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Natural Resource Stewardship and Science

Rocky Intertidal Community Shift Over 30 Years

1990–2020 Rocky Intertidal Long Term Trend Report

Natural Resource Report NPS/MEDN/NRR—2023/2501

ON THE COVER
Cabrillo National Monument staff member takes a photo of a rocky intertidal monitoring plot with the city in the background.
NPS Photo

Rocky Intertidal Community Shift Over 30 Years

1990–2020 Rocky Intertidal Long Term Trend Report

Natural Resource Report NPS/MEDN/NRR—2023/2501

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March 2023

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Please cite this publication as:

Pandori, L. L. M., L. Strope, and L. A. Cat. 2023. Rocky intertidal community shift over 30 years: 1990–2020 rocky intertidal long term trend report. Natural Resource Report NPS/MEDN/NRR—2023/2501. National Park Service, Fort Collins, Colorado .https://doi.org/10.36967/2297397

NPS 342/187811, March 2023

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Abstract

Cabrillo National Monument (CABR) is a unit of the National Park System located on the Point Loma peninsula in San Diego, CA, USA. Despite its small size (0.65 terrestrial km^2), the monument attracts 851,000 annual visitors (IRMA SRSS Reports 2011-2020), and acts as an "urban island", providing habitat for unique algal, plant and animal species in an area of increasing development and urbanization. The coastal area of the park also leads to the rocky intertidal zone, which is regarded by many as the best conserved shorelines in mainland southern California. Due to the high-quality habitat and proximity to an urban area, it is critical to monitor community composition and visitor use of the rocky intertidal area. We leveraged over 30 years of long-term monitoring data of both rocky intertidal communities and visitation to investigate: (1) whether visitation has increased over time, (2) if community composition has changed over time across intertidal management zones. We found that visitation to management Zone I has increased over time. Additionally, we found that visitation doesn't scale linearly across management zones: 73% of people were observed in Zone I, 19% of people in Zone II, and 4% of people in Zone III. PERMANOVA analyses indicated that community composition differed over time and across management zones for all plot types. Documenting community shifts, rather than changes in populations of single species, allows NPS staff to capture, and respond to, ecological transformation. Using the Resist-Accept-Direct (RAD) framework, we recommend that CABR either accept or direct changes to the rocky intertidal (*e.g.*, directing changes in higher visitation areas by implementing a timed entry or shuttle system, and accepting changes in closed or very low visitation areas). Looking forward, long-term rocky intertidal monitoring will inform the effectiveness of resisting, accepting, or directing actions the park takes to uphold the NPS mission at CABR and other NPS units with rocky intertidal habitat, which span the Pacific coast.

Acknowledgments

Funding and data management for this project were provided by the Mediterranean Coast Inventory and Monitoring Network (MEDN) and the Cabrillo National Monument Resources Management & Science division (CABR). Long-term monitoring programs are not feasible without the time, careful work, and dedication of volunteers and program staff. Over 500 volunteers have contributed to the Cabrillo National Monument Rocky Intertidal Monitoring Program. Visitation data was collected by a dedicated group of Volunteers-in-Parks led by Pam Zuckerman. We express sincere thanks to those who have made these programs outstanding and contributed to their success.

Introduction

Cabrillo National Monument (CABR) is a unit of the National Park System located at the southern tip of the Point Loma peninsula in San Diego, CA, USA. Since three sides of the park are surrounded by water and the fourth abuts a Navy base, the park acts as an "urban island", providing habitat for unique algal, plant and animal species in an area of increasing development and urbanization. Further, the coastal area of the park contains fragile maritime succulent scrub habitat, a sub-division of coastal sage scrub habitat. The coastal area of the park also leads to the rocky intertidal zone, which is regarded by many as the best conserved rocky intertidal shoreline in mainland southern California. Despite its small size (0.65 terrestrial km^2), the monument attracts 851,000 annual visitors (IRMA, SRSS Reports, mean visitation 2011–2020). Due to the high-quality habitat and proximity to an urban area, it is critical to monitor community composition and visitor use of the rocky intertidal area.

Rocky intertidal communities in southern California are subject to natural and anthropogenic stressors that affect their composition and functioning. On a climatic scale, global average temperature increases (Hobday & Pecl 2014, IPCC 2022) and decreases in oceanic pH (Caldeira & Wickett 2003, Caldiera & Wickett 2005, IPCC 2022) are already affecting the community composition and ecosystem functioning in marine habitats (Harley *et al.* 2006, IPCC 2022). Moreover, extreme events such as heat waves (Meehl & Tebaldi 2004, IPCC 2022) and intense storms (IPCC 2022) are expected to become more frequent. Southern California rocky intertidal communities are less stable over time than other regions along the eastern Pacific coast (Miner *et al.* 2021). This is of particular concern, as the community is also subject to accelerated ocean warming (Hobday & Pecl 2013) and high levels of both naturally occurring (*e.g.,* coastal erosion, boulder movement, storms) and anthropogenic (*e.g.,* rock-turning, trampling, collecting) disturbance. While the community at large is subject to such stressors, spatial dominants recover from deleterious effects at varying rates; red algal turf and barnacles recover from disturbance more quickly than mussels or rockweeds (Conway-Cranos 2012). Thus, resource managers must consider both resilience to disturbance (Conway-Cranos 2012), community composition, and community stability (Miner *et al.* 2021) when making management decisions.

In addition to abiotic stressors, the rocky intertidal zone at Cabrillo National Monument (CABR) is subject to intense visitation pressure. For example, while overall park visitation at CABR has declined between 1990 and 2020 (from attracting 1.4 million visitors in 1990 and 520,000 in 2020), visitation to the coastal area of the park has increased from 220,000 visitors in 2011 to 380,000 visitors in 2020 (Phillips *et al.* 2013, Pandori & Cat 2022). While increased visitation to public lands brings additional funding and community support, visitation – even within a Marine Protected Area (MPA) – can have deleterious effects on the rocky intertidal zone. Visitor activities such as trampling, rock-turning, and handling, can lead to shifts in intertidal community composition including lower mussel coverage (Smith *et al.* 2006, 2008), algae abundance and intertidal biodiversity (Huff 2011), which are related to community stability (Miner *et al.* 2021, Stachowicz *et al.* 2008). The rocky intertidal monitoring programs at CABR was planned with visitation stress in mind. Site selection in the 1990s was designed to capture areas of high, low and increasing visitation across both park units, allowing researchers to understand if changes observed may be attributed to visitation stress or other factors.

To understand flux in natural ecosystems, the Cabrillo Rocky Intertidal Monitoring Program began in 1990 with the goals of: (1) establishing limits of variation, (2) determining present health, and (3) diagnosing abnormal conditions in natural ecosystems to inform conservation and resource management decisions (Engle & Davis 1996, Becker 2006). In the first five years of data collection (1990-1995), 7 of the 13 focal taxa declined or disappeared from the study area (Engle & Davis 2000). These findings spurred management decisions such as the closure of a portion of the rocky intertidal area (management Zone III) to visitors in 1996, creation of the Tidepool Protection, Education and Restoration volunteer docent Program (TPERP) in 1997, founding of the Multi-Agency Rocky Intertidal Network (MARINe), and establishment of the Cabrillo State Marine Reserve as part of the California Marine Life Protection Act (MLPA) in 1999. As a result of these and other successes, the National Park Service established a service-wide Inventory and Monitoring (I&M) Program to provide scientific information on ecosystem health. In 2011, the Cabrillo Rocky Intertidal Monitoring Program was formally incorporated as a "Vital Sign" in the Mediterranean Coast Network (MEDN) of the I&M Program.

While the decline of focal taxa was critical to management decisions at the end of the 20th century, 21st century natural resource management requires a more holistic understanding of other organisms in the ecosystem to determine if park managers should resist, accept, or direct ecosystems impacted by climate change (Schuurman *et al.* 2020). Community ecology approaches to analysis of long-term monitoring data are critical to implementing this framework because they consider all taxa observed, utilizing more of the information collected by existing monitoring protocols. Since some focal taxa are extirpated, and other taxa not included at the beginning of the monitoring program may now be at risk, a community ecology approach to long-term monitoring data is better suited to inform park management decisions than approaches that focus only on spatial dominant taxa.

In this study, we document changes in visitation over time to three rocky intertidal sites at CABR, which represent a gradient of human use. We also test whether community composition has changed in fixed plots monitored annually between 1990 and 2020. More specifically, we aim to answer the following questions:

1) Has visitation to the rocky intertidal sites changed over time?
2) Does community composition differ significantly across management zones?
3) Has community composition, in each management zone, changed over time?

We hypothesized that visitation in all publicly accessible management zones (Zones I and II) between 1990 and 2020 had increased in concert with Coastal Trail visitation (Phillips *et al.* 2013, Pandori & Cat 2022). Since Zone III has been closed to the public since 1997, we expected that visitation to that zone would remain low throughout the study period. Since rocky intertidal taxa (Smith & Murray 2005, Smith *et al.* 2006, 2008) and communities (Huff 2006) are sensitive to trampling, we predicted community composition would differ significantly across zones. We also anticipated that communities would change significantly over time, as southern California communities are less stable than other regions along the coast (Miner *et al.* 2021).

Methods

Site Selection

The west side of the park contains 1.5 km of rocky intertidal habitat comprised of gently sloping sandstone benches with metavolcanic boulders scattered at the base of sandstone cliffs. While the site is similar in taxonomic makeup, geological history, currents and wave exposure, the shoreline differs in habitat type (some areas are dominated by benches and others by boulder fields) and encompasses a steep visitation gradient. Around 380,000 park guests traversed the coastal area of CABR in 2020 (Pandori & Cat 2022), so visitation pressure is a major resource management concern.

The intertidal area is subdivided into three management zones (I, II, and III; Figure 1), which represent a gradient in human visitation (Engle & Davis 2000b). There is a single public access point in the northern area of the CABR rocky intertidal zone. Zone I is in the intertidal area immediately surrounding the entrance to the tidepool area of the park and receives the most visitation of each of the management zones. Very few visitors made the ~ 1 km trek southward to the end of Point Loma, so this area became Zone III. While Zone III was open to the public when monitoring began in 1990, it was closed in November 1996, and has remained closed. Zone III is accessed by researchers and occasionally members of the U.S. Coast Guard, which are landowners directly adjacent to Zone III. To represent moderate visitation levels between that of Zones I and III, Zone II was established between the other sites. The management zones also vary in physical characteristics: Zone I has boulders and a compact vertical gradient, while Zones II and III have larger extents of flat rock benches.

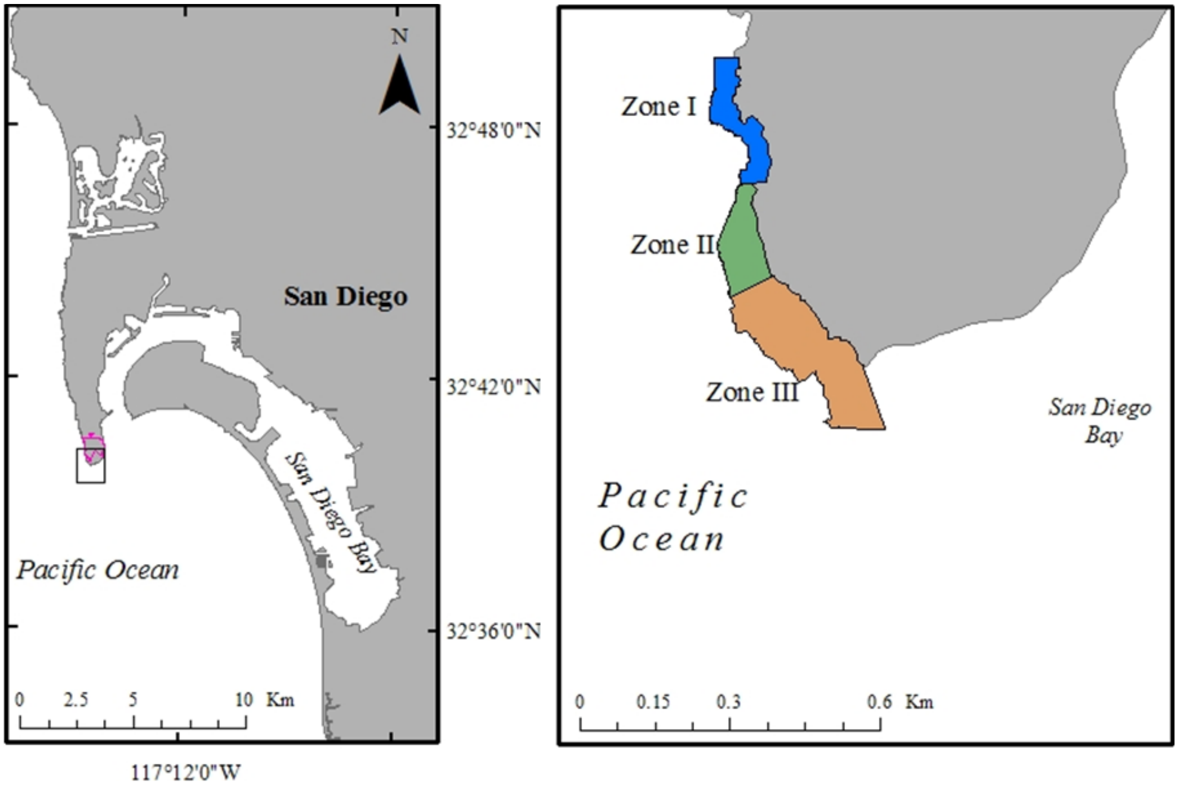

Figure 1. Map of the intertidal of Cabrillo National Monument, in San Diego, CA. The three management zones of the park represent different levels of human visitation: Zone I is high use, Zone II is intermediate use, Zone III is low use and has been closed to the public since November 1996. Zone III is occasionally accessed by researchers and U.S. Coast Guard personnel, who are landowners adjacent to the area.

Visitation Assessments

Assessments of intertidal visitation from 1990-2020 were conducted as part of the shorebird monitoring program by the Cabrillo National Monument Volunteers-in-Parks (VIP) program. Up to three VIPs conduct 40-50 sampling events each year during daytime (10 am - 4 pm) low tides (< 0 m below MLLW). While most years fall within this range, it is worthwhile to note that some years, such as those during the COVID-19 pandemic, have as few as 3 surveys and other years have as many as 99 surveys. Due to this variability, the rate of observance (mean number of visitors observed per survey) for each year and management zone was calculated and used for statistical tests. Sampling events consist of a 60-minute observation period, centered around the time of low tide, during which VIPs walk a single, unidirectional pass through the intertidal from the northernmost (Zone I) to the southernmost management zone area (Zone III) of the park. As surveyors pass people (park staff, VIPs, and visitors) in the intertidal zone, they are counted. No people on the cliffs or trail areas are counted.

Rocky Intertidal Community Surveys

Long-term rocky intertidal monitoring program surveys are based on a fixed-plot re-survey design. Rectangular photo-plots were established to document percent cover of four target taxa: (1) *Mytilus californianus* (California mussels), (2) *Chthamalus* spp./*Balanus glandula* (acorn barnacles) and

Tetraclita rubescens (volcano barnacles), (3) *Pollicipes polymerus* (goose barnacles), and (4) *Silvetia compressa* (golden rockweed). Five replicate plots per target taxa in each management zone were established in areas of high abundance in 1990. Plots were photographed during sampling events. Additionally, plots were field scored using a 50 cm x 75 cm PVC quadrat strung to create a grid of 100 evenly spaced points, under which the type of cover was identified and recorded on paper to yield percent cover. When field scoring was not possible, digital photos were scored by overlaying a similar grid with image processing software. Prior to 1995, three line transects per zone targeting *Pollicipes polymerus* were monitored. In 1995, each line transect was converted into two photo-plots, yielding six *Pollicipes* photo-plots per zone.

Rocky intertidal monitoring surveys were conducted twice per year, in the spring and fall, of 1990-2016. From 2017 onwards, sampling was reduced to one visit per year in the fall to allow time for additional data collection related to climate change (Raimondi *et al.* 2018). While a summary of methodology is presented in this report, parks in the Mediterranean Coast Inventory & Monitoring Network (MEDN) adhere to the core Multi-Agency Rocky Intertidal Monitoring Network (MARINe) protocol (Engle *et al.* 2022). Other survey methods, such as line transects, and circular owl limpet plots (*Lottia gigantea*) are completed annually – and summaries of long-term data can be found in the latest annual reports (Pandori *et al.* 2021, Pandori & Cat 2022b). These data were not included in this 30-year trend report because we focused on community shifts and potential for ecological transformation. In particular, line transect data were not included due to low taxonomic resolution.

Data Wrangling

Data assembly script:
https://github.com/llmpandori2/cabr_intertidal_community_ms/blob/main/scripts/lt_report_script_wrangling.R

Data files were quality checked, then assembled using RStudio (Wickham & Bryan 2019, Firke 2021, Garnier *et al.* 2021, Wickham *et al.* 2019). The quality-checking process involved two steps: (1) reviewing plots surveyed each year to eliminate plots surveyed inconsistently or added after 1995, and (2) reviewing taxa surveyed each year to come up with a list of taxa surveyed all years 1990-2020. Based on these assessments, we only considered plot replicates 1-6 for *Pollicipes*, and plot replicates 1-5 for other target taxa (*Silvetia*, *Mytilus* and *Chthamalus/Balanus/Tetraclita*), as they were surveyed consistently throughout the study period (Appendix 1, Table S1). The list of taxa surveyed each year changed throughout the study period (Appendix 2, Figure S1). To standardize across years, we created a crosswalk table of all taxa surveyed throughout the study period, and what their assignments would have been in 1995 (Appendix 2, Table S2). For most survey years, we limited data to surveys conducted in the fall season – between October of the study year and January of the following year. Collectively, these considerations resulted in two data gaps in 2009 and 2018, where data were not collected in the fall season. To fill in data gaps, we substituted data from spring of the following year (Spring 2010 replaces Fall 2009 and Spring 2019 replaces Fall 2018). The above criteria maximize available data for our trend report, while keeping measurements comparable over time.

Data Analysis

Data analysis script:
https://github.com/llmpandori2/cabr_intertidal_community_ms/blob/main/scripts/lt_report_script_analyses.R

All computations and data visualization were done in RStudio (Bui *et al.* 2021, Firke 2021, Grantham 2019, Oksanen *et al.* 2020, R Core Team 2021, Robinson *et al.* 2021, Wickham *et al.* 2019), and data are available upon request from MEDN. To test whether visitation changes over time, we calculated the annual mean number of visitors per survey in each management zone and conducted a linear regression of visitation across survey years. We used a multivariate approach to test whether rocky intertidal community composition differed across management zones, and if composition changed over time. Annual percent cover of nine taxonomic categories were calculated for each plot across survey years. We constructed community matrices and used permutational analysis of variance (PERMANOVA) to test whether community composition differed across management zones, and present ordination plots (NMDS) of community composition across zones. We also visualized community change over time through stacked bar plots illustrating mean plot composition over time for each management zone. This accessory data visualization allows for more intuitive representation of how taxa change over time across management zones and plot types.

Results

Over the study period (1990-2021), 4,183 visitation surveys were conducted to capture differences in visitation across management zones and assess whether intertidal visitation has increased over time. Overall, visitation differed across management zones (Figure S2 in Appendix 3). Pooling all surveys, 77% of people were observed in management Zone I – which is closest to the single visitor entrance to the tidepool area of the park, 19% of people were in Zone II, and 4% of people were in Zone III, which has been closed to the public since 1997. Park staff and researchers are included in visitation surveys, so most of the people observed in Zone III are not visitors. Since four times more visitors were observed in Zone I in comparison to Zone II, visitation levels do not increase in a linear fashion across zones. Over time, visitation increased in Zone I (Figure 2). There was a significant, positive linear relationship between time and visitation in Zone I ($p < 0.01$, $R^2 = 0.48$). While linear relationships between visitation and time were significant for all management zones, R^2 values were not strong (Table S3).

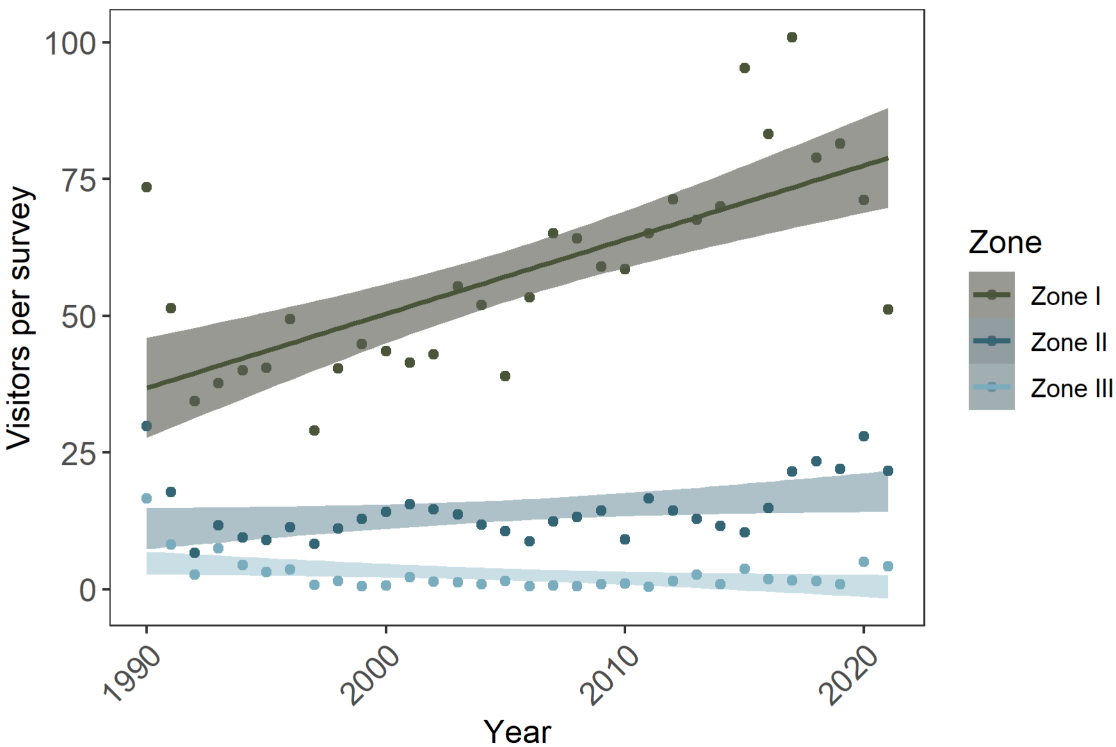

Figure 2. Visitation has increased over time in management Zone I ($p < 0.01$, $R^2 = 0.48$). Visitation to Zones II and III have changed ($p < 0.05$), but strong correlations between visitation and time are not present (Zone II $R^2 = 0.10$, Zone III $R^2 = 0.14$) Visitation has increased in management zones accessible to the public (Zones I and II) and has declined over time in Zone III. While Zone III has been closed to the public since November 1996, researchers, park staff and Coast Guard housing residents are counted in visitation surveys.

Among all plot types (*Chthamalus/Balanus*, *Mytilus*, *Pollicipes*, and *Silvetia*), NMDS (stress values ≤ 0.22) and PERMANOVA revealed that communities differed over time and across management zones (Appendix 4, Tables S4-S15). In plots targeting *Chthamalus/Balanus* (acorn barnacles), community composition differed over time (PERMANOVA $F = 14.88$, $R^2 = 0.03$, $p < 0.01$) and across management zones ($F = 24.82$, $R^2 = 0.09$, $p < 0.01$), but there was no interaction between time and management zone ($F = 1.62$, $R^2 < 0.01$, $p = 0.12$; Figure 3). Barnacle cover fluctuates more than other target taxa over time (Figure 4). While most barnacle plots are primarily comprised of algae/plants, substrate, and barnacles, *Silvetia compressa* (golden rockweed) cover is most prevalent in barnacle plots in management zones II and III. In plots targeting *Mytilus* (mussels), community composition differed over time ($F = 58.09$, $R^2 = 0.07$, $p < 0.01$) and across management zones ($F = 137.26$, $R^2 = 0.34$, $p < 0.01$), and there was a significant interaction between time and management zone ($F = 13.30$, $R^2 = 0.03$, $p < 0.01$, Figure 5). In Zone I, mussel cover increases over time for the first decade of monitoring and declines sharply around 2014 (Figure 6). While mussel cover drops dramatically within the first decade of monitoring (1990-2000), Zone II is dominated by algal cover after 2000, and Zone III shows a rapid increase in *Silvetia* cover after 2000. Similarly, community composition differed over time in plots targeting *Pollicipes polymerus* (goose barnacles; $F = 14.95$, $R^2 = 0.02$, $p < 0.01$) and across management zones ($F = 70.88$, $R^2 = 0.23$, $p < 0.01$), and there was a significant interaction between time and management zone ($F = 7.65$, $R^2 = 0.02$, $p < 0.01$, Figure 7). Across all management zones, *Pollicipes* plots are dominated by substrate, *Pollicipes* and algae/plants. Zone II has more invertebrates than either Zone II or Zone III, and Zone III has more *Balanus* spp. and *Chthamalus* spp. (acorn barnacle) cover than the other management zones (Figure 8). Finally, in plots targeting *Silvetia compressa* (golden rockweed), community composition differed over time ($F = 135.19$, $R^2 = 0.22$, $p < 0.01$) and across management zones ($F = 17.34$, $R^2 = 0.06$, $p < 0.01$), but there was no interaction between time and management zone ($F = 1.14$, $R^2 < 0.01$, $p = 0.30$, Figure 9). Across management zones, *Silvetia* cover has decreased over time, particularly after the year 2000. Communities have shifted from dominant *Silvetia* cover to dominant cover of algae/plants (Figure 10).

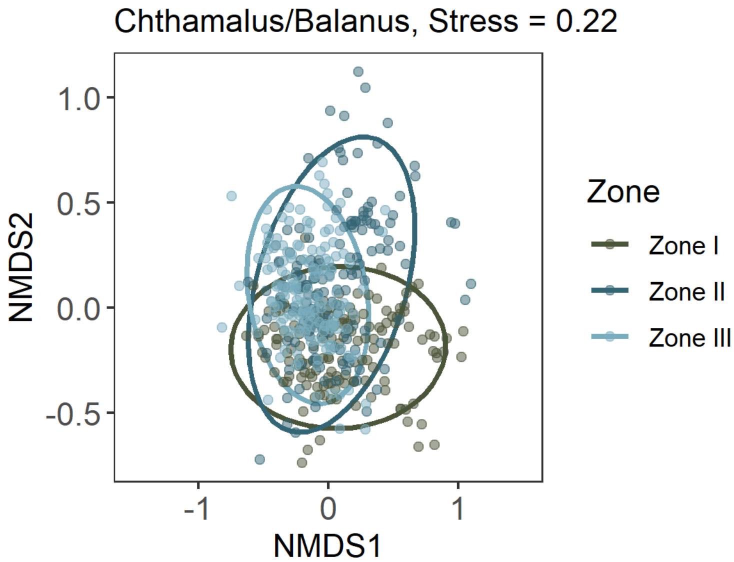

Figure 3. Non-metric multidimensional scaling (NMDS, stress = 0.22) plot representing community composition in fixed plots targeting *Chthamalus spp.* and *Balanus spp.* (acorn barnacles) at Cabrillo National Monument. Points represent taxonomic composition of plots across three management zones and 31 years of survey data (1990-2021). Community composition differed over time (PERMANOVA year + zone + year*zone: F = 14.88, R^2 = 0.03, p < 0.01) and across management zones (F = 24.82, R^2 = 0.09, p < 0.01), but there was no interaction between time and management zone (F = 1.62, R^2 < 0.01, p = 0.12). Full PERMANOVA results in tables S4-6.

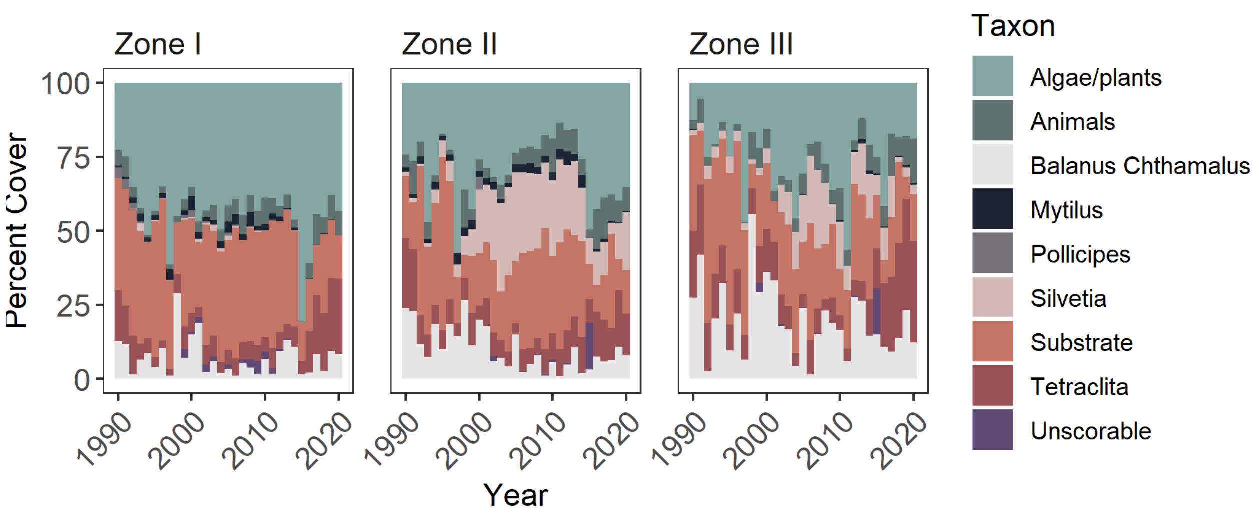

Figure 4. Stacked bar plots show taxonomic shifts in composition of fixed plots targeting *Chthamalus spp.* and *Balanus spp.* (acorn barnacles) across three management zones at Cabrillo National Monument. Note that the *Chthamalus/Balanus* is the bottom bar in each plot. Barnacle cover fluctuates over time. While most barnacle plots are primarily comprised of algae/plants, substrate, and barnacles, *Silvetia* (golden rockweed) cover is most prevalent in barnacle plots in management zones II and III.

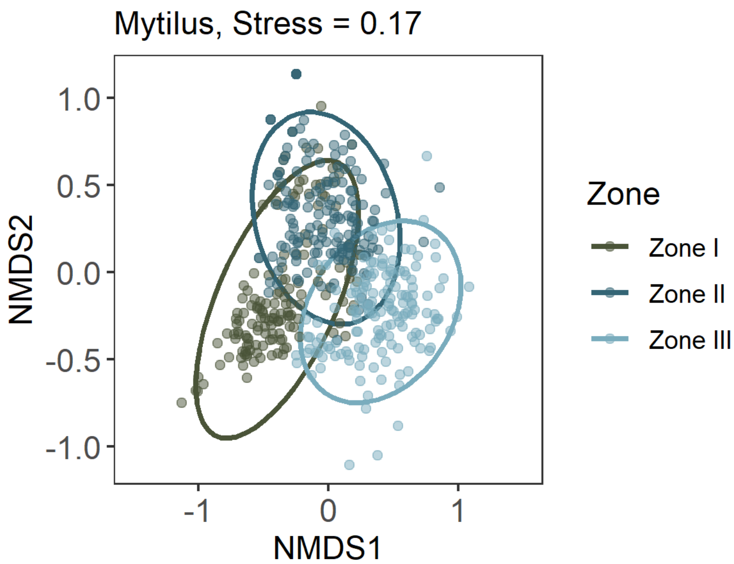

Figure 5. Non-metric multidimensional scaling (NMDS, stress = 0.17) plot representing community composition in fixed plots targeting *Mytilus* (mussels) at Cabrillo National Monument. Points represent taxonomic composition of plots across three management zones and 31 years of survey data (1990-2021). Community composition differed over time (PERMANOVA year + zone + year*zone: F = 58.09, R^2 = 0.07, p < 0.01) and across management zones (F = 137.26, R^2 = 0.34, p < 0.01), and there was a significant interaction between time and management zone (F = 13.30, R^2 = 0.03, p < 0.01). Full PERMANOVA results in tables S7-S9.

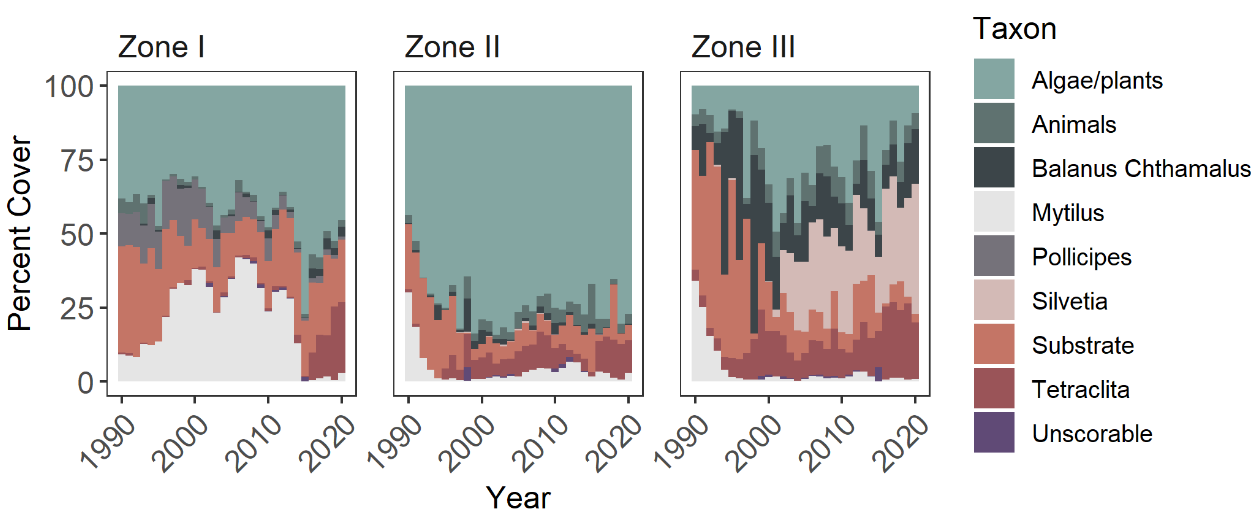

Figure 6. Stacked bar plots show taxonomic shifts in composition of fixed plots targeting *Mytilus* (mussels) across three management zones at Cabrillo National Monument. Note that *Mytilus* is the bottom bar in each plot. Composition differs significantly over time and across management zones (PERMANOVA, Tables S6-S8). In Zone I, mussel cover increases over time for the first decade of monitoring and declines sharply around 2014. While mussel cover drops dramatically within the first decade of monitoring (1990-2000), Zone II is dominated by algal cover after 2000, and Zone III shows a rapid increase in *Silvetia* (golden rockweed) after 2000.

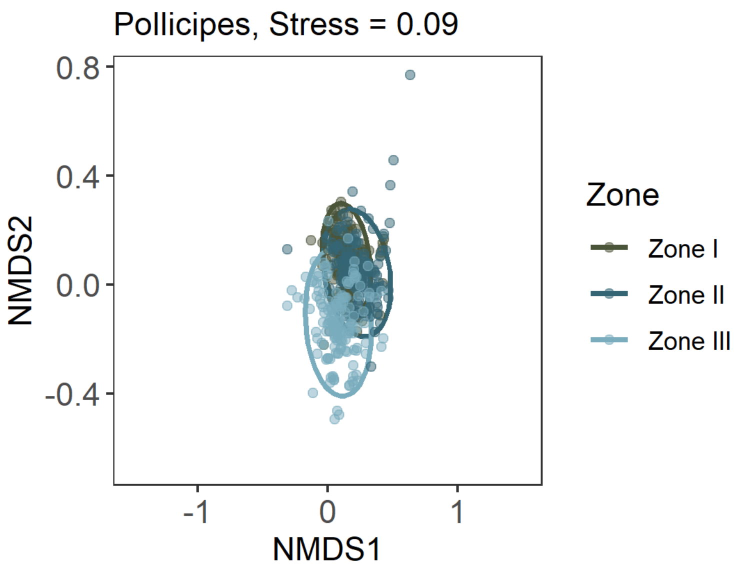

Figure 7. Non-metric multidimensional scaling (NMDS) plot representing community composition in fixed plots targeting *Pollicipes polymerus* (goose barnacles) at Cabrillo National Monument. Points represent taxonomic composition of plots across three management zones and 26 years of survey data (1995-2021). Community composition differed over time (PERMANOVA year + zone + year*zone: $F = 14.95$, $R^2 = 0.02$, $p < 0.01$) and across management zones ($F = 70.88$, $R^2 = 0.23$, $p < 0.01$), and there was a significant interaction between time and management zone ($F = 7.65$, $R^2 = 0.02$, $p < 0.01$). Full PERMANOVA tables S10-S12.

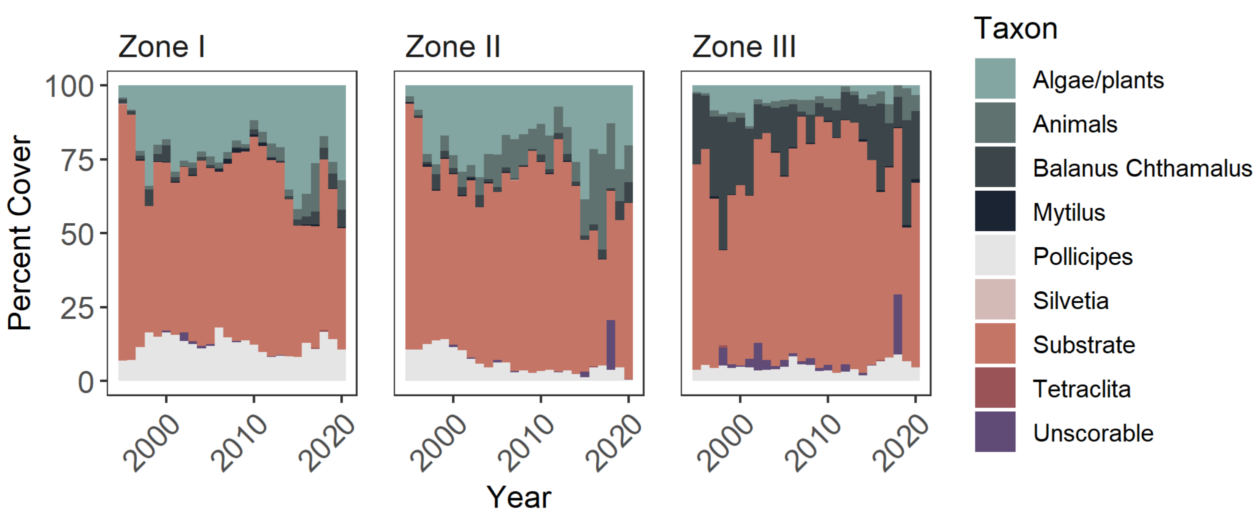

Figure 8. Stacked bar plots show taxonomic composition of fixed plots targeting *Pollicipes polymerus* (goose barnacles) across three management zones at Cabrillo National Monument. Note that *Pollicipes* is the bottom bar in each plot. Composition differs significantly over time and across management zones (PERMANOVA, Tables S9-S11). Across all management zones, plots are dominated by substrate, *Pollicipes* and algae/plants. Zone II has more invertebrates than either Zone II or Zone III, and Zone III has more *Balanus* spp. and *Chthamalus* spp. (acorn barnacle) cover than the other management zones.

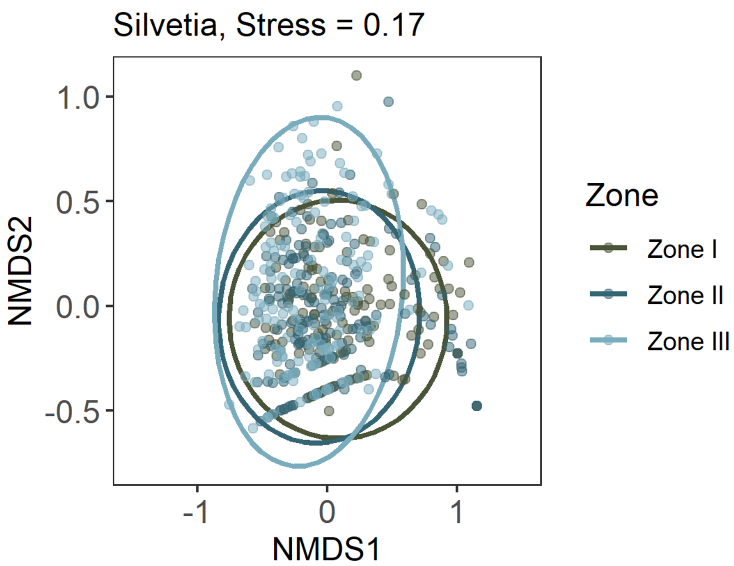

Figure 9. Non-metric multidimensional scaling (NMDS, stress = 0.17) plot representing community composition in fixed plots targeting *Silvetia compressa* (golden rockweed) at Cabrillo National Monument. Points represent taxonomic composition of plots across three management zones and 31 years of survey data (1990-2021). Community composition differed over time (PERMANOVA year + zone + year*zone: F = 135.19, R^2 = 0.22, p < 0.01) and across management zones (F = 17.34, R^2 = 0.06, p < 0.01), but there was no interaction between time and management zone (F = 1.14, R^2 < 0.01, p = 0.30). Full PERMANOVA tables S13-S15.

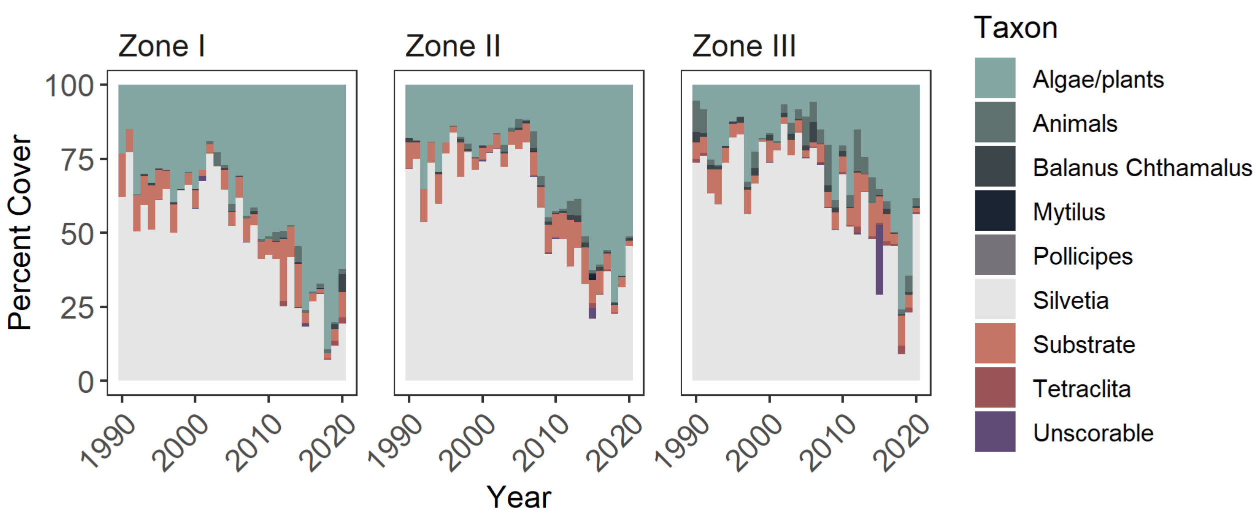

Figure 10. Stacked bar plots show taxonomic shifts in composition of fixed plots targeting *Silvetia compressa* (golden rockweed) at Cabrillo National Monument. Note that the *Silvetia* is the bottom bar in each plot. Across management zones (panels in the plot), *Silvetia* cover has decreased over time, particularly after the year 2000. Communities have shifted from dominant *Silvetia* cover to dominant cover of algae/plants.

Discussion

The 30 years of long-term rocky intertidal monitoring at CABR occurred during a time where climate change was unidirectional and rapidly exceeding the bounds of historical variability (Schuurman *et al.* 2020). We found that all rocky intertidal communities monitored have changed over time, and that community composition differs across management zones. We also found that visitation to the most heavily trampled management Zone I has increased over time. Given that most target species decline in their respective plots over time, these findings highlight the importance of considering all taxa in communities, not just individual target species, to effectively capture and manage shifts in the rocky intertidal.

When the program was established, the target species plots were intended to serve as baselines for future management of CABR, however, natural resource managers and decision-makers need new approaches to understand viable options for management under climate change. Ecological transformation is a large, enduring shift in multiple characteristics of an ecosystem and not only a change in a single species. For example, in Figures 4, 6, 8, and 10, the focus taxon is shown as the bottom bar in stacked bar graph. If managers were only looking at fluctuations in focus taxon variability, they would miss other important changes in community composition that are visualized and described in each figure that could inform decision-making.

Documenting community shifts rather than changes in populations of target species allows NPS staff to capture ecological transformation in marine systems, which are changing more rapidly than other ecosystems (Staudinger *et al.* 2013, Wiens 2016, Pecl *et al.* 2017). The lack of stability of southern California intertidal systems may also explain changes in community composition over time. Southern California is also considered a "marine hotspot", warming at some of the fastest rates on the planet (Hobday & Pecl 2014). Extreme heatwaves have been shown to shift community composition toward an increase in species that are tolerant to warm conditions, and a decrease in foundation species (Miner *et al.* 2021). CABR and Channel Islands National Park (CHIS) has responded to community changes in plots by implementing modified biodiversity surveys designed to evaluate whether plot-level community changes are reflected in survey sites at large.

When transformation or major change is detected, the Resist-Accept-Direct (RAD) framework will guide natural resource management decisions (Schuurman *et al.* 2020). To summarize, managers can resist transformation by working to maintain or restore ecosystems based on historical or acceptable current conditions; accept transformation by allowing change without intervention; or direct transformation by actively shaping ecosystem processes towards desired new conditions (Schuurman *et al.* 2020). At this time, we recommend that CABR either accept or direct changes to the rocky intertidal. Since RAD management strategies are not mutually exclusive, both managerial responses are possible in various zones of the park (*e.g.*, directing changes in higher visitation areas by implementing a timed entry or shuttle system, and accepting changes in closed or very low visitation areas). The resist response would require large and unfeasible amounts of staff time and funding with a very uncertain outcome. Regardless of the management decision, outcomes can be measured using rocky intertidal community composition and visitation pressure data.

High variation in rocky intertidal communities through time is typical, and plots chosen in 1990 to represent certain species may not be representative, or even contain that original target species in 2020. Community changes can result from a variety of sources, including abiotic changes and disturbance events (Becker 2005). Abiotic changes vary in scale, including worldwide phenomena such as climate change (IPCC 2022) and local processes like the Pacific Decadal Oscillation (Mantua & Hare 2002) or El Nino Southern Oscillation (Philander 1986). Disturbance events at the park are generally caused by long-term visitation pressure and short-duration events such as shipwrecks and oil spills. We observed significant changes in community composition over time and across management zones in all plot types. Given that time and visitation are autocorrelated, additional mechanistic studies disentangling the effects of climate change, climatic cycles, and disturbance events are needed to parse visitation impacts on the rocky intertidal zone. These studies are especially important given increasing visitation to the coastal area of CABR.

Long-term monitoring programs, such as the rocky intertidal and visitation monitoring programs, are important tools in understanding the interplay between climate change and increased visitation at national park units to carry out the NPS mission: "The National Park Service preserves unimpaired the natural and cultural resources and values of the National Park System for the enjoyment, education, and inspiration of this and future generations." Meeting the NPS mission requires balancing access to visitors with preserving the ecosystems they enjoy visiting in the most effective way possible, in the face of ongoing climate change. Looking forward, long-term rocky intertidal monitoring will inform the effectiveness of resisting, accepting, or directing actions the park takes to uphold the NPS mission at CABR and other NPS units with rocky intertidal habitat, which span the entire Pacific coast.

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Appendix 1: Plot Selection Process

Table S1. Photo-plot coverage table shows plots 1-5 for each management zone and target taxa are consistently surveyed over time. Other plots are not surveyed consistently. Thus, only plots 1-5 for each target taxa and management zone were included in analyses. Note that Spring 2010 data replaces Fall 2009 and Spring 2019 data replaces Fall 2018 prior to these coverage assessments.

Management Zone	Target Taxa	Replicate(s)	Coverage
Zone I	*Chthamalus/Balanus*	1	Missing 2018
	Chthamalus/Balanus	2-5	Complete record 1990-2021
	Mytilus	1-5	Complete record 1990-2021
	Mytilus	6*	Missing 2008, 2014* Excluded from analyses*
	Pollicipes	1, 3-5	Complete record 1995-2021 *Pollicipes* plots established 1995
	Pollicipes	2	Missing 1996
	Pollicipes	6	Missing 1995
	Silvetia	1-3, 5	Complete record 1990-2021
	Silvetia	4	Missing 1994
Zone II	*Chthamalus/Balanus*	1-5	Complete record 1990-2021
	Mytilus	1	Missing 1998
	Mytilus	2-5	Complete record 1990-2021
	Pollicipes	1, 2, 5, 6	Complete record 1995-2021 *Pollicipes* plots established 1995
	Pollicipes	3	Missing 2020
	Pollicipes	4	Missing 2019, 2020
	Pollicipes	7*	Missing 1995-2007, 2020* Plot established 2007* Excluded from analyses*
	Pollicipes	8*	Missing 1995-2019* Plot established 2020* Excluded from analyses*
	Silvetia	1,2,4,5	Complete record 1990-2021
	Silvetia	3	Missing 1994

*Plots excluded from analyses (also indicated by gray cell fill).

Table S1 (continued). Photo-plot coverage table shows plots 1-5 for each management zone and target taxa are consistently surveyed over time. Other plots are not surveyed consistently. Thus, only plots 1-5 for each target taxa and management zone were included in analyses. Note that Spring 2010 data replaces Fall 2009 and Spring 2019 data replaces Fall 2018 prior to these coverage assessments.

Management Zone	**Target Taxa**	**Replicate(s)**	**Coverage**
Zone III	*Chthamalus/Balanus*	1-5	Complete record 1990-2021
	Mytilus	1-5	Complete record 1990-2021
	Pollicipes	1-3, 5, 6	Complete record 1995-2021 *Pollicipes* plots established 1995
	Pollicipes	4	Missing 1995
	Silvetia	1, 2, 4, 5	Complete record 1990-2021
	Silvetia	3	Missing 2015

*Plots excluded from analyses (also indicated by gray cell fill).

Appendix 2: Addressing Taxonomic Changes over Time

Taxonomic Complexity Increases over Time

The list of taxa surveyed each year changed throughout the study period. In 1990, only nine taxonomic categories were used for surveying plots – eight of which had non-zero abundance values (Figure S1).

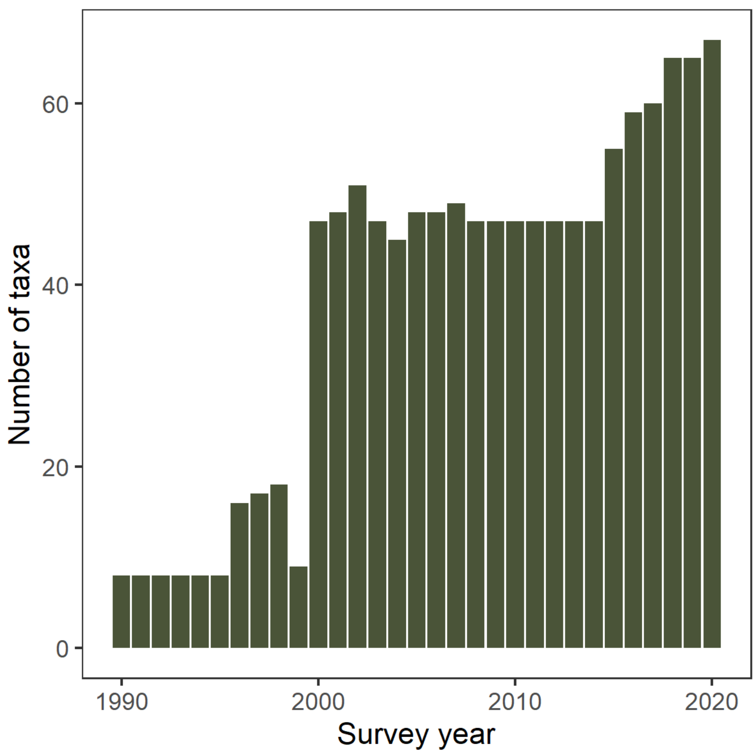

Figure S1. Survey taxonomic complexity increases over time as the list of taxa surveyed changes. Values are the number of taxa with non-zero abundances during the study period (1990-2020).

Taxonomic Crosswalk Table

The list of taxa surveyed each year changed throughout the study period. To standardize across years, we created a crosswalk table of all taxa surveyed throughout the study period, and what their assignments would have been in 1990-1995 (since methods for *Pollicipes* abundance were changed from transects 1990-1994 to permanently marked photo-plots in 1995) (Table S2).

Table S2. Taxonomic crosswalk table. Codes and names from 1990 are paired with all taxonomic codes and scientific names from future surveys included in those categories in our analyses.

1990 Code	1990 Name	Taxa Code	Taxa Name
BARESUB	Substrate	ROCK	Bare rock
	Substrate	BARESUB	Bare substrate
	Substrate	OTHSUB	Other substrate
	Substrate	ROCKBOLT	Rock-bolt
	Substrate	ROCKZSPAR	Rock-z-spar
	Substrate	SAND	Sand
	Substrate	TAR	Tar
OTHANI	Animals	UNIINV	Unidentified invertebrates
CHTBAL	*Balanus/Chthamalus*	CHTBAL	*Balanus/chthamalus*
	Balanus/Chthamalus	DEABAL	Dead *balanus glandula*
	Balanus/Chthamalus	DEACHT	Dead *chthamalus dalli; fissus*
MYTCAL	*Mytilus*	DEAMCA	Dead *mytilus californianus*
	Mytilus	DEAMTR	Dead *mytilus trossulus; galloprovincialis; edulis*
	Mytilus	MUSSEL	Mussel
	Mytilus	MYTCAL	*Mytilus californianus*
OTHANI	Animals	ANEMON	Anemones (generic)
	Animals	ANTELS	*Anthopleura elegantissima/sola*
	Animals	ANTSPP	*Anthopleura* species
	Animals	CHITON	Chiton
	Animals	LIMPET	Limpet
	Animals	LOTGIG	*Lottia gigantea*
	Animals	MEXLUG	*Mexacanthina lugubris*
	Animals	OTHANI	Miscellaneous animal
	Animals	OTHBAR	Other barnacles

Table S2 (continued). Taxonomic crosswalk table. Codes and names from 1990 are paired with all taxonomic codes and scientific names from future surveys included in those categories in our analyses.

1990 Code	1990 Name	Taxa Code	Taxa Name
OTHANI (continued)	Animals	DEAINV	Other dead invertebrate
	Animals	OTHINV	Other invertebrates
	Animals	PHRCAL	*Phragmatopoma californica*
	Animals	PISOCH	*Pisaster ochraceus*
OTHPLA	Algae/plants	ARTCOR	Articulated corallines
	Algae/plants	CAUUST	*Caulacanthus ustulatus*
	Algae/plants	CENSPP	*Centroceras* spp
	Algae/plants	CHOCAN	*Chondracanthus canaliculatus*
	Algae/plants	CHOSPI	*Chondracanthus spinosa*
	Algae/plants	CLACOL	*Cladophora columbiana*
	Algae/plants	COLPOM	*Colpomenia*
	Algae/plants	CRUCOR	Crustose corallines
	Algae/plants	EGRMEN	*Egregia menziesii*
	Algae/plants	EISARB	*Eisenia arborea*
	Algae/plants	ENDPET	*Endarachne / petalonia*
	Algae/plants	ENDMUR	*Endocladia muricata*
	Algae/plants	FUCGAR	*Fucus gardneri*
	Algae/plants	GASTRO	*Gastroclonium* species
	Algae/plants	GELSPP	*Gelidium* species
	Algae/plants	HALCYS	*Halidrys dioica/cystoseira* spp
	Algae/plants	HESCAL	*Hesperophycus californica*
	Algae/plants	LAUSPP	*Laurencia*
	Algae/plants	MASPAP	*Mastocarpus papillatus*
	Algae/plants	MAZAFF	*Mazzaella affinis*

Table S2 (continued). Taxonomic crosswalk table. Codes and names from 1990 are paired with all taxonomic codes and scientific names from future surveys included in those categories in our analyses.

1990 Code	1990 Name	Taxa Code	Taxa Name
OTHPLA	Algae/plants	MAZSPP	*Mazzaella* spp
	Algae/plants	NONCRU	Non-coralline crust
	Algae/plants	OSMSPP	*Osmundea* species
	Algae/plants	OTHBRO	Other brown algae
	Algae/plants	OTHGRE	Other green algae
	Algae/plants	OTHPLA	Other plants
	Algae/plants	OTHPLALG	Other plants/algae
	Algae/plants	OTHRED	Other red algae
	Algae/plants	PELLIM	*Pelvetiopsis limitata*
	Algae/plants	PHYOVR	*Phyllospadix scouleri/torreyi*
	Algae/plants	PORSPP	*Porphyra* spp
	Algae/plants	REDTF	Red algal turf
	Algae/plants	SARMUT	*Sargassum muticum*
	Algae/plants	SCYSPP	*Scytosiphon* spp
	Algae/plants	STEDIO	*Stephanocystis dioica*
	Algae/plants	STESPP	*Stephanocystis* spp
	Algae/plants	TURF	Turf low filamentous (undifferentiated)
	Algae/plants	ULVSPP	*Ulva* spp
	Algae/plants	ULVENT	*Ulva/enteromorpha*
	Algae/plants	UNIALG	Unidentified algae
POLPOL	*Pollicipes polymerus*	POLPOL	*Pollicipes polymerus*
SILCOM	*Silvetia compressa*	PELCOM	*Pelvetia compressa*
	Silvetia compressa	SILCOM	*Silvetia compressa*

Table S2 (continued). Taxonomic crosswalk table. Codes and names from 1990 are paired with all taxonomic codes and scientific names from future surveys included in those categories in our analyses.

1990 Code	1990 Name	Taxa Code	Taxa Name
TETRUB	*Tetraclita rubescens*	DEATET	Dead *tetraclita*
	Tetraclita rubescens	TETRUB	*Tetraclita rubescens*
UNSCORE	Unscorable	UNIDEN	Unidentified
	Unscorable	UNSCORE	Unscorable
	Unscorable	UNSCOREALGAE	Unscorable-drift algae
	Unscorable	UNSCOREROCK	Unscorable-off rock edge
	Unscorable	UNSCORESHADOW	Unscorable-shadow
	Unscorable	UNSCORESHOE	Unscorable-shoe

Appendix 3: Regression Analysis of Visitation across Management Zones

Figure S2 shows the percent of total visitors to CABR rocky intertidal management zones, and Table S3 shows the linear regression results across the three management zones.

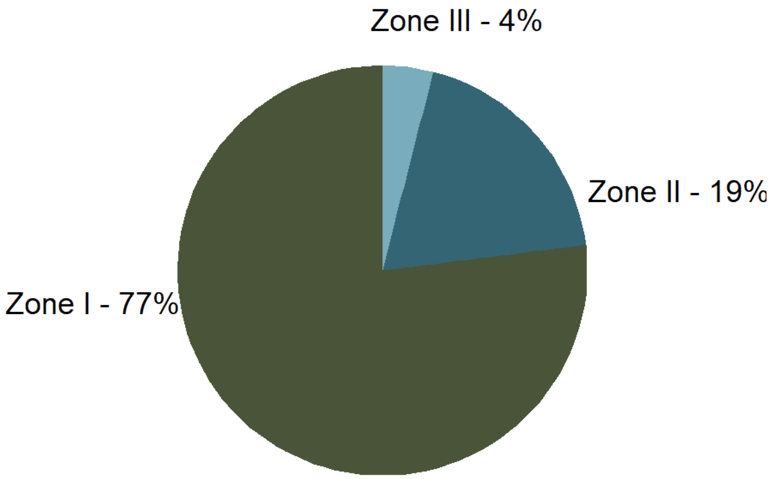

Figure S2. Percent of total visitors observed in three management zones at Cabrillo National Monument (1990-2021). Most visitors were observed in Zone I. Fewer visitors were observed in Zone II, and only 4% of observations were in Zone III, which has been closed to the public since 1997.

Table S3. Linear regression results across three management zones.

Management Zone	Slope	Y - Intercept	R^2 value	P value
Zone I	1.36	-2663.93	0.48	< 0.01
Zone II	0.22	-425.45	0.10	0.04
Zone III	-0.14	280.84	0.14	0.02

Appendix 4: Community Changes over Time and across Management Zones (PERMANOVA)

Chthamalus **spp. and** ***Balanus*** **spp. (acorn barnacle) Plots**

The PERMANOVA results for *Chthamalus* spp. and *Balanus* spp. (acorn barnacle) plots are provided in Tables S4 through S6.

Table S4. *Chthamalus/Balanus* PERMANOVA: Community ~ Year.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Year	1	1.90	1.90	13.46	0.03	0.001
Residuals	463	65.38	0.14	–	0.97	–
Total	464	67.28	–	–	1.00	–

Table S5. *Chthamalus/Balanus* PERMANOVA: Community ~ Zone.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Zone	2	6.34	3.17	24.04	0.09	0.001
Residuals	462	60.94	0.13	–	0.91	–
Total	464	67.28	–	–	1.00	–

Table S6. *Chthamalus/Balanus* PERMANOVA: Community ~ Year + Zone + Year*Zone.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Year	1	1.90	1.90	14.88	0.03	0.001
Zone	2	6.34	3.17	24.82	0.09	0.001
Year*Zone	2	0.41	0.21	1.62	< 0.01	0.119
Residuals	459	58.62	0.13	–	0.87	–
Total	464	67.28	–	–	1.00	–

Mytilus (mussel) Plots

The PERMANOVA results for *Mytilus* (mussel) plots are provided in Tables S7 through S9.

Table S7. *Mytilus* PERMANOVA: Community ~ Year.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Year	1	5.46	5.46	35.35	0.07	0.001
Residuals	462	71.30	0.15	–	0.93	–
Total	463	76.76	–	–	1.00	–

Table S8. *Mytilus* PERMANOVA: Community ~ Zone.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Zone	2	25.80	12.90	116.71	0.34	0.001
Residuals	461	50.96	0.11	–	0.66	–
Total	463	76.76	–	–	1.00	–

Table S9. *Mytilus* PERMANOVA: Community ~ Year + Zone + Year*Zone.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Year	1	5.46	5.46	58.09	0.07	0.001
Zone	2	25.78	12.89	137.26	0.34	0.001
Year*Zone	2	2.50	1.25	13.30	0.03	0.001
Residuals	458	43.02	0.09	–	0.56	–
Total	463	76.76	–	–	1.00	–

Pollicipes (goose barnacle) Plots

The PERMANOVA Results for *Pollicipes* (goose barnacle) plots are provided in Tables S10 through S12.

Table S10. *Pollicipes* PERMANOVA: Community ~ Year.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Year	1	0.73	0.73	11.22	0.02	0.001
Residuals	460	29.92	0.07	–	0.98	–
Total	461	30.65	–	–	1.00	–

Table S11. Pollicipes PERMANOVA: Community ~ Zone.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Zone	2	6.89	3.44	66.51	0.22	0.001
Residuals	459	23.76	0.05	–	0.78	–
Total	461	30.65	–	–	1.00	–

Table S12. *Pollicipes* PERMANOVA: Community ~ Year + Zone + Year*Zone.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Year	1	0.73	0.73	14.95	0.02	0.001
Zone	2	6.92	3.46	70.88	0.23	0.001
Year*Zone	2	0.75	0.37	7.65	0.02	0.001
Residuals	456	22.25	0.05	–	0.73	–
Total	461	30.65	–	–	1.00	–

Silvetia (golden rockweed) Plots

The PERMANOVA Results for *Silvetia* (golden rockweed) plots are provided in Tables S13 through S 15.

Table S13. *Silvetia* PERMANOVA: Community ~ Year.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Year	1	10.23	10.23	126.15	0.22	0.001
Residuals	460	37.31	0.08	–	0.78	–
Total	461	–	–	–	1.00	–

Table S14. *Silvetia* PERMANOVA: Community ~ Zone.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Zone	2	2.68	1.34	13.73	0.05	0.001
Residuals	459	44.86	0.10	–	0.94	–
Total	461	47.64	–	–	1.00	–

Table S15. *Silvetia* PERMANOVA: Community ~ Year + Zone + Year*Zone.

Term	DF	Sum of Squares	Mean Squares	F-value	R^2 value	P-value
Year	1	10.23	10.23	135.19	0.22	0.001
Zone	2	2.63	1.31	17.35	0.06	0.001
Year*Zone	2	0.17	0.09	1.14	< 0.01	0.286
Residuals	456	34.51	0.08	–	0.73	–
Total	461	47.54	–	–	1.00	–

NPS 342/187811, March 2023

National Park Service
U.S. Department of the Interior

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