23% (Table 6).

Table 6. Sampling timeframe, temperature data and observed bleaching at Kalaupapa National Historical Park. Information is for fixed transects (n = 15) by year (2006–2019) with a comparison of the month(s) that surveys were conducted to warmest reported month, average weekly sea surface temperature (SST) and maximum degree heating week (DHW) value recorded for the year as derived from NOAA 2020. The percent of images where bleaching or disease were present (one value per transect derived from presence/absence score by photo) is reported. The percent of bleached coral cover (as a percent of total coral cover) is reported for 2019, when the bleached cover analysis was added to the monitoring routine and bleaching and/or disease prevalence was greater than 30%. For this year, all coral points identified along the transects were given an additional score to indicate whether bleaching was present.

Time Frame		Temperature Data (Moloka‘i, Hawai‘i [NOAA 2020])			Observations	
Year	Month(s) Surveys Conducted	Warmest Month	Average Weekly SST (°C)	Max DHW (°C-week)	Images with bleaching and/or disease (%)	Bleached Coral Cover (%) *
2006	Jul, Aug	Oct	26.3	0	0.3	*N.D.*
2007	Jul, Aug	Sep	26.3	0	0.3	*N.D.*
2008	Jul, Aug	Sep	26.1	0	0.5	*N.D.*
2009	Jul, Aug	Oct	26.4	0	2.0	*N.D.*
2010	Aug	Oct	25.9	0	2.3	*N.D.*
2011	Jul	Sep	26.1	0	5.1	*N.D.*
2012	Jul, Aug	Oct	25.6	0	4.9	*N.D.*
2013	Aug, Sep	Sep	26.5	0	3.1	*N.D.*
2014	Jul, Aug	Oct	27.5	5.6 (Oct–Dec)	8.5	*N.D.*
2015	Aug	Sep	28.0	8.7 (Sep–Oct)	0.5	*N.D.*
2016	Jul, Aug	Aug	26.9	0	1.3	*N.D.*
2017	Aug, Sep	Sep	27.3	0	5.9	*N.D.*
2018	Aug, Sep	Oct	27.3	0	5.1	*N.D.*
2019	Aug, Sep	Sep	27.8	4.4 (Oct–Nov)	40.5	23.3

* 2006–2018 presence of bleaching and/or disease is less than 30% so bleached cover analysis was not conducted. N.D. = No data.

Little information is available regarding coral bleaching in Moloka‘i during the 2014–2017 GCBE, but severe bleaching was recorded on Oahu, Kauai, and Maui in 2014 and Maui and Hawai‘i Island in 2015 (University of Hawai‘i 2017). The reefs of Moloka‘i were exposed to heat stress similar to the other islands, surpassing the Alert Level 2 threshold in September 2015 (NOAA 2020). However, two temperature loggers located at PACN transects F03 and F13 show that water temperatures experienced at KALA were about 0.5 degrees Celsius cooler over the entire survey period and 0.8 degrees cooler in September 2015 than temperatures reported by the NOAA coral reef watch products (NPS unpublished data, NOAA 2020). This may explain why bleaching was not as severe as in other locations. In 2019, when the DHW index reached a maximum of Alert Level 1, bleaching was reported on the south shores of Moloka‘i (DLNR 2019). Temperature data is not yet available from the local loggers to assess how temperatures at F03 and F13 compared to NOAA’s findings.

If severe bleaching had occurred at KALA outside of the survey times, a decline in live coral cover would be expected. Over the whole survey period of 2006 to 2019 coral cover declined significantly from 8.1% (95% CI = 6.6–9.6%) to 4.4% (95% CI = 3.5–5.2%) ($t(194) = -3.17$, $p = 0.002$, Figures 17 and 18). However, there was no significant difference between coral cover in 2014 and 2016 ($t(14) = 0.01$, $p = 0.993$), and coral cover increased slightly from 2014 to 2017 (Figures 17 and 18). These results indicate that the decline in coral cover over the long-term was not related to heat stress associated with the 2014–2017 GCBE. Likewise, cover of the most abundant coral species, *P. meandrina*, declined significantly over the whole survey period ($t(194) = -5.41$, $p < 0.001$), but saw no significant decline between 2014 and 2016 ($t(14) = 1.86$, $p = 0.084$, Figure 19). *P. lobata* cover also declined significantly over the whole survey period ($t(194) = 3.02$, $p = 0.003$), but increased significantly between 2014 and 2016 ($t(14) = -2.33$, $p = 0.035$, Figure 20). The causes of the decline in coral cover are unknown. A trend analysis of water quality in the area revealed no concerns and generally stable conditions 2008–2015 (Raikow et al. 2021) and the park is isolated, receiving very little boat traffic.

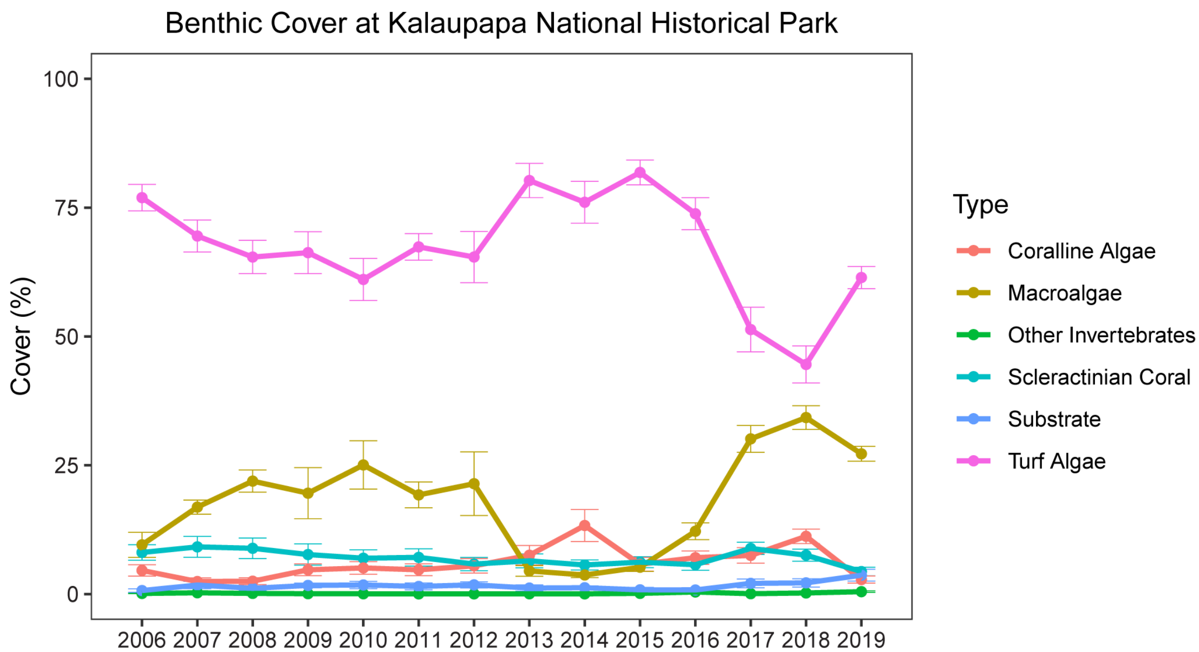

Figure 17. Mean percent benthic cover by type (color-coded) on fixed transects (n = 15) by year at Kalaupapa National Historical Park 2006–2019. Error bars are the 95% confidence interval centered on the mean. Scleractinian coral cover declined significantly from 2006 to 2019 ($t(194) = -3.17$, $p = 0.002$), but there was no significant difference between coral cover in 2014 and 2016 ($t(14) = 0.01$, $p = 0.993$). This is shown in more detail in Figure 18.

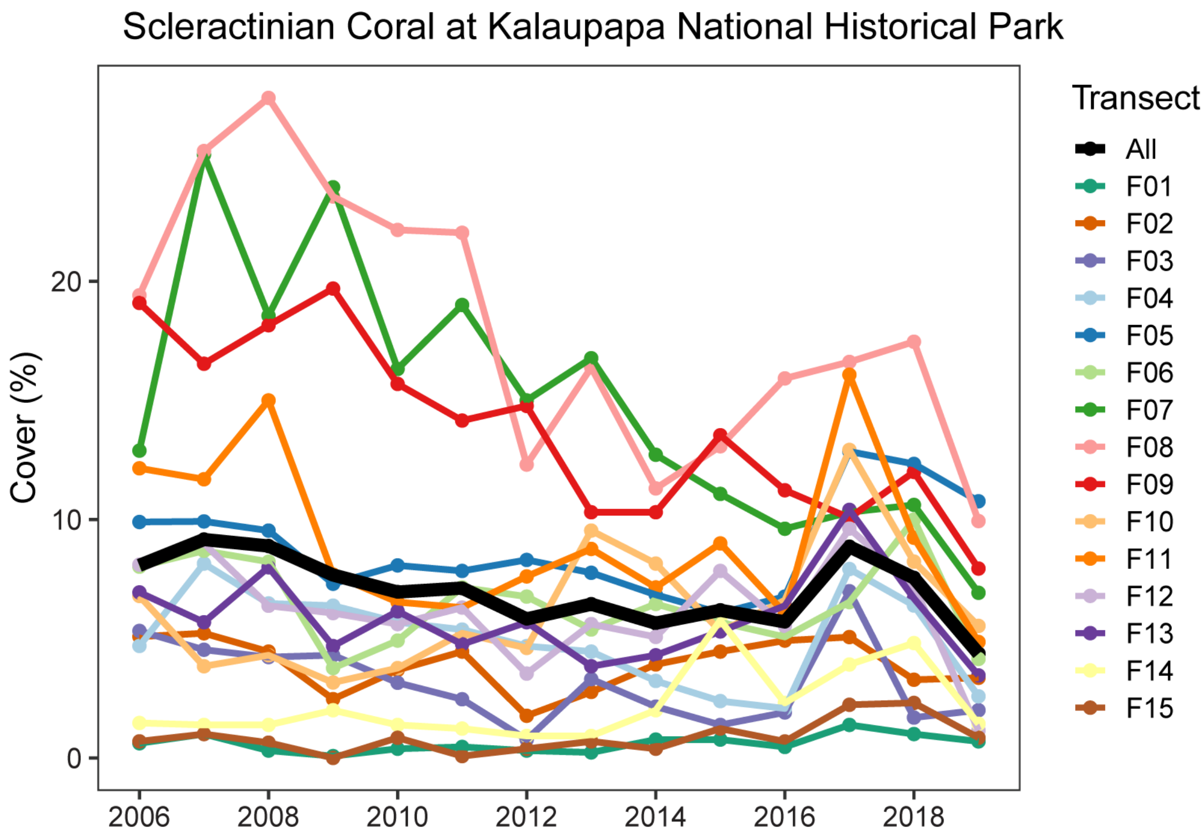

Figure 18. Percent cover of scleractinian coral at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at Kalaupapa National Historical Park 2006–2019. Black line represents mean percent cover calculated from all 15 transects for each year. Scleractinian coral cover declined significantly from 2006 to 2019 ($t(194) = -3.17$, $p = 0.002$), but there was no significant difference between coral cover in 2014 and 2016 ($t(14) = 0.01$, $p = 0.993$).

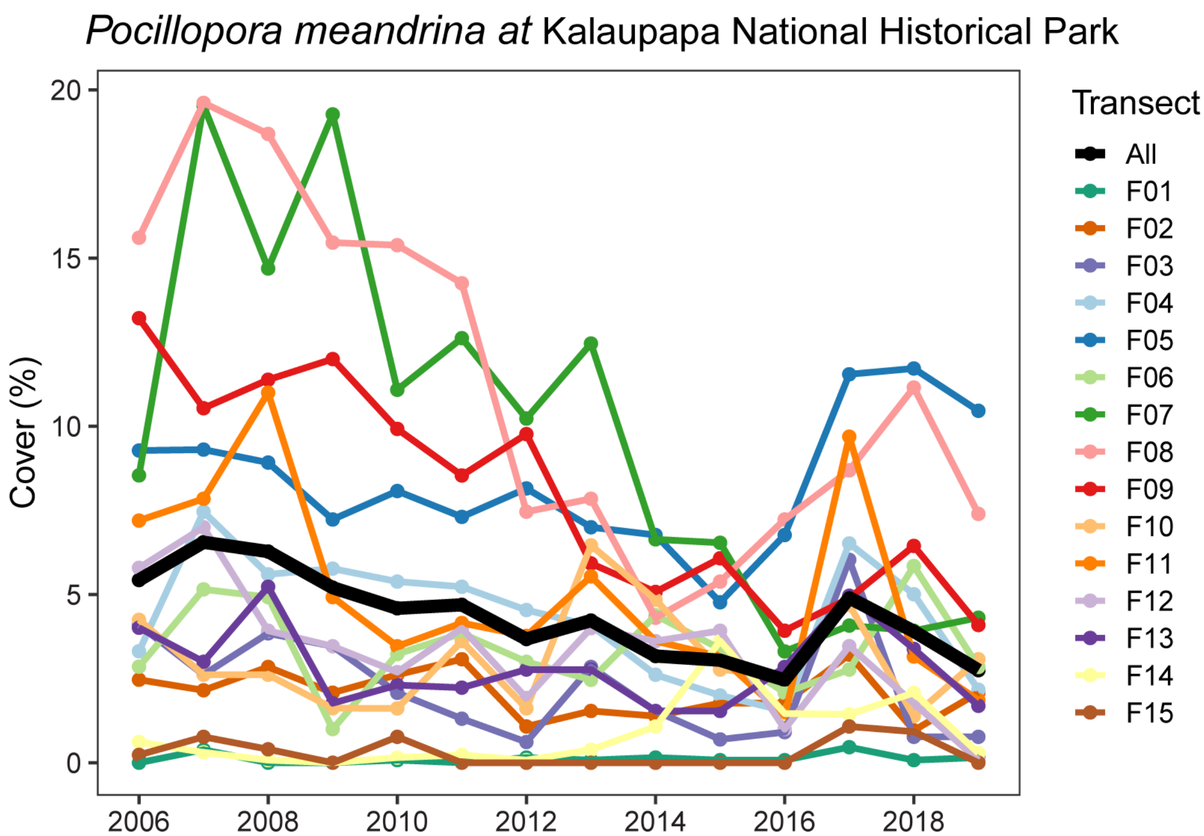

Figure 19. Percent cover of *Pocillopora meandrina* at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at Kalaupapa National Historical Park 2006–2019. Black line represents mean percent cover calculated from all 15 transects for each year. Cover of *P. meandrina* declined significantly between 2006 and 2019 ($t(194) = -5.41$, $p < 0.001$), but there was no significant difference between cover in 2014 and 2016 ($t(14) = 1.86$, $p = 0.084$).

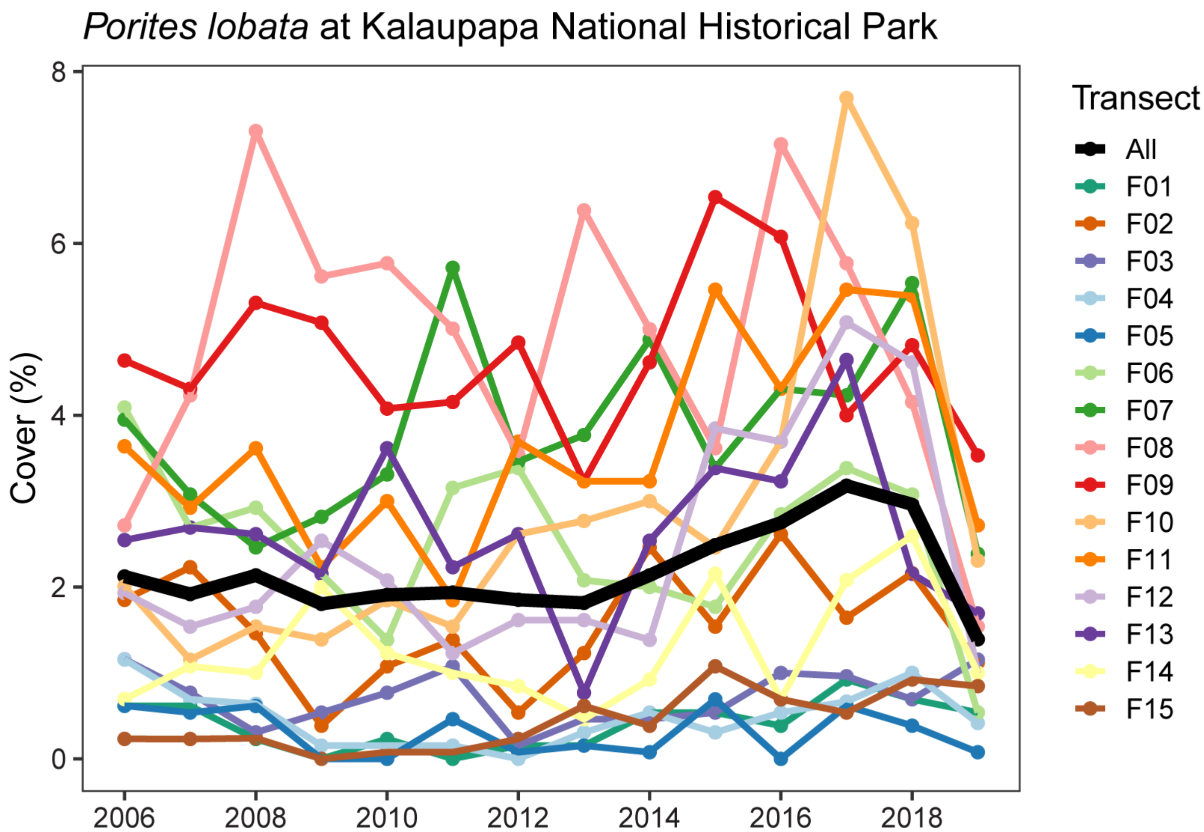

Figure 20. Percent cover of *Porites lobata* at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at Kalaupapa National Historical Park 2006–2019. Black line represents mean percent cover calculated from all 15 transects for each year. Cover of *P. lobata* declined significantly between 2006 and 2019 ($t(194) = 3.02$, $p = 0.003$) but increased significantly between 2014 and 2016 ($t(14) = -2.33$, $p = 0.035$).

Despite faring well after the 2014–2017 GCBE, bleaching and mortality remains a serious concern for the reefs of KALA. The bleaching recorded in 2019, highlights this issue. Bleached cover ranged from 0 to 66% by transect with no spatial pattern (Figure 21). Depth, date of survey, and species composition do not account for the range in bleaching. Bleached cover for the two most abundant coral species was 30% for *P. meandrina* and 8% for *P. lobata*. Bleached cover was also high, 42%, for *Montipora* spp., which accounted for less than 1% of the benthic cover. Future surveys will reveal whether bleaching-related mortality has occurred. Reports from west Hawaiʻi Island and across the state have shown that *P. meandrina,* which accounts for more than half of the coral cover at KALA, is highly susceptible to bleaching and is prone to high post-bleaching mortality (Kramer et al. 2016, Maynard et al. 2016, University of Hawaiʻi 2017, DLNR 2019). As a result of mass mortality of this species following the 2015 bleaching event in the main Hawaiian Islands, *P. meandrina* was considered for listing as a threatened or endangered species under the Endangered Species Act (NOAA National Marine Fisheries 2018), but listing was found to be not warranted at this time (NOAA National Marine Fisheries 2020).

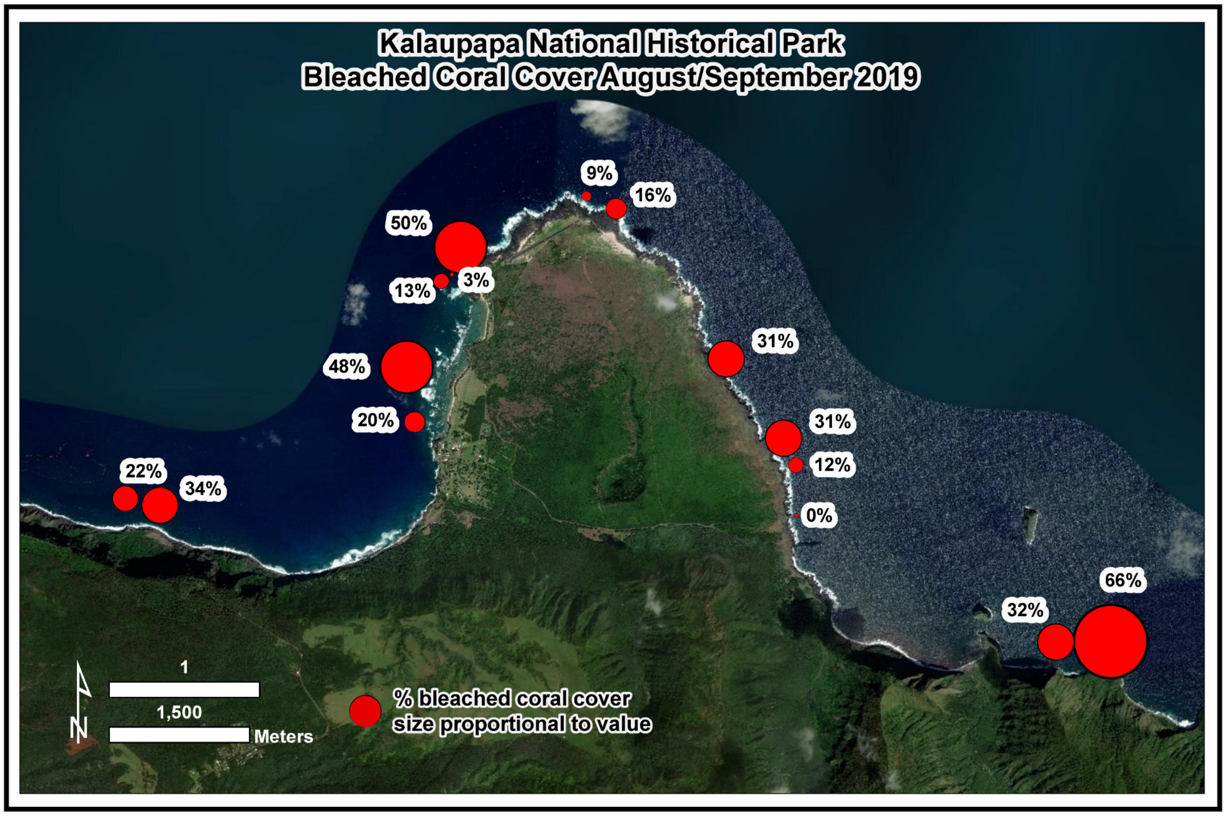

Figure 21. Percent bleached cover in August/September 2019 at the 15 fixed transects at Kalaupapa National Historical Park. Bubble size is proportional to percentage.

National Park of American Samoa (NPSA)

Benthic cover was surveyed annually at 15 fixed transects at NPSA from 2007 to 2019. Surveys were occasionally conducted during or just after the warmest month of the year, but time of survey was not consistent year to year (Table 7). Therefore, these surveys may not have recorded the full extent of coral bleaching that occurred. Two notable heat stress events that resulted in widespread bleaching in American Samoa occurred in 2015 and 2017 (Eakin et al. 2017, Sudek and Lawrence 2016, Lawrence 2017, Morikawa and Palumbi 2019). The DHW index peaked at 3.0 °C-weeks (Warning Level) in April 2015 and 8.5 °C-weeks (Alert Level 2) in February 2017 (NOAA 2020). Both years, PACN surveys were conducted while the reefs were exposed to heat stress (Table 7); therefore, these surveys likely captured most of the bleaching on the park's reef slopes. In April 2016, NOAA (2020) indicated that the reefs experienced Alert Level 1 heat stress, but very little bleaching was observed on the reefs by local scientists and NPS staff (Lawrence 2017). Data on coral bleaching were collected only as the presence or absence of bleaching and/or disease (one score per photo) for most years. The *post hoc* point-by-point bleaching analysis was not warranted because the percentage of images containing bleaching and/or disease was low (Table 7). The exceptions are 2014, 2015, 2017, 2018, and 2019, when bleaching and/or disease was observed in more than 30% of photos. For those years, the in-depth point-by-point analysis revealed low bleached cover (Table 7, Figure 22).

The percent bleached cover was greatest in 2015 (6.4%) and 2017 (8%) during the peak heat stress events for each year (2015: Warning Level and 2017: Alert Level 2) (Table 7). Although no quantitative data was collected by other agencies for bleaching on reef slopes in Tutuila in 2015, Sudek and Lawrence (2016) estimated 1–10% of corals were bleached depending on site. Bleaching was more severe on reef flats and shallow backreef pools, with up to 100% of staghorn *Acropora* colonies affected and high mortality (Sudek and Lawrence 2016, Lawrence 2017). In 2017, more extensive bleaching on reef slopes was reported by local scientists (Lawrence 2017), and bleached cover ranged from 0 to 21% by transect on PACN transects with no apparent spatial pattern (Figure 22). In March–April 2017, NPSA marine staff observed coral colonies bleaching on shallow and deep reefs both inside and outside the park waters up to 130 ft (40 m) (I. Moffitt, personal communication, July 26, 2021, Lawrence 2017). Severe bleaching was again observed on reef flats and backreef pools on Tutuila in 2017, this time affecting both the highly susceptible staghorn *Acropora* as well as the more heat-tolerant *Porites* colonies (Lawrence 2017). In 2017, bleaching was also reported in Ofu within shallow coral nurseries and their parent reefs (Morikawa and Palumbi 2019) and in the historically heat-tolerant backreef pools (Lawrence 2017).

Table 7. Sampling timeframe, temperature data and observed bleaching at National Park of American Samoa. Information is for fixed transects (n = 15) by year (2007–2019) with a comparison of months that surveys were conducted to warmest reported month, average weekly SST for that month, and maximum degree heating week (DHW) value recorded for the year as derived from NOAA (2020). The percent of images where bleaching and/or disease were present (one value per transect derived from presence/absence score by photo) is reported. The percent of bleached coral cover (as a percent of total coral cover) is reported for 2014, 2015, 2017–2019, when bleaching and/or disease was greater than 30%. For these years a *post hoc* analysis of all coral points identified along transects was conducted to quantify those that were bleached.

Time Frame		Temperature Data (Tutuila, American Samoa [NOAA 2020])			Observations	
Year	**Month(s) Surveys Conducted**	**Warmest Month**	**Average Weekly SST (°C)**	**Max DHW (°C-week)**	**Images with bleaching and/or disease (%)**	**Bleached Coral Cover (%) ***
2007	Feb, Mar	Apr	29.8	0	22.9	*N.D.*
2008	Mar	Dec	29.0	0	18.9	*N.D.*
2009	Mar	Mar	29.7	0	4.4	*N.D.*
2010	Mar, Apr	Feb	29.9	0	10.2	*N.D.*
2011	Mar, Apr	May	29.1	0	6.4	*N.D.*
2012	Jun, Sep	Dec	29.5	0	4.4	*N.D.*
2013	Apr, May, Aug	Apr	29.8	0	15.1	*N.D.*
2014	Apr, May	Feb	29.9	0	56.7	2.5
2015	Mar, May	Mar	30.1	3.0 (Apr)	62.2	6.4
2016	Mar, Jun	Dec	30.1	6.1 (Apr, May)	10.4	*N.D.*
2017	Mar, Apr	Jan	30.1	8.5 (Feb)	67.5	8.1
2018	Jun, Aug, Sep, Oct	Jan	29.7	0	39.5	0.7
2019	Apr, May	Apr	30.1	5.0 (Apr)	34.4	1.7

* 2007–2013 and 2016 presence of bleaching and/or disease is less than 30% so bleached cover analysis was not conducted. N.D. = No data.

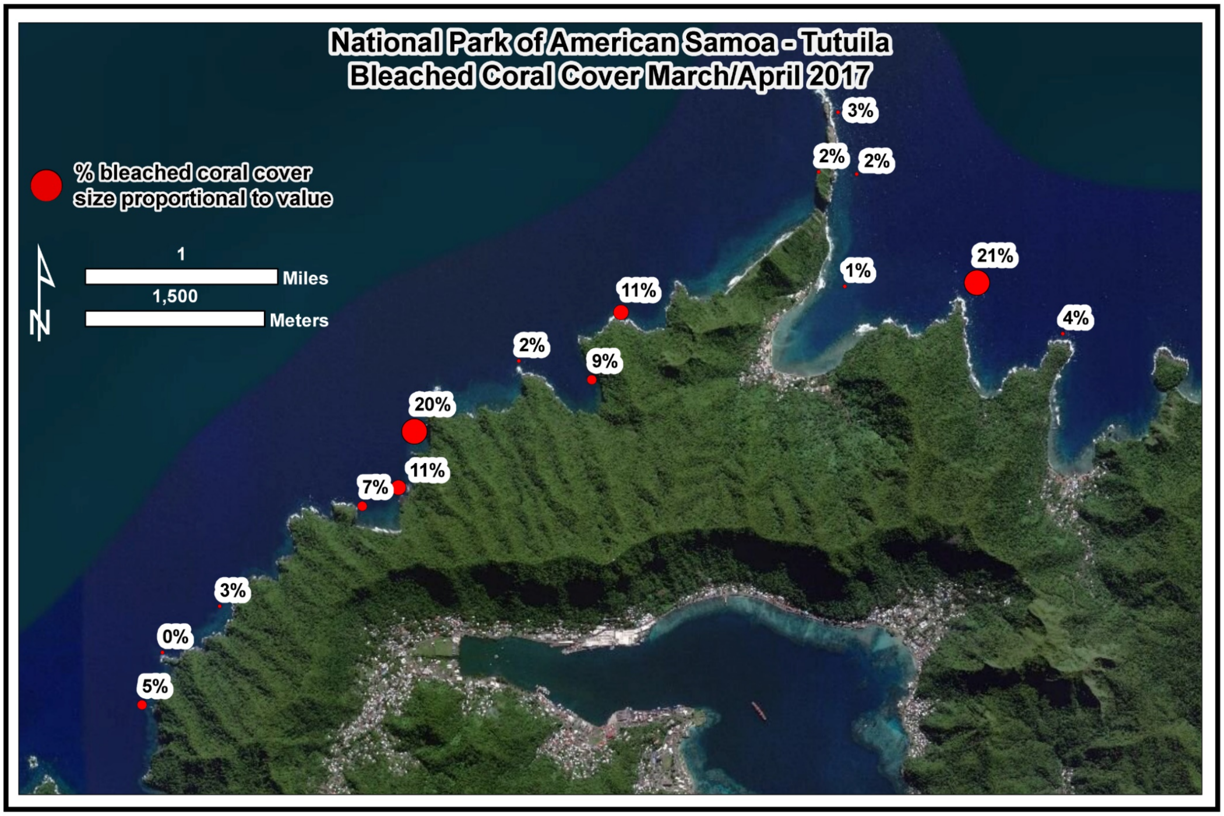

Figure 22. Percent bleached cover in March/April 2017 at the 15 fixed transects at NPSA. Bubble size is proportional to percentage.

Any significant change in benthic cover resulting from severe bleaching would be recorded in the annual surveys (Figure 23). There was no statistically significant change in scleractinian coral cover between 2014 (before the reported bleaching events) and 2018 (after the bleaching events) ($t(14) = 0.64$, $p = 0.534$). Over the 12-year survey period, scleractinian coral cover increased significantly on fixed transects (Figures 23 and 24, $t(179) = 3.28$, $p = 0.001$) from 23.6% (95% CI = 18.9–28.4%) to 33.4% (95% CI = 27.5–39.3%). Notably, some sites saw large changes in cover, while others remained relatively stable. F12 and F13 saw steep declines in coral cover between 2008 and 2011 (Figure 24). These declines are likely in response to the tsunami that occurred in September 2009 and Hurricane Wilma that passed through the area in January 2010. Fenner (2013) reported stable or increasing cover at 10 monitoring sites around American Samoa from 2005 to 2012, but one site, Vatia, which is near to F12 and F13 saw a similar decline in cover from 2008 to 2011. Coral cover at both F12 and F13 have since recovered (Figure 24). Both the decline and recovery are likely due to the quick-growing, yet fragile, *Acropora* and *Montipora* species that dominate those sites (Figure 24).

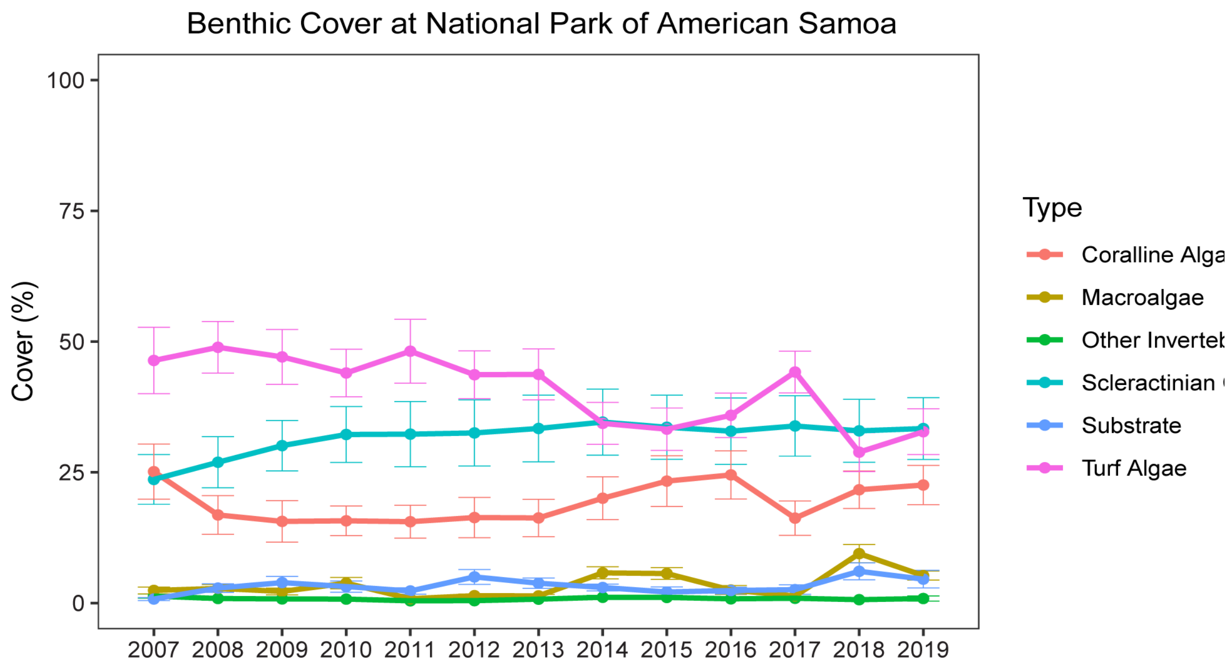

Figure 23. Mean percent benthic cover by type (color-coded) on fixed transects (n = 15) by year at the National Park of American Samoa 2007–2019. Error bars are the 95% confidence interval centered on the mean. Scleractinian coral cover increased significantly from 2007 to 2019 ($t(179) = 3.28$, $p = 0.001$). This is shown in more detail in Figure 24.

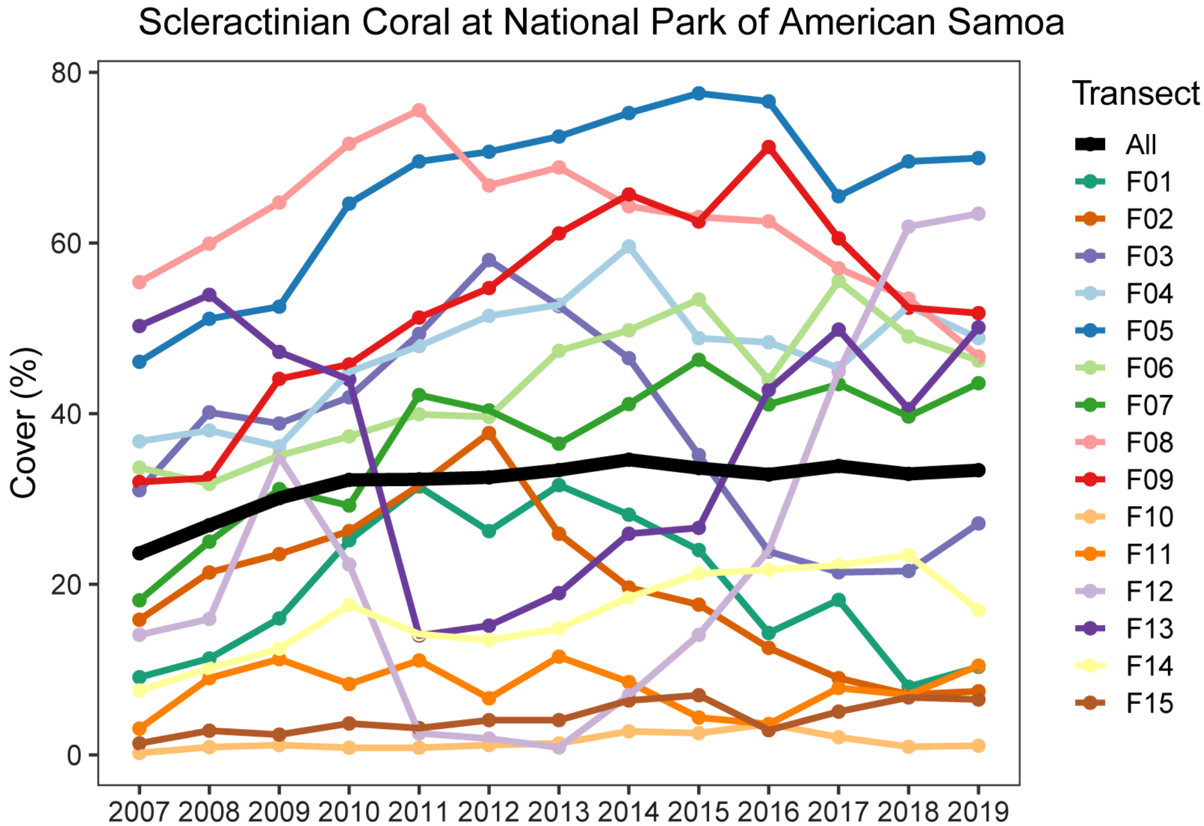

Figure 24. Percent cover of scleractinian coral at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at National Park of American Samoa 2007–2019. Black line represents mean percent cover calculated from all 15 transects for each year. Scleractinian coral cover increased significantly from 2007 to 2019 ($t(179) = 3.28$, $p = 0.001$).

In 2017, percent bleached cover for the most abundant coral taxa was 1% for *Montipora* spp., 0% for *P. rus*, 32% for *Porites* spp., 14% for *Acropora* spp., and 15% for *P. varians*. Of these, *Montipora* spp., *Porites* spp., and *P. varians* saw significant change over the survey period of 2007 to 2019 (Figures 25 to 29). Cover of *Montipora* spp. increased from 9.5% (95% CI = 7.0–11.9%) to 17.6 % (95% CI = 13.2–22.0%, t(179) = 3.59, $p < 0.001$), and saw no significant change from 2014 to 2018 (before and after the bleaching events, $t(14) = 0.12$, $p = 0.910$). The overall increase was mostly driven by a large increase in *Montipora* spp. cover at F12 (Figure 25). Cover of *Porites* spp. increased from 2.6% (95% CI = 1.5–3.7%) to 4.7% (95% CI = 3.0–6.3%, $t(179) = 2.96$, $p = 0.004$), and saw no significant change from 2014 to 2018, indicating that bleaching did not have long-term effects on cover ($t(14) = -0.51$, $p = 0.617$). Cover of *P. varians* decreased from 1.3% (95% CI = 0.5–2.2%) to 0.8% (95% CI = 0.5–1.1%, $t(179) = -2.71$, $p = 0.007$), but saw no significant change between 2014 and 2018 ($t(14) = 1.44$, $p = 0.173$), indicating the long-term change was likely not related to bleaching and heat stress. Change in *P. varians* cover was mainly driven by data from F08, which is the site with the greatest *P. varians* cover. The decline of P. varians beginning in 2011 at F08 may be due to a variety of confounding factors (e.g. recruitment, growth and competition). The increase in percent cover of the fast-growing weedy species, *P. rus* at F08 (Figure 26) suggests that *P. varians* may have been outcompeted by *P. rus*.

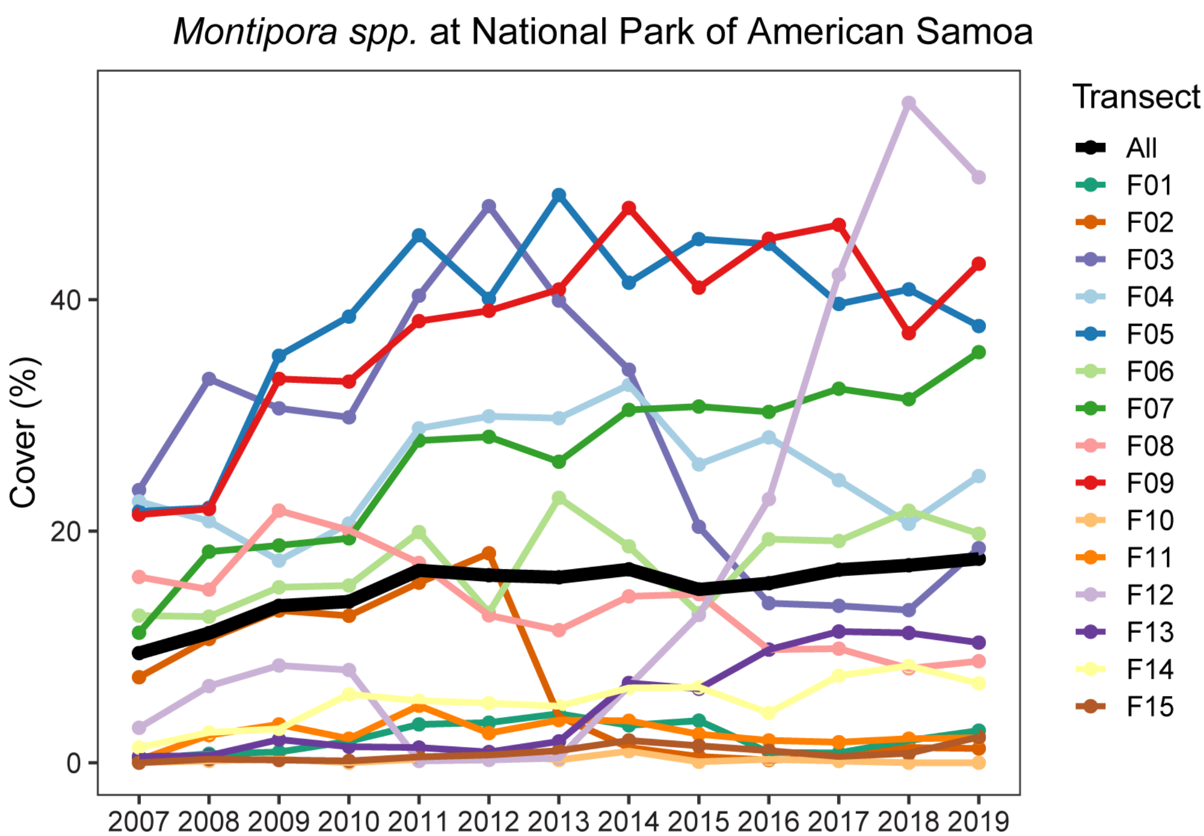

Figure 25. Percent cover of *Montipora* spp. at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at National Park of American Samoa 2007–2019. Black line represents mean percent cover calculated from all 15 transects for each year. Cover of *Montipora* spp. increased significantly from 2007–2019 ($t(179) = 3.59$, $p < 0.001$), and saw no significant change from 2014 to 2018 (before and after the bleaching events, $t(14) = 0.12$, $p = 0.910$).

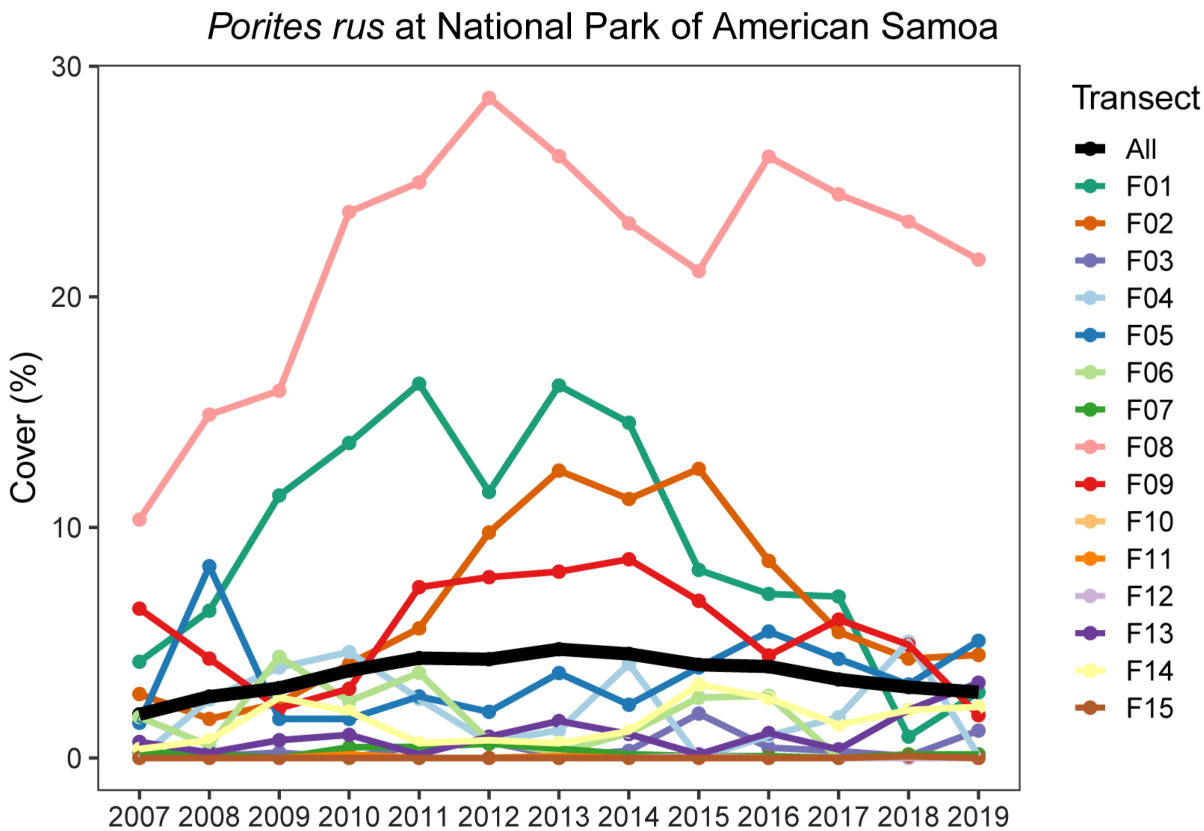

Figure 26. Percent cover of *Porites rus* at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at National Park of American Samoa 2007–2019. Black line represents mean percent cover calculated from all 15 transects for each year. There was no significant change in *P. rus* from 2007 to 2019 (t(179) = 0.87, p = 0.39).

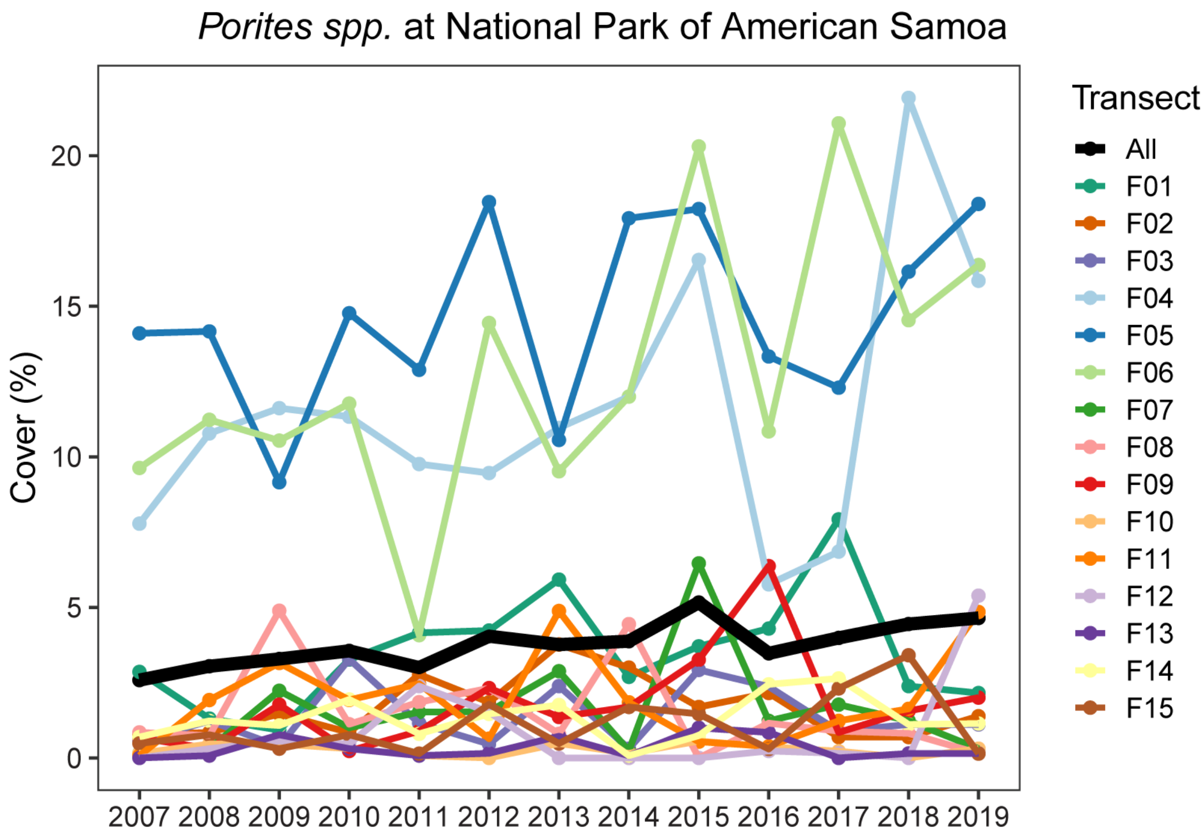

Figure 27. Percent cover of *Porites* spp. at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at National Park of American Samoa 2007–2019. Black line represents mean percent cover calculated from all 15 transects for each year. Cover of *Porites* spp. increased from significantly from 2007 to 2019 (t(179) = 2.96, p = 0.004), and saw no significant change from 2014 to 2018 (before and after the bleaching events, $t(14) = -0.51$, p = 0.617).

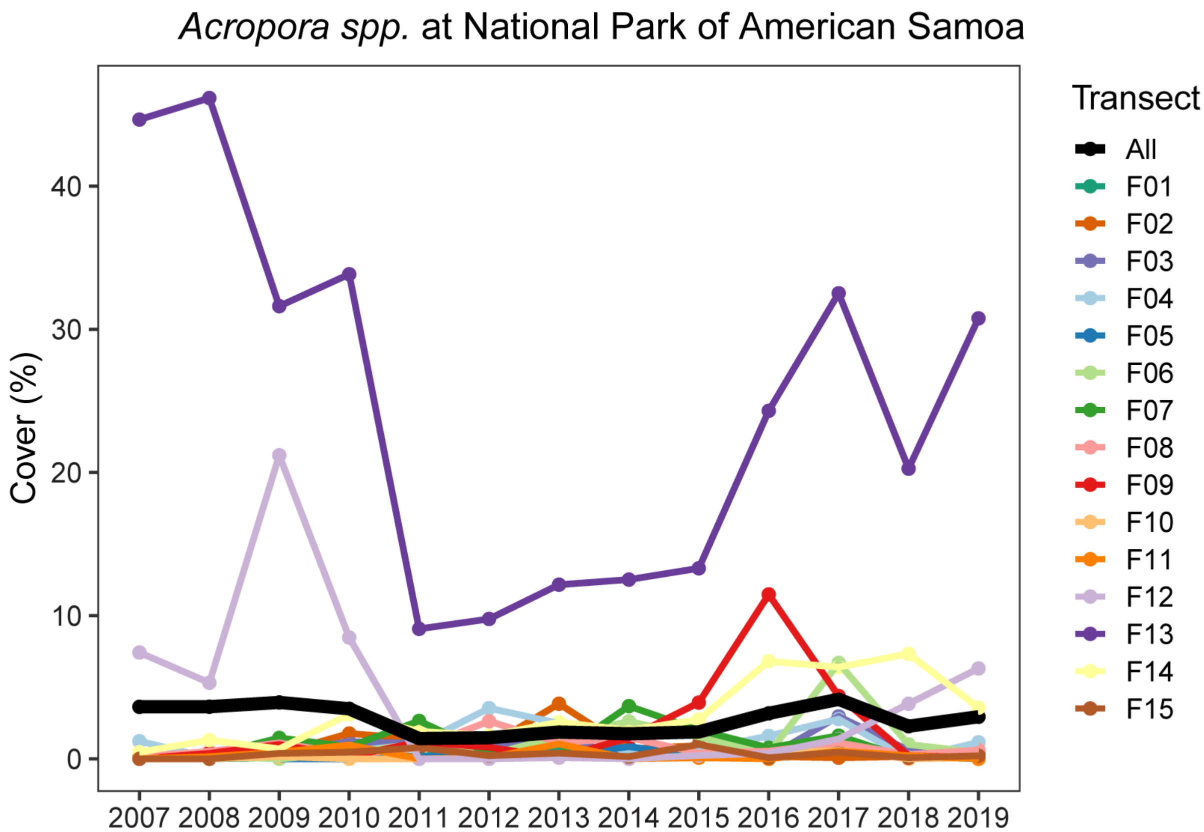

Figure 28. Percent cover of *Acropora* spp. at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at National Park of American Samoa 2007–2019. Black line represents mean percent cover calculated from all 15 transects for each year. There was no significant change in cover of *Acropora* spp. from 2007 to 2019 ($t(179) = 0.83$, $p = 0.41$).

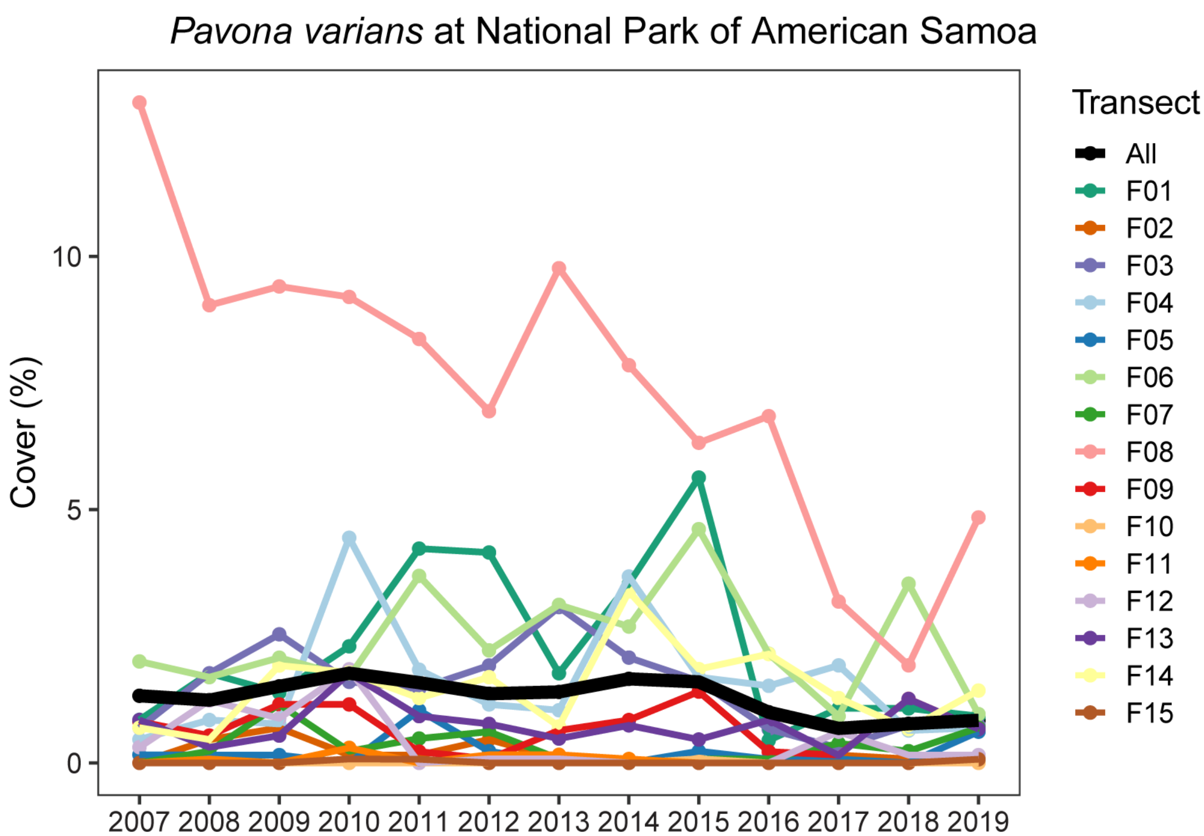

Figure 29. Percent cover of *Pavona varians* at the fixed transects (n = 15, where individual transects are color coded F01 through F15) at National Park of American Samoa 2007–2019. Black line represents mean percent cover calculated from all 15 transects for each year. Cover of *Pavona varians* decreased significantly from 2007 to 2019 (t(179) = −2.71, p = 0.007), but saw no significant change between 2014 and 2018 (before and after the bleaching events, $t(14)$ = 1.44, p = 0.173).

Even though bleaching does not appear to have significantly impacted coral cover on the fixed transects at NPSA during the survey period of 2007 to 2019, heat stress and bleaching remain threats to these reefs. Additional targeted surveys covering a broader reef area are recommended to ensure that the full extent of bleaching and other disturbances is recorded consistently. The reefs of American Samoa were reported to be some of the most hard-hit reefs during the 2014–2017 GCBE. (Eakin et al. 2016, Eakin et al. 2017, Vargas-Angel et al. 2019). PACN surveys provide important documentation of the 2015 and 2017 bleaching events, but these surveys are not always able to coincide with heat stress as that is not the main objective of the monitoring program. Therefore, it is recommended that targeted bleaching surveys are conducted when Alert Level 1 or 2 heat stress is detected on NOAA’s bleaching watch (NOAA 2020). Shallow backreef areas in Tutuila bleach annually, usually with little mortality (Fenner at al. 2008), but these reefs were greatly affected by severe bleaching and mortality in 2015 and 2017 (Sudek and Lawrence 2016, Eakin et al. 2016, Eakin et al. 2017, Fenner 2019). Backreefs on Ofu do not experience annual bleaching like Tutuila despite extreme temperature fluctuations. They are thought to have some natural bleaching resistance (Barshis et al. 2018, Morikawa and Palumbi 2019), but bleaching was reported to have affected these areas as well during 2017 (Lawrence 2017, Morikawa and Palumbi 2019). PACN surveys only target reef slope areas off Tutuila, but some shallow backreefs are also within the park boundaries (Craig et al. 2019). These shallow backreefs, have been observed to bleach and are likely to bleach in subsequent years; therefore, these areas should be considered for targeted bleaching surveys.

In the face of coral bleaching, reef resiliency is important to the survivorship of reefs. Schumacher et al. (2018) examined reef resiliency in Tutuila using data from NOAA's Reef Assessment and Monitoring Program. Sites on the north central area of Tutuila (designated "northeast" in the report), where the park is located, had medium-high resiliency scores compared to other sites around the island, which is encouraging. However, the study found that resiliency island-wide is impacted by highly manageable factors such as sedimentation, pollution, and fishing pressure. Crown-of-thorns seastars (COTs, *Acanthaster planci*) have also caused significant damage to reefs in American Samoa, reducing resiliency (Sudek and Lawrence 2016, Schumacher et al. 2018). A COTs outbreak was recorded within the parks areas in Tutuila in 2014 (Clark 2014), but there is no evidence of extensive damage on the PACN transects (Brown et al. 2016). Northeast Tutuila sites scored well for coral disease in the resiliency analysis (Schumacher et al. 2018), but coral disease is still an important factor for the health of the reefs of NPSA. Past studies have indicated that coral disease is widespread at low levels in American Samoa (Fenner et al. 2008, Aeby et al. 2008, Fenner 2019). Corals exhibiting apparent disease were common in the PACN benthic images, including both scleractinian corals and the hydrocoral *Millepora exaesa* (A. McCutcheon pers. obs.). This is reflected in the elevated bleaching and/or disease percentages reported for 2014, 2015, 2017, 2018, and 2019 compared to the low bleached cover values (Table 6). Coral disease levels may increase in response to heat stress (Brandt and McManus 2009, Brodnicke et al. 2019, Eakin et al. 2019). Benthic images are not a preferred method for quantitative study of coral disease (Raymundo et al. 2008). Additional *in situ* surveys of coral disease within the park is recommended.

War in the Pacific National Historical Park (WAPA)

Benthic cover was surveyed annually at 15 fixed transects at WAPA from 2008 to 2010 and 2014 to 2019. Surveys were conducted at 12 of the 15 fixed transects in 2011, and no surveys were conducted in 2012 and 2013. Surveys were conducted at least a month prior to the warmest month and before maximum DHW values were reached most years (Table 8). Therefore, these surveys likely did not record the full extent of coral bleaching that occurred. Data on coral bleaching were collected only as the presence or absence of bleaching and/or disease (one score per photo) through 2016. *Post hoc* point-by-point bleaching analysis was not warranted for the 2008 to 2016 surveys because the percentage of images containing bleaching and/or disease was less than 30%, indicating no widespread bleaching recorded by the survey (Table 8). Beginning in 2017, the in-depth point-by-point bleaching analysis was conducted simultaneously with the benthic cover analysis. This analysis was not targeted at a specific bleaching event, as no widespread bleaching was encountered during the surveys, but the analysis was added to the normal routine to capture information that might be helpful in assessing future bleaching events such as susceptible species (Maynard et al. 2017) and bleaching levels in the absence of heat stress (non-thermal bleaching, Raymundo et al. 2008, Ruiz-Moreno et al. 2012).

The percentage of images containing bleaching and/or disease was greatest in 2017 (29.7%). This value corresponded with 2.6% percent bleached cover. These results are in stark contrast to other studies around Guam, which reported severe bleaching nearly annually from 2013 to 2017 (Reynolds 2016, Burdick and Raymundo 2018, Raymundo et al. 2019). Two likely reasons for this discrepancy are 1) time of survey – PACN surveys were conducted before peak heat stress occurred, and 2) location – PACN surveys are conducted on the reef slope between 10 and 20 m (33 and 66 ft) depth, and the severe bleaching was mostly recorded on Guam's shallow reef flats and exposed shallow seaward slopes (2–6 m/6–20 ft depth, Reynolds 2016, Raymundo et al. 2019). The Guam Coral Reef Response Team (GCRRT) provides the only record of the extent and severity of the 2013 to 2017 bleaching events in Guam (Burdick and Raymundo 2018, Raymundo et al. 2019). In 2013, GCRRT reported 32% bleached cover on shallow seaward slopes island-wide. Severe bleaching was observed, but not surveyed in 2014. In 2015 and 2016, GCRRT reported low bleached cover on shallow seaward slopes with severe bleaching on reef flats. In 2017, GCRRT reported the most severe bleaching event to date with 48% bleached cover on shallow seaward slopes island-wide (Burdick and Raymundo 2018, Raymundo et al. 2019).

Table 8. Sampling timeframe, temperature data and observed bleaching at War in the Pacific National Historical Park. Information is for fixed transects (n = 15) by year (2008–2019) except for 2011 (where n = 11) with a comparison of months that surveys were conducted to warmest reported month, average weekly sea surface temperature (SST) for that month, and maximum degree heating week (DHW) value recorded for the year as derived from NOAA (2020). The percent of images where bleaching and/or disease were present (one value per transect derived from presence/absence score by photo) is reported. Bleached cover (as a percent of total coral cover) is reported for surveys 2017–2019 after that analysis was added to the monitoring routine. For these years, all coral points identified along the transects were given an additional score to indicate whether bleaching was present.

Time Frame		Temperature Data (Santa Rosa, Guam [NOAA 2020])			Observations	
Year	**Month(s) Surveys Conducted**	**Warmest Month**	**Average Weekly SST (°C)**	**Max DHW (°C-week)**	**Images with bleaching or disease (%)**	**Bleached Coral Cover (%)**
2008	Jan, Feb	Sep	29.9	0	2.1	*N.D.*
2009	May	Jul	29.9	0	0.5	*N.D.*
2010	May	Aug	29.7	0	18.1	*N.D.*
2011	Aug	Jul	29.6	0	22.7*	*N.D.*
2012	*No surveys*	Sep	30.0	0	*N.D.*	*N.D.*
2013	*No surveys*	Sep	30.8	10.4 (Oct–Nov)	*N.D.*	*N.D.*
2014	Jun, Jul	Sep	29.9	2.6 (Jan)	13.8	*N.D.*
2015	Jul, Aug	Aug	29.6	0	26.4	*N.D.*
2016	May	Jul	30.1	4.0 (Sep–Oct)	26.4	*N.D.*
2017	May	Aug	30.7	10.3 (Oct)	29.7	2.6
2018	May	Jun	29.4	0.5 (Jan)	11.0	1.1
2019	Jun	Jul	30.0	1.6 (Aug–Sep)	25.4	3.1

Bleached coral cover became part of regular benthic data analyses in 2017. No *post hoc* analysis was conducted for 2008 to 2016 because less than 30% of images contained bleaching and/or disease. N.D. = No Data.

* n = 11 transects in 2011, n = 15 all other years

Although the PACN surveys do not provide information on the full extent of bleaching on the reefs of WAPA, any substantial bleaching-related mortality would be reflected in the annual live coral cover values. From 2008 to 2019 there was no significant change in live coral cover in the Asan (Figures 30 and 31, $t(60) = 1.49$, $p = 0.140$) or Agat units (Figures 32 and 33, t(70) = 0.43, $p = 0.668$). Cover remained stable at about 22% in Asan (2008 – 21.8%, 95% CI = 10.7–32.8%; 2019 22.3%, 95% CI = 15.6–29.0%) and 3% in Agat (2008 – 3.0%, 95% CI = 2.4–3.7%; 2019 – 3.4%, 95% CI = 2.4–4.0%). There was also no significant difference between live coral cover before (2010) and after (2018) the period of severe bleaching (Asan $t(6) = -0.11$, $p = 0.919$, Agat $t(8) = 0.43$, $p = 0.680$). This result is consistent with GCRRT data, which showed significant mortality on reef flats (2012–2017 36% decline) and shallow seaward slopes on the east/windward coast of Guam (2013–2017 59% decline), but no significant change in cover on seaward slope sites on the west/leeward coast where Asan and Agat are located (Raymundo et al. 2017, Burdick and Raymundo 2018, Burdick et al. 2019, Raymundo et al. 2019). The Guam Long-Term Coral Reef Monitoring Program found stable or increasing coral cover between 2010 and 2018 at their three monitoring locations (depths 7–15 m) on the west/leeward coast (Burdick et al. 2019).

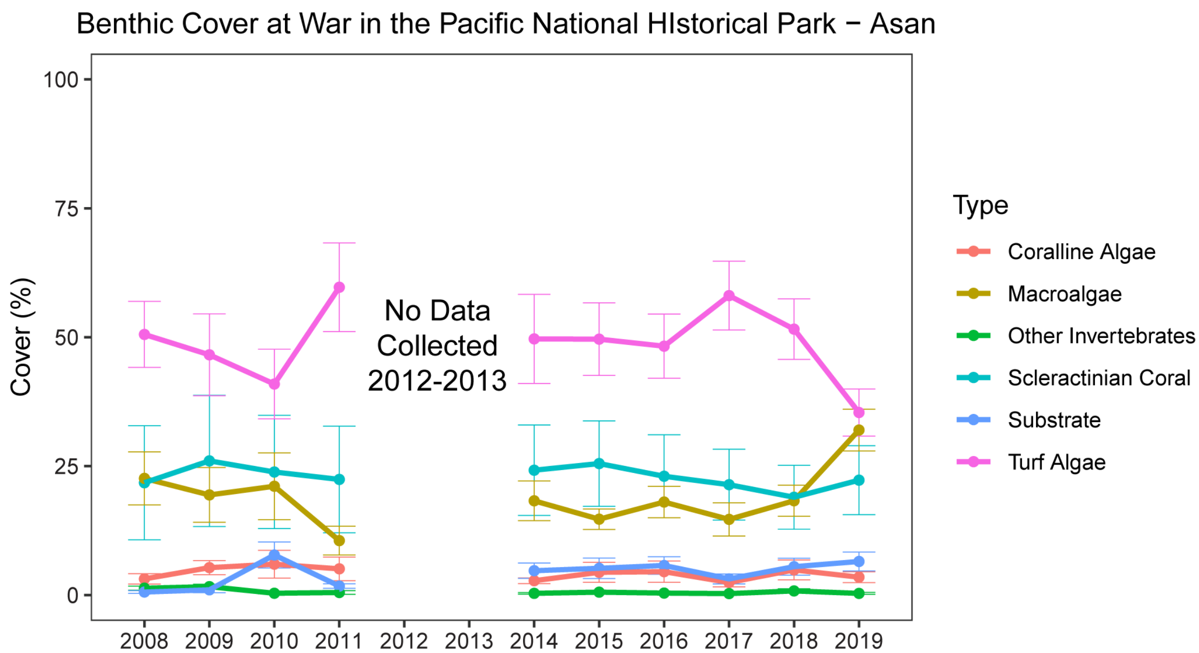

Figure 30. Mean percent benthic cover by type on fixed transects by year at the Asan marine unit of War in the Pacific National Historical Park 2008–2019 (n = 7 except for 2011 where n = 5, F01 and F07 were not surveyed). Error bars are the 95% confidence interval centered on the mean. No transects were surveyed 2012–2013. There was no significant change in scleractinian coral cover 2008–2019 ($t(60)$ = 1.49, p = 0.140).

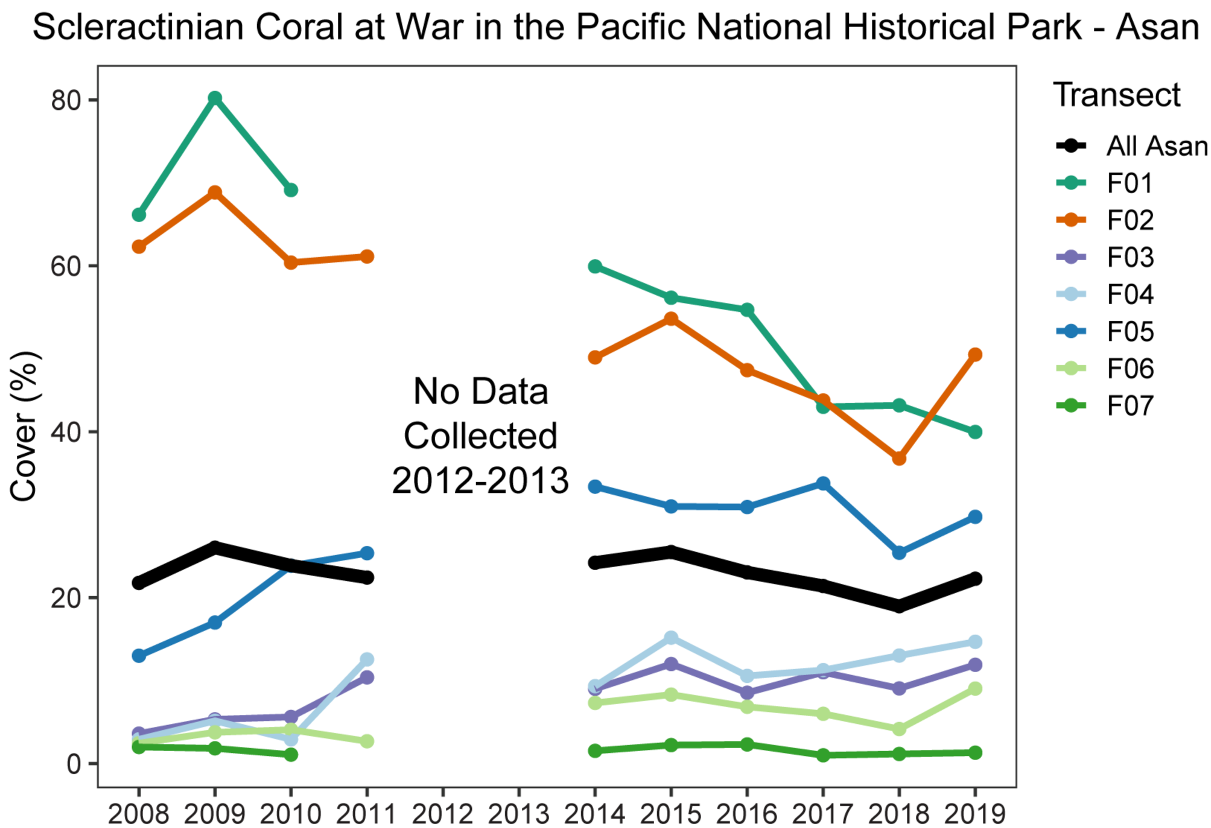

Figure 31. Percent cover of scleractinian coral on fixed transects by year at the Asan marine unit of War in the Pacific National Historical Park 2008–2019. Individual transects are color coded F01 through F07. Black line represents mean percent cover calculated from all transects surveyed for each year (n = 7 except for 2011 when n = 5, F01 and F07 were not surveyed). No surveys conducted 2012–2013. There was no significant change in scleractinian coral cover 2008–2019 ($t(60) = 1.49$, $p = 0.140$).

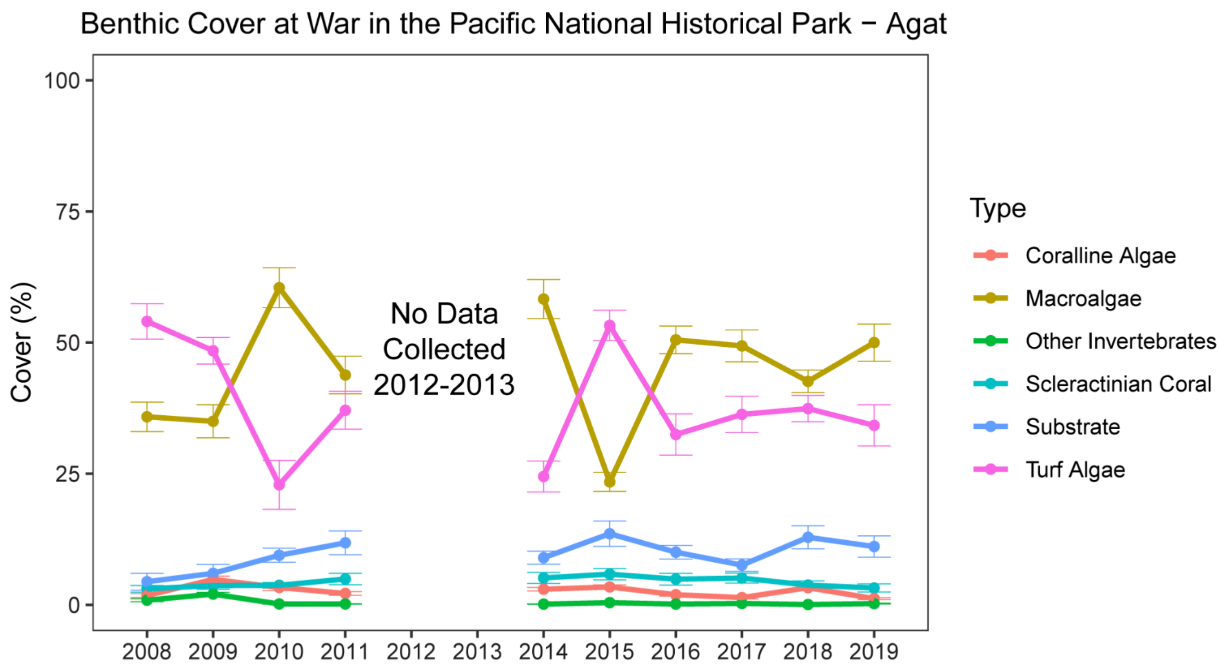

Figure 32. Mean percent benthic cover by type on fixed transects by year (n = 8 except for 2011 when n = 7, F12 was not surveyed) at the Agat marine unit of War in the Pacific National Historical Park 2008–2019. Error bars are the 95% confidence interval centered on the mean. No transects were surveyed 2012–2013. There was no significant change in scleractinian coral cover 2008–2019 ($t(70) = 0.43$, $p = 0.668$).

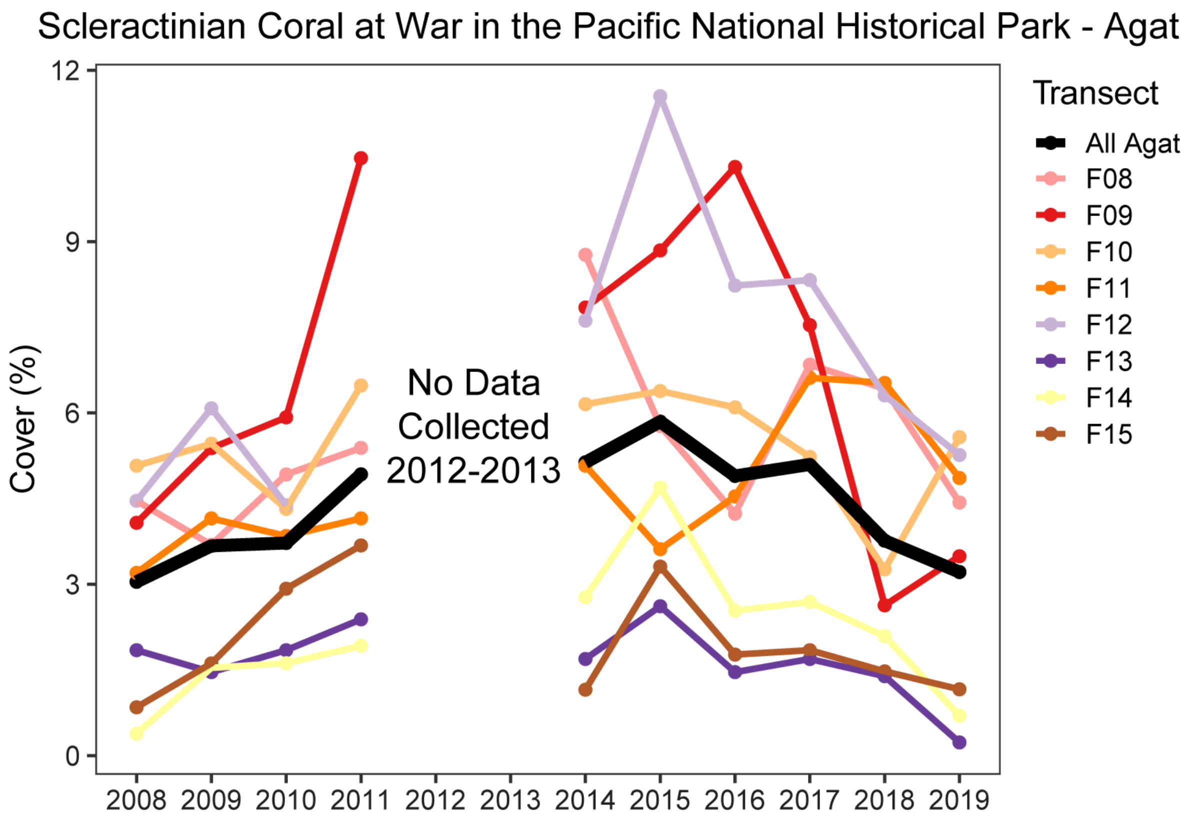

Figure 33. Percent cover of scleractinian coral on fixed transects by year at the Agat marine unit of War in the Pacific National Historical Park 2008–2019. Individual transects are color coded F08 through F15. Black line represents mean percent cover calculated from all transects surveyed for each year (n = 8 except for 2011 when n = 7, F12 was not surveyed). No surveys conducted 2012–2013. There was no significant change in scleractinian coral cover 2008–2019 ($t(70) = 0.43$, $p = 0.668$).

Species composition was an important factor distinguishing reefs that sustained significant mortality during the recent bleaching events in Guam and those that did not (Reynolds 2016, Raymundo et al. 2019, Burdick et al. 2019). Reefs composed of species in the genera *Acropora* and *Pocillopora* were found to be most susceptible to bleaching and subsequent mortality, while reefs dominated by *Porites* species showed low susceptibility to bleaching and no significant mortality (Reynolds 2016, Maynard et al. 2017, Raymundo et al. 2019). Massive *Porites* spp. is the most abundant coral taxa in both the Asan and Agat units (Figures 34 and 35). Significant gain of massive *Porites* spp. cover was detected over the survey period of 2008 to 2019 in both Asan and Agat (Asan $t(60) = 3.19$, $p = 0.002$, Agat $t(70) = 3.65$, $p < 0.001$). The change is most obvious at F05, but cover increased at 12 of the 15 sites. *P. rus* is also abundant in Asan, and no significant change was detected for *P. rus* in Asan between 2008 and 2019 ($t(60) = -0.37$, $p = 0.714$, Figure 36). In 2019, *Acropora* spp. and *Pocillopora* spp. accounted for 0.01% and 0.02% of the cover in Asan and 0% and 0.01% in Agat, respectively. High variability in detection of these species compared to low cover values made trend analysis impossible, but these values were greater than or equal to the cover values prior to the bleaching events (2010).

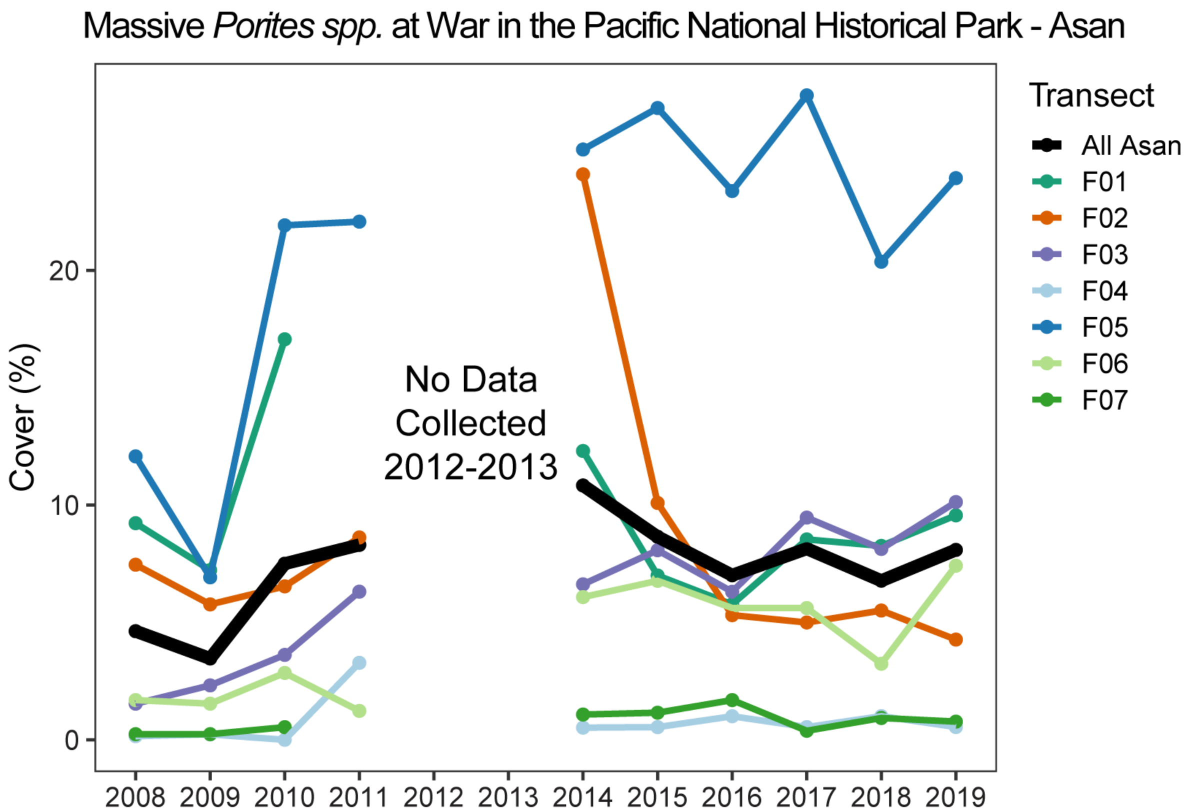

Figure 34. Percent cover of massive *Porites* spp. on fixed transects by year at the Asan marine unit of War in the Pacific National Historical Park 2008–2019. Individual transects are color coded F01 through F07. Black line represents mean percent cover calculated from all transects for each year (n = 7 except for 2011 when n = 5, F01 and F07 were not surveyed). No surveys conducted 2012–2013. Significant gain of massive *Porites* spp. cover was detected over the survey period of 2008 to 2019 ($t(60) = 3.19$, p = 0.002).

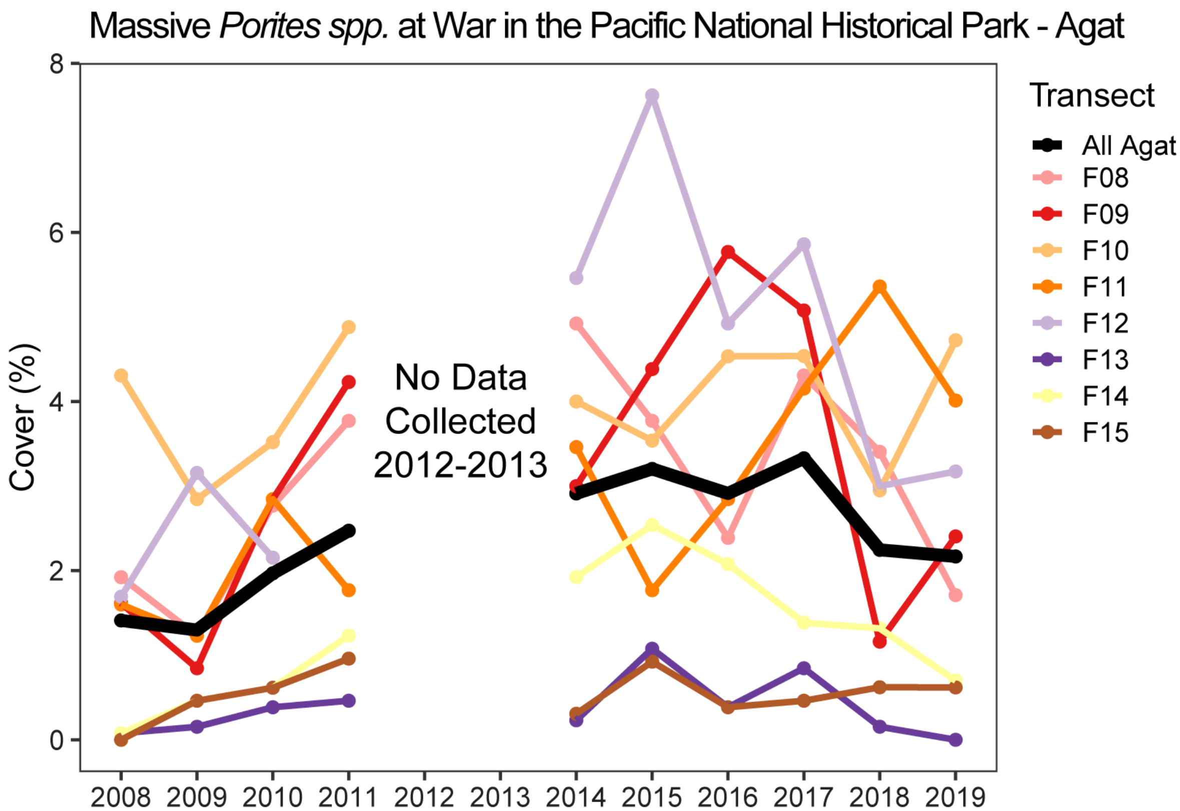

Figure 35. Percent cover of massive *Porites* spp. on fixed transects by year at the Agat marine unit of War in the Pacific National Historical Park 2008–2019. Individual transects are color coded F08 through F15. Black line represents mean percent cover calculated from all transects surveyed for each year (n = 8 except for 2011 when n = 7, F12 was not surveyed). No surveys conducted 2012–2013. Significant gain of massive *Porites* spp. cover was detected over the survey period of 2008 to 2019 (Agat $t(70) = 3.65$, $p < 0.001$).

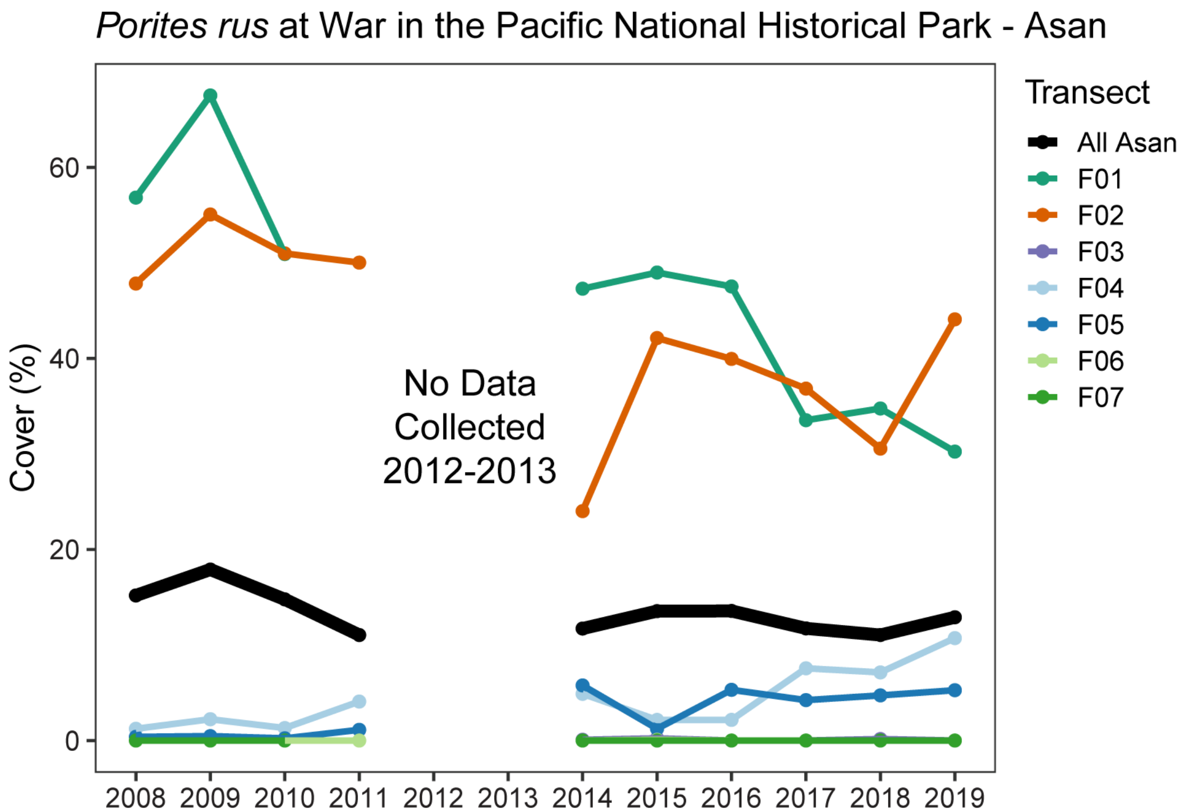

Figure 36. Percent cover of *Porites rus* on fixed transects by year at the Asan marine unit of War in the Pacific National Historical Park 2008–2019. Individual transects are color coded F01 through F07. Black line represents mean percent cover calculated from all transects surveyed for each year (n = 7 except for 2011 when n = 5, F01 and F07 were not surveyed). No surveys conducted 2012–2013. There was no significant change in *P. rus* cover 2008–2019 ($t(60) = -0.37$, $p = 0.714$).

Even though PACN surveys detected only low levels of bleaching and no discernable coral mortality on the reef slopes of WAPA from 2008 to 2019, bleaching remains an important metric in the monitoring program moving forward. Additional targeted surveys are recommended to monitor bleaching-susceptible species and locations within the park that are excluded by the current PACN protocol (Brown et al. 2011b). The GCRRT data showed that reef flat sites and areas dominated by *Acropora* and *Pocillopora* species were hit hard by the bleaching events (Reynolds 2016, Raymundo et al. 2017, Burdick and Raymundo 2018, Raymundo et al. 2019), and susceptible coral communities of these types exist within the park boundaries in both the Asan and Agat marine units (Amesbury et al. 1999, Raymundo et al. 2017, A. McCutcheon pers. obs.). One such site within the Asan unit was included in the reef flat sites monitored by Raymundo et al. (2017), and that site suffered an estimated 30% mortality from the 2014 bleaching event alone.

In addition to the concern over bleaching, coral disease is a potential threat to the reefs of WAPA. The proportion of images containing bleaching and/or disease has been consistently above 10% since 2011 despite low observed levels of bleaching (Table 8). Disease states observed in the images commonly include white syndrome and growth anomalies affecting *Porites* colonies (A. McCutcheon pers. obs.).

Meyers and Raymundo (2009) observed that the most abundant corals on Guam's reefs (including *Porites*) were also most affected by disease, which has the potential to have negative effects on the long-term health of Guam's reefs. Targeted studies on the prevalence of coral disease in the park and implications for long-term management of the reefs is recommended.

Another possible confounding threat is COTs (*A. planci*). COTs have been known to outbreak in Guam, severely damaging reefs (Hoot 2017). The triggers for COTs population outbreaks are a debated range of factors while the scale of the outbreaks is local (Timmers et al. 2011 and 2012). COTs are known to feed selectively, preferring fast-growing, branching corals like *Acropora* spp. over slower growing corals like *Porites* spp. (De'ath and Moran 1998, Pratchett 2001). This is particularly troublesome because the most bleaching susceptible species are among those most preferred by COTs, which can have impacts on diversity on the reef. Reefs such as those in Asan and Agat that are already dominated by *Porites* spp. (possibly due to historic COTs outbreaks, Burdick et al. 2019) are not as likely to see huge coral cover loss to COTs outbreaks, but COTs may reduce the already low diversity by eliminating preferred species from the area. COTs have also been observed feeding on less preferred coral such as *Porites* spp. when preferred species are less available (Burdick et al. 2008). COTs are occasionally noted in PACN transects and an outbreak could significantly reduce the reef's resiliency to withstand future coral bleaching events (Brown et al. 2016, Hoot 2017, PACN et al. 2021).

Summary and Recommendations

Summary

The PACN benthic monitoring protocol is designed to assess long-term trends in the abundance of macroinvertebrates and algae on nearshore hardbottom substrate (10–20 m, 33–66 ft) at 30 transects (15 fixed, 15 temporary) annually within each park. In this study, analysis of the 15 fixed transects in each park is reported. At KAHO, benthic community changes were related to coral bleaching mortality where coral cover was reduced by 63% (from 33% to 12% cover) between 2014 and 2016 in direct response to the unprecedented bleaching event that struck the park's reefs in 2015. At KALA, a significant decline in coral cover was detected from 8% to 4% between 2006 and 2019, but this decline is not suspected to be related to coral bleaching. At NPSA, coral cover significantly increased from 24% to 33% between 2007 to 2019, with no significant changes in cover detected related to recorded bleaching in 2015 and 2017. At WAPA, no significant changes were detected in coral cover between 2008 and 2019 nor in relation to suspected bleaching events; cover remained stable at about 22% in Asan and 3% in Agat.

Monitoring Recommendations

The ability of PACN surveys to assess bleaching and mortality in each park was limited by the chosen spatial design of the benthic community protocol and the nature of spatial variability in heat stress and species composition of the reefs. The PACN surveys target the reef slope communities between 10 and 20 m (33 and 66 ft) at each park, but shallower reef areas, especially coral-dominated reef flats, typically experience greater heat stress and are the location of the most severe bleaching and mortality documented by others in both Guam and American Samoa, where WAPA and NPSA are located, respectively. Reef flats are also subject to low tide events that do not affect reef slopes. Benthic communities in reef flat areas within the parks are also comprised of bleaching-susceptible species such as *acroporid* and *pocilloporid* species. We recommend fixed shallow (depth less than 10 m) reef transects be established at KAHO, WAPA, and NPSA, covering the range of variation in coral cover and taxa present within the park's shallow reef systems (Due to wave exposure, KALA does not have substantial shallow reef communities, and rough weather and difficult access would prevent safe survey areas less than 10 m.). These transects may require SCUBA or snorkel surveys depending on the park's unique conditions and should be photographed annually. Transect photos should be analyzed using the same point-count methods as the current PACN transects, including point-by-point bleaching assessment.

PACN benthic surveys provided valuable information on the extent and severity of bleaching on fixed transects when sampling coincided with heat stress at KAHO and NPSA during the 2014–2017 GCBE but provided only limited opportunity to assess bleaching at KALA and WAPA due to the typical month(s) of the PACN benthic survey not corresponding with heat stress events. At KAHO, severe coral bleaching with 77% bleached cover was recorded in October 2015 near the peak of the heat stress event. At NPSA, only low bleached cover values were recorded on the fixed transects during the heat stress events in 2015 and 2017. The missed opportunity to assess the extent and severity of bleaching during the GCBE is due to temporal factors at KALA and WAPA. Neither park was covered by other bleaching assessment efforts. This highlights the need for targeted bleaching surveys when heat stress is detected. The existing PACN surveys could be adjusted to occur during warmest months for KALA and WAPA to improve bleaching assessment. However, the warmest SST months overlap at KALA, KAHO, and WAPA, field staff is limited, and higher temperatures usually coincide with tropical storm (hurricane/typhoon) season and rougher ocean conditions, so intensive fieldwork at peak SST may not be practical or safe every year.

In addition to bleaching, other disturbances (e.g. coral diseases, COTs outbreaks, and storms) occur and more spatial coverage of the reefs within each park is needed. Coral diseases were not discussed fully in this report as PACN does not monitor coral disease quantitatively, but it is apparent in the data that coral diseases are present within the parks and requires further study. Coral diseases were observed commonly on transects in KAHO, NPSA, and WAPA. PACN and the parks should work together to submit inventory projects to assess coral diseases in the parks. Population outbreaks of COTs can occur at any time and are a concern in PACN parks as well, especially for NPSA and WAPA. Further, damage from tropical storms, tsunamis, and human activities (boat anchoring, groundings, etc.) are of concern to the reefs.

When a disturbance occurs, it is vital to have some record of the before, during, and after stages of the reef. Therefore, we recommend frequent broad-scale manta tow surveys (using snorkel or scuba pending depth; [Hill and Wilkinson 2004]) of the coral reefs be implemented within each park. Towed snorkeler and/or towed diver survey standard operating procedures developed and implemented by Australian Institute of Marine Science (Moran et al. 1989; Miller et al. 2018) and NOAA (Lino et al 2018) can be modified for each parks' needs. Ideally, manta tow surveys would occur at least monthly during the warmest months of the year and bi-monthly throughout the rest of the year to compliment the PACN benthic monitoring. If a NOAA bleaching watch or warning is issued for the region, we recommend increasing the frequency of manta tows to bi-weekly, if possible, until the warning level is downgraded to "no stress". Manta tows allow large areas of the reef to be surveyed with minimal equipment and staff time. Surveyors should record estimates of live coral cover, approximate boundaries of the disturbance, estimated percentage of coral or substrate affected by the disturbance, and any other information of interests (i.e. COTs counts). Details of the exact route and timing for the manta tows should be selected on a logistical and historical basis by the natural resource managers and staff in each park and in collaboration with PACN and other agencies, but it should be as broad as possible and include the areas of reef where PACN transects are located. Shallower reef areas that are inaccessible by boat for manta tow should be observed by snorkeling from shore using a similar broad-scale approach with the same frequency of survey as the deeper reef areas. We recognize that the frequency of survey proposed will not be possible at all locations. For example, KALA does not have access to a boat during much of the year so winter manta tows will be impossible. If frequent manta tow surveys are not practical at KAHO, NPSA, and WAPA, the parks can consider soliciting observations through citizen science programs and park users such as local fishers and commercial dive and tour operations that regularly spend time in the park. PACN will work with park resource staff to determine the best strategy for individual parks. In order to more thoroughly document the disturbance and its effect on the reef, when a disturbance (i.e. bleaching, COTs, storm damage) is detected through these broad-scale surveys, we recommend that this triggers a rapid-response survey of the PACN fixed transects (and other park sites of interest), followed by frequent additional surveys of the transects until the event is over.

The 2014–2017 GCBE was an unprecedented event, but heat stress events are predicted to become more frequent and severe. Continued monitoring of the benthic assemblages along these PACN transects within the parks will provide valuable insight into how corals and reef ecosystems respond to global environmental change. Continuous sea temperature loggers are deployed at several transects at KAHO beginning in October 2016 and WAPA beginning June 2019 to monitor small-scale variations in heat stress that may influence coral bleaching. Loggers are also deployed at two transects at KALA since October 2005. These data combined with NOAA's bleaching alert system data, which was refined in scale from 50 km to 5 km resolution in April 2020 (NOAA 2020), will help to the assess how spatial variation in heat stress affects benthic assemblages and bleaching within and among the parks. We recommend that continuous sea temperature loggers are installed at a few sites at NPSA to compliment the datasets at the other parks. Augmenting the PACN benthic protocol to include continuous sea temperature loggers and adding frequent broad-scale surveys to detect bleaching (and other disturbances) will aid in addressing future bleaching events and provide valuable ground truthing data on the actual response by corals reef for the NOAA bleaching alert levels.

The other PACN monitoring protocols (i.e. fish and water quality) implemented in and adjacent to the marine areas of these parks also can provide insight to benthic community assemblages, bleaching and other disturbances on these reefs as well. The marine fish protocol is conducted along the same transects used to monitor benthic communities and analyses are underway to determine if and how fish communities were impacted in KAHO due to disturbances. The PACN water quality protocol monitors many of the same reef locations at each park quarterly. These data will provide insight into how small-scale variations in nutrients (nitrogen, phosphorus, and nitrates plus nitrites) and physical parameters (pH, salinity, dissolved oxygen, turbidity, chlorophyll, and temperature) affect the reef's susceptibility to disturbances.

Management Recommendations

There is scientific consensus that severe bleaching events like that which affected KAHO in 2015 are likely to become a more common occurrence in the future. Management interventions are necessary to promote resiliency of the coral reefs of the national parks so that they may survive these inevitable future events. We recommend proactive management actions to reduce direct impacts of commercial and recreational use on park coral reefs when 1) the reefs are known to be under stress due NOAA bleaching alert level 2 heat stress, 2) coral spawning events are occurring, and 3) other disturbance events are observed, such as outbreaks of coral disease or COTS. The State and County of Hawaiʻi recently implemented multiple beach closures during coral spawning so there is a precedent and support from local agencies (DLNR 2021). Additional proactive visitor management strategies that may be implemented include: regulating the number of visitors to certain reef areas; improving enforcement of existing marine regulations for extraction of non-sustainable fish and invertebrate species from reefs and establishing additional regulations; and setting up designated mooring buoys and underwater trails to regulate diver traffic as with terrestrial trails within parks.

NPS collects broadscale visitor data with counting procedures specified by park (NPS 2021). We highly recommend that specific data on the number of visitors and their activity in the marine portion of each of these four parks (KAHO, KALA, NPSA, and WAPA) be collected and monitored. Similarly, identifying the location of the healthiest assemblages of coral species in the park marine boundary and prioritizing their protection from potential visitor impacts and other stressors should be considered.

In addition to visitor management, improved management of point source pollution issues could improve reef resiliency if inadequate wastewater treatment or runoff from potentially polluted or sediment-laden water is originating in adjacent terrestrial environments. One current limitation is that the marine water quality monitoring protocol is not set up to track or identify such events. Future monitoring should consider a framework that allows for a better understanding of potential point source pollution events. This would enable park managers to develop strategies to work within and outside of parks with neighboring communities to mitigate the localized impacts from pollution.

Replacing lost corals and building more heat-tolerant or resilient reefs have become the focus of many scientists and natural resource managers around the world. Researchers are working to determine whether heat-tolerant coral species can be successfully grown in nurseries and out-planted to build more resilient reefs. NPS managers should be aware of these efforts and work with scientists (within and outside the agency) to determine the efficacy and long-term outcomes of these techniques. It is important to note that any coral, whether reared in a nursery or not, requires the proper conditions (e.g. good water quality) to survive, thrive, and reproduce. For example, many small pieces of coral in nurseries can survive while growing from a rope or other apparatus suspended above the bottom, but once transplanted to the benthos and subject to sedimentation stress, there is a high probability the coral will die. Therefore "coral nursery" activities should be carefully planned out with water quality and other stressors of the park area being actively monitored and addressed as well.

These recommended actions are made recognizing that reducing global emissions of greenhouse gases will have the greatest impact on countering future thermal stress events. U.S. National Parks can lead by example by reducing the carbon footprint of everyday park operations and should advocate for community, national, and international changes that will reduce emissions on a larger scale.

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