Long Term Effect of Marine Protected Areas (MPAs) on Kelp Forest Ecosystems Surrounding the California Channel Islands

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ABSTRACT

Marine Protected Areas (MPAs) in the Channel Island National Park contain one third of Southern California kelp forests. Kelp forests provide food and shelter for many marine species, making them essential as the foundation of kelp forest ecosystems. This study looks to determine the effect of MPAs on kelp forest ecosystem function and resilience by comparing kelp establishment, species richness, and functional diversity in paired study sites using California Channel Islands Kelp Forest Monitoring Program data from 2005 to 2019. Survey sites inside MPAs (protected sites) and outside MPAs (non-protected sites) were paired assuming the paired sites will experience similar environmental conditions such that any differences were a result of differing protection status. By comparing ecosystem response between paired sites, one can determine the effect of MPAs on kelp forest ecosystems. I found that pairwise comparisons resulted in largely non-significant differences in kelp establishment, species richness, and functional diversity between protected and non-protected sites. Though over time, there have been trends of high variability in kelp establishment and an overall increase in species richness. I also found evidence of ecosystem resiliency as a drop in functional diversity was followed by recovery to pre-disturbance levels. The observed increase in species richness and evidence of ecosystem resiliency supports the mission of MPAs to protect and restore marine populations, though it may not be sufficient at protecting kelp forests, which may be influenced by factors outside the scope of MPA protections (e.g., climate change).

KEYWORDS

functional diversity, species richness, ecosystem resilience, marine protected areas, kelp forests

INTRODUCTION

Marine Protected Areas (MPAs) are areas of marine habitat that are legally protected by limiting human activities such as commercial fishing and recreational use. MPAs can serve many roles including as wildlife refuges, research areas, and reservoirs to supplement neighboring fisheries. Under the Marine Life Protection Act passed in California in 1999, a network of MPAs was established with goals to protect marine life, habitats, and ecosystems over the long term using ecosystem based management (California Department of Fish and Wildlife 2016). Ecosystem-based management implements large scale management that integrates both the biotic and abiotic components of ecosystem, rather than in isolation, necessary to maintain ecosystem stability (Christensen et al. 1996). MPAs have documented success at increasing the abundance and biomass of exploited species (Gell and Roberts 2003) in addition to increasing fishing yield outside MPAs due to spillover of larvae and mobile species from inside MPAs borders (Lenihan et al. 2021).

Marine Protected Areas often are established with goals to preserve and increase biodiversity and ecosystem stability, accomplished by alleviating the anthropogenic pressures on marine species and habitat. Potential methods for measuring ecosystem stability include measuring species diversity (Jiang and Pu 2009), which can be effective in determining the direct and early impact of MPAs. However, measuring functional diversity may be a stronger determinant of ecosystem health because functional diversity has a greater impact on ecosystem processes than species diversity (Tilman et al. 1997). Given that functional groups are formed based on factors such a trophic level and mobility, evaluating the response of functional groups can serve as an indicator to how an area may be changing (California Dept. of Fish & Game 2004). Additionally, functionally related species have been shown to experience similar rates of decline (Oliver et al. 2015) and certain functional groups are dependent on the earlier establishment of other functional groups (Claudet et al. 2008). Looking at functional diversity informs how ecosystem interactions may be changing under management and if MPAs are serving their general role in acting as a sanctuary for anthropogenically impacted groups as fishing often removes whole functional groups from ecosystems (Micheli and Halpern 2005). As marine ecosystems face increased anthropogenic and natural disturbances, determining if MPAs are effective in improving the resilience of ecosystems is important to in MPA design and management. For these reasons, we will be comparing functional diversity at MPA (protected) and paired non-MPA (non-protected) sites to evaluate the direct impact of MPA protections on ecosystem health.

As reduced anthropogenic pressures in MPAs allow new or returning species to establish populations, the expected increase in functional diversity should result in a more resilient ecosystem. Ecosystem resilience can be measured as a function of the functional role of each species (Petchey and Gaston 2002). This allows for prediction of how an ecosystem may respond to disturbance (Hughes et al. 2003). Given that long term marine ecosystem support is a goal of MPAs, improving ecosystem resilience in the face of increasingly frequent nature of disturbances should be a management priority (Hopkins et al. 2016). However, evaluations of a no take reserve (later reclassified as an MPA) from 1986 to 2003 in the California Channel Islands determined that while there an increase in species richness and functional richness, there was low functional diversity and functional redundancy due to over half of the functional groups having one species or less (Micheli and Halpern 2005). An updated analysis on species richness and functional diversity in the expanded MPA network around the Channel Islands would provide insight on the long-term effect of MPAs on ecosystem resiliency.

My central research question seeks to evaluate the long-term effect of MPAs on kelp forest ecosystem functional diversity in the area surrounding the CA Channel Islands. I plan to answer this question by looking into 1) how average kelp stipe count compares between protected and non-protected sites 2) how species richness compares between protected and non-protected sites and 3) how functional diversity compares between protected and non-protected sites. Respectively, my predictions are that 1) protected sites will have greater average kelp stipe count than non-protected sites due to increased protections from anthropogenic pressure 2) protected sites will have higher richness than non- protected sites due to increased protections from anthropogenic pressures and 3) protected sites will have greater functional diversity than non- protected sites due to increased protections resulting in the recruitment and establishment of species who fill both new and existing functional groups. These questions will be answered using data from the CA Channel Islands Kelp Forest Monitoring program which includes species abundance and kelp stipe count data from paired protected and non-protected sites in and around an MPA.

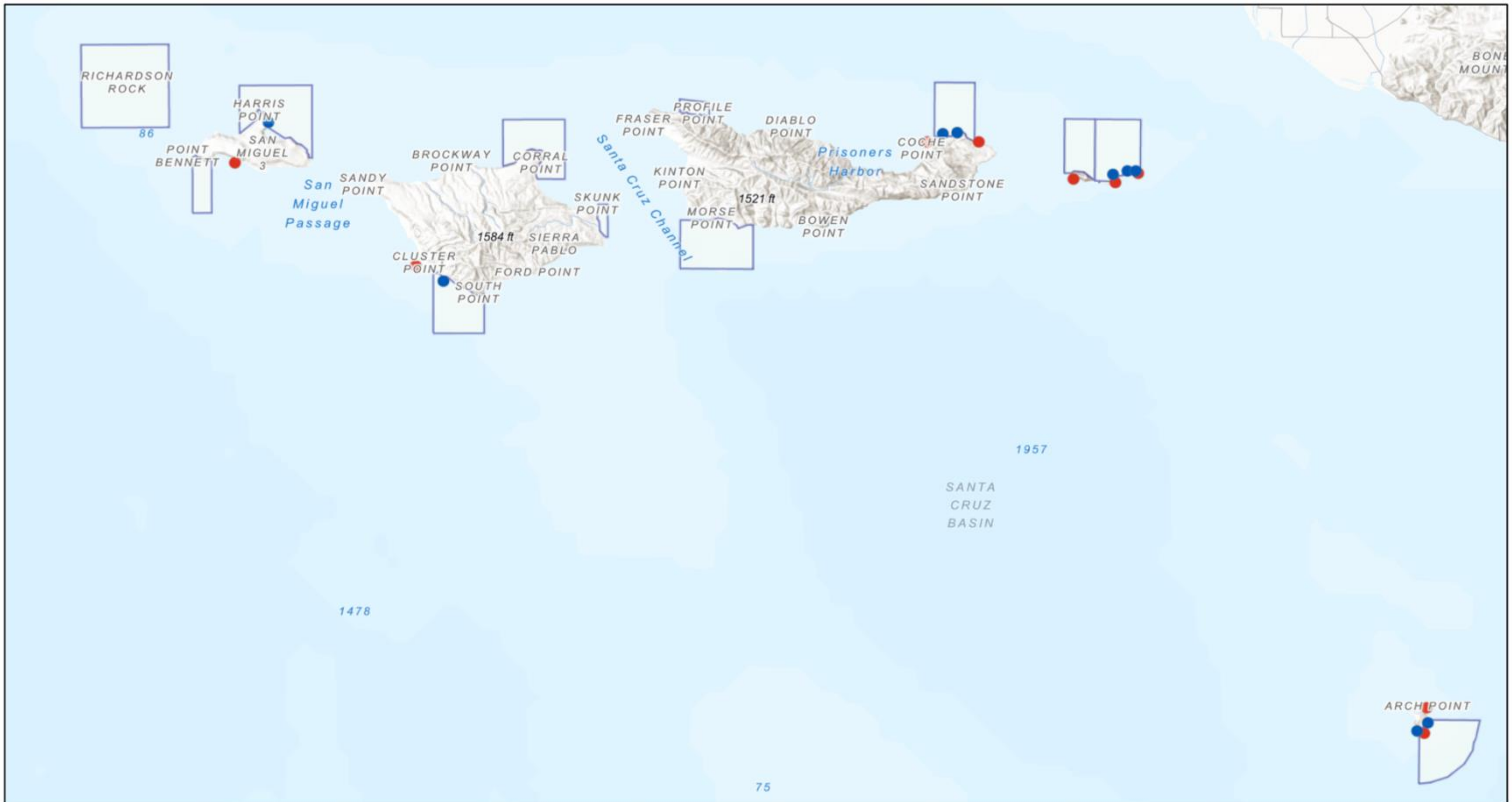
METHODS

Study Site Description

The site I focused on in this study is a kelp forest ecosystem surrounding the California Channel Islands. I used a dataset from the Channel Islands National Park Kelp Forest Monitoring Program, which includes survey data collected from multiple sites surrounding the islands. The islands are surrounded by a network of MPAs, and the dataset includes survey data from areas both inside and outside of MPA boundaries (Figure 1). In my study I will be using paired sites that I have paired based on whether they were inside or outside of a State Marine Reserve MPA boundary, proximity to one another, mean depth, and biogeographical region. The paired sites I used in my study include adjacent sites where one was in an area designated as a State Marine Reserve MPA in 2003 and the other was not. Data collection for the sites I used began in 2005 once the permanent survey sites were established, though survey sites established at different times exist throughout the MPA network.

Data Set

The type of data collected by the kelp forest monitoring project was influenced by the specific goals for this MPA network, which were to determine the effect of MPAs on species, ecosystems, habitats, and sustaining local fisheries. This data was collected in the California Channel Islands by the National Park Service Kelp Forest Monitoring Project using survey methods outlined in Davis et al. 1997. The chosen survey sites were either current or historical kelp forests, meant to be representative of the different states of kelp forest ecosystems. For my study, I used the average stipe count of giant kelp from 14 sites (7 protected, 7 non-protected) and species abundance data from 64 species that were surveyed using permanent band transects and quadrats at 18 sites (9 protected, 9 non-protected) surrounding the MPA network. I adapted the functional group categorizations I used for calculating functional diversity from Micheli and Halpern 2005 (Table 1), who previously conducted a study on functional diversity using the Kelp Forest Monitoring Project survey data from 1986 to 2003. I used these same functional group categorizations to look at the long-term changes in functional diversity at the selected paired sites within the MPA network from 2005 to 2019.



Site Name (Protected)	Graveyard Canyon	Cat Canyon	Trancion Canyon	Hare Rock	Potato Pasture	Cavern Point	Landing Cove	Cathedral Cove	Black Sea Bass Reef
Latitude	33.47307	33.46442	33.90855	34.06438	34.05223	34.05428	34.01667	34.01587	34.0126
Longitude	-119.027	-119.039	-120.156	-120.357	-119.583	-119.567	-119.362	-119.372	-119.389
Site Name (Non-protected)	**Arch Point**	**Southeast Reef**	**Cluster Point**	**Miracle Mile**	**Devil's Peak Member**	**Little Scorpion**	**Lighthouse**	**East Fish Camp**	**Admiral's Reef**
Latitude	33.48753	33.46293	33.92303	34.0237	34.04493	34.04415	34.0141	34.0045	34.00775
Longitude	-119.028	-119.031	-120.187	-120.395	-119.601	-119.542	-119.359	-119.386	-119.434

Figure 1: Map of Study Survey Sites. Protected sites in blue and non-protected sites in red. Shaded areas are within MPA boundary.

Table 1: Functional Group Categorizations. Adapted from Micheli and Halpern 2005 and modified to include newly recruited species

Functional Group	Species
Fleshy algae	Eisenia arborea, Pterygophora californica, Laminaria farlowii, Sargassum horneri, Undaria pinnatifida, Dictyoneuropsis reticulata/Agarum fimbriatum
Giant kelp	Macrocystis pyrifera
Herbivorous invertebrates	Strongylocentrotus purpuratus, Strongylocentrotus franciscanus, Lytechinus anamesus, Haliotis corrugata, Haliotis rufescens, Haliotis fulgens, Haliotis assimilis, Haliotis sorenseni, Lithopoma undosums, Megathura crenulata, Aplysia californica, Cryptochiton stelleri, Megastraea undosa, Lithopoma gibberosa, Tegula regina
Omnivorous/scavenger invertebrates	Parastichopus parvimensis, Asterina miniata, Cypraea spadicea, Patiria miniata, Centrostephanus coronatus
Sessile planktivorous invertebrates	Crassedoma giganteum, Stylaster californica/Stylaster californicus, Urticina lofotensis, Corynactis californica, Balanophyllia elegans, Serpulorbis squamigerus, Astrangia lajollaensis, Lophogorgio chilensis/Lophogorgia chilensis, Muricea fruticosa, Muricea californica, Tethya aurantia, Diaperoecia californica, Phragmatopoma californica, Dioptra ornata, Styela montereyensis
Predatory invertebrates	Pisaster giganteus, Pisaster ochraceus, Pycnopodia helianthoides, Kelletia kelletii, Panulirus interruptus
Herbivorous fish	Girella nigricans
Planktivorous fish	Chromis punctipinnis, Sebastes mystinus
Mobile small-invertebrate-eating fish	Embiotoca jacksoni, Embiotoca lateralis, Oxyjulis californica, Damalichthys vacca, Hypsypops rubicundus, Alloclinus holderi, Oxylebius pictus
Territorial small-invertebrate-eating fish	Rhinogobiops nicholsii, Lythrypnus dalli, Coryphopterus nicholsi
Invertebrate-eating fish/piscivores	Sebastes serranoides, Sebastes atrovirens, Paralabrax clathratus

Data Analysis

Kelp stipe count

Between protected and non-protected sites. To determine if MPAs influenced kelp establishment, I compared kelp stipe counts between protected and non-protected survey sites using the average kelp stipe count for each survey year. I did this by conducting a Mann-Whitney U-test in R Commander (Version 2.8-1). I used Mann-Whitney U-test to compare the paired sites as they are being treated as independent from one another and have a non-normal distribution, meeting the assumptions of the Mann-Whitney U-test. Data was visualized in RStudio (Version 2022.02.2+485) using the ggplot2 package (Version 3.3.5).

Over time. I looked at the change in average stipe count over time in protected and non-protected sites. I used RStudio (Version 2022.02.2+485) and the ggplot2 package (Version 3.3.5) to visualize the data and performed a visual inspection of the graph to determine how kelp stipe count (proxy for kelp size and establishment) was changing over time. Increasing kelp stipe count over time was considered as a sign of increased kelp forest establishment whereas decreasing kelp stipe count was considered to be a sign of decreased kelp forest establishment.

Species richness

Between protected and non-protected sites. To determine if MPAs influenced species richness, I compared species presence data between protected and non-protected sites. I calculated the species richness for each site each year in RStudio (Version 2022.02.2+485) using species presence data. I then compared species richness between protected and non-protected sites using a Mann-Whitney U-test in R Commander (Version 2.8-1) as the data had a non-normal distribution and because the two sites are being treated as independent, meeting the assumptions of the test. Data was visualized in RStudio (Version 2022.02.2+485) using the ggplot2 package (Version 3.3.5).

Over time. I looked at the change in species richness over time in protected and non-protected sites. I used RStudio (Version 2022.02.2+485) and the ggplot2 package (Version 3.3.5) to visualize the data and performed a visual inspection of the graph to determine how species richness was changing over time.

Functional diversity

Between protected and non-protected sites. To determine if MPAs influenced functional diversity, I compared functional diversity between each protected and paired non-protected site. I did this by recategorizing species abundance data into functional group abundance according to the functional group categorization adapted from Micheli and Halpern 2005 (Table 1). I calculated functional diversity using the Shannon-Wiener diversity index on the functional group abundances in RStudio (Version 2022.02.2+485) using the vegan package (Version 2.5-7). I then compared functional diversity between the protected and non-protected sites using Hutcheson's t-tests in RStudio (Version 2022.02.2+485) using the ecolTest package (Version 0.0.1) packages as this test is used to compare Shannon-Wiener diversity indices. Data was visualized in RStudio (Version 2022.02.2+485) using the ggplot2 package (Version 3.3.5).

Over time. I looked at the change in functional diversity over time in protected and non-protected sites. I used RStudio (Version 2022.02.2+485) and the ggplot2 package (Version 3.3.5) to visualize the data and performed a visual inspection of the graph to determine how functional diversity was changing over time.

RESULTS

Kelp Stipe Count Comparison

From 2005 to 2019, there was no clear trend of average kelp size increase or decrease in either protected or unprotected areas (Figure 2). There however are coupled patterns of increase and decrease in average kelp stipe count when looking at all protected study sites and all non-protected study sites over time (Figure 3).

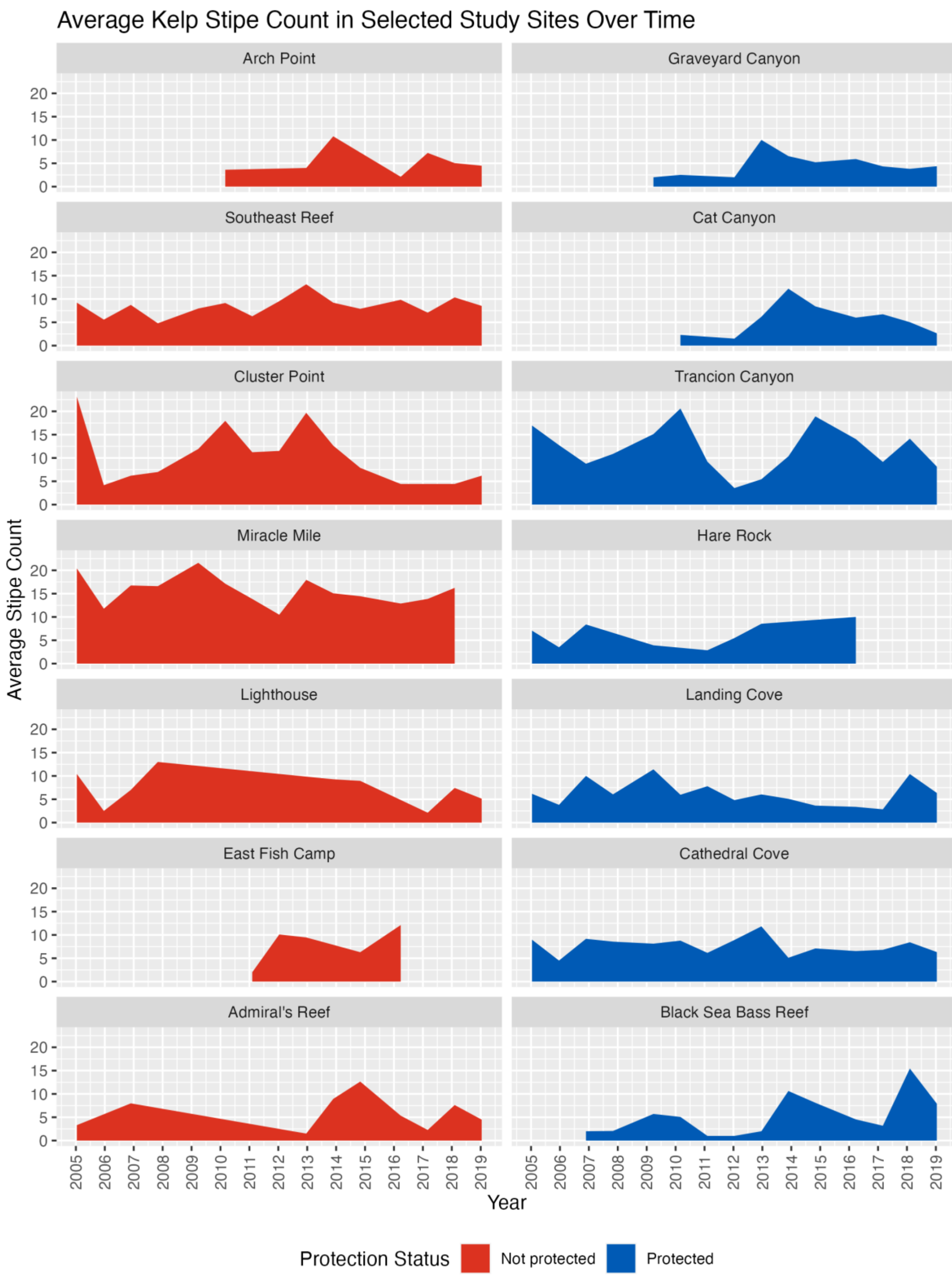


Figure 2: Average kelp stipe count in protected and non-protected areas from 2005 to 2019.

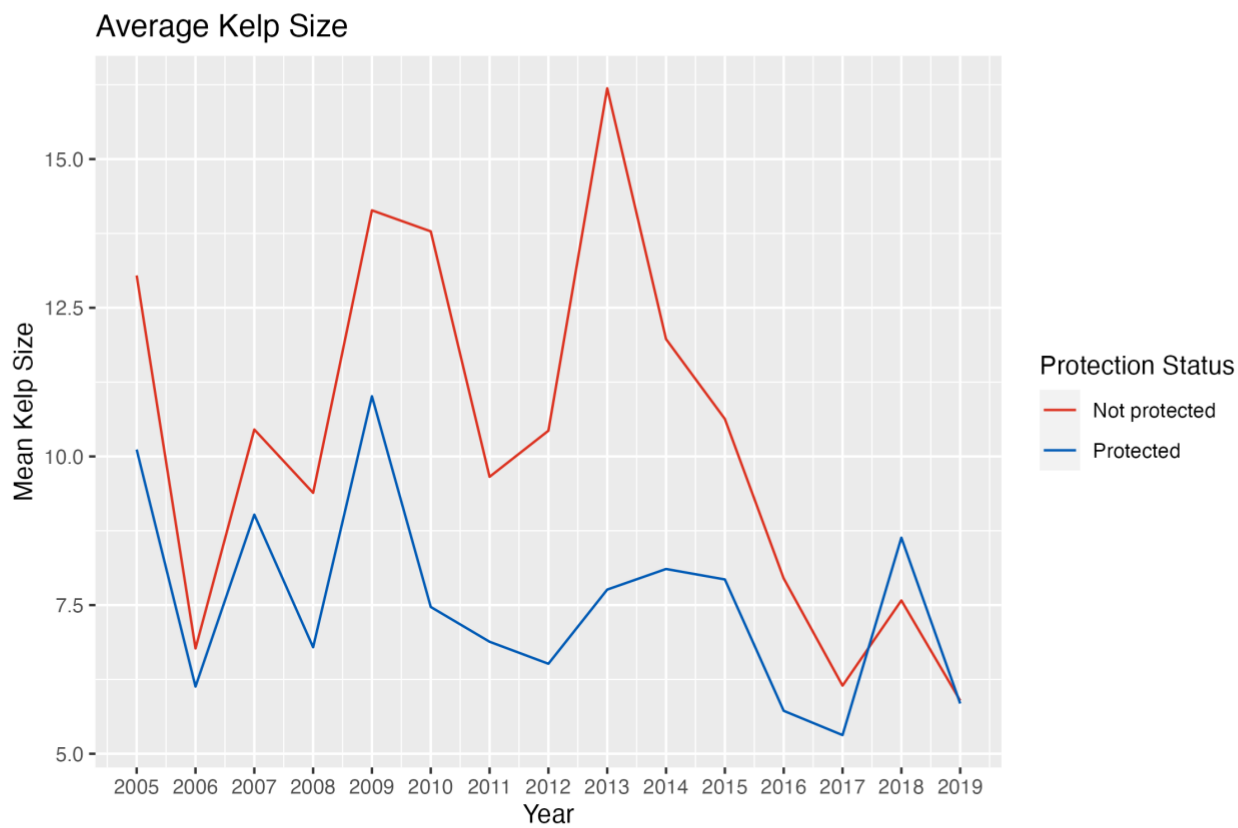


Figure 3: Average kelp stipe count in all protected study sites versus all non-protected study sites from 2005 to 2019.

I found that there was not a significant difference in average kelp stipe count between protected areas and non-protected areas (Figure 4) in 5 out of 7 pairs (Table 2). There was a significant difference in the remaining 2 out of 7 pairs, where non-protected areas had greater average stipe count (Table 2).

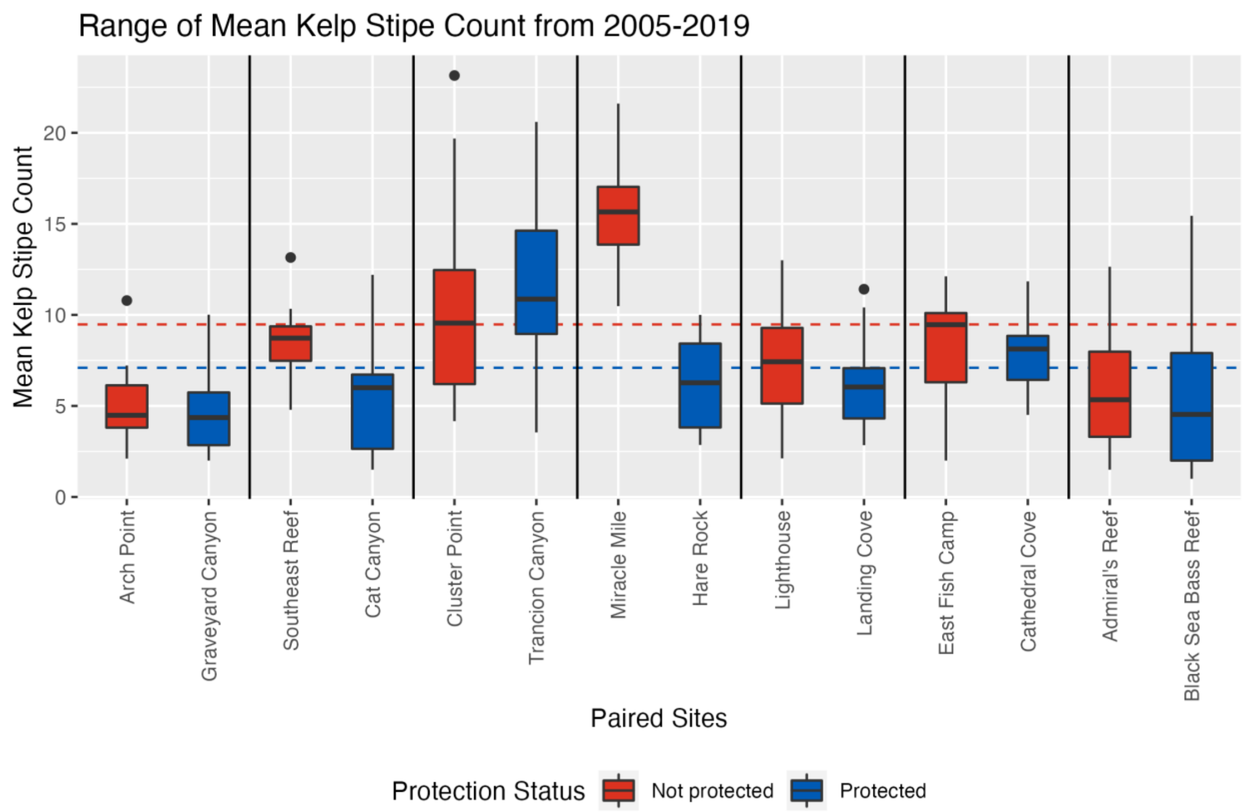


Figure 4: Range of average kelp stipe count in protected and non-protected areas from 2005 to 2019. Dotted line represents average kelp stipe count across all protected (mean = 7.1) and all non-protected (mean = 9.5) sites.

Table 2: Mann Whitney U-test on Average Kelp Stipe Count in Protected versus Not Protected Sites from 2005-2019.

Group	N	Median	Test Statistics	
Graveyard Canyon (Protected)	10	4.36	U Z	40 -0.44
Arch Point (Not Protected)	7	4.49	p	0.6604
Cat Canyon (Protected)	9	6.00	U Z	107 -2.33
Southeast Reef (Not Protected)	15	8.73	p	0.02004*
Trancion Canyon (Protected)	15	10.87	U Z	85 -0.85
Cluster Point (Not Protected)	14	9.55	p	0.3947
Hare Rock (Protected)	8	6.27	U Z	174.5 -2.340848
Miracle Mile (Not Protected)	14	15.65	p	0.00962*
Landing Cove (Protected)	15	6.04	U Z	81 -0.78
Lighthouse (Not Protected)	9	7.43	p	0.4382
Cathedral Cove (Protected)	15	5.34	U Z	46 -0.70
East Fish Camp (Not Protected)	5	9.46	p	0.485
Black Sea Bass Reef (Protected)	13	4.54	U Z	69 -0.67
Admiral's Reef (Not Protected)	9	5.34	p	0.504

N: Years with data available at given site
*: Significant (p<0.05)

Species Richness Comparison

From 2005 to 2019, there was no clear trend in species richness increase or decrease in either protected or unprotected areas (Figure 5). However, I found somewhat coupled patterns of increase and decrease in species richness in all the protected and all the non-protected sites over time (Figure 6).

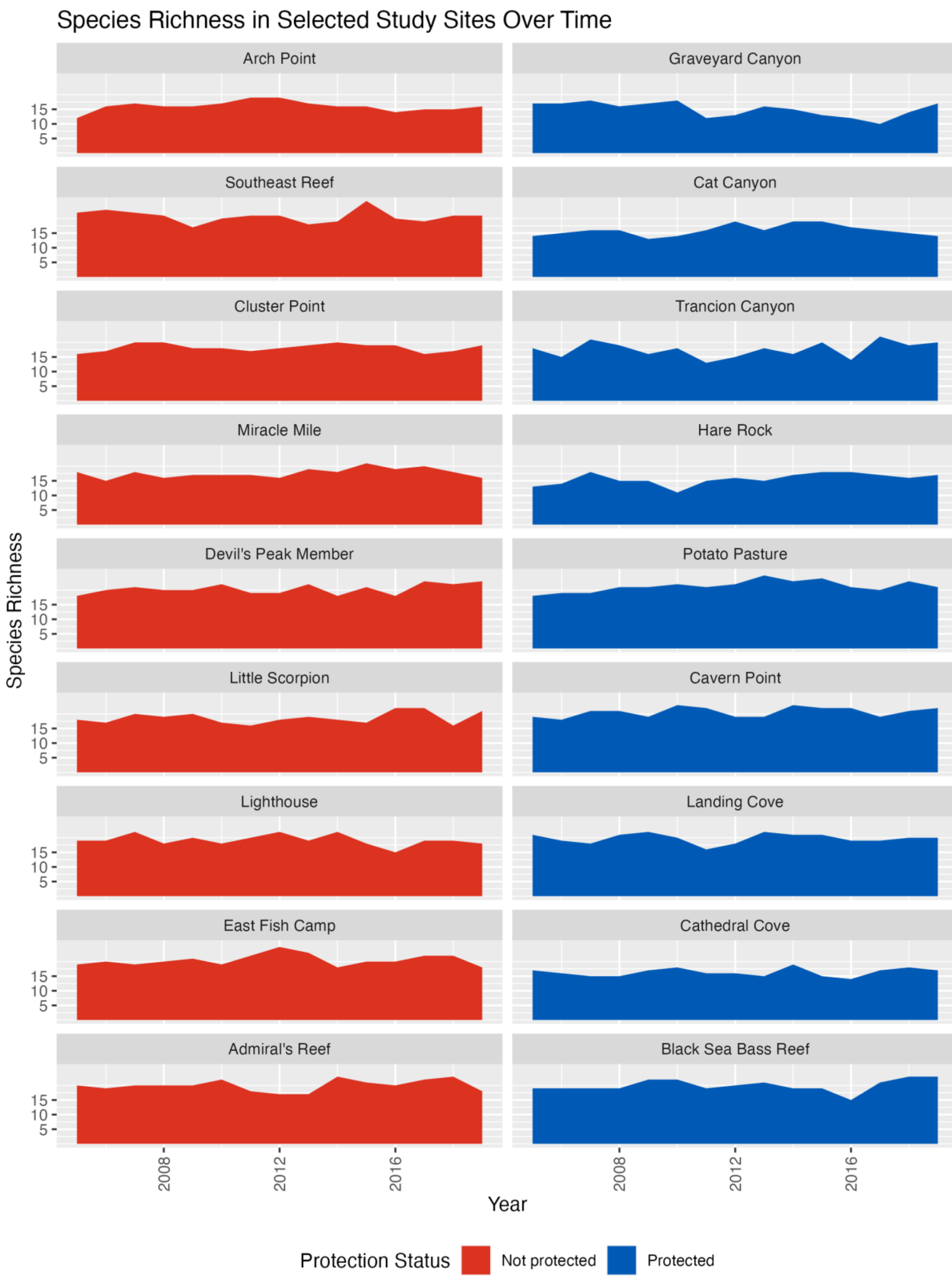


Figure 5: Species richness in protected and non-protected areas from 2005 to 2019.

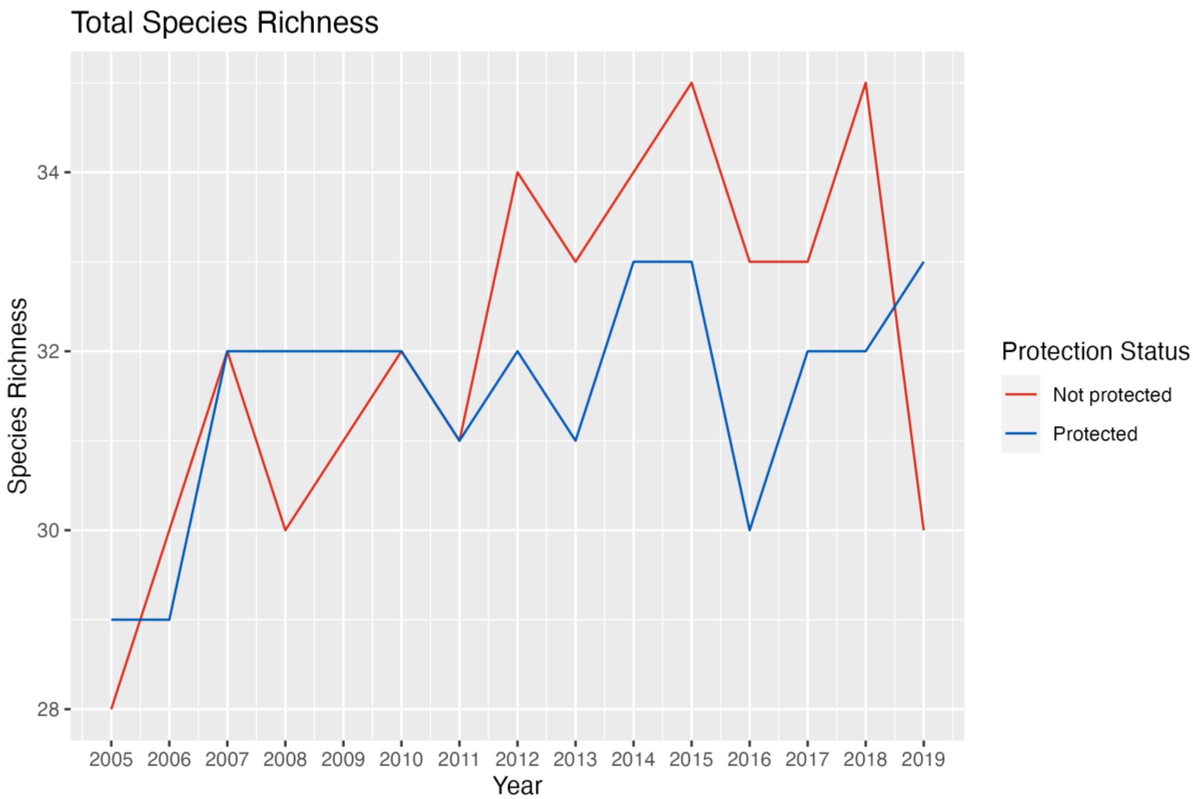


Figure 6: Species richness in all protected study sites versus all non-protected study sites from 2005 to 2019.

I found that there was not a significant difference in species richness between protected areas and non-protected areas (Figure 7) in 5 out of 9 pairs (Table 3). There was a significant difference in the 4 out of 9 pairs, where 3 pairs had greater species richness in non-protected areas and 1 pair with greater species richness in protected areas (Table 3).

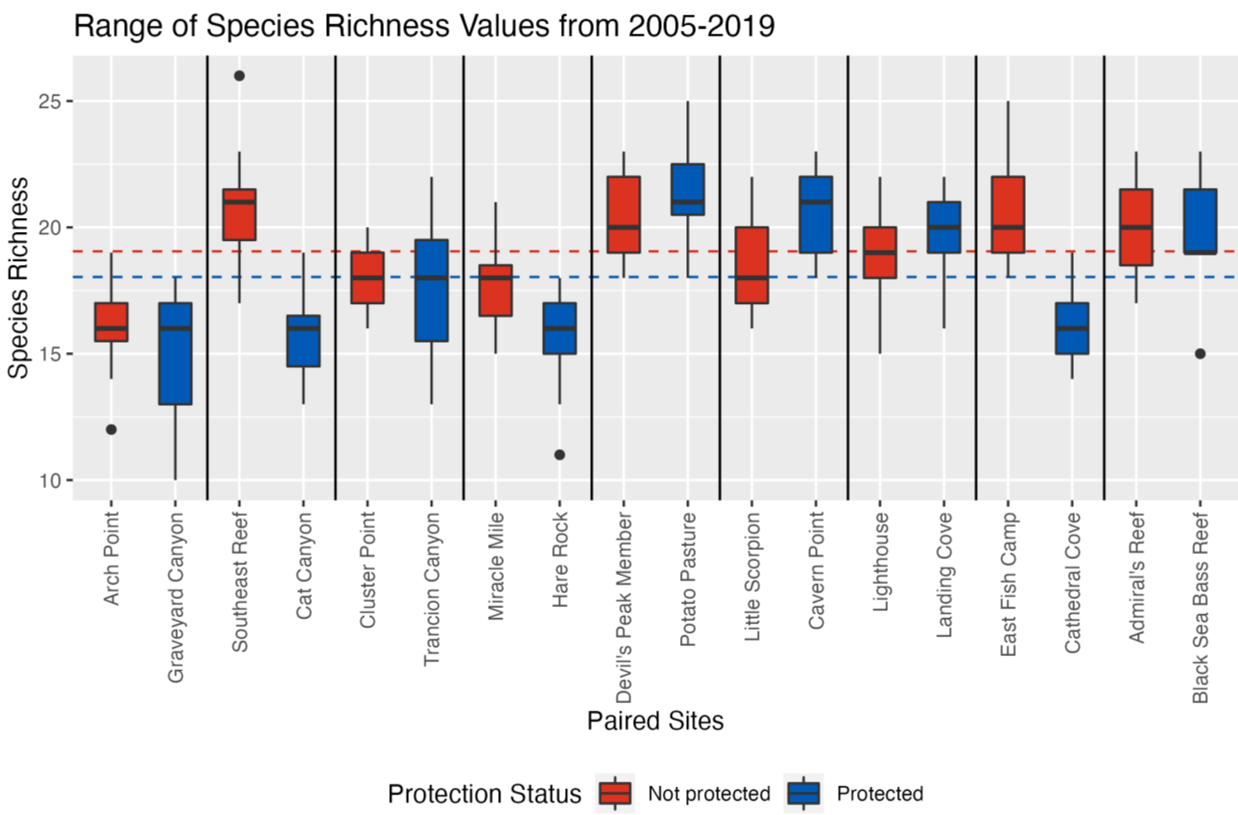


Figure 7: Range of species richness values in protected and non-protected areas from 2005 to 2019. Dotted line represents average species richness across all protected (mean = 18.0) and all non-protected (mean = 19.1) sites.

Table 3: Mann Whitney U-test on Species Richness in Protected versus Non-protected Sites from 2005-2019.

Group	N	Median	Test Statistics	
Graveyard Canyon (Protected)	15	16	U	131.5
			Z	-0.1636585
Arch Point (Not Protected)	15	16	p	0.435
Cat Canyon (Protected)	15	16	U	215.5
			Z	-4.1273297
Southeast Reef (Not Protected)	15	21	p	0.00001835*
Trancion Canyon (Protected)	15	18	U	126.5
			Z	0.1789207
Cluster Point (Not Protected)	15	18	p	0.571
Hare Rock (Protected)	15	16	U	174.5
			Z	-2.340848
Miracle Mile (Not Protected)	15	18	p	0.00962*

Potato Pasture (Protected)	15	21	U	83
			Z	-0.7621005
Devil's Peak Member (Not Protected)	15	20	p	0.223
Cavern Point (Protected)	15	21	U	50
			Z	-2.3591267
Little Scorpion (Not Protected)	15	18	p	0.009159*
Landing Cove (Protected)	15	20	U	87.5
			Z	-0.5235379
Lighthouse (Not Protected)	15	19	p	0.3003
Cathedral Cove (Protected)	15	16	U	219.5
			Z	-4.2948392
East Fish Camp (Not Protected)	15	20	p	0.000008741*
Black Sea Bass Reef (Protected)	15	10	U	113
			Z	Infinite^
Admiral's Reef (Not Protected)	15	11	p	1^

N: Years with survey data available at given site
*: Significant ($p<0.05$)
^: due to Bonferroni correction

Functional Diversity Comparison

From 2005 to 2019, there was no clear trend in functional diversity increase or decrease in either protected or unprotected areas (Figure 8). There was little to no coupling in patterns of increase or decrease in functional diversity in all the protected and all the non-protected sites over time (Figure 9).

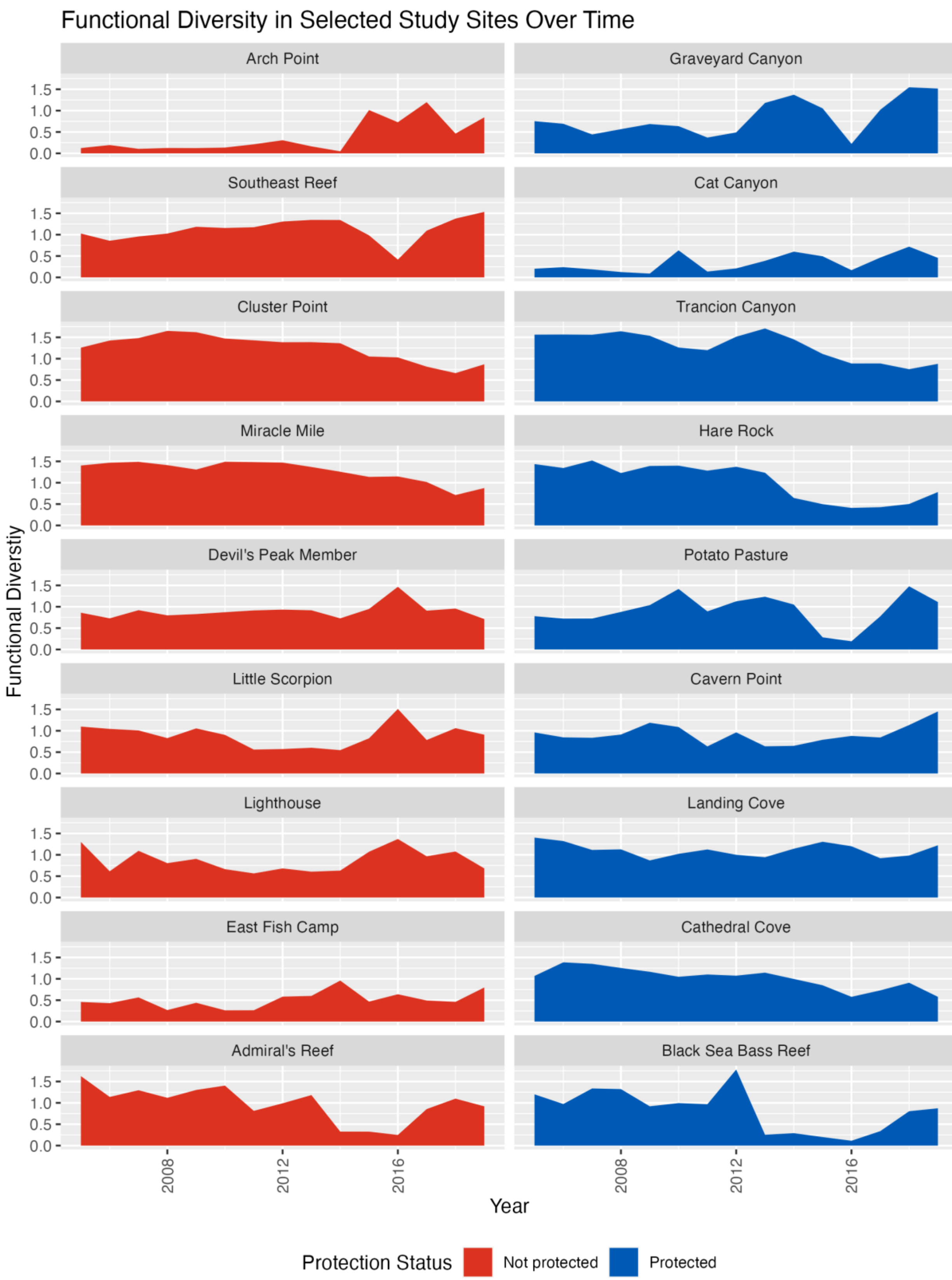


Figure 8: Functional Diversity in protected and non-protected areas from 2005 to 2019.

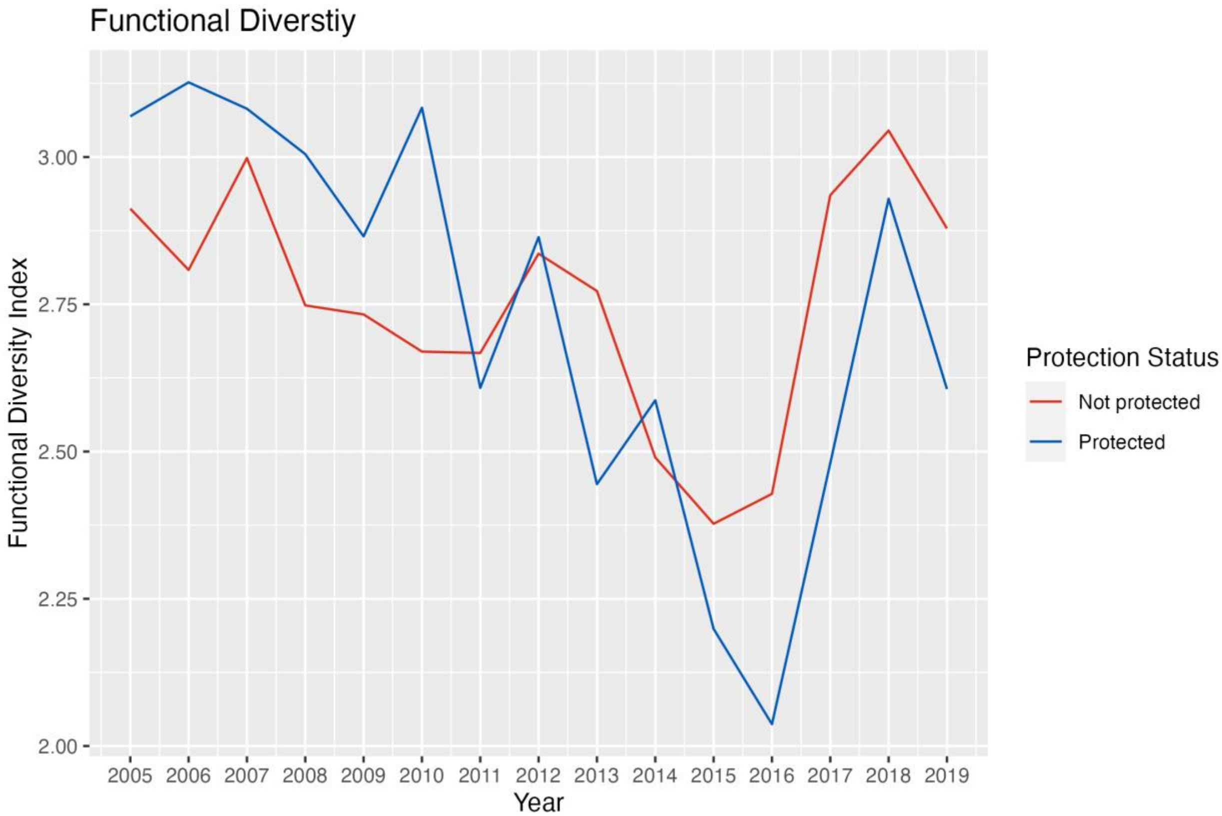


Figure 9: Functional diversity in all protected study sites versus all non-protected study sites from 2005 to 2019.

I found that there was not a significant difference in functional diversity between protected areas and non-protected areas each year (Figure 10) in 14 out of 135 pairs (Table 4, Appendix A). There was a significant difference in the 121 out of 135 pairs, where 63 pairs had greater functional diversity in non-protected areas and 58 pairs had greater functional diversity in protected areas (Table 4, Appendix A).

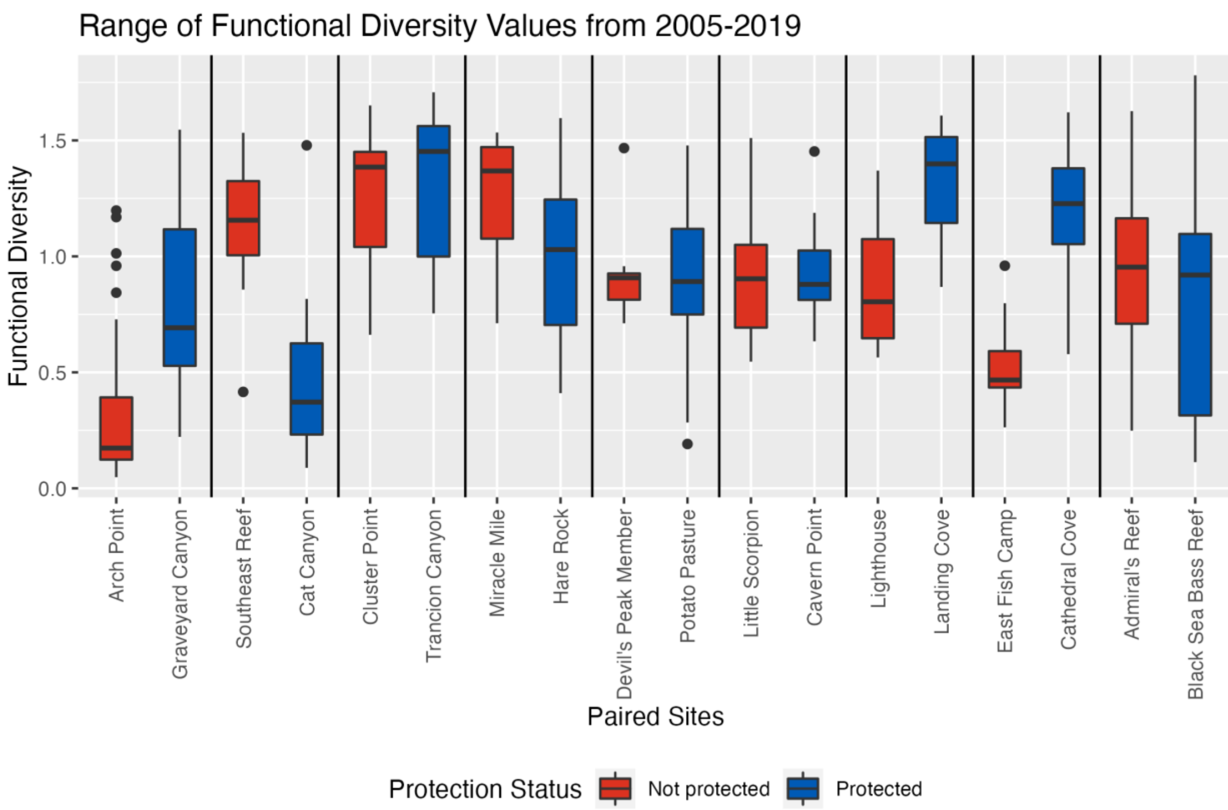


Figure 10: Range of functional diversity values in protected and non-protected areas from 2005 to 2019.

Table 4: Summary of Hutcheson's t-test results comparing functional diversity in protected versus non-protected sites each year from 2005-2019. Full results in appendix A.

Result	Number of Pairs
Higher functional diversity in protected sites	63
Higher functional diversity in non-protected sites	58
No significant difference between protected and non-protected sites	14

DISCUSSION

I found that direct comparisons of protected and non-protected sites in and around MPAs did not have significant differences in kelp establishment, species richness, and functional diversity. These findings do not support my hypothesis that protected areas will have improved kelp establishment, species richness, and functional diversity over non-protected areas. However, I found that from 2005 to 2019, there has been high variability in average kelp stipe count, a strong increase in species richness, and evidence of ecosystem resiliency as measured by functional diversity response to disturbance. These findings inform my central research question which considers the influence of MPAs on functional diversity and support conclusions in literature about species richness increasing in MPAs with time (Halpern 2003) and that by increasing species richness (a component of biodiversity), ecological function and resilience to disturbance should increase. (Hughes et al. 2003). However, my results also challenge findings of increased kelp biomass in MPAs (Babcock et al. 1999). Given the mixed results of this study, I considered the limitations of my study design and methods for each sub-question.

Protections on Kelp Establishment

Foundation species create locally stable conditions which stabilize ecosystem processes. The stability of kelp as a foundation species has been found to support increased species richness and species richness stability (Lamy et al. 2020). Due to the significance of giant kelp (Macrocystis pyrifera) as a foundation species in kelp forest ecosystems, they have been designated their own functional group in this study. Average kelp stipe count fluctuated from 2005 to 2019 in both protected and non-protected sites with no clear trend of increase or decrease over time (Figure 2). If MPAs were effective at supporting kelp forest growth and establishment, we would expect to see an increased average kelp stipe count in protected sites compared to non-protected sites. However, average kelp stipe count had no significant difference between protected and non-protected sites in 5 out of 7 pairs and was significantly greater in non-protected sites for the remaining 2 out of 7 sites (Table 2). These results do not support my hypothesis that protected sites would have greater average kelp stipe count than non-protected sites. They also challenge existing literature, where MPAs have been document to support more extensive kelp forests and primary productivity (Babcock et al. 1999). Additionally, after MPAs are established, we expect to see an increase in average kelp stipe count over time in protected sites as the kelp forests have had more time to grow larger without human disturbance. The similar patterns of average kelp stipe count increase and decrease in the protected and non-protected sites over time (Figure 3) suggests that the factors limiting kelp forest establishment and growth are not strongly influenced by MPA protections and act on all kelp forests regardless of protection status. One such example is increasing water temperature, which has adverse effects on kelp biomass and increases urchin growth (Provost et al. 2016). Not only would kelp biomass decrease under warmer temperatures, but increased grazing pressure from growing urchin populations will alter the rate of kelp forest thinning, ultimately altering ecosystem interactions. These factors largely affect all sites regardless of protection status as they are not influenced by the protections afforded by MPAs. Such factors may alter ecosystems at faster rates than in the past, especially under the current climate regime (Byrnes et al. 2011). This means that despite past studies suggesting success in kelp forest growth under MPAs (Babcock et al. 1999) current MPA designs may not be sufficient for meeting management goals involving kelp forest growth going forward. This is especially important when considering the shifts in threats to kelp forests, as climate change is now a bigger threat to marine ecosystems than overfishing (Steneck et al. 2003), which is now deemed manageable. The changes place an even greater importance on maintaining functionally significant populations such as kelp to increase ecosystem stability.

Protections on Species Richness

Total species richness in all sites from 2005 to 2019 saw a peak of 38 species in 2014 and low of 29 species in 2005. If MPAs were effective at increasing species richness, we would expect to see greater species richness in protected areas over non-protected areas. However, from 2005 to 2019, species richness was not significantly different between protected and non-protected areas in 5 out of 9 pairs, had greater species richness in protected sites in 1 out of 9 pairs, and had greater species richness in non-protected sites for the remaining 3 out of 9 pairs (Table 3). While these results do not support my hypothesis that protected areas will have increased species richness over non-protected areas, looking at the total species richness of all sites, we see a steady increase from

2005 up to a peak in 2014 (Figure 6) which supports conclusions from other studies that species richness increases in MPAs (Halpern 2003). While direct comparisons of paired protected and non-protected sites suggest that MPA protections are not effective in increasing species richness, the increase from 2005 to 2014 along with the conclusions from other studies (Buxton and Smale 1989, Alcala 1998), is suggestive that MPAs are indeed effective at increasing species richness. The insignificant difference in species richness between protected and non-protected survey sites around the MPA may be due to a limitation in my study design in isolating the effect of spillover. Spillover, or the transfer of individuals outside the protected area boundary, was found to have an observable effect on species abundance and biomass hundreds of meters outside an MPA (Harmelin-Vivien et al. 2008, García-Rubies et al. 2013, Di Lorenzo et al. 2016). My paired survey sites may have too close to one another such that spillover from the protected areas supplemented populations in non-protected areas. If the rate of spillover exceeds the rate of fishing or harvesting in non-protected areas, this would result in the appearance that there is little to no difference between the protected and non-protected sites. Due to the degree of fishing pressures in the area being largely non-commercial, I expect the effects of spillover to be particularly pronounced. The inability to separate the effects of spillover is a limitation in my study design which may be addressed by comparing MPA sites to paired sites outside the range of spillover.

Protections on Functional Diversity

Functional diversity was compared in nine pairs of protected and non-protected sites each year from 2005 to 2019 with mixed results on whether protection status influences functional diversity (Table 4, Appendix A). If MPAs were effective at increasing functional diversity, we would expect to see more consistent results of increased functional diversity in protected areas over non-protected areas. However, this was not the case in my study which challenges findings of greater functional diversity in protected areas (Villamor and Becerro 2012). However, my result of non-significant different in functional diversity between protected and non-protected sites may be explained by the variability seen in kelp establishment, as the functional diversity of kelp forest ecosystem is associated with the presence of a kelp forest (Graham 2004). Additionally, the difference between functional diversity in protected sites and non-protected sites fluctuated over time but did not trend in a particular direction (Figure 9). While these results do not support my hypothesis of protected areas having increased functional diversity over non-protected areas, looking at functional diversity over time in each site (Figure 8) shows many sites where there was a sharp drop in functional diversity, possibly due to disturbance, followed by a return to previous functional diversity levels. If the drop was result of disturbance, this pattern would suggest ecosystem resiliency. Upon further inspection of overall functional diversity in protected and non-protected sites (Figure 9), from 2013 to 2016, a drop in functional diversity affected sites regardless of protection status. This period of functional diversity decline coincides with a marine heat wave that took place from 2014 and 2016, suggesting the heat wave disturbance may be responsible for the drop in functional diversity. This marine heat wave from 2014 to 2016 has been described as the most intense and persistent warming event to date causing a decrease in the size and number of giant kelp individuals (Cavanaugh et al. 2019, Arafeh-Dalmau et al. 2019). Arafeh-Dalmau also found changes in community structure as species responded to loss of the kelp forest and warmer water temperatures during this heat wave event (Arafeh-Dalmau et al. 2019). While my direct comparison of protected and non-protected areas does not show differences in functional diversity making it difficult to compare resiliency, after the drop in functional diversity from 2013-2016, the return to previous functional diversity levels in both protected and non-protected areas from 2016-2018 suggests that both areas have ecosystems resilient to some degree of disturbance. Limitations in comparing functional diversity between protected and non-protected sites are similar to the limitations in addressing species richness, as functional diversity is derived from the abundance of species in each functional group.

Synthesis

Kelp establishment, species richness, and functional diversity are three ecosystem metrics being measured in protected and non-protected sites surrounding an MPA network to determine the effect of MPAs over time. None of the three metrics produced consistent results of any difference between protected and non-protected sites, but over time, it looks like there are trends of variable kelp stipe count, increasing species richness, and stagnant but resilient functional diversity. This suggests that MPAs are effective in increasing species richness and resilience but not kelp establishment.

Future Directions

Using the same survey methods as the California Channel Islands Kelp Forest Monitoring Project, data collection at non-protected reference sites at a greater geographic distance from an MPA may better reveal the true effect of MPAs free from the confounding variable of spillover. Nonetheless, the findings of this project suggest that kelp forest habitat may require alternative management strategies to increase the stability of kelp populations, as both protected and non-protected kelp populations experience remarkable variation in average stipe count from year to year. Developments in kelp forest management to improve kelp forest protection that can be implemented as part of the MPA regime may be able to support further increases in species richness and functional diversity. Lasty, MPAs are necessary but not a complete solution for marine conservation. Decisions about MPA locations and management plants must made with scientific justification in order to remain effective (Allision et al 1998).

Conclusions

The benefit of MPAs lie in their ability to reduce direct human impacts such as habitat destruction, overharvesting, and overfishing. While there has been documented success in increasing species richness and kelp establishment in MPAs, there remains challenges in managing indirect anthropogenic impacts such as rising water temperatures and ocean acidification (Cheung et al. 2016, Hoegh-Guldberg et al. 2007). Despite the largely stagnant functional diversity in both protected and non-protected sites since 2005, both areas have demonstrated resilience in the face of a marine heat wave disturbance from 2014 to 2016. This suggests that current MPA design is supportive of establishing resilient ecosystems at current functional diversity levels, though a severe enough disturbance may push the ecosystem past its point of resilience.

Given the increasing frequency and intensity of environmental disturbance under climate change, the ability for MPAs to support the formation and maintenance of increasingly resilient ecosystems will be important for the persistence of kelp forest ecosystems. Management goals should prioritize increasing kelp establishment due to the increasing pressures currently faced by kelp and its role as a foundation species in kelp forest ecosystems. Overall, the MPA network in the California Channel Islands has demonstrated success, meeting goals of increased species richness and ecosystem resiliency, making them an important management strategy as marine conservation.

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Appendix A: Hutcheson's t-test results comparing functional diversity in protected versus non-protected sites each year from 2005-2019.

Year	Protected Site	Non-Protected Site	Protected Site Functional Diversity	Non-Protected Site Functional Diversity	Hutcheson t-statistic	p-value	df	Result:
2005	Arch Point	Graveyard Canyon	0.7540009	0.1232002	15.139	1.38E-46	959.18	Lower FD in Protected
2005	Southeast Reef	Cat Canyon	0.2014607	1.02585	-17.813	4.20E-63	1190.4	Higher FD in Protected
2005	Cluster Point	Trancion Canyon	1.562857	1.257658	6.4421	1.88E-10	938.35	Lower FD in Protected
2005	Miracle Mile	Hare Rock	1.436465	1.402386	1.0533	0.2923167	1938.5	No Significant Difference
2005	Devil's Peak Member	Potato Pasture	0.7793145	0.860336	-2.1036	0.03551566	2356.8	Higher FD in Protected
2005	Little Scorpion	Cavern Point	0.9612362	1.0979319	-3.8301	0.000131799	2115.8	Higher FD in Protected
2005	Lighthouse	Landing Cove	1.402582	1.300702	3.6736	0.000244168	2512.7	Lower FD in Protected
2005	East Fish Camp	Cathedral Cove	1.0676237	0.4587491	17.032	5.75E-62	2789.8	Lower FD in Protected
2005	Admiral's Reef	Black Sea Bass Reef	1.199212	1.62615	-7.1908	1.65E-12	705.58	Higher FD in Protected
2006	Arch Point	Graveyard Canyon	0.6921497	0.194319	12.185	7.42E-32	957.94	Lower FD in Protected
2006	Southeast Reef	Cat Canyon	0.2394133	0.8568621	-13.311	2.12E-38	1582.4	Higher FD in Protected
2006	Cluster Point	Trancion Canyon	1.565695	1.425069	4.3547	1.40508E-05	1851.1	Lower FD in Protected
2006	Miracle Mile	Hare Rock	1.344196	1.46843	-4.2776	1.9699E-05	2204.6	Higher FD in Protected
2006	Devil's Peak Member	Potato Pasture	0.7224426	0.7288043	-0.14216	0.8869678	1776.3	No Significant Difference
2006	Little Scorpion	Cavern Point	0.845464	1.043961	-5.1233	3.27309E-07	2124.1	Higher FD in Protected
2006	Lighthouse	Landing Cove	1.3215538	0.6147522	26.622	7.19E-144	3988.6	Lower FD in Protected
2006	East Fish Camp	Cathedral Cove	1.3865017	0.4299849	30.878	1.38E-180	2818.5	Lower FD in Protected
2006	Admiral's Reef	Black Sea Bass Reef	0.9729002	1.1383047	-2.56	0.01062024	959.18	Higher FD in Protected
2007	Arch Point	Graveyard Canyon	0.4423706	0.1053067	11.165	5.89E-28	1653.6	Lower FD in Protected
2007	Southeast Reef	Cat Canyon	0.187447	0.9569228	-19.116	1.59E-74	1863.1	Higher FD in Protected
2007	Cluster Point	Trancion Canyon	1.560665	1.481851	2.5544	0.01070155	2286.3	Lower FD in Protected
2007	Miracle Mile	Hare Rock	1.52003	1.488455	1.1064	0.2686645	2465.3	No Significant Difference
2007	Devil's Peak Member	Potato Pasture	0.7234967	0.9195063	-5.2345	1.77774E-07	2772.1	Higher FD in Protected
2007	Little Scorpion	Cavern Point	0.8353029	1.0080335	-4.4957	7.28501E-06	2261.4	Higher FD in Protected
2007	Lighthouse	Landing Cove	1.113711	1.093163	0.67825	0.4976559	3878.9	No Significant Difference
2007	East Fish Camp	Cathedral Cove	1.350481	0.565526	23.628	9.08E-114	3149.8	Lower FD in Protected
2007	Admiral's Reef	Black Sea Bass Reef	1.337463	1.295647	0.68459	0.493846	654.2	No Significant Difference

2008	Arch Point	Graveyard Canyon	0.5660931	0.125261	12.614	4.90E-34	1034.7	Lower FD in Protected
2008	Southeast Reef	Cat Canyon	0.1245124	1.0256582	-25.22	1.97E-115	1358.4	Higher FD in Protected
2008	Cluster Point	Trancion Canyon	1.641855	1.650671	-0.41536	0.6779166	2452.6	No Significant Difference
2008	Miracle Mile	Hare Rock	1.227383	1.411406	-5.299	1.33584E-07	1517.7	Higher FD in Protected
2008	Devil's Peak Member	Potato Pasture	0.8785301	0.7981039	2.053	0.04017206	2548.8	Lower FD in Protected
2008	Little Scorpion	Cavern Point	0.9116198	0.827888	2.0501	0.04047674	2166.7	Lower FD in Protected
2008	Lighthouse	Landing Cove	1.127558	0.804222	10.148	7.13E-24	3549.8	Lower FD in Protected
2008	East Fish Camp	Cathedral Cove	1.254328	0.2683715	34.612	4.07E-225	3396	Lower FD in Protected
2008	Admiral's Reef	Black Sea Bass Reef	1.322006	1.117957	3.4979	0.000487516	1109.3	Lower FD in Protected
2009	Arch Point	Graveyard Canyon	0.6862134	0.1226246	16.899	5.31E-58	1283.6	Lower FD in Protected
2009	Southeast Reef	Cat Canyon	0.08840839	1.18392394	-25.845	2.47E-103	685.08	Higher FD in Protected
2009	Cluster Point	Trancion Canyon	1.536032	1.61994	-3.279	0.001057123	2326.4	Higher FD in Protected
2009	Miracle Mile	Hare Rock	1.391749	1.307649	2.4381	0.01487441	1583.5	Lower FD in Protected
2009	Devil's Peak Member	Potato Pasture	1.0379033	0.8281694	5.4177	6.61931E-08	2479.2	Lower FD in Protected
2009	Little Scorpion	Cavern Point	1.187686	1.055618	3.2823	0.001048363	1880.2	Lower FD in Protected
2009	Lighthouse	Landing Cove	0.8683846	0.9048426	-1.2485	0.2119286	4683.6	No Significant Difference
2009	East Fish Camp	Cathedral Cove	1.1651378	0.4391821	25.529	1.07E-132	3756.1	Lower FD in Protected
2009	Admiral's Reef	Black Sea Bass Reef	0.9196659	1.3018864	-8.305	1.83E-16	1969.5	Higher FD in Protected
2010	Arch Point	Graveyard Canyon	0.6364647	0.135113	14.373	1.28E-43	1314	Lower FD in Protected
2010	Southeast Reef	Cat Canyon	0.632661	1.155956	-13.949	1.16E-41	1494.9	Higher FD in Protected
2010	Cluster Point	Trancion Canyon	1.2611	1.471583	-5.7886	8.09747E-09	2237.1	Higher FD in Protected
2010	Miracle Mile	Hare Rock	1.399254	1.490849	-3.0677	0.002202578	1272.7	Higher FD in Protected
2010	Devil's Peak Member	Potato Pasture	1.4167719	0.8719301	13.052	1.58E-37	2156.8	Lower FD in Protected
2010	Little Scorpion	Cavern Point	1.0878174	0.9033385	5.4951	4.29642E-08	2526.5	Lower FD in Protected
2010	Lighthouse	Landing Cove	1.022619	0.6638677	14.18	1.53E-44	3898.9	Lower FD in Protected
2010	East Fish Camp	Cathedral Cove	1.0478071	0.2627388	32.294	3.71E-207	4783.3	Lower FD in Protected
2010	Admiral's Reef	Black Sea Bass Reef	0.9939894	1.4037452	-8.6708	8.83E-18	1959.2	Higher FD in Protected
2011	Arch Point	Graveyard Canyon	0.3693568	0.2117379	5.9053	3.94152E-09	2815.1	Lower FD in Protected
2011	Southeast Reef	Cat Canyon	0.135863	1.173528	-31.318	1.51E-167	1564.2	Higher FD in Protected
2011	Cluster Point	Trancion Canyon	1.1988	1.42956	-7.5286	7.75E-14	1978.3	Higher FD in Protected
2011	Miracle Mile	Hare Rock	1.282279	1.482705	-7.1453	1.27E-12	1929.7	Higher FD in Protected

2011	Devil's Peak Member	Potato Pasture	0.8913906	0.913492	-0.56356	0.5730995	2720.3	No Significant Difference
2011	Little Scorpion	Cavern Point	0.6338103	0.5596273	3.0342	0.002426167	4400	Lower FD in Protected
2011	Lighthouse	Landing Cove	1.1253364	0.5641754	21.948	7.43E-102	4831.2	Lower FD in Protected
2011	East Fish Camp	Cathedral Cove	1.1017993	0.2640776	34.781	1.20E-235	4622	Lower FD in Protected
2011	Admiral's Reef	Black Sea Bass Reef	0.9679311	0.8126312	3.1684	0.00155925	1760.9	Lower FD in Protected
2012	Arch Point	Graveyard Canyon	0.4899476	0.3068174	4.914	9.81686E-07	1636.6	Lower FD in Protected
2012	Southeast Reef	Cat Canyon	0.2099032	1.3065008	-29.628	1.20E-149	1376.8	Higher FD in Protected
2012	Cluster Point	Trancion Canyon	1.514087	1.384985	3.3187	0.000924888	1585.1	Lower FD in Protected
2012	Miracle Mile	Hare Rock	1.373583	1.471517	-2.6924	0.007178328	1419.2	Higher FD in Protected
2012	Devil's Peak Member	Potato Pasture	1.1269306	0.9329391	4.9131	9.5796E-07	2360	Lower FD in Protected
2012	Little Scorpion	Cavern Point	0.9625187	0.5721277	14.711	5.66E-48	4904.4	Lower FD in Protected
2012	Lighthouse	Landing Cove	0.9999016	0.6814141	10.474	2.50E-25	3818.5	Lower FD in Protected
2012	East Fish Camp	Cathedral Cove	1.0739025	0.5833774	16.124	7.95E-57	4281.2	Lower FD in Protected
2012	Admiral's Reef	Black Sea Bass Reef	1.780574	0.9893397	18.906	3.32E-71	1404.5	Lower FD in Protected
2013	Arch Point	Graveyard Canyon	1.1804769	0.1630996	31.032	4.31E-137	757.82	Lower FD in Protected
2013	Southeast Reef	Cat Canyon	0.3872214	1.3450165	-22.515	4.62E-96	1401.1	Higher FD in Protected
2013	Cluster Point	Trancion Canyon	1.707326	1.386937	10.07	3.06E-23	1795	Lower FD in Protected
2013	Miracle Mile	Hare Rock	1.234194	1.368292	-4.2334	2.39166E-05	2320.1	Higher FD in Protected
2013	Devil's Peak Member	Potato Pasture	1.2348094	0.9168175	8.2886	1.85E-16	2502.8	Lower FD in Protected
2013	Little Scorpion	Cavern Point	0.6358644	0.6022322	1.1464	0.2517406	2293.4	No Significant Difference
2013	Lighthouse	Landing Cove	0.9435509	0.6051902	10.818	6.78E-27	3920	Lower FD in Protected
2013	East Fish Camp	Cathedral Cove	1.1443613	0.5995771	16.252	1.53E-57	3949.1	Lower FD in Protected
2013	Admiral's Reef	Black Sea Bass Reef	0.2539159	1.182054	-23.917	1.10E-93	726.21	Higher FD in Protected
2014	Arch Point	Graveyard Canyon	1.3717274	0.0479279	70.803	0	1292.5	Lower FD in Protected
2014	Southeast Reef	Cat Canyon	0.6017875	1.3425389	-18.78	2.70E-73	2287.6	Higher FD in Protected
2014	Cluster Point	Trancion Canyon	1.452442	1.361475	2.7587	0.005851335	2216	Lower FD in Protected
2014	Miracle Mile	Hare Rock	0.6432641	1.257153	-16.094	2.87E-55	2270.4	Higher FD in Protected
2014	Devil's Peak Member	Potato Pasture	1.0511104	0.7284916	10.033	2.49E-23	3054.3	Lower FD in Protected
2014	Little Scorpion	Cavern Point	0.6472982	0.5462466	3.186	0.001465784	1934	Lower FD in Protected
2014	Lighthouse	Landing Cove	1.1424489	0.6299644	16.079	3.14E-56	3591.1	Lower FD in Protected
2014	East Fish Camp	Cathedral Cove	0.997336	0.9596184	1.5462	0.1221412	3975.1	No Significant Difference

2014	Admiral's Reef	Black Sea Bass Reef	0.2903491	0.3272493	-2.2007	0.02777647	14082	Higher FD in Protected
2015	Arch Point	Graveyard Canyon	1.052834	1.012725	0.99299	0.3209424	1065.2	No Significant Difference
2015	Southeast Reef	Cat Canyon	0.4938527	0.9834375	-17.366	1.10E-64	3269.3	Higher FD in Protected
2015	Cluster Point	Trancion Canyon	1.110025	1.051182	1.7137	0.08669961	2856.9	Lower FD in Protected
2015	Miracle Mile	Hare Rock	0.4984419	1.1360414	-18.839	2.86E-75	3295.1	Higher FD in Protected
2015	Devil's Peak Member	Potato Pasture	0.2838364	0.9482908	-20.847	1.50E-83	1306.6	Higher FD in Protected
2015	Little Scorpion	Cavern Point	0.7891749	0.8238212	-0.95141	0.3415369	1626.9	No Significant Difference
2015	Lighthouse	Landing Cove	1.305313	1.071547	7.104	1.51E-12	2970.1	Lower FD in Protected
2015	East Fish Camp	Cathedral Cove	0.8491225	0.4668982	26.322	1.02E-147	10045	Lower FD in Protected
2015	Admiral's Reef	Black Sea Bass Reef	0.199297	0.3264577	-8.6732	4.93E-18	8998.1	Higher FD in Protected
2016	Arch Point	Graveyard Canyon	0.2218947	0.7283624	-36.894	8.89E-284	13295	Higher FD in Protected
2016	Southeast Reef	Cat Canyon	0.168518	0.4156751	-18.233	4.69E-73	9679	Higher FD in Protected
2016	Cluster Point	Trancion Canyon	0.8878826	1.0299862	-4.3622	1.3317E-05	2940.6	Higher FD in Protected
2016	Miracle Mile	Hare Rock	0.4101007	1.1467208	-21.696	1.73E-96	2751.4	Higher FD in Protected
2016	Devil's Peak Member	Potato Pasture	0.1911051	1.4668637	-52.237	3.2884E-315	1236.9	No Significant Difference
2016	Little Scorpion	Cavern Point	0.8793767	1.5103015	-17.296	1.78E-63	2559.9	Higher FD in Protected
2016	Lighthouse	Landing Cove	1.200298	1.369814	-5.3965	7.46753E-08	2386.4	Higher FD in Protected
2016	East Fish Camp	Cathedral Cove	0.5783709	0.6390212	-3.3864	0.000710633	11533	Higher FD in Protected
2016	Admiral's Reef	Black Sea Bass Reef	0.1128265	0.2486139	-12.866	1.07E-37	16185	Higher FD in Protected
2017	Arch Point	Graveyard Canyon	1.019755	1.197635	-6.3071	3.38E-10	2373	Higher FD in Protected
2017	Southeast Reef	Cat Canyon	0.4630582	1.0929235	-21.634	2.36E-95	2524.3	Higher FD in Protected
2017	Cluster Point	Trancion Canyon	0.8885077	0.8135749	2.8233	0.004783127	3071.1	Lower FD in Protected
2017	Miracle Mile	Hare Rock	0.4275271	1.0165081	-20.112	1.45E-85	3791.2	Higher FD in Protected
2017	Devil's Peak Member	Potato Pasture	0.7755085	0.9075565	-6.5505	6.09E-11	7953	Higher FD in Protected
2017	Little Scorpion	Cavern Point	0.8428621	0.7834178	2.575	0.01004185	7723.5	Lower FD in Protected
2017	Lighthouse	Landing Cove	0.9203566	0.9649157	-1.7424	0.08150657	5153.3	No Significant Difference
2017	East Fish Camp	Cathedral Cove	0.7300019	0.4928038	7.6285	3.49E-14	2233.6	Lower FD in Protected
2017	Admiral's Reef	Black Sea Bass Reef	0.338227	0.8542542	-30.635	1.59E-196	9389.1	Higher FD in Protected
2018	Arch Point	Graveyard Canyon	1.5462542	0.4626886	29.312	7.18E-133	893.52	Lower FD in Protected
2018	Southeast Reef	Cat Canyon	0.7190689	1.375471	-22.482	4.05E-104	3230.1	Higher FD in Protected
2018	Cluster Point	Trancion Canyon	0.7541398	0.6620076	3.9217	8.92018E-05	4684.7	Lower FD in Protected

2018	Miracle Mile	Hare Rock	0.5020429	0.7115993	-8.5748	1.28E-17	5456.7	Higher FD in Protected
2018	Devil's Peak Member	Potato Pasture	1.47819	0.957491	18.233	3.22E-70	2754	Lower FD in Protected
2018	Little Scorpion	Cavern Point	1.134054	1.061314	2.166	0.03036668	4295.5	Lower FD in Protected
2018	Lighthouse	Landing Cove	0.9836185	1.0771862	-3.6122	0.000306624	5004.2	Higher FD in Protected
2018	East Fish Camp	Cathedral Cove	0.9087805	0.4611783	13.544	1.71E-40	2719.4	Lower FD in Protected
2018	Admiral's Reef	Black Sea Bass Reef	0.8037781	1.0989339	-10.475	1.73E-25	6962.9	Higher FD in Protected
2019	Arch Point	Graveyard Canyon	1.5166991	0.8434418	11.121	4.63E-23	218.52	Lower FD in Protected
2019	Southeast Reef	Cat Canyon	0.4557444	1.5328593	-28.785	1.08E-154	2178	Higher FD in Protected
2019	Cluster Point	Trancion Canyon	0.8790352	0.8688959	0.39972	0.6893834	3615.9	No Significant Difference
2019	Miracle Mile	Hare Rock	0.7817868	0.8749212	-3.9098	9.35948E-05	5061	Higher FD in Protected
2019	Devil's Peak Member	Potato Pasture	1.1100809	0.7114114	12.579	2.50E-35	2768.7	Lower FD in Protected
2019	Little Scorpion	Cavern Point	1.4523658	0.9080728	17.118	1.86E-60	1601.7	Lower FD in Protected
2019	Lighthouse	Landing Cove	1.2225817	0.6816989	20.788	1.21E-91	4414	Lower FD in Protected
2019	East Fish Camp	Cathedral Cove	0.5785616	0.797864	-6.4257	1.64E-10	1999.2	Higher FD in Protected
2019	Admiral's Reef	Black Sea Bass Reef	0.8731321	0.9181122	-2.3958	0.01660601	8679.3	Higher FD in Protected