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SEASCAPE ECOLOGY AND 3D PHOTOGRAMMETRY CAN ELUCIDATE THE RELATIONSHIPS BETWEEN CORAL PATCH CHARACTERISTICS AND CHAETODONTIDAE ASSEMBLAGE PATTERNS AT LAEHALA, HILO.

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Abstract

Seascape ecology involves the study of habitat patches, in particular this field focuses on investigating how patch characteristics (e.g., size, shape, and spatial configuration) influence ecological processes. Laehala is a small and semi-enclosed tide pool reef system that exhibits an arrangement of heterogeneous coral patches. This study identified five coral patches with distinct physical characteristics and conducted butterflyfish surveys within each patch to determine how patch characteristics influence fish assemblage patterns. The abundance and diversity of butterflyfish were found to have a statistically significant inverse relationship among the coral patches (R-sq = 0.4576, $p < 0.001$). One patch in particular hosted both the highest abundance and the lowest diversity of butterflyfish. Both patch size and isolation (measured as average distance from all other patches) were significantly different among patches (ANOVA, $p < 0.05$), but only size exhibited a significant relationship with fish abundance, indicating that smaller patches have higher fish abundance (R-sq = 0.2707, $p < 0.01$). It is possible that the three-dimensional complexity of each coral patch also influences butterflyfish assemblage patterns. Future analyses will use 3D reconstructions of each coral patch to examine how habitat complexity may be influencing butterflyfish assemblages at this location.

Keywords: Coral reef, seascape ecology, 3D photogrammetry, Chaetodontidae, patch reef, habitat heterogeneity.

TABLE OF CONTENTS

Introduction

Coral reefs have long been recognized as one of the most diverse, productive, and economically valuable ecosystems on the planet (Moberg & Folke 1999; Woodhead et al. 2019). Human societies depend on these ecosystems extensively as they provide global food security (Grafeld et al. 2017), valuable coastal protection by dissipating wave energy (Beck et al. 2018), and a substantial amount of income from tourism and recreation (Spalding et al. 2017; Cesar and Beukering 2004). In addition, the highly complex three-dimensional architecture of coral reefs provides critical habitat for millions of reef organisms (Fisher et al. 2015). Unfortunately, coral reefs are experiencing severe ecosystem degradation driven by anthropogenic stressors including global climate change, coastal pollution, and overexploitation of resources (Hoegh-Guldberg et al. 2017; Carlson et al. 2019; Jackson et al. 2001). The degradation of these systems has a profound detrimental impact on the availability of valuable ecosystem goods and services (Pratchett et al. 2014; Bellwood et al. 2004; Halford et al. 2004).

Scleractinian corals are important ecosystem engineers, and their structural characteristics directly affect the assemblages of associated fauna (Kerry & Bellwood, 2012). For example, *Chaetodontidae*, or butterflyfish, are obligate corallivores that depend directly on living corals for both food and shelter, and their assemblage is thus largely influenced by the reefscape (Graham et al. 2009). Additionally, butterflyfish are known to exhibit strong microhabitat selectivity, which has been found to be driven by both percent of live coral cover and the reef's structural complexity (Pratchett & Berumen 2008; Barbosa et al. 2019). While relationships between fish assemblages and structural complexity have been well studied (Nanami et al. 2005; Komyakova et al. 2013), how their microhabitat selectivity may be influenced by the reef's spatial heterogeneity has not yet been explicitly examined.

The distribution of organisms relative to their habitat is of central importance to ecology and habitat-based management. A seascape is a marine area containing a mosaic of habitat patches, and seascape ecology is the study of how patch characteristics influence ecological processes. Seascape ecology is essentially the marine version of landscape ecology, which has been applied to study terrestrial ecosystems for decades (Wu 2006; Turner 1989; Turner 2005). Landscape ecology has proven to be an incredibly insightful approach in understanding how organisms respond to the spatial patterning in their environment, and use this knowledge to effectively plan and design habitat-based conservation (Liu and Taylor 2002). While the field of seascape ecology has been applied to study coastal ecosystems, the majority (81%) of them are focused on seagrass beds and saltmarshes, while only 11% of these studies have focused on coral reefs (Boström et al. 2011). Coral reefs deserve more focus, as they are ideally suited for a seascape ecology approach as they can exist as an intricate mosaic of habitat patches, each with distinct characteristics and thus potentially providing varying levels of ecosystem services.

The field of seascape ecology accounts for a number of seascape features that may or may not influence the ecology of an organism (Grober-Dunsmore 2007). These include seascape matrix, context, corridors, species relationships, patch size, structure, isolation, and depth variation. In terrestrial ecosystems, landscape ecology studies have consistently shown that each species responds to specific landscape features, at different spatial scales, and in a very unique way (Fischer and Lindenmayer 2006; Turner 2005). These findings have also been corroborated by coral reef seascape ecology studies by Grober-Dunsmore et al. (2007) and Pittman and McAlpine (2003). The spatial scale of this study was focused on the home range area of the fish family Chaetodontidae, investigating how patch size, isolation, and structure may influence their assemblages and microhabitat selectivity.

While seascape features such as patch size and isolation can be relatively simple to quantify, patch structure can be much more complicated. Recent technological innovations such as structure-from-motion photogrammetry have been widely utilized to build 3D reconstructions of coral reef habitats and quantify their 3D structural complexity metrics using spatial analysis tools (Burns et al. 2019; Fukunaga et al. 2019; Ferrari et al. 2016). These technologies have now revealed in increasing detail how complex the structure of a habitat can actually be. A habitat's structure is best explained by a number of parameters (e.g., slope, ruggedness, curvature) that encompass overall complexity, and each parameter can influence ecosystem functions at varying levels (Burns et al. 2015; Fukunaga et al. 2019**).** For this reason, in order to appropriately decipher the specific patch characteristics that influence such intricate relationships between organisms and seascape, it is important to obtain highly accurate 3D complexity data.

In the face of rapidly increasing anthropogenic stressors affecting coastal ecosystems, it is critical that we seek to better understand organism-seascape relationships on coral reefs. As these ecosystems degrade and coral species decline, obligate corallivores will invariably decline as well (Pratchett et al. 2006, Graham et al. 2009, Thompson et al. 2019). Adopting a seascape ecology approach along with novel technologies to reef fish ecology research has the potential to uncover important insights on the dynamics of this highly heterogeneous and complex ecosystem.

The aim of this study was to investigate how the reef's spatial heterogeneity influences Chaetodontidae assemblages. A total of 7 butterflyfish species were surveyed within 5 coral patches with distinct size, isolation, and structure. Namely, I hypothesized that;

1) Coral patches with higher structural complexity support a greater abundance of fish,
2) Coral patches with greater spatial distances to adjacent clusters support lower abundance of fish, and
3) Bigger coral patches support a greater abundance of fish.

Study Site

The study site is a small semi-enclosed tide-pool located on the Hilo coast of Hawaii island (19° 44' N 155° 01' W) (Fig 1). There are two small openings connecting the tide-pool to the open ocean, providing a pathway for fish and turtles to access these semi-protected coral patches. Inside this tide-pool there is a highly complex and diverse patch reef system, in which 5 coral patches with distinct characteristics were identified to conduct the study. The spatial distribution among the patches is within 13-40 meters. The context of the tide-pool is rocky and patches are separated by rubble and smaller coral colonies. The site is very shallow, has limited wave action, high fresh-water input, and low anthropogenic disturbance given it is located on private land.

In seascape ecology, the spatial scale, seascape elements, and features of interest are usually arbitrarily chosen by the researcher based on the question of interest (Grober-Dunsmore et al. 2009). Despite the potential of providing more explicit insights on species-seascape relationships, rarely are spatial scales aligned with the species' of interest home-range (Boström et al. 2011). For this study, the spatial scale was confined to the home-range area of butterflyfish within this enclosed tide pool. Patch boundaries were determined based on personal observations and the seascape features of interest were patch size, isolation, and structure.

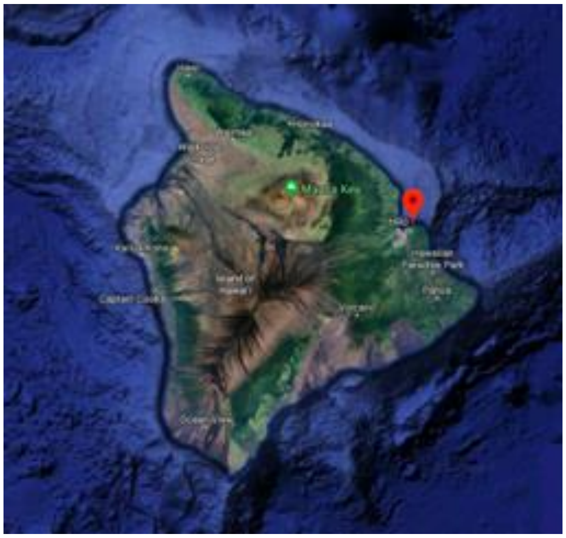

Figure 1: Study site at Laehala, Hilo.

Methods

Fish Assemblage

Fish assemblage data was collected via snorkel using a 10-minute stationary point count (SPC) survey method. A total of seven butterflyfish species were surveyed (C. auriga, C. quadrimaculatus, C. multicinctus, C. lunula, C. unicinctus, C. ornatissimus, and C. miliaris). There were three surveyors, and they all conducted the surveys at the same time at different patches. Each surveyor was stationed at the center of a patch for 10 consecutive minutes, and every one minute, each butterflyfish present within the defined perimeter of that patch were counted down to species. Surveyors were careful to not double-count the same fish. A total of 5 surveys per patch were conducted in two field days, and same-day surveys were conducted at different times of the day.

Patch Characteristics

Patch size and isolation were partly measured in the field with a transect and then validated using remote sensing data available through google earth. Size was measured as patch area in meters squares, and isolation was measured as the average distance from one patch to adjacent four patches. Structural complexity data was collected for each patch using 3D structure-from-motion photogrammetry techniques following Burns et al. 2015 methods. The snorkeler swam across each one of the patches using an overlapping 'back-and-forth' pattern while taking continuous overlapping (70-80%) photographs from both oblique and planar angles. All photographs were taken with a Canon SL2 10-50mm lens in an Ikelite housing.

Results

All statistical analyses were conducted in R version 3.6.1 (R Core Team, 2019). Butterflyfish abundance was calculated using the plyr package and was then log-transformed to reduce the distribution's high skewness (Hadley Wickham, 2011). A series of rank-based nonparametric kruskal-wallis tests were conducted to examine how butterflyfish abundance differs among patch characteristics.

Butterflyfish abundance was found to be significantly different among patch isolation measurements (KW, $p < 0.001$), showing that more isolated patches support greater butterflyfish abundance (Fig 2). Butterflyfish abundance was also found to be significantly different among different patch sizes (KW, $p < 0.001$), showing that smaller coral patches support a greater abundance of butterflyfish (Fig 3).

Given that seven species of butterflyfish were surveyed, butterflyfish diversity was calculated as the Shannon Wiener diversity index using the vegan package (Oksanen et al. 2019). A simple linear regression was run to examine if there was a relationship between butterflyfish abundance and diversity. These parameters exhibited a statistically significant inverse relationship (R-sq = 0.4576, $p < 0.001$, Fig 4). One patch in particular hosted both the highest fish abundance among all patches and also the lowest fish diversity. Model assumptions were examined with various residual plots, revealing heteroscedasticity. Thus, the stability of this relationship is in question and more data is needed to confidently determine the relationship.

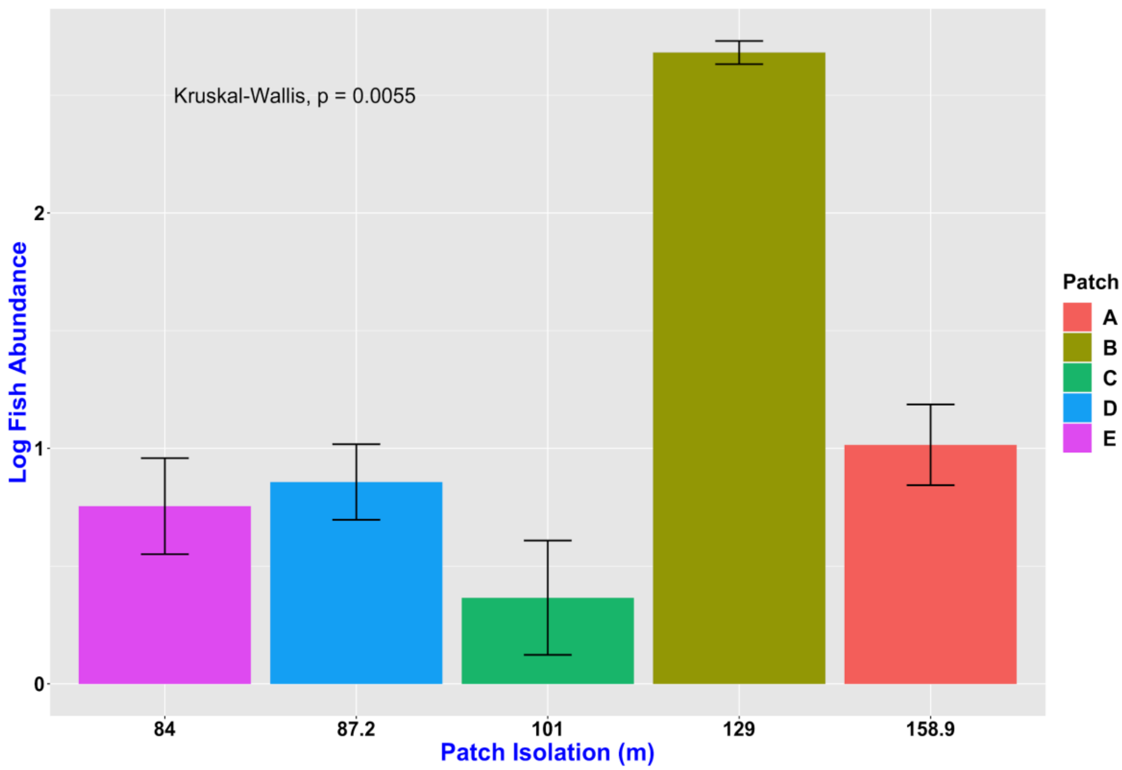

Figure 2: Log-transformed butterflyfish abundance among patch isolation (average distance from one patch to adjacent four patches). Patches A and B showed to support the highest butterflyfish abundance while being the most isolated patches.

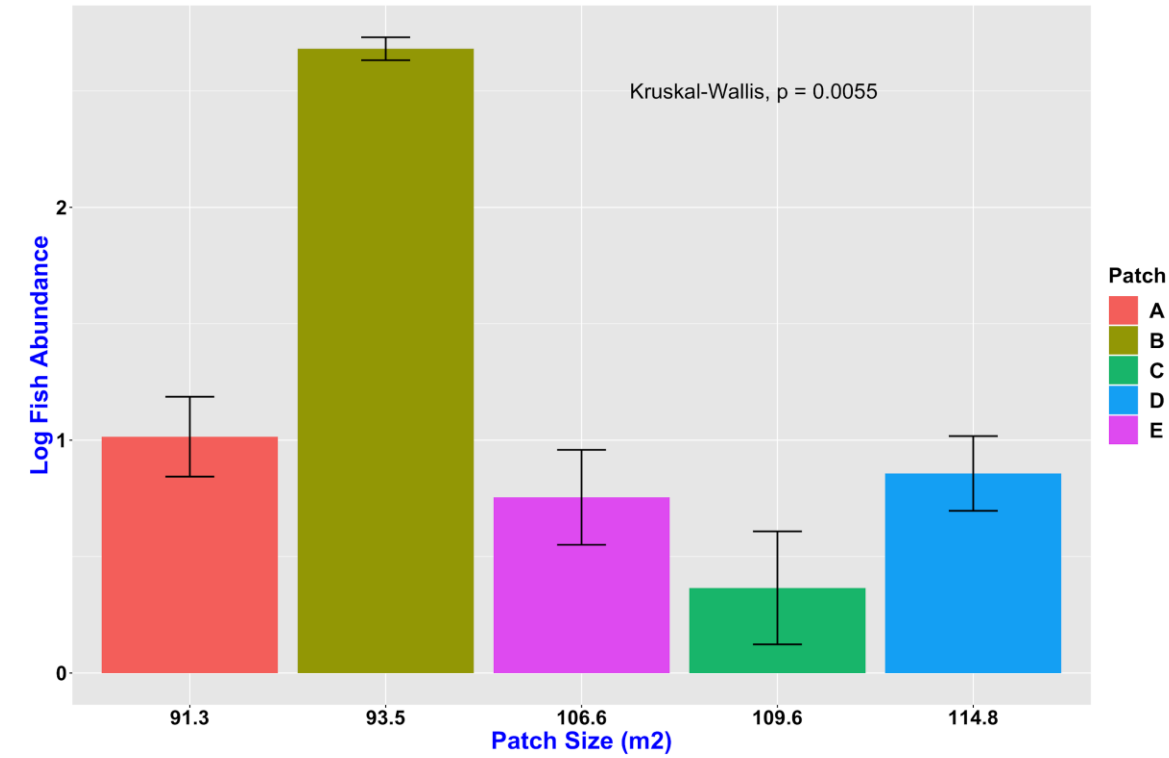

Figure 3: Log-transformed butterflyfish abundance among patch size (area in m2). Patches A and B showed to support the highest fish abundance while being the two smallest patches.

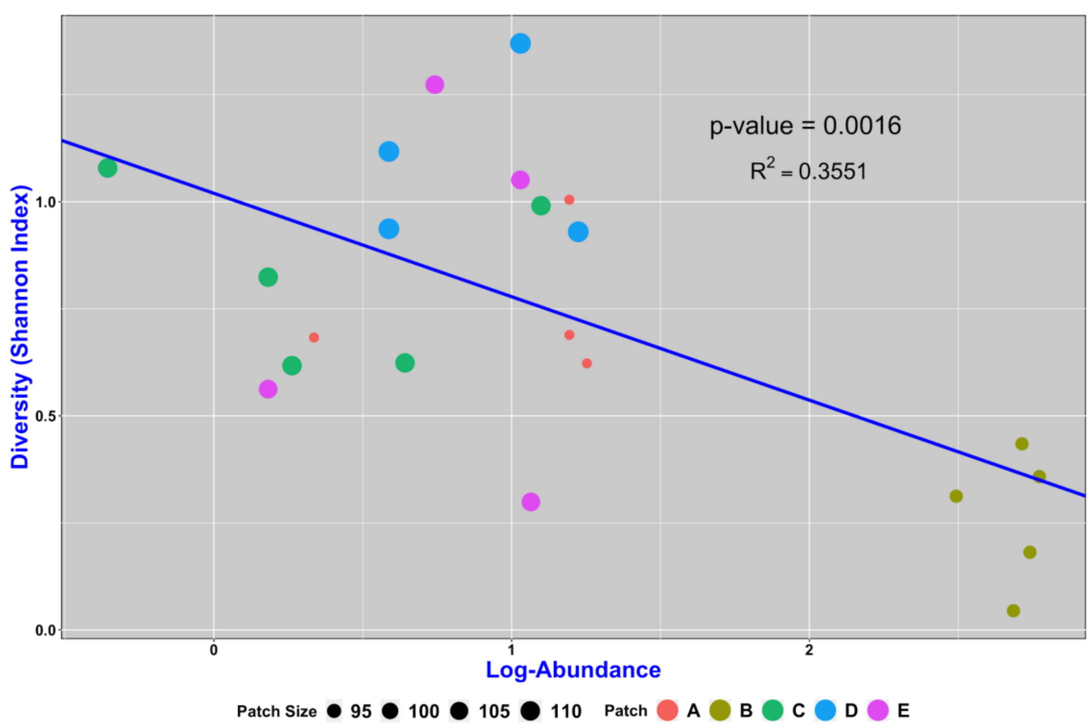

Figure 4: Simple linear regression model showing a significant inverse relationship among log-transformed butterflyfish abundance and diversity (H'). Patches are colored by their letter code and the size of the circle reflects the patch size. Patch B (the green one on the right bottom corner), hosted the highest fish abundance of all while having the lowest H' diversity index and being one of the smallest patches.

Discussion

Contrary to expectations based on terrestrial studies, neither bigger coral patches nor less isolated patches supported a greater abundance of butterflyfish. Interestingly, there are a few seascape ecology studies on coral reefs that found similar unexpected results. Grober-Dunsmore et al. (2007) examined how reefscape features may influence 117 reef fish species assemblages, and found reef size to show no significant relationship with any fish parameter. Wagner et al. (2015), however, found cleaner fish abundance and species richness to be significantly positively related to bigger coral patch size. Additionally, Boström et al. (2011) reviewed the progress made in the field of seascape ecology on coastal ecosystems thus far, explaining the great variability in organisms' responses to reefscape features and at varying scales. The findings presented in this study show relationships among fish assemblage patterns and reefscape may be dependent on scale and thus highly variable among different locations.

While smaller coral and more isolated coral patches showed the highest butterflyfish abundance in this study, no clear pattern emerged, and thus these seascape features were of limited value in explaining the variability observed in butterflyfish abundance at Laehala. However, the fact that there was some variability in butterflyfish abundance among the five patches suggests there may be other seascape features that play an important role. Numerous studies have found that the reef context can play a significant role in predicting fish abundance and diversity (Grober-Dunsmore et al. 2007; Kendall et al. 2011; Dorenbosch et al. 2005). Considering that this project's study site is a tide-pool, there is a possibility that the context of this enclosed system may be playing a bigger role in butterflyfish assemblages than individual patch characteristics. The variability observed in butterflyfish assemblages may also be driven by habitat selection at time of juvenile settlement and/or intra and inter-specific competition. Further investigation into the fish demographics and behaviour patterns may elucidate preferential selections of patches based on life-history traits.

Butterflyfish abundance has not yet been examined in relation to patch structural complexity. Given the shallow depth of the study site, an optimal overlap and number of images was difficult to obtain, and thus the 3D models have yet to be rendered. Examining fish assemblage relative to patch structure may offer valuable insights. A reef's structural complexity has been shown to positively influence fish assemblages numerous times (Darling et al. 2017; Nanami et al. 2005; Komyakova et al. 2013), but the explicit focus on individual patches has received less attention. Exceptions include Wagner et al. (2015), who found that patch structural characteristics such as the presence of shelters (caves/holes) on individual patches was largely positively related to fish abundance and diversity. Further studies are needed to determine what seascape features best explain butterflyfish assemblage at Laehala. This study will continue by developing an ideal structure-from-motion photogrammetry methodology to 3D model the five coral patches within this shallow tide-pool. Once the models are built, patch structural complexity will be quantified and examined in relation to butterflyfish abundance.

Conclusion

In conclusion, this study showed important implications considering my results contradicted hypotheses based on studies conducted in terrestrial environments. Patch size and isolation did not appear to be appropriate predictors of butterflyfish assemblages at Laehala. Organism-seascape relationships on coral reefs remain understudied and there is a need to further examine these relationships. Coastal ecosystems are presently the most heavily impacted ecosystems on earth (Lotze et al. 2006, Duarte 2009). Natural and human-induced disturbances will keep re-structuring these seascapes, and very little is known on how this may affect ecosystem functionality. If we are to effectively manage an exceptionally productive and valuable ecosystem like coral reefs, then we must seek to unravel the ecological intricacies of fish-seascape relationships. Our lack of knowledge on seascape patterns and their ecological consequences represents a considerable void in coral reef ecology and a promising new frontier for research. Applying the well-developed and interdisciplinary seascape ecology framework along with newer technologies presents a powerful tool to bridge important knowledge-gaps and elucidate a more complete understanding on key factors and mechanisms of reefscape resilience**.**

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