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Role of managed marine areas on the diversity and individual responses of rocky intertidal shore grazers in Central Chile

A Thesis Presented

by

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Abstract

Many different types of marine benthic herbivores or "grazers" inhabit coastal intertidal zones and play a crucial role in inter- and shallow subtidal ecosystems. Chile has one of the most diverse intertidal zones, but many intertidal grazers are exploited for human consumption. Marine protected areas (MPAs) and marine management and exploitation areas (MEAs) are promising tools for Chile to combat over exploitation of these grazer and other marine resources. This study surveyed the impact of sites with contrasting management on the diversity and abundance of all intertidal grazers and their impact on the size frequency and shell length-body weight allometry of the keyhole limpet *Fissurella crassa*, the chiton *Chiton granosus*, the scurrinid limpet *Scurria araucana*, and the pulmonated limpet *Siphonaria lessoni*, four of the most abundant intertidal grazers. Data was collected from three sites: an open access site in Las Cruces, Chile, a limited removal management area in El Quisco, Chile, and a no-take marine reserve at the Estación Costera de Investigaciones Marinas (ECIM) in Las Cruces, Chile. Field experiments examined species diversity and abundance at each site and length and weight measurements were also collected from the four previously mentioned species. A total of 6 different families and 21 different species were observed across all sites. Site diversity and the abundance of 17 species among sites were not significantly different. However, the lengths and length-weight relationships of some species were significantly impacted by human disturbance. The results show *F. crassa* and *C. granosus* having the lowest abundance in the open access site and the longest lengths in the marine reserve reflecting their exploitation by humans. All species' individual body weight increased with increasing length as expected, but shell length-body weight allometries varied among sites for *F. crassa* and *C. granosus*. Their body mass was highest in the management area or marine reserve suggesting there is a behavior response to management areas needing further research to pinpoint the mechanism. This study demonstrates that protected marine areas have the potential to be greatly beneficial, especially to exploited species, but their creation is not enough, they need to also be effectively managed and enforced.

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Introduction

Intertidal zone

Understanding the species diversity of the intertidal zone along with the population and individual level effects of humans on specific consumer guilds, such as intertidal herbivores, grows increasingly important for researchers as the human population grows and encroaches on that habitat. Substantiating these anthropogenic effects, most of which negatively impact natural communities, is crucial to advocate for the creation of various types of protected marine areas (Daily et al. 2009; Gelcich et al. 2012)**.** Oceans cover roughly 70% of the Earth's surface and are essential for life on Earth providing oxygen, moderating climate and weather, and absorbing carbon dioxide, much of which is released by humans (National Research Council 2010; "Living Ocean" 2019). Oceans and the diverse marine ecosystems associated with them also provide a host of services to humans from providing sustenance, supporting economic activity, facilitating cultural practices, and aiding scientific advances in medicine (Mumby and Steneck 2008). There is only approximately 620,000 km of coastline globally but more than one-third of the total population, almost 2.4 billion people, live within 100 km of the coast (The Ocean Conference).

The intertidal zone of the coast is where land and sea interweave and is characterized by the area of the shoreline that is covered by water during high tide and exposed to the air during low tide (NOAA 2018; "Intertidal Zone"). Coastal intertidal zones experience a broad range of abiotic environmental conditions and fluctuations due to interacting effects of variable aerial exposure, wave action, temperature, salinity, etc. The most inland zone of the shore is known as the backshore followed by the spray zone which makes up the section just above where the high tide typically reaches. The main intertidal zone can be subdivided into the high, middle, and low zones, according to shore height. The subtidal fringe is located just below the main low intertidal zone and is almost always submerged, except during unusually low tides, and it leads into the subtidal zone (NOAA 2018; "Intertidal Zone"). Intertidal habitats are diverse, including rocky ledges, sandy beaches, and mudflats that support a diverse variety of marine life (NOAA 2018).

Intertidal grazers

Many species that reside in the intertidal ecosystem are confined between the upper-littoral and lower-littoral zones, sometimes extending into the subtidal zone, and by arranging themselves vertically, create distinct assemblages within the unique sections of the intertidal zone (Wilson 2013; "Intertidal Zone"). Pronounced biotic belts can often be identified in rocky shores around the world, where different invertebrate and algal species inhabit specific and distinct horizontal bands and sequential tidal levels (Wilson 2013). The zonation can be attributed to a variety of factors including availability of resources and environmental temperature vital in regard to thermal physiology of the organisms (Somero 2002).

Marine benthic herbivores or "grazers" play a crucial role in intertidal and shallow subtidal ecosystems (Branch and Moreno 1994; Aguilera 2011). Herbivory is considered one of the most important ecological processes in marine and terrestrial ecosystems that determines spatial and temporal distribution of algae (Lubchenco and Gaines 1981; Hawkins and Hartnoll 1983). Most of these herbivores are invertebrates, like limpets, chitons, and marine snails, that consume and survive on living plant tissue. As the algal composition varies across the intertidal zone, interspecific interactions within consumer guilds can change the way grazers exploit food as they compete for space and shelters (Aguilera and Navarrete 2012).

Anthropogenic effects

Intertidal grazers have been exploited by human populations around the world for centuries. Evidence of this is seen by the discarded shells and pieces of limpets and other organisms that accumulate along the shore (as cited by Branch and Moreno 1994). Within the last century, the expansion of the human population has put pressure on intertidal grazers due to increased demand for food, intrinsic commercial value now placed on certain species, and technological advances that make it easier to harvest at greater quantities and faster speeds (Branch and Moreno 1994). As human populations grow, they expand closer to the oceans and are impacting marine coastal communities through activities such as fishing, development, and tourism (Navarrete et al. 2010; NOAA 2019). Environmental human interferences have the potential to cause declines in biodiversity and functional shifts to a wide array of ecosystems (Hughes et al. 2003). The removal and exploitation of grazers can have predictable direct positive and negative impacts on the growth and establishment of intertidal algal communities, but it can also have subtle indirect effects across and between trophic levels, that are difficult to predict as effects flow from one species to another (Branch and Moreno 1994). Harvested species are present in all trophic levels of the marine food web and trophic links and consumer nodes are all affected by human impact (Pérez-Matus et al. 2017).

One potential solution to try and combat those negatives impacts on intertidal grazers, among other marine communities, is through the establishment of marine protected areas (MPAs). MPAs are designated terrestrial and marine areas set up with goals of protection, resource management, and/or to meet any other goals of the stakeholders that govern the specific MPA (Jentoft et al. 2011). MPAs hold a variety of titles from parks to reserves to sanctuaries and aim to preserve and protect the ecosystem that lies within it through the conservation of biodiversity and its goods and services. This is achieved through the minimization of human impact on the environment with bans on removal of organisms and other natural goods. This usually results in an increase or persistence of important biological ecosystems, however MPAs in reality are difficult to set up since there is typically push back from local communities. Marine MPAs typically include coral reefs and intertidal zones and the fish and other food sources the local communities are dependent upon (Jentoft et al. 2011; Gill et al. 2017).

Location

Chile is a uniquely shaped country that is situated along the western edge of South America. It is on average 140 kilometers wide and roughly 4,200 kilometers long, stretching across thirty-eight degrees of latitude (Collier and Sater 1996). The Andes mountain range lies along the country's eastern side and the Pacific Ocean lies on its west. Chile's landscape and climate are full of extremes due to its expansive latitudinal coverage with part of the country situated in the tropics while another part is the closest continental section of land to Antarctica. The country is often divided up into five zones latitudinally, the greater north (Norte Grande), the lesser north (Norte Chico), the Central Zone, the Southern Zone, and the Austral Zone in the far south (Collier and Sater 1996; Johnson et al. 2019).

The Humboldt Current System (HCS) travels along the west coast of South America and runs along Chile up to Ecuador and the Galapagos Islands. It is characterized by a predominantly northward flow of sub-antarctic surface water and a strong upwelling of deeper, cooler, nutrient-rich equatorial water. Upwellings are generally localized along the northern and central coast of Chile and are a-seasonal in the north but have a more seasonal pattern in the south (Thiel et al. 2007). El Niño weather events occasionally interrupt the HCS by introducing warm and nutrient-depleted equatorial waters, suppressing cold nutrient-rich waters, and reducing upwelling intensity for several years (Palma et al. 2006; Thiel et al., 2007). Upwellings brings nutrient-rich waters to the surface and support a rich intertidal community (“Intertidal Zone”). Chile has one of the most diverse intertidal zones fueled by nutrients from the Humboldt Current (Muir). Due to the expansive geography of the country, much of Chile’s extensive coast and the assemblages which inhabit it have yet to be explored or studied (Santelices 1990). Algal composition plays a large role in the abundance and diversity of species present in intertidal habitats. Mollusks are one of the most diverse and locally abundant groups of herbivores in Chile’s intertidal zone (Santelices et al. 1986). While most species are generalist grazers and morphologically similar across intertidal zones, their abundance is regulated by symmetric competitive competition (Santelices 1990).

Humans directly influence grazers in Chile through targeted fishing via three types of exploitation. Intertidal mollusks and other marine organisms are collected by “mariscadores de orilla” or artisanal fishers. Shallow water organisms are targeted by skin-divers, typically for personal or local use, while “hooka divers” fish commercially, particularly for export (Durán and Oliva. 1987; Branch and Moreno 1994). The most targeted intertidal and shallows subtidal grazers are fissurellid (keyhole) limpets, sea urchins, chitons, and snails (Branch and Moreno 1994). While all benthic herbivores are considered “grazers” that can feed on microalgae, spores, and early-stage algae, they do not all impact the algae community equally. Hidalgo et al. (2008) found snails to have little effect on erect macroalgae, and other studies state that only large, adult keyhole limpets appear to be able to “browse”, such that they eat adult algae. Indeed, these species are suggested to be critical to control the dominant mid-intertidal canopy-forming algae *Mazzaella laminarioides* (Aguilera 2010). At sites of intense human impact, the direct impact of harvesting on grazer assemblages alters algal succession and the structure and abundance of invertebrate populations, which further impact other organisms' populations such as the establishment of chironomid fly larvae laid on algal mats (Aguilera and Navarrete 2007).

Marine management and exploitation areas (MEAs) and marine protected areas (MPA)

Marine protected areas (MPAs) and marine management and exploitation areas (MEAs) are promising tools for managing marine resources in Chile (Castilla 1996). There are five conservation objectives as defined by Chilean law N° 18.362 "Del Establecimiento del Sistema Nacional de Areas Silvestres Protegidas del Estado" that apply to terrestrial and aquatic protected areas which include maintaining areas with unique biodiversity, maintaining and improving flora and fauna resources, and preserving and improving aesthetic natural resources and cultural elements (Carmona 2017a; Carmona 2017b). Of Chile's 165 protected areas, only 20 are marine protected areas and the marine reserve of the Estacíon Costera de Investigaciones Marinas (ECIM) is the only marine reserve with an effective management plan (Navarrete 2010; Petit et al. 2018). Since there is a strong social, cultural, and economic dependence on marine resources in Chile, it is difficult to implement and enforce more no-take MPAs, however MEAs could provide a compelling solution to benefit biological systems as well as the fishers that depend on them financially (Daily et al. 2009; Gelcich et al. 2012).

Chile created a policy in 1991 permitting artisanal fisher organizations in well-defined inshore marine MEAs to have exclusive territorial user rights for fisheries (TURFs) (Gelcich et al. 2008). The Chilean TURF system, locally known as Áreas de Manejo y Explotación de

Recursos Bentónicos (AMERBs), is one of the largest area-based fishing rights programs in the world (as cited by González et al. 2006; “Chilean National Benthic…” 2019). There are hundreds of communities and tens of thousands of artisanal fishers along Chile’s expansive coast that are part of the TURF system which was formally implemented in 1997 (as cited by González et al. 2006). Marine management and exploitation areas (MEAs) are managed as a collaboration between the government and local fishermen organizations that are given the rights to the area (Castilla 1996). There are currently over 700 established TURFs in along the coast of Chile that include more than 1100 km2 of shallow coastal ecosystems (SUBPESCA 2010). Species have been seen to increase in density and size in well-enforced TURFs compared to open access areas (Gelcich 2008). Well-managed MPAs have seen even higher increases, for example the no-take MPA at ECIM in Las Cruces, although smaller than the TURFs that Gelcich et al. (2012) studied, showed higher density, biomass, and species richness of macroinvertebrates and reef fishes than TURFs.

Previous research and knowledge/gaps

The results of the creation of the marine reserve at the Estación Costera de Investigaciones Marinas (ECIM) were incredibly enlightening. The reserve saw increases in the abundance of locos, a keystone predator species, leading to decreases of *Perumytilus purpuratur* mussels which are a main prey of the locos. As mussel populations decreased, areas of rock were left barren for other organisms, like barnacles, to colonize. Keystone grazers such as the *Fissurella crass and Fissurella limbata*, also increased in size and biomass leading to reduction and reshaping of algal coverage and macroalgae canopies (Aguilera and Navarrete 2012; “ECIM History”). This showed that on a global scale, human intervention can dramatically impact coastal and marine ecosystems and greatly affect exploited species populations. MEAs in Chile generally elicit positive results, but their performance has not been extensively studied (San Martín et al. 2003; González et al. 2006). Studies that compare protected areas such as MEAs and TURFs to MPAs and open access areas aid in assessing the potential and success of site-based conservation effects. There have been various efforts, such as that of Broitman et al. (2011), that provide an exhaustive community-based assessment on local species richness and spatial variation of intertidal species in central Chile and that of Moreno et al. (1984) which explored how grazers abundance may be affected by human disturbance, but it is important to incorporate a range of management types, monitor these changes overtime, and test other responses such as the length-weight relationship to get a glimpse at other potential species responses occurring as a result of exploitation. Studies like that of Navarrete et al. (2010) show an example of long-term monitoring of organisms, but efforts like these are scarce due to limited funding and resources but are nonetheless important for increasing general understanding and for conservation efforts.

This study will examine how intertidal grazer species diversity, abundance, and evenness differ at sites of varying human disturbance. It will also survey the impact of the open access area, marine management area, and marine reserve on the size frequency and the length-weight relationships of *Fissurella crassa, Chiton granosus, Scurria araucana,* and *Siphonaria lessoni* individuals. The primary hypotheses of this study include: (1) If human interference generally decreases biodiversity, grazer diversity will be lowest in the open access site. (2) If humans target larger individuals of *F. crassa* and C. granosus, then longer individuals of these two exploited species should be present in the management area with the longest appearing in the marine reserve due to total restrictions and bans on removal.

Research Question

Do the diversity, size frequency, and length-weight relationship of the low to mid rocky intertidal zone grazer guild differ between open access, marine management, and marine reserve sites in Central Chile?

Research Objectives

- To understand how diversity and abundance of the intertidal grazer assemblage differ across sites of varying human disturbance in Central Chile

- To understand the individual level responses (size frequency and length-weight relationship) of four previously cited most abundant intertidal grazer species in Central Chile

Methods

Study area

This study was conducted at three sites in the rocky intertidal zone along the central coast of Chile. Sites were selected based on their ease of access as well as their level of human disturbance: marine reserve (none), marine management area (low), and open access area (high) (Figure 1). Site 1 (33°50.16'S, 71°63.16'W) is a wave-exposed site in the open access area adjacent to the Estación Costera de Investigaciones Marinas (ECIM) of the Pontificia Universidad Católica de Chile in the locality of Las Cruces, Chile. This stretch of rocky intertidal zone spans almost a kilometer from ECIM to Playa Chica, the main local beach, and sections of it are in close proximity (50-150 m) to houses and other buildings. Site 2 (33°50.26'S, 71°63.41'W) is an area located inside of the ECIM reserve, a no-take marine protected area (MPA) founded in 1982 prohibiting removal of inter- and subtidal organisms.

The site is not accessible to the general public and is exposed to strong wave action. The reserve consists of roughly 500 m of protected rocky shoreline along with 10 hectares of subtidal rocky reefs. It is the only existing and effective marine reserve in Chile that has ecological information and long-term monitoring (Navarrete et al., 2010). Las Cruces is considered to be located in an upwelling shadow lying between two major upwelling centers in Punta Roncura-Toro and Punta Curaumilla (as cited by Wieters 2005). It has lower nutrient levels and higher sea surface temperature compared to those upwelling centers (Wieters et al. 2003; Nielsen and Navarrete 2004; Wieters 2005). Las Cruces is a small town with an area of roughly 10 km2 and, as of 2017, a population just shy of 5,500 that varies seasonally (Censos de Población y Vivienda).

Site 3 (33°23.53'S, 71°41.42'W) is located in the former marine management and exploitation area (MEA) in El Quisco, Chile located approximately 16 km north of ECIM. El Quisco is an area of intermediate upwelling intensity where upwellings only occur due to strong, prolonged southerly winds (as cited by Wieters 2005). The site is located near a recreational center on its eastern end and homes and hotels are situated approximately 50 m inland from the rocky shore. Legal rights to the El Quisco MEA were given to the El Quisco fisherman's' Union by the government in 1993 for co-management of the marine resources to combat overexploitation, especially of locos, and consisted of a subtidal area of roughly 54 ha (Castilla and Fernandez 1998; Manríquez and Castilla 2001). The terms of the El Quisco MEA agreement expired in 2017 and have not been officially reinstated (Carmona 2017a; Carmona 2017b). Local sustenance and commercial fishing are extremely prominent along central Chile, including in Las Cruces and El Quisco, with large key-hole limpets *Fissurella crassa* and *F.*

limbata being some of the organisms of focus for harvesting. *Chiton granosus* is also an intertidal species of economic importance to the region (as cited by Durán and Oliva 1987).

Figure 1. Location of study sites along the central coast of Chile. Site 1 is the open access area located in Las Cruces. Site 2 is the marine reserve of ECIM located in Las Cruces. Site 3 is the marine management area located in El Quisco. Images retrieved from Google Maps.

Data collection: abundance

All sampling was conducted during low tide conditions. At each site, three belt transects of 5x2 m were set up spanning the mid-low intertidal zone beginning at or just above the kelp (*Lessonia*) belt and terminating in the mid zone dominated by *Perumytilus purpuratus* mussel beds (Figure 2). Transects were separated by at least 1 meter and three sampling methods were used to scale for the size of the species being observed. The entire 5x2 m area of each transect was searched systematically, recording the abundance of each individual keyhole limpet (*Fissurella spp.*), large chiton (mainly *Acanthopleura echinata*), and sea urchin (mainly *Tetrapygus niger*) observed. Within each transect, five 1x1 m quadrats were set up alternating along the transect to record the abundance of mid-sized grazers such as all *Chiton spp.*, *Tonicia spp.*, and *Chaetopleura spp.* (Figure 3a). Small-sized species were sampled in six 0.5x0.5 m quadrats that were placed randomly along the transect and the abundances of *Scurria spp.* and *Siphonaria lessoni* lying within the diagonal of 10x10cm squares in each quadrat were recorded (Santelices et al. 1981) (Figure 3b). The habitat type (rock, crevice, turf algae, crustose coralline algae, ephemeral algae, kelp and its holdfast) along with the orientation (vertical, horizontal, upside-down) of individuals were also noted.

Figure 2. Example of transect line of 5x2 m set up at Site 3 (management area) in El Quisco with 1x1 m quadrat shown laying within the transect. Photo by Kathy Liu.

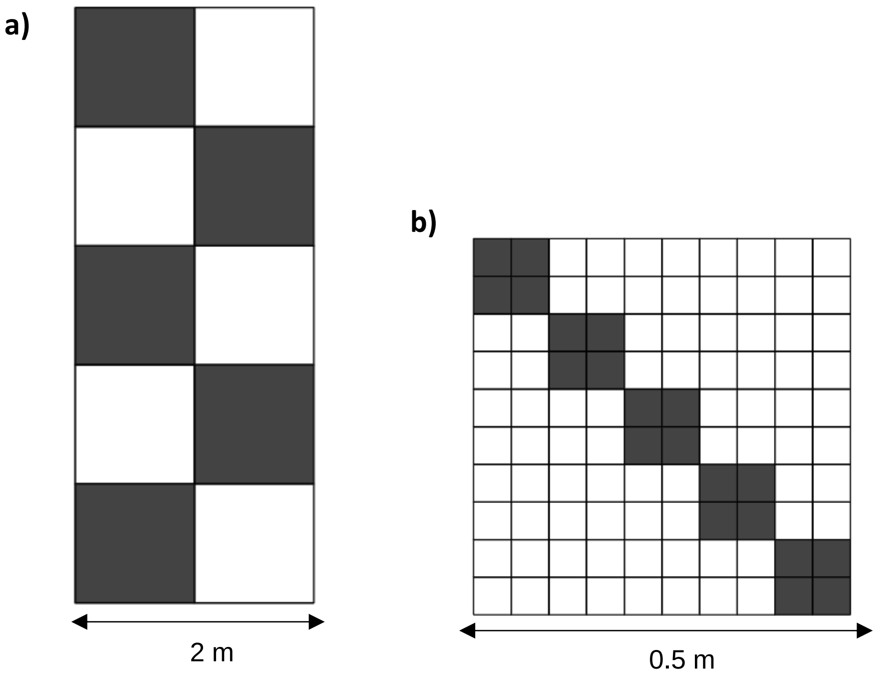


Figure 3. a) The full 5x2 m transect. The shaded areas indicate placement of the five 1x1 m quadrats within the larger transect from which *Chiton spp.*, *Tonicia spp.*, and *Chaetopleura spp*. data was collected. **b)** Shaded area indicates the diagonal of the 0.5x0.5 m quadrat from which *Scurria spp* and *Siphonaria lesson* data was collected.

Data collection: size frequency and length-weight

To estimate size frequency and length-weight relationship of the four most abundant species, as described by Santelices et al. (1981) and Aguilera and Navarrete (2012), the first 10-28 individuals each of the keyhole limpet *Fissurella crassa*, the chiton *Chiton granosus*,ke the scurrinid limpet *Scurria araucana*, and the pulmonated limpet *Siphonaria lessoni* were collected at each site. Their length to the nearest mm was measured using a caliper and weight to the nearest 0.1g was measured using a digital pocket scale either in the field or back in the ECIM laboratory. The longest fixed linear dimension of each species was measure as its length. Before weighing the individuals, external extraneous debris was removed as best as it could be with fingers and a small wire brush, and excess water was removed with paper towels.

Data analysis: statistical

Shannon-Wiener and Simpson Diversity Indices were calculated on the total count data of the open access, management area, and marine reserve sites to determine species abundance and evenness in each site (Shannon 1948; Pielou 1966). The Sorensen Coefficient was also calculated to compare the similarity of species between the different sites. One-way ANOVA tests and Tukey HSD post-hoc comparisons were conducted on Vassarstats to compare the abundance of each grazer species among sites. Each of the three transects within a site were treated as a different independent sample (n=3). In RStudio, one-way ANOVA tests and Tukey HSD post-hoc comparisons were conducted to compare the lengths of *Fissurella crassa, Chiton granosus, Scurria araucana, and Siphonaria lessoni* individuals. Length data were transformed using square root transformations to meet homogeneity of variances and normality assumptions of ANOVA. The least square means and upper and lower confidence levels were then back transformed after analysis and reported.

The length and weight data were log transformed using the natural log to fit a linear regression used for statistical analyses to meet homogeneity of variances and normality assumptions of ANOVA. An ANCOVA test and Tukey HSD post-hoc comparisons were conducted in RStudio on the linear regression of the length weight relationship in order to compare the differences in the effect of length and site on the weight of the four species.

Ethical considerations

This project was conducted in a manner to ensure minimal harm and impact to the organisms that were studied and the environments they reside in. Permission was granted by ECIM to access their rocky platforms inside of the marine reserve. The individuals removed from the sites and brought back to the research station to be weighed and measured were kept in tanks with water and air circulation and then returned to the sites from which they were removed. Organisms of the four focal species of the length-weight study were extracted using the most humane methods possible.

Results

Site observations

Data were collected from the open access site just outside of ECIM in Las Cruces, Chile (Site 1) between July 1st - 3rd, 2019 during afternoon low tides which averaged 0.37 m. The weather was mild and sunny with few clouds and the average water temperature was 12.82°C. Data collection on July 2nd, 2019 overlapped with the total solar eclipse which reached totality in La Serena, Chile approximately 500 km north of Las Cruces. At the open access site, *Chiton granosus* was the most abundant species (14.7 ind/m_2), followed by *Scurria araucana* (8.31 ind/ m_2), and *Scurria variabilis* (8.03 ind/ m_2) (Table 1).

Data were collected from the ECIM marine reserve (Site 2) on July 8th, 2019 during the morning and evening low tides which averaged 0.45 m. Data was collected before and into dawn as well as after dusk. The water was very still, and no wave action was experienced during either collection period. The water temperature during collection periods averaged 12.53°C. The most abundant species in the marine reserve were *Chiton granosus* (16.7 ind/ m_2), *Siphonaira lessoni* (13.8 ind/ m_2), and *Scurria ceciliana* (9.78 ind/ m_2) (Table 1).

Data from the marine management area (Site 3) in El Quisco, Chile was collected on July 27th, 2019 during the afternoon low tide of 0.69 m. Water temperature averaged 12.2°C and the weather began sunny and became slightly overcast. Of the three sites, Site 3 had the greatest amount of intertidal algae present. *Chiton granosus* was also the most abundant at this site (17.7 ind/ m^2) and the next most abundant species were *Scurria ceciliana* (8.67 ind/ m^2) and *Siphonaria lessoni* (4.67 ind/ m^2) (Table 1).

Intertidal grazers statistics: diversity, abundance, and evenness

A total of 6 families and 21 different species were observed across the three sites. At the open access and marine reserves sites 18 species were observed, and at the management area 14 species were observed (Table 2). The total abundance (individual/m^2) is shown in Table 1. Overall grazer density was not significantly different among sites ($F_{2,60} = 0.23$, $p = 0.795$) however some individual species' densities were significantly different. Statistically significant differences ($p<0.05$) were observed of *Fissurella costata* ($F_{2,6} = 11.23$, $p = 0.0094$), *Chiton magnificus* ($F_{2,6} = 5.67$, $p = 0.041$), *Tonicia atrata* ($F_{2,6} = 11.32$, $p = 0.0092$), and *Siphonaria lessoni* ($F_{2,6} = 15.43$, $p = 0.0043$) abundances among sites, while the remaining species showed no statistically significant differences (Table 1). *F. costata* were significantly more abundant in the open access site than both the management area and marine reserve. A similar pattern can be observed with *T. atrata*. *C. magnificus* were also significantly more abundant in the open access site than the management area were no individuals were observed, however the open access site was not significantly more abundant than the marine reserve. *S. lessoni* were significantly more abundant in the marine reserve than in the management area and open access site. *Chiton cumingsii* and *Scurria cumingsii* were only observed at the open access site and *Fissurella latimarginata* and *Chaetopleura peruviana* were only observed at the marine reserve.

The three sites had relatively low to moderate grazer diversity as indicated by the Shannon Diversity Index whose values range between 1.5 and 3.5 and rarely exceed 4 (Table

2). The marine management area had the lowest Shannon Diversity Index (H=1.79) and the open access site had the greatest (H=2.10) with the marine reserve falling in the middle with H=1.95, but there were no statistically significant differences of the Shannon Diversity Indices among the sites (Figure 4). The Sorenson coefficient was calculated to evaluate the similarities of grazer species between each site. The open access and marine reserve both had an 81.25% similarity with the management area and the open access and marine reserve were 83.33% similar.

Table 1. Average number of individuals per meter squared of intertidal grazer species observed at each site including SD. Different letters next to abundances indicate statistically significant differences ($p < 0.05$) among sites (Tukey HSD post-hoc comparison after one-way ANOVA).

Family/Species	Open Access	Management Area	Marine Reserve
FISSURELLIDAE			
Fissurella crassa	1.30 ± 0.31	2.37 ± 0.91	2.23 ± 0.45
Fissurella costata	0.57 ± 0.31$_{b}$	0.10 ± 0.02$_{a}$	0$_{a}$
Fissurella latimarginata	0	0	0.03 ± 0.00
Fissurella limbata	0.20 ± 0.05	0.13 ± 0.02	0.60 ± 0.15
Fissurella maxima	0.07 ± 0.00	0	0.10 ± 0.00
CHITONIDAE			
Chiton cumingsii	0.10 ± 0.03	0	0
Chiton granosus	14.65 ± 6.20	17.73 ± 2.05	16.67 ± 4.24
Chiton magnificus	0.85 ± 0.29$_{a}$	0$_{b}$	0.27 ± 0.09$_{ab}$
Acanthopleura echinata	0.27 ± 0.07	0.07 ± 0.00	0.20 ± 0.05
Tonicia atrata	3.05 ± 1.02$_{b}$	0.27 ± 0.00$_{a}$	0.53 ± 0.10$_{a}$
Tonicia chilensis	0	0.27 ± 0.09	0.07 ± 0.00
CHAETOPLEURIDAE			
Chaetopleura peruviana	0	0	0.27 ± 0.04
LOTTIIDAE			
Scurria araucana	8.31 ± 3.46	2.89 ± 1.10	7.78 ± 1.66
Scurria ceciliana	4.54 ± 1.95	8.67 ± 4.87	9.78 ± 2.37
Scurria cumingsii	0.08 ± 0.00	0	0
Scurria plana	0.31 ± 0.12	0	1.11 ± 0.00
Scurria variabilis	8.08 ± 3.31	3.11 ± 0.00	5.78 ± 1.43
Scurria viridula	0.69 ± 0.34	0.67 ± 0.16	0.44 ± 0.00
Scurria zebrina	1.85 ± 0.80	0.67 ± 0.00	0.67 ± 0.16
SIPHONARIIDAE			
Siphonaria lessoni	2.92 ± 1.14$_{a}$	4.67 ± 1.54$_{a}$	13.8 ± 4.00$_{b}$
ARBACIIDAE			
Tetrapygus niger	0.57 ± 0.12	0.20 ± 0.00	0.27 ± 0.00

Table 2. Summary data of intertidal grazer richness, diversity, and evenness

	Open Access	Management Area	Marine Reserve
Richness	18	14	18
Shannon-Wiener Diversity Index (H)	2.10	1.79	1.95
Simpson Diversity Index (E$_{h}$)	0.849	0.832	0.776

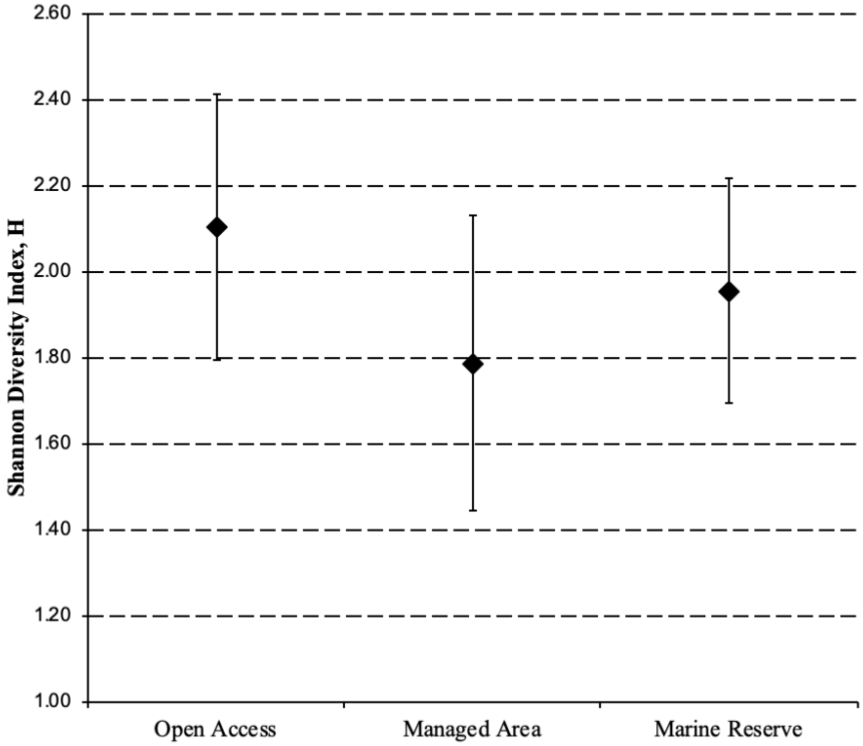


Figure 4. Graph of Shannon-Wiener Diversity Indices (H) including error bars for the three sites. There were no statistically significant differences ($p<0.05$) between sites.

Length variation of F. crassa, C. granosus, S. araucana, and S. lessoni

There was a significant effect ($p<0.05$) of human disturbance on *F. crassa* length ($F_{2,234} = 23.04$, p = 7.32e-10). The Tukey HSD post-hoc comparison indicated that the mean lengths for open access, management area, and marine reserve were all statistically significant from one another (Figure 5a). *F.* crassa in the open access site were on average the smallest (M = 3.69, SD = 1.13), with their mean length increasing in the management area (M = 4.37, SD = 1.46), and larger individuals in the marine reserve (M = 5.61, SD 2.32). The *C. granosus* lengths were significantly different among sites ($F_{2,323} = 10.89$, p = 2.65e-10). The length trend is similar to that of the *F. crassa*. The *C. granosus* individuals in the open access site were on average the shortest (LMS=2.59; 95% CI, 2.27-2.92), the management area individuals were significantly longer than the open access individuals (LMS=3.13; 95% CI, 3.02-3.60), and the marine reserve individuals were the longest and also significantly longer than those from the open access site (LMS=3.80; 95% CI, 3.39-4.23) (Figure 5b). There was no significant difference between the management area and marine reserve.

Scurria araucana individuals were the longest in the management area (LMS=1.65; 95% CI: 1.34-1.93) followed by the open access site (LMS=1.42; 95% CI, 1.24-1.62) and were on average the shortest in the marine reserve (LMS=1.13; 95% CI, 0.94-1.35). As shown by the Tukey HSD post-hoc comparison, the mean length of the individuals from the open access site is statistically significant from the management area and marine reserve lengths, but the management area and marine reserve lengths are not significantly different from each other ($F_{2,126}$ = 4.74, p = 0.1035) (Figure 5c). *Siphonaria lessoni* were also the shortest in the marine reserve (LMS=0.61; 95% CI, 052-0.71) and longest in the management area (LMS=0.96; 95% CI, 0.84-1.08). The mean length of organisms from the open access site falls in between the other two sites (LMS=0.91; 95% CI, 0.80-1.02). Length of *S. lessoni* in the marine reserve is statistically significant from the lengths of *S. lessoni* in the open access site and marine management area ($F_{2,119}$ = 12.11, p = 1.64e-5) (Figure 5d). Longer *F. crassa* and *C. granosus* individuals were observed in the marine reserve while longer *S. araucana* and *S. lessoni* individuals were not but were observed in the other sites (Figure 6).

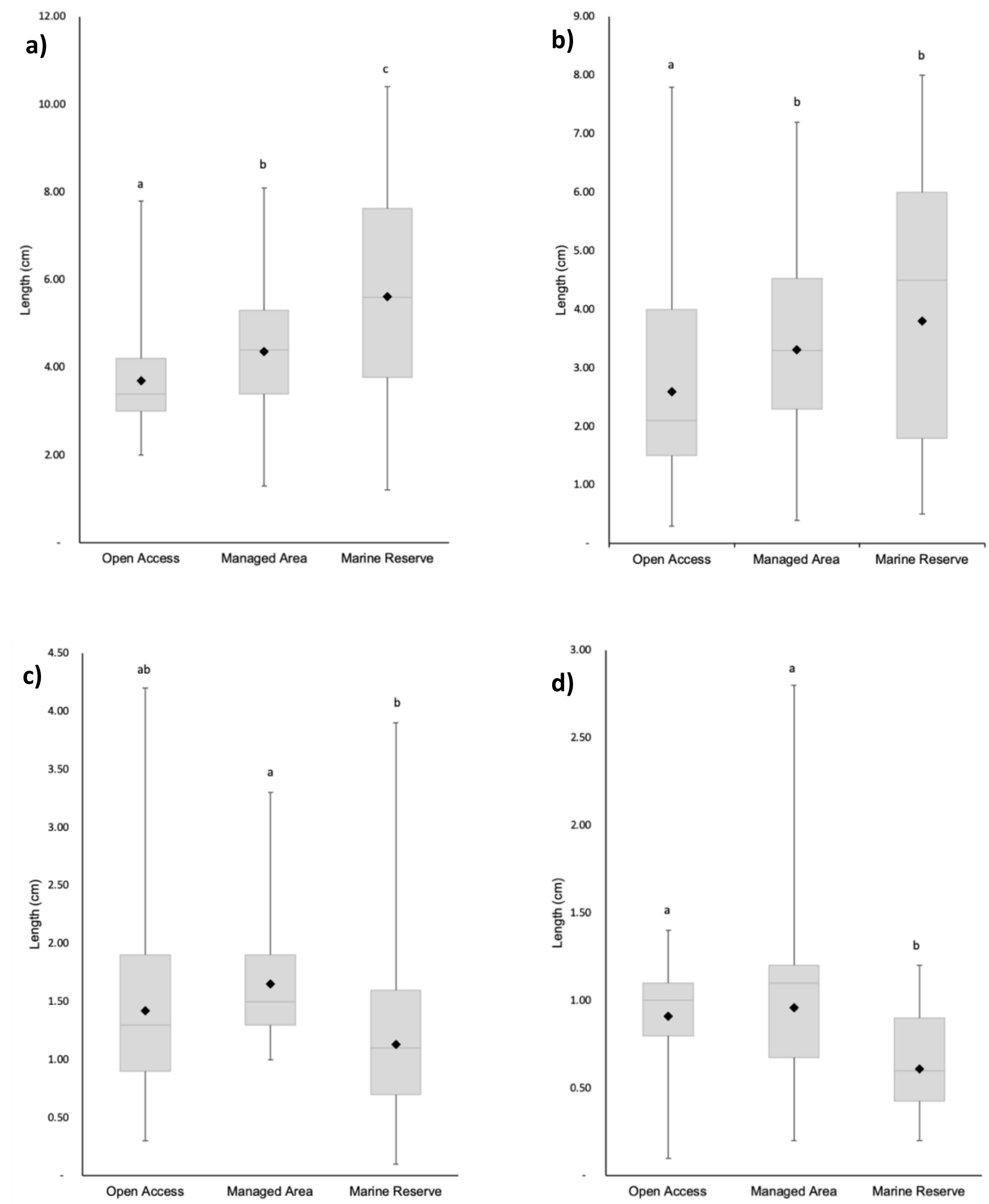
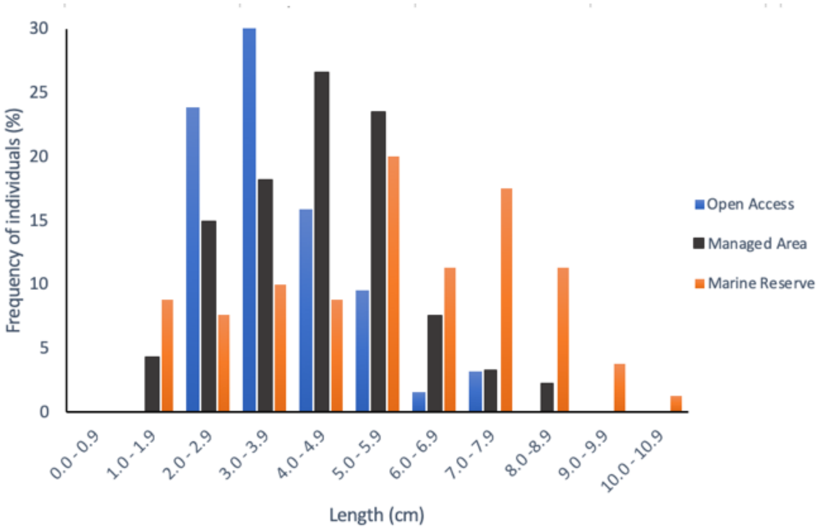
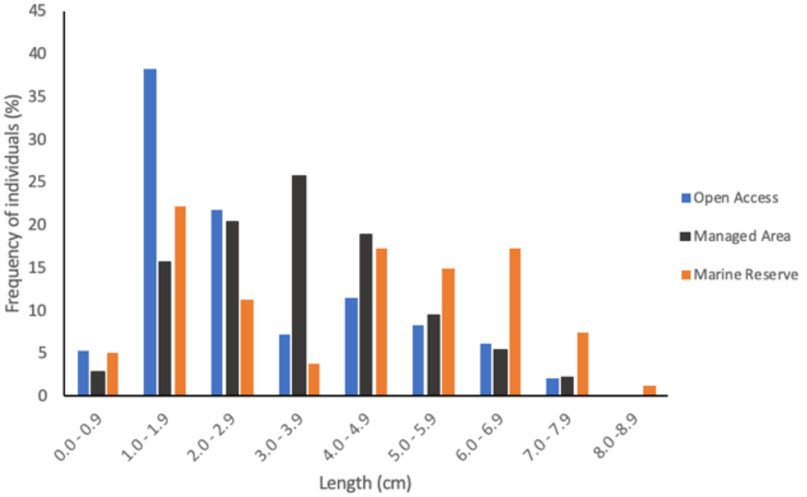


Figure 5. Length boxplots of grazer individuals at the different sites. Mean values are show using ♦. Letters above bars indicate statistically significant differences of means ($p<0.05$) among sites. **a)** *F. crassa* length at open access (n=63), management area (n=94), and marine reserve (n=80) sties. **b)** *C. granosus* length at open access (n=97), management area (n=148), and marine reserve (n=81) sties. **c)** *S. araucana* length at open access (n=58), management area (n=32), and marine reserve (n=39) sties. **d)** *S. lessoni* length at open access (n=44), management area (n=40), and marine reserve (n=38) sties.

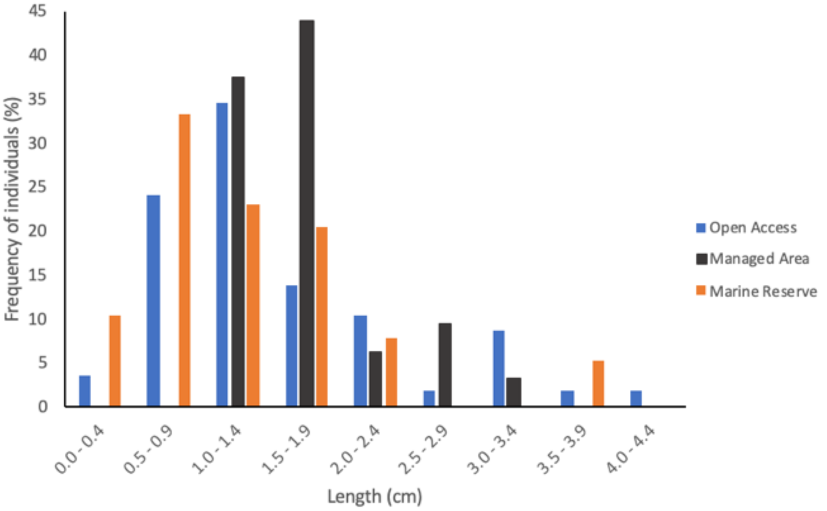
a)


30
25
20
15
10
5
0
Frequency of individuals (%)
0.0 - 0.9
1.0 - 1.9
2.0 - 2.9
3.0 - 3.9
4.0 - 4.9
5.0 - 5.9
6.0 - 6.9
7.0 - 7.9
8.0 -8.9
9.0 -9.9
10.0 - 10.9
Length (cm)
Open Access
Managed Area
Marine Reserve

b)


45
40
35
30
25
20
15
10
5
0
Frequency of individuals (%)
0.0 - 0.9
1.0 - 1.9
2.0 - 2.9
3.0 - 3.9
4.0 - 4.9
5.0 - 5.9
6.0 - 6.9
7.0 - 7.9
8.0 -8.9
Length (cm)
Open Access
Managed Area
Marine Reserve

c)


45
40
35
30
25
20
15
10
5
0
Frequency of individuals (%)
0.0 - 0.4
0.5 - 0.9
1.0 - 1.4
1.5 - 1.9
2.0 - 2.4
2.5 - 2.9
3.0 - 3.4
3.5 - 3.9
4.0 - 4.4
Length (cm)
Open Access
Managed Area
Marine Reserve

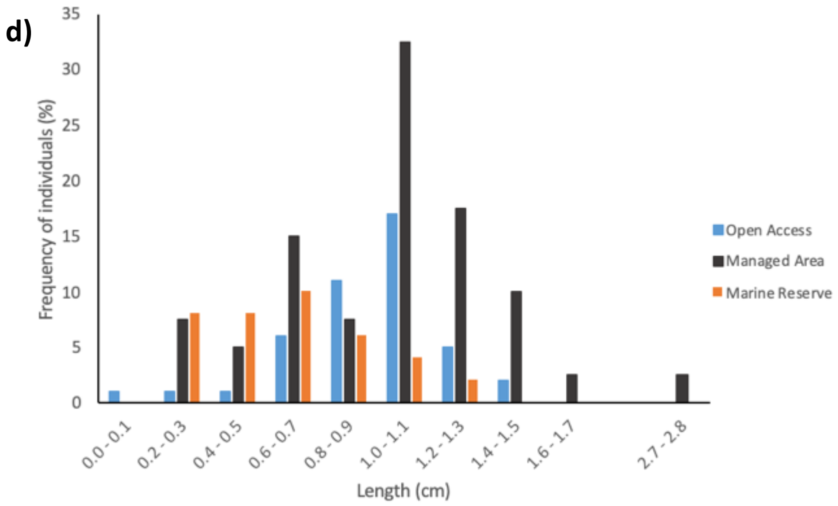


Figure 6. Size frequency distribution of **a)** *F. crassa*, **b**) *C. granosus*, **c)** *S. araucana*, and **d)** *S. lessoni* individuals at the different sites.

Length-weight relationship of F. crassa, C. granosus, S. araucana, and S. lessoni

F. crassa weight was significantly affected by length ($F_{1,63} = 1883.13$, p = <2.2e-16) and site ($F_{2,63} = 28.08$, p = 1.91e-09). At all sites, as individuals increased in length, they also increased in weight (Figure 7). Even though a few longer and heavier individuals were found in the marine reserve, resulting in the mean weight at that site being the greatest of the three sites, generally, individuals from the management area weighed more at almost all lengths than individuals from the marine reserve. Individuals from the open access site weighed the least for any given lengths (Figure 7). The weights of *F. crassa* from each site were compared statistically at the following lengths: 5.4cm, 6cm, and 7.8 cm. The Tukey HSD post-hoc comparison indicated that the mean weight of open access (M = 72.97, SD = 1.61), management area (M = 48.42, SD = 1.71), and marine reserve (M = 12.30, SD = 2.37) *F.* crassa were all statistically significant from each other.

C. granosus individuals also displayed a significant effect of length ($F_{1,72} = 3340.64$, p = <2e-16) and site ($F_{2,72} = 38.71$, p = 3.84e-12) on weight. From the Tukey comparison, the mean weights at lengths of 4.5cm, 5.75cm, and 7cm of open access (M = 4.35, SD = 3.67), management area (M = 5.47, SD = 3.35), and marine reserve (M = 31.19, SD = 1.72) are all statistically different from one another. The marine reserve individuals generally weighed the most at each length, followed by the management area individuals, then the open access individuals (Figure 7). The largest and longest individuals of *F. crassa* and *C. granosus* were both found in the marine reserve.

The longest and largest *S. araucana* individual was also found in the marine reserve, but the sites did not have a significant effect ($F_{2,44}$ = 0.1419, p = 0.87) on the weight of the organisms of the same length (open access: M = 0.79, SD = 2.16; management area: M = 0.63, SD = 1.65; marine reserve: M = 0.85, SD = 3.46). The length however did have a significant effect ($F_{1,44}$ = 222.17, p = <2.2e-16). As organisms got longer, they increased in weight which was observed at all sites (Figure 9). *S. lessoni* individuals' weights were also significantly impacted by length ($F_{1,41}$ = 175.35, p = <2e-16) but not by site ($F_{2,41}$ = 2.56, p = 0.089). At all sites, the weight increased as length increased (Figure 10). The mean weight of the individuals from the marine reserve (M = 0.20, SD = 1.62) is significantly different from both the management area (M = 0.34, SD = 2.16) and the open access area (M = 0.34, SD = 1.65) but the management area and open access mean weights are not significantly different from one another.

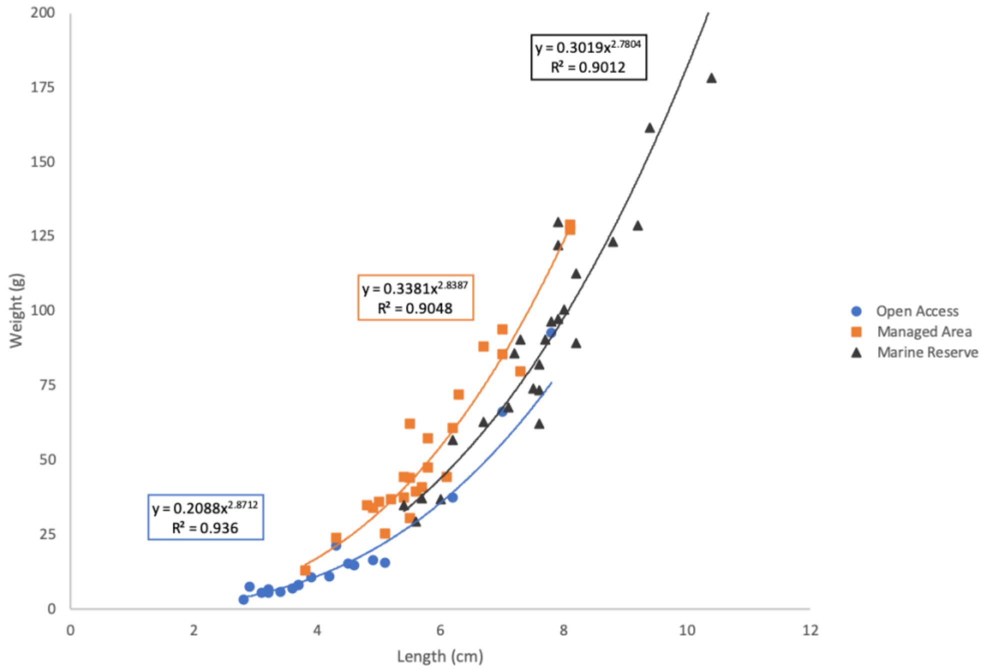


Figure 7. Length-weight relationship of *Fissurella crassa* from open access (n=19), management area (n=25), and marine reserve (n=25).

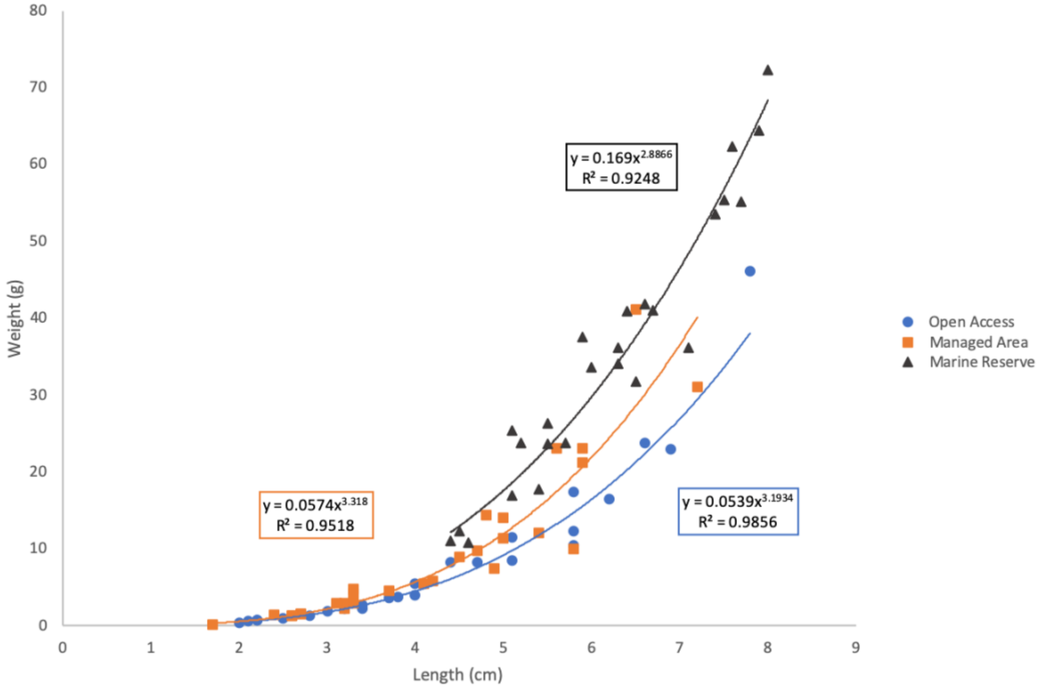


Figure 8. Length-weight relationship of *Chiton granosus* from open access (n=25), management area (n=28), and marine reserve (n=25).

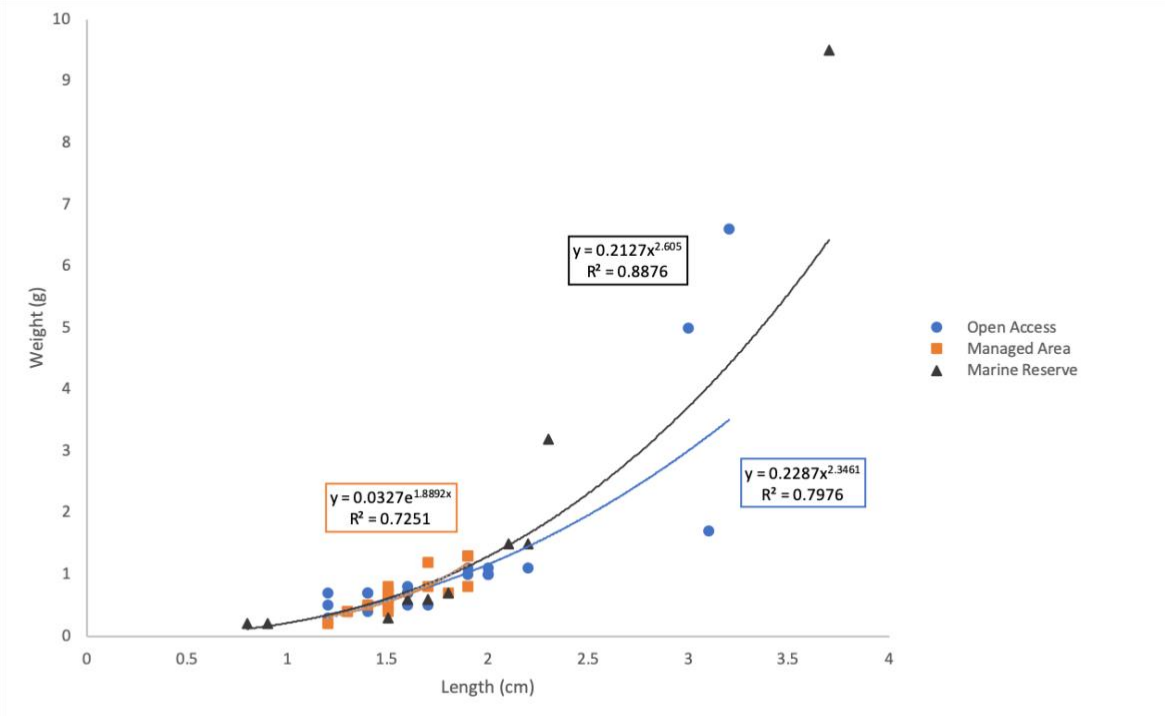


Figure 9. Length-weight relationship of *Scurria araucana* from open access (n=24), management area (n=16), and marine reserve (n=10).

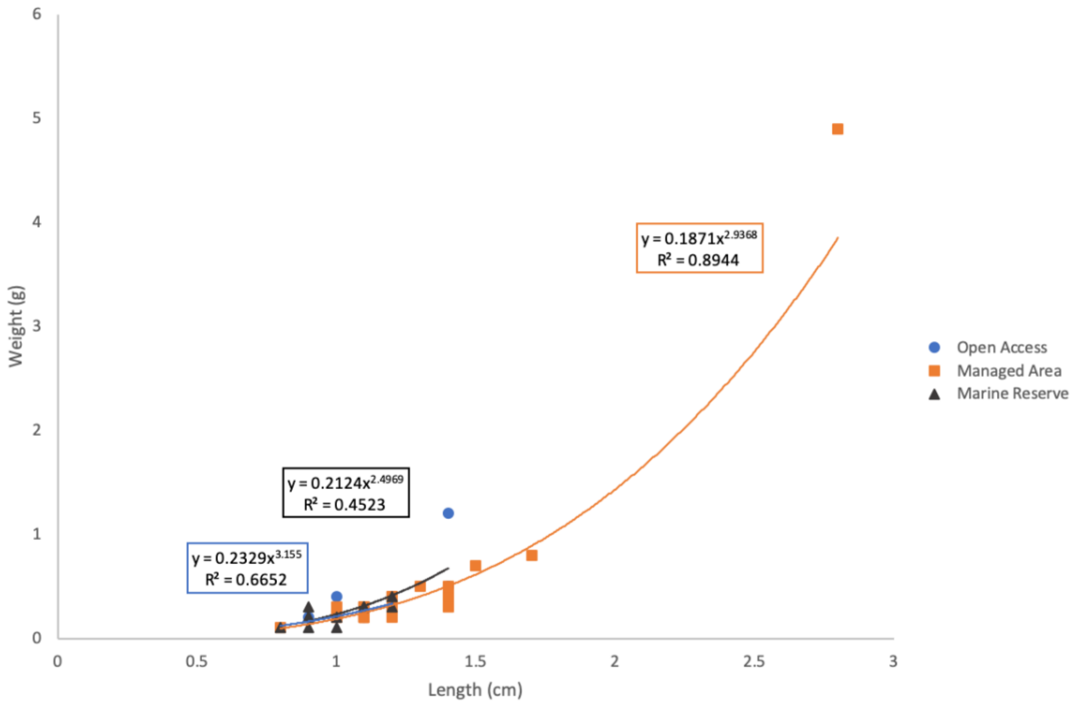


Figure 10. Length-weight relationship of Siphonaria lessoni from open access (n=13), management area (n=22), and marine reserve (n=12)

Discussion

Intertidal grazers statistics: diversity, abundance, and evenness

This study provides a comprehensive assessment of overall grazer abundance and diversity in open access, management area, and marine reserve sites in Central Chile. Along with grazer assemblage diversity, it also examined the effects of the different management areas and the effects of humans as a predator on the size frequency and shell length-body weight allometry of *F. crassa*, *C. granosus*, *S. araucana*, and *S. lessoni*.

The diversity and richness of the open access, management area, and marine reserve sites are all relatively low and not significantly different from one another. This rejects my hypothesis that the open access site, having no restrictions on grazer removal, would have less benthic grazer biodiversity. Although diversity is moderately low for all sites, the open access site was the most diverse of the three with a Shannon Diversity Index of 2.10. Isbell et al. (2015) along with other studies show that biodiversity can increase ecosystem stability. The similar diversities may be a result of the close proximity and general similarity of habitat morphology and composition. It can also suggest that in this intertidal ecosystem, the presence and disturbance of humans through harvesting does not have a strong effect on the stability of the ecosystem through a community level effect regarding the number of species present but instead has a population and individual level impact on the organisms themselves which can then impact the ecosystem through other trophic connections (Moreno et al. 1984; Pérez-Matus et al. 2017).

The abundance of three species (*Fissurella costata*, *Chiton magnificus*, and *Tonicia atrata*) were significantly greater in the open access site while eight other species were generally more abundant at the same site than at the management area or the marine reserve.

This may be due to complicated grazer species interactions as well as interactions between the grazer and algal communities not taken into account for this study. It could also be an example of humans as a keystone predator that is able to select for the largest individuals of dominant competitors like *F. crassa* and *C. granosus*, who are dominant due to their larger size than other grazers, whose absence opens up more space and resources for less competitive species to take advantage of and may lead to functional shifts within grazer assemblages, which could be observed through future research (Moreno et al. 1984; Aguilera and Navarrete 2012).

F. crassa acts as an intertidal keystone herbivore (Aguilera and Navarrete 2012) and *C. granosus* is another key intertidal grazer of the region and both are harvested for human consumption which is reflected in the results as the abundance of these two species were the lowest in the open access site. As restrictions increased on the removal of intertidal organisms, this study found that the organisms that are most targeted by harvesters generally increase in abundance which is consistent with findings of Moreno et al. (1984) and Aguilera & Navarrete (2012). *Siphonaria lessoni* is not a species targeted for harvesting and this study found that it was the only species that was significantly more abundant in the marine reserve than the other sites.

Length variation of F. crassa, C. granosus, S. araucana, *and* S. lessoni

The study of length of the four focal species showed that for *F. crassa* and *C. granosus*, mean length increased from open access to management area to marine reserve. The smaller lengths of *F. crassa* and *C. granosus* in the open access site is likely due to larger individuals being removed by harvesters. This supports the hypothesis that more restrictions and bans on the removal of these exploited species results in larger individuals being present. For *S.*

araucana and *S. lessoni*, their mean length was the smallest in the marine reserve, and individuals on average got larger in the open access then management area sites. This is consistent with the findings of Aguilera & Navarrete (2012) that *S. lessoni* individuals are typically smaller inside the marine reserve and *F. crassa* individuals are larger and more abundant compared with open access areas.

Length-weight relationship of F. crassa, C. granosus, S. Araucana, and S. lessoni

As expected for all species, individual body weight increased as the length of the organisms increased. However, shell length-body weight allometries varied among sites for *F. crassa* and *C. granosus*, which consistently presented lower body mass conditions at the open access sites. This suggests that energetic costs and/or feeding may be limiting body mass. Highest body mass conditions were observed in the management area (*F. crassa*) or marine reserve (*C. granosus*), suggesting these two grazers respond behaviorally different to management areas. These differences may be due, at least in part, to size-dependent differences in diet. While both species are active grazers that scrape the rock surface to remove micro- and small algae, when *F. crassa* reaches about 4-5cm in length it also browses on adult algae, including the tougher corticated groups (particularly canopy-forming *Mazzaella*). Thus, the higher abundance of adult algae (including *Mazzaella*) at the management site (Broitman 2001) may provide increased food availability and/or energetic value. Alternatively, augmented competition among greater abundance of grazers within the marine reserve may limit body weight at the same lengths. *S. arauacana* and *S. lessoni* did not show significant differences in weight by site, but this could be due to the small sample size of both of the species.

Possible limitations and sources of error

This study was limited by a short study period, a limited number of days in the field due to oceanic and weather conditions, and a small sample size. Collecting data only in the afternoon at sites 1 and 3 could have impacted the abundance of individuals observed compared to site 2, where data was collected at dawn and after dusk. Some species in the Fissurellidae and Chitonidae families are nocturnal (Moreno et al. 1984; Aguilera and Navarette 2011) thus more might have been out and easier to observe during data collection at site 2. Grazer observation and identification could have been impacted by human error. Many of the species reside in crevices and in other nooks in the heterogenous rocky terrain and could have been overlooked as it is difficult to observe all the surfaces of the rocky platforms with the naked eye. Although, a field guide was used to help with species identification, not all individuals were easily identifiable, especially individuals of the Lottiidae family due to ambiguous coloration. There could also have been error in the readings from the calipers and/or instrumental error in the measurements of the digital pocket scale.

Due to the MEA in El Quisco having not been actively defined and managed for a couple years after the terms of its agreement expired, it may not clearly represent the full impact of an MEA on intertidal grazers. Due to lack of long-term data of the same focus as this study, it is difficult to conclude how great the effects of the MEA still are or if the effects have diminished in magnitude due to an increase in human disturbance. Even so, this study did observe positive benefits in abundance and size of grazers at this site compared to the open access site with no removal restrictions and future studies can continue to include sites of a wide range of management intensities to show the benefits of management on grazers, especially exploited species. The management site in El Quisco is separated geographically from the other two sites which are adjacent to each other, however it is difficult to find three sites all adjacent to one another due to the scarcity of no-take MPAs across Chile. It still contributes to the comparison of human impact on intertidal grazers and when combined with a greater number of sites along the coast of central Chile, can give a better overview of the grazer guild in the region as a whole.

Suggestions for further research

The goal of future research on this subject should be to better understand the effects of human disturbance on the diversity, abundance, and size of intertidal grazer assemblages. Further research on this topic would benefit from having a larger sample size with more transects and sites, as well as data collection over a longer period of time so that low tides can be observed throughout the entire day to minimize daily temporal separation and to observe long-term community changes. This would give more accurate insight into the total number of species present at each site. Conducting this study long term would be beneficial in integrating the algal composition of the rocky platforms to create a more holistic and complex view of interactions between grazers and between grazers and algae that may exist and be affected by humans. A higher quality scale could be utilized to obtain a more accurate reading of the weight of individuals as well as to obtain the weight of smaller individuals less than 0.1g that the pocket scale wasn’t able to measure.

Conclusion

This study demonstrates that while most intertidal species’ diversity and abundance did not change significantly in the open access, management area, and marine reserve in central

Chile, the lengths and length-weight relationships of some species were significantly impacted by human disturbance. The species that are exploited by humans are longer in the management area and marine reserve sites where there are restrictions on their harvesting. For the same exploited species, individuals of the same length weighed more at management area and marine reserve sites than in the open access sites suggesting that management has a positive impact.

Human disturbance of grazers can have lasting impacts on community structure and species interactions within intertidal ecosystems. Studying the anthropogenic effects on intertidal grazer assemblages is important in assessing the impact growing human populations are having on marine organisms as well as the importance and benefits of having protected marine areas. These protected areas not only need to be created, but also need to be well managed locally and regionally as biological processes that occur are not exclusive to the area of a single MEA or MPA.

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