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SPECIAL FEATURE: SCIENCE FOR OUR NATIONAL PARKS' SECOND CENTURY

Informing coral reef management decisions at four U.S. National Parks in the Pacific using long-term monitoring data

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Abstract. Effective management of coral reefs is challenging because of local and global stressors. Robust monitoring data are critical to managing these resources. Between 2006 and 2008, the Pacific Island Network Inventory and Monitoring Program of the U.S. National Park Service implemented monitoring protocols at four national parks in Hawai'i (Kaloko-Honokōhau National Historical Park [KAHO], Kalaupapa National Historical Park [KALA]), Guam (War in the Pacific National Historical Park [WAPA]), and American Samoa (National Park of American Samoa [NPSA]). Benthic marine community, marine fish, and land-based surface and groundwater quality monitoring protocols used a split-panel sampling design to collect data on ecosystem "vital signs" and processes. Vital signs included coral species richness, percent coverage of benthic community types, fish abundance and biomass, rugosity, and a suite of surface and groundwater quality parameters. Data on key processes included top-down (e.g., fish trophic structure, bleaching, and disease) and bottom-up (e.g., coral larval settlement, turbidity, pH, temperature, nitrogen, phosphorus, salinity, groundwater levels) controls. The importance of these monitoring data is highlighted in four case studies that described how the information was used to manage a diverse array of issues at the parks. First, coral reef areas vulnerable to *Acanthaster planci* (crown-of-thorns sea star) outbreaks at NPSA and WAPA were identified to determine whether, and where, to focus culling efforts. Second, data were used at KALA to delineate zones with high fish biomass that were sensitive to fishing activities and warranted increased management. Third, coral settlement data at KALA identified sensitive regions within the park. Fourth, land-based surface water quality and groundwater dynamics monitoring data at KAHO were used to support management actions that mitigate land-based threats to park coral reefs. Advantages of the monitoring program included the split-panel sampling design, which provided a more complete picture of the resources with statistically robust data, and the efficacy of colocating and co-visiting sites for multiple protocols. The case studies demonstrated the usefulness of these data in the short term. In the long term, these data will continue to yield significant information about ecosystem responses to anthropogenic impacts and natural events, vital to park planning processes.

Key words: coral reef; crown-of-thorns starfish (COTS); land-based pollution; long-term ecological monitoring; Pacific; resource management; Special Feature: Science for Our National Parks' Second Century; U.S. National Park; vital signs.

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Introduction

Coral reefs are under increasing global pressure due to a variety of natural (Grigg and Dollar 1990) and anthropogenic stressors (Hughes et al. 2003), resulting in severe ecosystem degradation (Pandolfi et al. 2003). Major anthropogenic threats include pollution derived from land-based sources, sedimentation, overfishing, and climate change (Hughes et al. 2003). A variety of actions have been undertaken to understand coral reef components over time, mitigate threats, and ultimately protect these ecosystems. These actions include establishing and maintaining marine protected areas (MPAs; e.g., Kelleher and Kenchington 1992), conducting research studies and long-term monitoring programs to inform management decisions and evaluate the efficacy of management measures (e.g., Friedlander et al. 2007), changing or controlling adjacent land-use patterns (e.g., Bond et al. 2004, Packett et al. 2009), and providing educational programs to change behavior patterns (e.g., Bunce et al. 2000). For coral reef conservation, MPAs have emerged as the leading tool with varying degrees of success (McClanahan et al. 2006). In many areas of the world, including the United States, MPAs have been integrated into national and local park systems (Spalding et al. 2001) with existing place-based management frameworks.

The U.S. National Park Service (NPS) manages nine parks that include coral reefs within their boundaries and are monitored by the NPS Inventory and Monitoring (I&M) Program (Fancy et al. 2009). The Pacific Island Network (PACN) of the I&M Program developed monitoring protocols at four parks located in Hawai'i (Kaloko-Honokōhau National Historical Park [KAHO], Kalaupapa National Historical Park [KALA]), Guam (War in the Pacific National Historical Park [WAPA]), and American Samoa (National Park of American Samoa [NPSA]) to provide spatial and temporal data on various ecosystems. Three protocols have been implemented within marine areas of these parks beginning in 2006, focusing on fish (Brown et al. 2011*a*), benthic communities (Brown et al. 2011*c*), and water quality (Jones et al. 2011). In addition, land-based monitoring protocols for surface water quality (Jones et al. 2011) and groundwater dynamics (Izuka et al. 2011) have been employed at KAHO to monitor for early signs of potential impacts of land-based pollution from the increasing urban development around the park. The monitoring protocols use a split-panel sampling design to annually collect colocated data on vital signs at 30 reef sites per park (Brown et al. 2011*a*), and at eight coastal pools in KAHO (Jones et al. 2011). The groundwater protocol relies on continuous data collection (Izuka et al. 2011). As defined by the NPS, "vital signs" are a subset of physical, chemical, and biological elements and processes of park ecosystems that are selected to represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values (HaySmith et al. 2006). In these protocols, vital signs included coral species richness, percent coverage of benthic substrate types, reef structural complexity (rugosity), fish abundance and biomass, and a suite of surface and groundwater quality parameters. Vital signs on key ecological processes included top-down (e.g., fish trophic structure, bleaching, and disease) and bottom-up (e.g., coral larval settlement, turbidity, pH, temperature, and suspended nutrient levels) controls.

Many research and monitoring programs state how data can be used to inform resource managers (e.g., Maynard et al. 2015) or provide guidelines on how best to monitor (e.g., Hill and Wilkinson 2004) and manage (e.g., Bunce et al. 2000) coral reef ecosystems, but few studies have specifically examined how scientific studies including long-term monitoring programs have directly influenced management decisions. Recently, however, data from long-term monitoring programs have shown how this information can be used to impact management actions in Micronesia (Montambault et al. 2015) and evaluate the effectiveness of management activities as demonstrated in the Great Barrier Reef (McCook et al. 2010). In the United States, place-based monitoring programs such as the NPS Program described in this study can be nested within broader monitoring frameworks, such as the Coral Reef Assessment and Monitoring Program in Hawai'i (Jokiel et al. 2004) and National Oceanic and Atmospheric Administration's (NOAA) Pacific Reef Assessment and Monitoring Program (McCoy et al. 2016) to examine ecosystem trends at several spatial scales.

Here we describe four case studies in which place-based data and scientific findings from the I&M monitoring data have contributed to informing management decisions within four parks, including: (1) use of benthic monitoring data to identify coral reef areas vulnerable to the *Acanthaster planci* (crown-of-thorns sea star) outbreaks to prioritize mitigation activities in NPSA and WAPA; (2) use of marine fish data to delineate and protect high fish biomass zones sensitive to resource extraction activities such as fishing tournaments in KALA; (3) use of coral settlement data to determine sensitive areas needing protection within KALA; and (4) use of monitoring data to quantify land-based threats to coral reefs and applying these data in local (county and state) administrative proceedings to secure controls and minimize pollutants to KAHO's coral reefs.

Materials and Methods

Study areas

The four parks and marine areas examined here span the North to South Pacific (Fig. 1). The subtidal habitats vary considerably among the four parks and are briefly summarized in Table 1 along with spatial extent of the marine boundary, habitat characteristics, and current threats.

Methods common to all marine protocols

A split-panel field sampling design was implemented for monitoring, with 30 randomly selected sites sampled annually in each park on hard substrata in an isobath between 10 and 20 m depth. This depth range was selected for ecological and safety reasons. Fifteen sites were fixed (permanent) and revisited annually. The remaining sites were randomly selected each year and

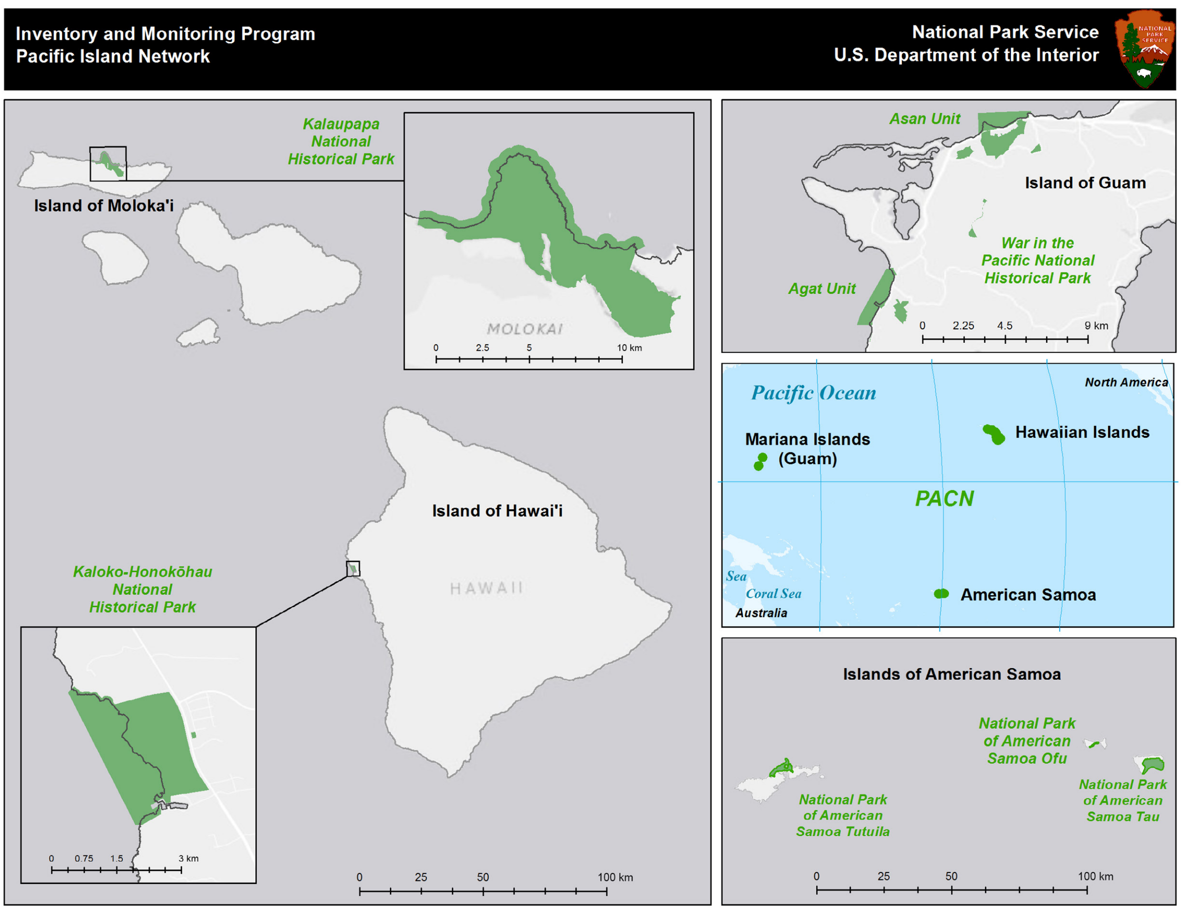

Fig. 1. U.S. National Parks that are part of the Pacific Island Network Inventory and Monitoring Program.

Table 1. Summary information for four U.S. National Parks in the Pacific describing spatial extent of marine area, habitat characteristics, and threats.

Park	Marine boundary area	Highlights/diversity/number of coral and fish species detected	Threats
KAHO	2.4 km^2	Coral reefs comprised of a basalt boulder habitat with aggregated reef structure interspersed. Sea turtles, spinner dolphins, turtle resting beaches Fishponds 137 fish species 26 coral species	Adjacent land use, groundwater, and runoff Marina (boating, groundings, contaminants) and recreational issues (fishing, SCUBA) Fishpond threatened by invasive red mangroves (*Rhizophora* sp.) and red algae (*Acanthophora spicifera*)
KALA	Quarter mile offshore and three offshore islands 8.1 km^2	Sea turtles Endangered monk seals Coral reefs comprised of basalt boulder habitat with isolated coral colonies Endemic Hawaiian limpets 25 coral species 200 fish species	Upland development, including sedimentation and other runoff-associated issues Harvesting limpets, commercial fishing vessels operating within park Primary physical disturbance 8- to 10-m Pacific swells
NPSA	Quarter mile offshore and four separate islands 18.2 km^2	Coral reefs comprised of aggregated coral reef areas Sea turtles and nesting beaches Marine mammals 200 coral species 900 fish species	Rapid population growth and development Runoff-associated issues, animal wastes, and other contaminants, landfills Fishing Increasing the prevalence of coral diseases and bleaching crown-of-thorns starfish (COTS) predation
WAPA	Six offshore islands 4.0 km^2	Part of marine protected area Aggregated coral reef areas with high coral cover and hard substrate with <10% coral cover Seagrass beds comprised mostly of *Enhalus acoroides* Approximately 1000 fish species Approximately 400 coral species Endangered sea turtles Marine mammals	Sedimentation/runoff Intense fishing Sewage and litter World War II military wreckage including sixty tons of unexploded ordnance dumped within diving depths Increasing the prevalence of coral diseases and bleaching COTS predation

Note: 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.

labeled as temporary as they were not revisited. Sampling was typically conducted during the summer months in each hemisphere. This sampling regime was designed to provide a robust scientific inference based on power analyses and also represented reasonable goals given current logistic and fiscal realities. The two marine monitoring protocols (benthic marine community and marine fish) were typically colocated and covisited at each of the sites using the same SCUBA dive team. A marine water quality monitoring protocol was also established at each of the parks to collect ancillary data that assisted in the interpretation of trends in the other protocols. For the purposes of this study, however, we focus on the land-based water quality. A brief summary of each protocol is provided below with a listing of the vital signs measured provided in Table 2. More detailed methods can be found in Brown et al. (2011*a*, *c*), Jones et al. (2011), and Izuka et al. (2011).

Benthic marine community protocol

The primary objective for this protocol is to determine long-term trends in the abundance (percent cover of the benthic substrata) of benthic marine macroinvertebrate (e.g., corals, zoanthids, octocorals, sponges, mollusks, and echinoderms) and algal (including large fleshy macroalgae, crustose coralline, and turf algae) assemblages. The second objective is to determine trends in benthic local scale topography or rugosity at each of these sites. The third objective was to determine trends in settlement rate of hard corals to uniform artificial surfaces at the fixed monitoring sites. The last objective was to determine long-term trends in the incidence of coral disease and bleaching.

Table 2. Year of implementation for marine protocols at four U.S. National Parks in the Pacific. The vital signs measured within each protocol are included.

Protocol	Vital sign (unit)	KAHO	KALA	NPSA	WAPA
Benthic marine community	Coral species richness (no./transect)	2007	2006	2007	2008
	Benthic cover by substrate type (%)				
	Rugosity (index)				
	Coral settlement rate (no.·m^2·5 months)	†		NA	NA
	Disease/bleaching (frequency of occurrence)				
Marine fish	Species richness (no./125 m^2)	2007	2006	2007	2008
	Abundance (no./125 m^2)				
	Biomass (g/m^2)				
	Diversity (H′)				
Water quality	Chlorophyll *a* (μg/L)	2007	2007	2009	2007
	Dissolved oxygen (mg/L, %)				
	Nitrite + nitrate (μgN/L)				
	pH (scale)				
	Salinity (‰)				
	Specific conductance (mS/cm)				
	Total dissolved nitrogen (mgN/L)				
	Total dissolved phosphorus (μgP/L)				
	Temperature (°C)				
	Turbidity (NTU)				
Groundwater	Salinity (‰)	2010	NA	NA	NA
	Specific conductance (μS/cm at 25°C)				
	Total dissolved nitrogen (mgN/L)				
	Total dissolved phosphorus (μgP/L)				
	Total nitrate (μgN/L)				
	Water level (DTW)				

Notes: 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.
† Partnership program with the State of Hawai'i, Division of Aquatic Resources.

At each site, one diver followed the fish observer and photographed the substrate at 1-m intervals along the 25-m transect at a perpendicular height of 0.5 m above the substrate. Total area sampled on each transect was approximately 4.7 m^2 (n = 26, 0.50 × 0.36 m photoquadrats) for a total area of ~140 m^2 across all 30 sites, but actual area sampled varied according to surface topography/rugosity.

Rugosity was measured using the chain and tape method (McCormick 1994). A light brass chain, marked off in 1-m intervals, was draped over the bottom and contoured along the entire length of each 25-m transect. The amount of chain necessary to span the distance (contour distance = cd) between the two marker pins was divided by the straight line tape measurement (linear horizontal distance = ld) to generate an index of spatial relief or rugosity of r = cd/ld.

The larval supply of corals within two parks (KAHO and KALA) was examined by providing artificial substrates for larval settlement and then documenting abundance and distribution patterns using a dissecting scope (English et al. 1997). For the purposes of this paper, we focus on KALA, which deployed a pair of terracotta tiles 2.5 m inshore of the transect at the 0, 12.5, and 25 m marks at all 15 fixed transects several weeks prior to the onset of the peak summer spawning period for the major reef-building coral genera (e.g., *Montipora* spp. and *Porites* spp.). The tiles were collected in September following the cessation of peak spawning. Settlement rate (no.·m^2·5-month peak spawning period^1) was standardized to the 5-month peak spawning period to account for differences in deployment period.

Post hoc image analysis of the photoquadrats was conducted using Photogrid© software (or other suitable software such as CPCe, http://www.nova.edu/ocean/cpce/) on each nonoverlapping photoquadrat on a transect with 50 randomly selected points per quadrat image. Percent cover was tabulated (by lowest possible taxon, preferably species) for coral, macroinvertebrates, and other benthic substrate types (e.g., crustose coralline algae, turf algae, fleshy macroalgae, or sand).

Marine fish protocol

The primary objective is to annually determine the density, biomass, and size of daytime, noncryptic reef fishes at the monitoring sites. At each study site, one 25-m transect was positioned parallel to the reef crest along a constant depth contour. One observer enumerated the fish as the line was deployed. On the initial pass at NPSA and WAPA, only fishes >20 cm were counted and sized by species within a 4 m wide by 4 m high corridor (400 m^3). On the return pass, fishes <20 cm were counted and sized by species within a 2 m wide by 4 m high corridor (200 m^3). The amount of time spent in the water varied somewhat depending on how speciose the fish assemblage was at each sampling site. At KAHO and KALA, only one pass was required due to the more depauperate fauna and all fish were enumerated and sized by species within the corridor. This nondestructive technique focused on one major component of the coral reef fish community, the diurnal or day-active fish species that were highly visible due to their typically bright coloration and generally large size.

Water quality protocol (land-based; KAHO)

The primary objective of water quality monitoring is to examine spatial patterns and temporal trends in temperature, pH, salinity/conductivity, dissolved oxygen, turbidity, total dissolved nitrogen (TDN), total dissolved phosphorous (TDP), nitrate + nitrite (NO_3 + NO_2), and chlorophyll in land-based, coastal, brackish-water pools. Four fixed, and four rotating coastal pool sites were sampled quarterly using a split-panel design. Three replicate, field-filtered (0.7 μm GF/F filter) 125-mL samples were taken during daylight hours at each sample site within 3 h of low tide to maximize freshwater input. Water was collected from just below the surface of the coastal pool to avoid disturbance of sediment on the bottom or collection of floating material. Sample bottles were placed on ice in the field inside an insulated backpack and frozen on the day of collection before submitting samples for laboratory analyses. Minimum analytical detection limits were 15.0 μgP/L for TDP, 0.07 mgN/L for TDN, and 1.0 μgN/L for NO_3 + NO_2. Further details on field methodology, QA/QC, and data analyses are found in Jones et al. (2011).

Groundwater dynamics protocol (KAHO)

The primary objective of groundwater monitoring is to collect continuous, long-term conductivity, temperature, and depth data and define seasonal and long-term patterns and trends in water levels, temperature, and salinity of aquifers underlying KAHO and WAPA. Data were collected in 10-min intervals by continuously deployed sensors over quarterly time periods in three observation wells within KAHO. Nutrient data consistent with the water quality protocol have been collected quarterly since 2012 (Raikow and Farahi 2016). Long-term groundwater monitoring data are necessary to predict responses of island aquifers and natural ecosystems to changes in sea level, climate change, groundwater withdrawals, and human land use. Details on field methodology, QA/QC, and data analyses are found in Izuka et al. (2011), and Raikow and Farahi (2016).

Data analysis

Spatial analysis utilized ArcGIS to display abundance patterns of the dependent variables on park maps. Brown et al. (2014, 2015) provide examples of more detailed trend analyses for the benthic marine community and marine fish assemblage. Data analyses unique to certain case studies are presented below.

Spatial patterns in fish density and biomass at KALA (case study 2) were investigated using a general linear model one-way ANOVA in Statistica 13.0 (StatSoft, Inc. 2015). To meet the assumptions of normality, data were transformed using a $\log(x + 1)$ transformation for density and biomass (Zar 1999). Post hoc analysis used contrasts to examine a priori assumptions about locations (northern and southern) around the park.

Spatial and temporal patterns in the rate of total coral settlement from 2006 to 2014 at KALA (case study 3) were examined with a general linear model repeated-measures ANOVA in Statistica 13.0 (StatSoft, Inc. 2015). Prior to analysis, data were $\ln(x + 1)$-transformed to meet the assumptions of normality and homogeneity of variances (Zar 1999). A Wilks multivariate test was used to identify significant differences among years (2006–2014) and locations (western, northern, and eastern) around the park to avoid issues with compound symmetry and sphericity. Post hoc analysis used contrasts to examine a priori assumptions about locations around the park.

In KAHO (case study 4), coastal pools were divided into three geographically defined groups: north, south, and central pools. Measurements from a series of water samples taken at an individual site within minutes of each other were assumed to be normally distributed around the true value of the parameter. Details on the trend analyses for TDN and TDP using general linear mixed models are found in Raikow and Farahi (2016). To meet the assumptions of normality and homogeneity of variances (Zar 1999), TDN data were $\log(x + 1)$-transformed and TDP data were square-root-transformed.

Results and Discussion

*Case study 1: identify coral reefs vulnerable to crown-of-thorns sea star (*Acanthaster planci*) populations and outbreaks in WAPA and NPSA*

The indigenous crown-of-thorns starfish (COTS) play a critical role in maintaining coral diversity on reefs due to their preference for eating fast growing species in the genera *Acropora* and *Pocillopora* (Birkeland and Lucas 1990). Normally, populations of COTS are low and do not pose a problem, but under appropriate conditions, populations can expand to reach unsustainable densities or outbreaks (defined when densities exceed 30 individuals/ha; CRC Research Center 2003) that can decimate reefs (Birkeland 1982, De'ath et al. 2012). These outbreaks can result in localized coral species extinctions, while severe outbreaks can lead to the removal of all living coral species on a reef (Moran 1986).

Dense destructive infestations of COTS were recorded in Guam and Micronesia in the late 1960s (Marsh and Tsuda 1973). These decreased in subsequent years, but cycles of smaller infestations occurred in the next few decades. Since at least 2003, chronic widespread outbreaks of COTS have been observed outside park boundaries on the coral reef areas of Guam (Fig. 2; Burdick et al. 2008, NOAA Coral Reef Ecosystem Division, *unpublished data* from 2009, 2011, and 2014). The majority of observed outbreaks have occurred on the east and northwest coasts of Guam. Two COTS towed-diver surveys documented one concentration of *Acanthaster planci* individuals in/near WAPA's Asan unit in 2005 while a large outbreak was observed in/near WAPA's Agat unit 2003 (Burdick et al. 2008). Independent data from the WAPA benthic marine community monitoring from 2008 to 2011 and 2014 indicated that no individuals of *A. planci* were detected for the fixed (n = 15 per year except for 2011 where n = 12) or temporary transects (n = 75 over 5 yr). Further, the percent live coral cover by year did not drop drastically and there was no indication of a potential outbreak or other detrimental event (e.g., disease or bleaching). Based on this information, no targeted management action was deemed necessary by resource managers.

In American Samoa, COTS outbreaks were first detected outside the boundaries of the NPSA in 2011 (Clark 2014), but no management action was taken. In 2013, an outbreak of COTS occurred threatening the reefs within the Tutuila unit of NPSA (Clark 2014). In 2014 and 2015, semi-monthly towed snorkeler surveys conducted by NPSA were used to determine the location of the COTS outbreaks and focus eradication efforts (Fig. 3). COTS typically were first detected at the base of the reef slope in approximately 30–40 m water depth, moving up the reef slope into shallower waters over time.

In November 2013, divers started eradicating COTS by injecting them with sodium bisulfate and then switching to oxbile in 2014 because it is more efficient, requiring only a single injection per animal vs. up to ten, and has shown no evidence of side effects to other reef organisms (Rivera-Posada et al. 2014). Efforts were made to eradicate COTS outbreaks when they were first detected in deeper waters to minimize damage to more shallow reefs. To date, NPSA divers have killed 8983 COTS in park waters during 436 dive hours, with catch per unit effort ranging from a high of 26 COTS/hr in 2013 to 18 and 19 COTS/hr in 2014 and 2015, respectively.

The NPSA I&M data from 2007 to 2015 detected *A. planci* present within park boundaries in 2013 in only one photoquadrat. The I&M data showed a statistically significant increase in coral cover (t = 2.60, P = 0.015) over this same

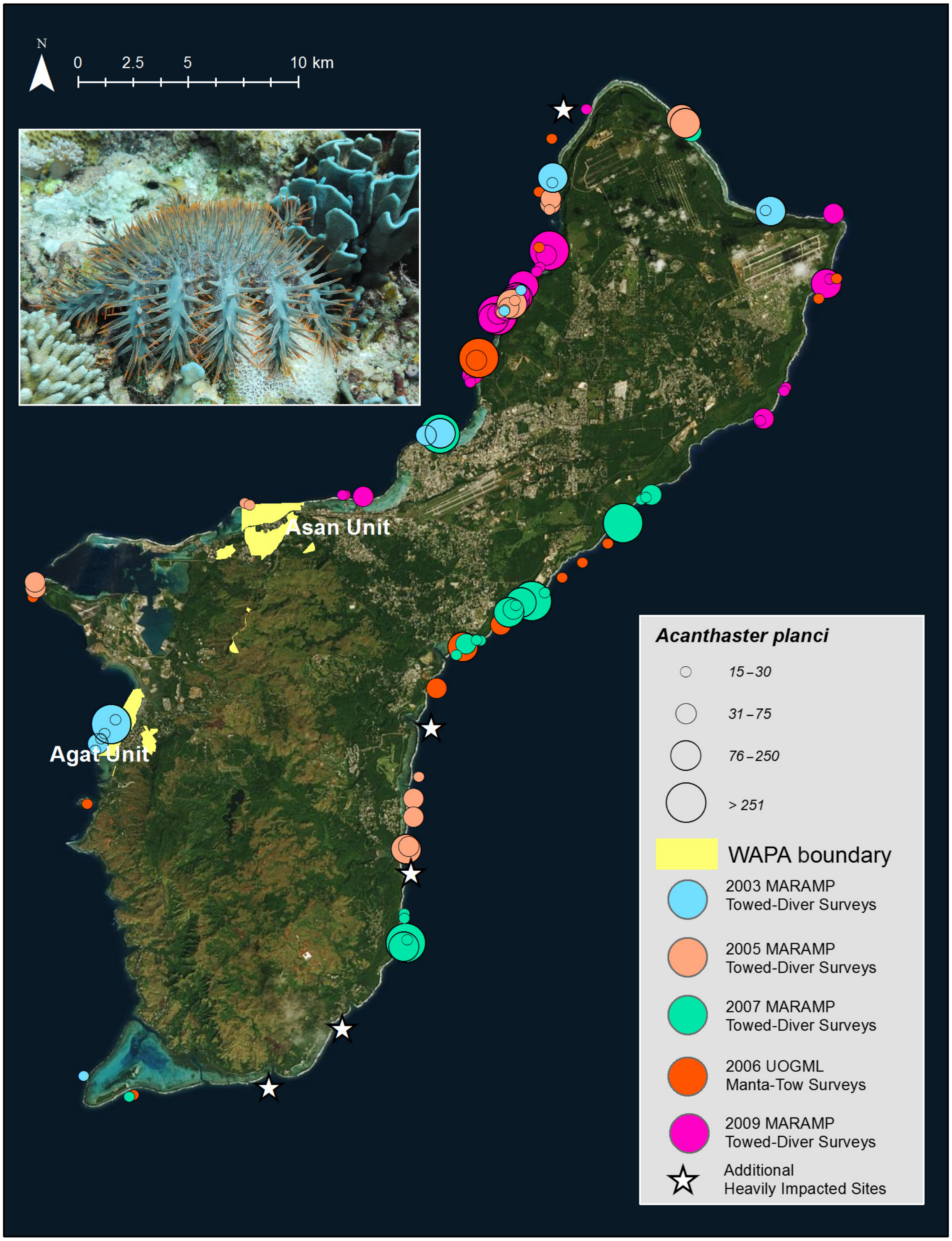

Fig. 2. Abundance (no./ha) of crown-of-thorns sea stars (*Acanthaster planci*) around the island of Guam. Figure modified from Burdick et al. (2008) with additional data provided for years 2009, 2011, and 2014 by National Oceanic and Atmospheric Administration Coral Reef Ecosystem Program. The War in the Pacific National Historical Park boundary is highlighted in yellow.

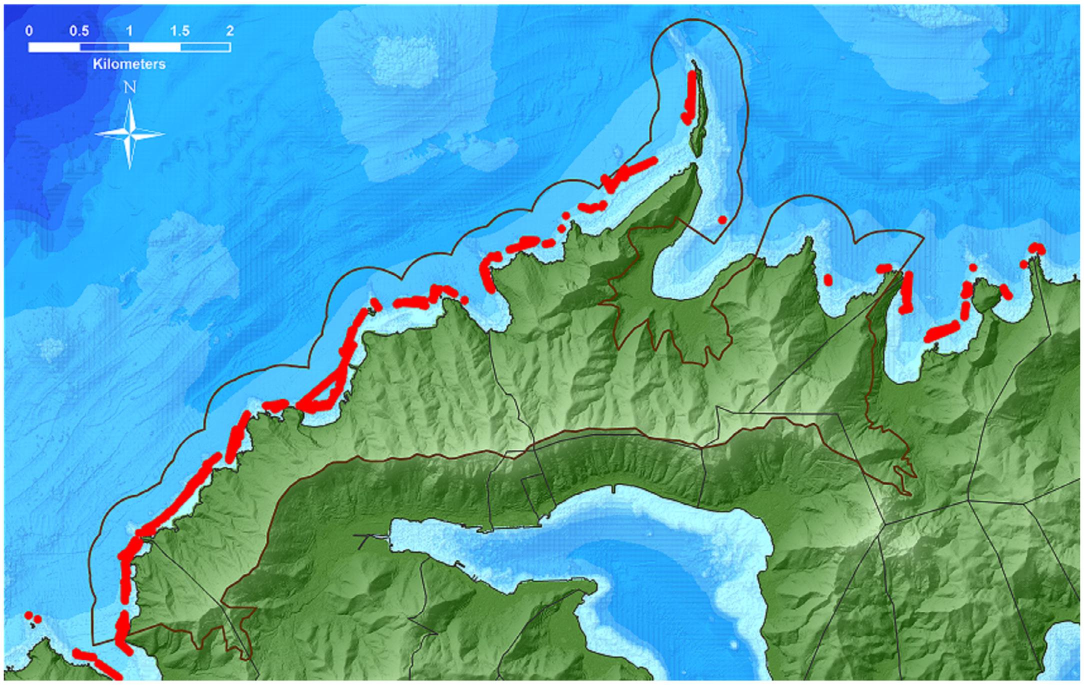

Fig. 3. All outbreak locations (red dots) observed during towed snorkeler surveys conducted in 2014 in the National Park of American Samoa. The park boundary is outlined in gray.

time period, suggesting COTS eradication efforts were successful in minimizing damage to shallower reef areas in the park (Fig. 4). However, COTS continue to be found in low densities within NPSA so eradication efforts are ongoing. Continuation of long-term monitoring coupled with surveys at larger spatial scales will be useful in determining whether COTS eradication efforts are ultimately successful in minimizing damage to park reefs. In addition, partnering with other monitoring efforts in the region can provide contextual information about potential upcoming COTS outbreaks.

Case study 2: delineate reef areas with high fish biomass that are sensitive to resource extraction at KALA

In this example, both fishery-dependent (park-specific creel survey) and fishery-independent (I&M data-derived density and biomass) data from KALA were used to locate nearshore areas that were resource rich and might be sensitive to fishing activities. The creel surveys conducted by Tom (2011) found that the majority of the fishing effort (51.7% of the fishers) was along 3 km of coastline adjacent to the settlement and the predominant gear type around the park was rod and reel (63.7% of the fishers; Fig. 5). Importantly, 19.4% of fishers used a 3-km stretch of coastline off the northern part of the peninsula that exhibited the highest levels of fish density ($F_{1,298} = 58.1$, $P < 0.001$; Fig. 6) and biomass ($F_{1,298} = 18.3$, $P < 0.001$) relative to other sections of the coastline. These northern reef areas also contained the greatest apex predator density ($F_{1,298} = 4.7$, $P = 0.03$) and biomass ($F_{1,298} = 15.4$, $P < 0.001$), which the fishers were targeting, a practice that has negative impacts on top-down ecological processes (Boaden and Kingsford 2015). Average size of the apex predators, however, was not significantly different in this area ($F_{1,479} = 3.4$, $P = 0.07$), indicating that these large predators were simply more abundant at the north end of the peninsula. The importance of having numerous, large fish within a population and an assemblage has been well documented (Jennings et al. 2005). The largest bodied species and individuals within species have a disproportionate contribution to the population and community dynamics through higher reproductive output and greater habitat

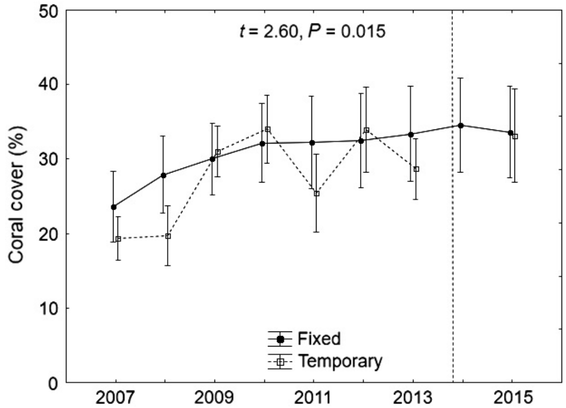

Fig. 4. Percent coral cover at the 15 fixed sites (solid line) and 15 temporary sites (dashed line) surveyed in each year at the National Park of American Samoa from 2007 to 2015 with the exception of temporary sites in 2014 that were not surveyed (no data). The vertical dashed line indicates the start of the COTS eradication effort. Error bars are one standard error of the mean. Trend analysis t statistics are displayed.

modifications in terms of ecosystem functioning (DeMartini and Smith 2015). These contributions of numerous, large fish, especially apex predators, stress the importance of regulating and protecting areas where these conditions exist (Friedlander 2015). Excessive fishing pressure can reduce or even eliminate these predators, changing the dynamics of fish assemblages through prey release (Boaden and Kingsford 2015), bottom-heavy biomass pyramids (Sandin et al. 2008), and negative cascading effects on coral disease and recruitment (Sandin et al. 2008).

In 2014, a fishing tournament sponsored by patients and residents of the Kalaupapa settlement was held within the park. The tournament was open to all residents and up to 80 sponsored guests from outside of the settlement. The tournament organizers scheduled several planning meetings to discuss the rules and after examining the fishery-independent data, it was decided to restrict access to certain areas that had been frequented in the previous tournament in 2004 (Fig. 6). This restriction included the area north of the airport that had the highest fish density and biomass as well an abundance of apex predators. The fishers were amicable to the new boundaries when presented with the rules at the opening ceremonies because it meant participating in a more sustainable tournament. This outcome was an important sociological aspect of the management decision because the fishers bought in to the rule change. Admittedly, restricting access through the airport at the northern end of the peninsula was easier due to a state law that prohibits access across the runway. In addition, park-specific monitoring data identified an important pupping habitat for the endangered Hawaiian monk seal (Brown et al. 2011*b*) that was also used by the park management staff and the tournament organizers to limit access to one of the beach areas north of the settlement (E. English, *personal communication*). The community tournament planned in 2016 will feature a tag-and-release category that will enable fishers to participate in a mark-and-recapture program conducted throughout the state of Hawai'i.

Case study 3: a resource management tool to help identify sensitive biogeographical zones within KALA needing additional protection

These zones or regions were based on differences in wave exposure, benthic community structure, and seasonal wind patterns (Fung Associates Inc. and SWCA Environmental Consultants 2010). The I&M data for this case study were acquired from the benthic marine community protocol using the coral settlement tiles. Over a period of 9 yr, the northern region of the peninsula at KALA had higher coral settlement rates than the western (Wilks $F_{3,10}$ = 668.6, $P < 0.001$) and eastern (Wilks $F_{3,10}$ = 34.5, $P < 0.001$) regions of the park (Fig. 7). The eastern region of the park, especially offshore of the peninsula, had higher coral settlement than the western region (Wilks $F_{3,10}$ = 239.4, P < 0.001). Within these regions, the spatial and temporal patterns were consistent across years (Wilks $F_{16,10}$ = 0.76, P = 0.70), indicating that larval supply was typically higher at the northern tip of the peninsula followed by the eastern side of the peninsula and then the western side of the peninsula. The high levels of coral settlement at the northern region of the park also corresponded well to the higher coral cover in this area (Brown et al. 2014). These biological observations suggest that current patterns are favorable for larval delivery and retention at the north end of the peninsula. Lumpkin (1998) reported that at a regional scale, the principal surface current flow around the Hawaiian

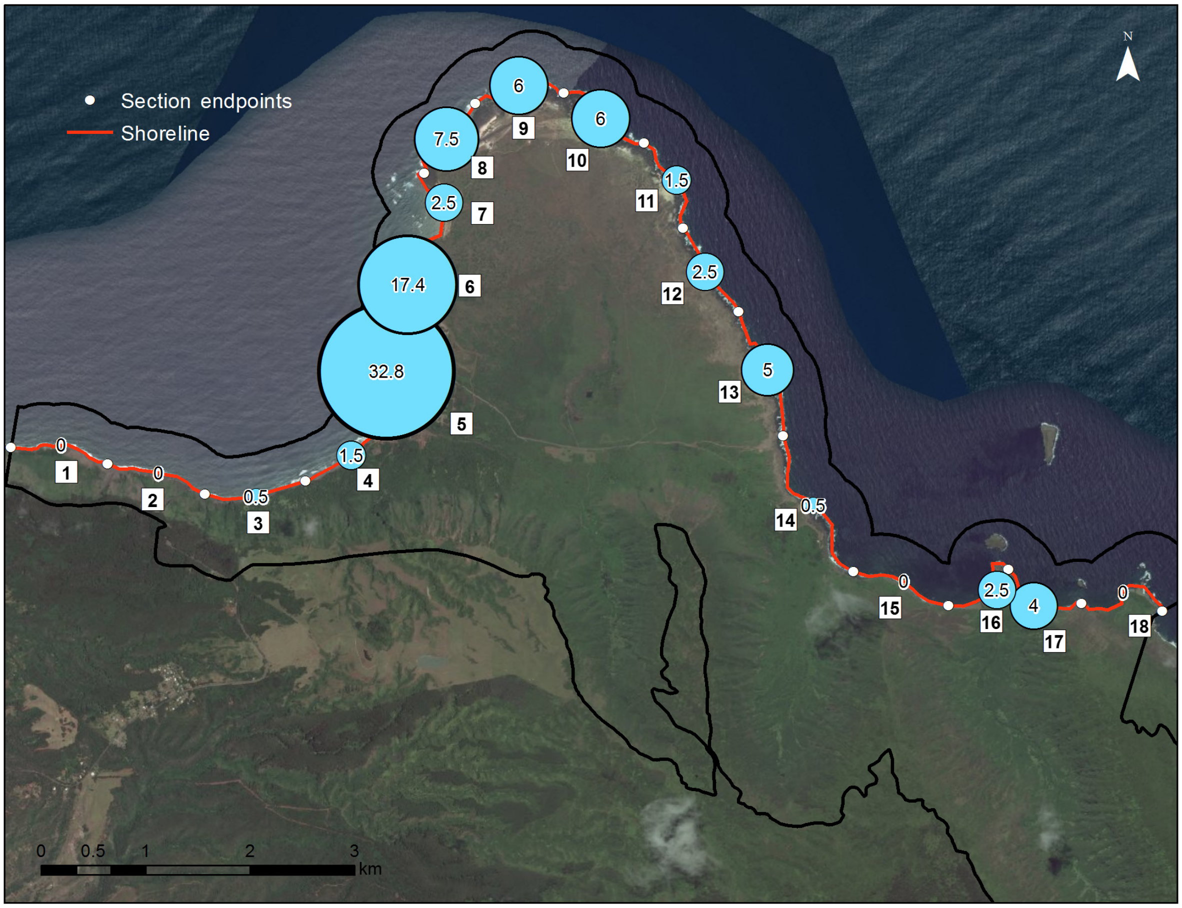

Fig. 5. Percentage of fishers observed in 1-km shoreline segments around Kalaupapa National Historical Park. Numbered shoreline segments are in square boxes. Data are from Tom (2011).

archipelago was from east to west, which supports the hypothesis that a reef area perpendicular to current flow such as the Kalaupapa Peninsula would be an optimal area for larval recruitment. In addition to ocean currents, other factors influencing coral settlement rates and the resulting adult community structure include adult fecundity, toxic chemicals, predation, and space availability (Richmond 1997). These factors may be examined in the future at KALA to help explain the existing spatial patterns in coral community structure.

These findings, in conjunction with the high fish density and biomass observed in this region, identified the northern part of the peninsula as an ecologically important area for management to protect. These resource-rich areas appear to be in better condition relative to other reefs in close proximity supporting the designation of marine managed or protected areas within park boundaries. Even though formal protection has not occurred to date, all of these components provide information critical for developing planning documents such as a park General Management Plan. The concern going forward is that an increasing human population in Hawai'i coupled with better technology and climate change impacts will put increasing pressure on these sensitive areas. The results also offer the opportunity to determine the importance of both bottom-up and top-down ecological processes, for which there is a critical need in Hawai'i. This approach helps determine the relative importance of ecological and anthropogenic disturbances to coral reef ecosystems in terms of reef resistance and resilience (Grimsditch and Salm 2006).

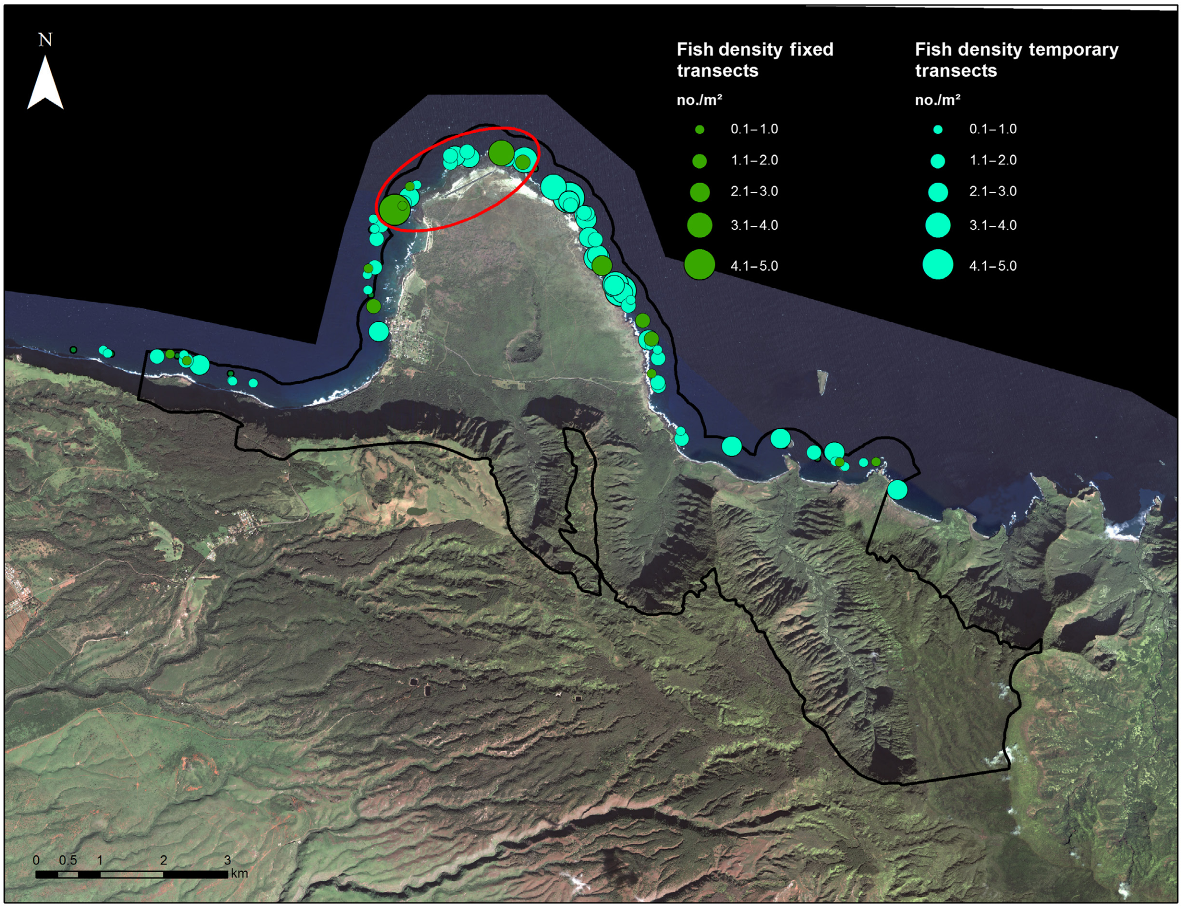

Fig. 6. Fish biomass (g/m^2) at the 15 fixed sites and 75 temporary sites surveyed in Kalaupapa National Historical Park from 2006 to 2010 (n = 150 total transects [15 fixed averaged for 5 yr, 75 temporary]). Area restricted from fishing in the 2014 and 2016 fishing tournaments is outlined by a solid red line.

Case study 4: identify potential sources of land-based threats to minimize impacts to coral reefs in KAHO

Kaloko-Honokōhau National Historical Park is a small, 486-ha park situated in a growing urban area on the western, dry side of Hawai'i Island (Fig. 1). No permanent or intermittent streams exist within the park or the surrounding area. Although the parklands are arid (~48 cm/yr rainfall), orographic convection produces high rainfall upslope (Giambelluca et al. 2013). Rainfall and entrained pollutants originating from upslope urban development are rapidly conducted to the coastal aquifer, which is highly transmissive and tidally influenced (Oki et al. 1999). Fresh groundwater discharges at the coast through coastal brackish pools and as submarine groundwater (SGD) on the coral reef (Oki 1999, Oki et al. 1999, Johnson et al. 2008). The park's reef ecosystem evolved under high freshwater discharge conditions (~24.6 million liters per day [6.5 million gallons per day]; Oki et al. 1999). Recent studies indicate that some nearshore areas of the park are bathed in cooler, groundwater-fed, low-salinity waters to depths of 3–5 m (Presto et al. 2007, Grossman et al. 2010). The role of SGD in structuring the park's coral reef community is not yet determined; however, the potential for buffering or mitigating temperatures during warming events by SGD is under investigation (E. Grossman, *personal communication*). However, SGD also carries significant nutrient loads and contaminates to the sea (Burnett et al. 2006, Knee et al. 2008), which may adversely affect coral reef ecosystems that

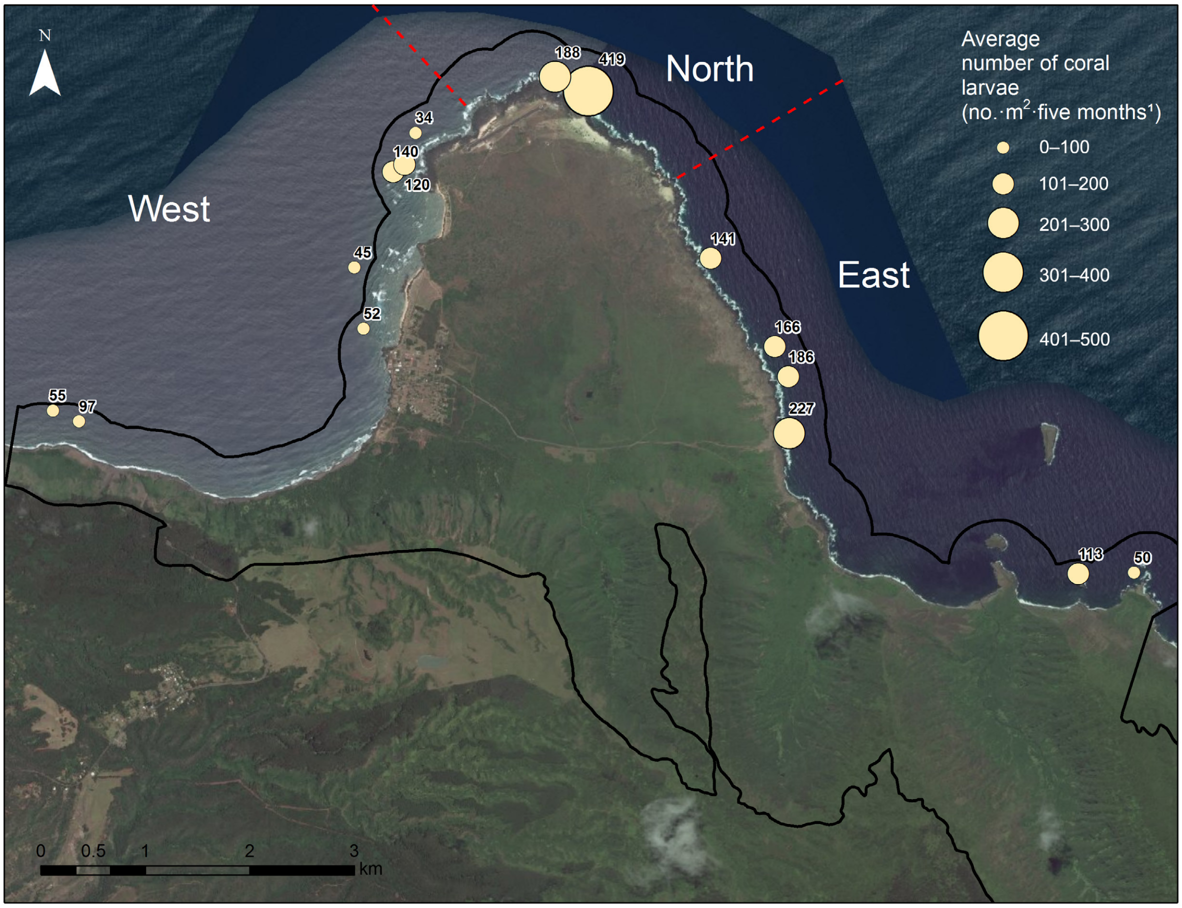

Fig. 7. Average number of coral larvae (no.·m^2·5-month peak spawning period^1) settling from April to September at 15 fixed sites in Kalaupapa National Historical Park from 2006 to 2014. Biogeographical regions in the park are separated by dashed red lines and identified by white text.

are already experiencing bleaching events from higher ocean temperatures (E. K. Brown, S. A. McKenna, and S. C. Beavers, *personal observations*).

The economic costs of environmental remediation are high in comparison with those of controlling polluted runoff (Ribaudo et al. 1999). Since 2001, park managers have proactively and successfully participated in six state administrative proceedings to seek protective conditions on proposed developments upslope of and adjacent to the park to control nonpoint-source pollution (e.g., requirements for stormwater runoff containment, enhanced nutrient removal wastewater systems rather than cesspool and septic systems, best management practices, and pollution prevention plans; Bond et al. 2004). The NPS had cause for concern because contaminants had been detected in the park's groundwater observation wells, fish tissue, and pool sediments (Oki et al. 1999); some waters showed nitrification; park marine waters were designated impaired under the Clean Water Act Section 303(d) for elevated total nitrogen and nitrate + nitrite in 2006 (Hawai'i State Department of Health Clean Water Branch (DOH-CWB) 2008); and groundwater modeling indicated that park water resources were vulnerable to overdevelopment of groundwater (Oki et al. 1999). Although the NPS had several excellent, scientifically sound studies to back up its concerns, noticeably lacking was the ability to rely on well-designed, long-term monitoring data sets (Bond et al. 2004).

Starting in 2008, the I&M water quality and groundwater protocols replaced park-based

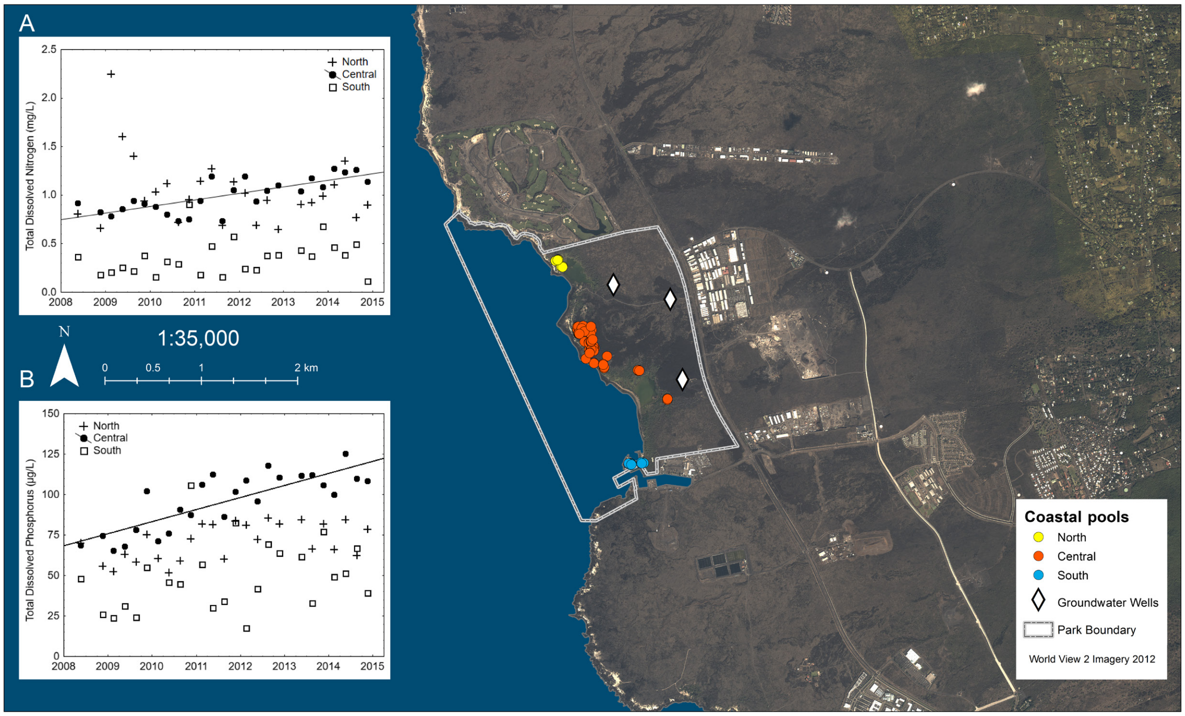

Fig. 8. Nutrient levels for total dissolved nitrogen (A) and total dissolved phosphorus (B) in coastal brackish-water pools at Kaloko-Honokōhau National Historical Park from 2008 to 2014. Data in the scatterplots are means by region (north—cross, central—closed circle, or south—open square) during each quarter of the year. Linear regression slopes within each nutrient chart are plotted for pool regions with significant trends at an $\alpha < 0.05$. Pool sites on the map are color-coded by region with groundwater sampling wells depicted by white diamonds. The park boundary is displayed by the dashed yellow line.

monitoring. These data have enabled the NPS to identify potential sources of anthropogenic nutrient input including a transient spike of nitrogen-enriched irrigation water attributable to a neighboring golf course (Fig. 8; Hunt 2014, Raikow and Farahi 2014), and pronounced changes in nutrient levels at some locations proximal to urban development (Fig. 8; Raikow and Farahi 2016). TDN levels have increased significantly ($t = 4.5$, $P < 0.001$) in the central pool sites from 2008 to 2014 suggesting potential anthropogenic input (Fig. 8). TDP levels also increased in the central pool sites ($t = 2.3$, $P = 0.02$) from 2008 to 2014 (Fig. 8). Overall, the south pool sites located near the small boat harbor had statistically lower TDN levels ($t = -2.2$, $P = 0.03$) than the other pool sites. Lower TDN and TDP in the south pools may be attributed to nutrient uptake by the abundant macroalgae in these pools and by their location on a small peninsula with high connectivity to the sea. The south pools, however, did show the greatest variation in TDP levels, indicating that a more dynamic environment exists in these pools than the pools in the north and central areas of the park.

Also critical in this effort to identify threats and potential sources are the long-term continuous water-level and salinity records from observation wells, which have been instrumental in detecting irrigation signals that can be obscured by tidal fluctuations (~0.6 m range; P. Cutillo, *personal communication*). These continuous data demonstrate the importance of sampling duration and frequency in correctly identifying trends in tidally influenced settings.

Summary

These four case studies illustrate how the PACN I&M long-term monitoring data have been used to impact management decisions. In the first case study, spatial distribution patterns of the predatory crown-of-thorns sea star (COTS, *Acanthaster planci*) dictated two different management strategies within the PACN. NPSA staff chose to mitigate the COTS given the high abundance levels within the park. WAPA staff, on the other hand, elected to focus on higher priority issues because COTS abundance patterns were relatively light in comparison with other areas of Guam. In the second case study, monitoring data showing high levels of fish density and biomass in certain areas of KALA, especially apex predators around the peninsula, were used to designate restricted areas for resource extraction activities such as the periodic fishing tournaments sponsored by patients and residents. The third case study highlighted the importance of understanding how key ecological processes such as coral settlement can provide scientific evidence supporting the establishment of marine managed areas. Finally, the fourth case study illustrated that statistically rigorous, long-term monitoring data were critical for identifying trends in nutrient levels from potential land-based threats to coral reefs. These data are essential to support NPS participation in local (county and state) administrative proceedings to secure administrative controls that minimize impacts to KAHO's coral reefs. Ultimately, the long-term monitoring data have enabled resource managers to identify reef sites impacted by disturbances and prioritize management activities to protect these areas.

A valuable attribute of the marine monitoring program is the colocation and covisitation of the sampling sites for the different vital signs. For example, in case studies 2 and 3, all of the KALA data pointed to the north part of the peninsula as being particularly important in terms of large fish, high coral cover, and high coral recruitment (Figs. 6, 7). Thus, the ability to overlay multiple types of monitoring results was advantageous to current park management and future planning efforts such as a General Management Plan. In addition, this sampling approach was more efficient in terms of time (23% of the time) and cost (27% of the cost) than conducting each sampling protocol separately (NPS, *unpublished data*).

Another important aspect of the NPS Monitoring Program is the split-panel sampling design coupled with the quality control measures implemented for each of the protocols. The combination of permanent and annually rerandomized sites allowed visitation of far more monitoring sites than if we had simply sampled 30 permanent reef sites and eight coastal pools through time. This design resulted in a more complete picture of the current status (distribution and relative abundance) of marine resources within the parks, and more statistically robust temporal and spatial water quality data (Skalski 1990, 2005, Starcevich 2013). This information is immediately useful to managers in the short term as was demonstrated in the case studies. In the long term, we expect the trend data from the permanent marine sites, the groundwater observation wells, and the coastal pools to continue to yield significant information about ecosystem responses to anthropogenic impacts and natural events, and provide information vital to park planning processes.

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