

**IMPERIAL COLLEGE LONDON**  
Faculty of Natural Sciences

**Centre for Environmental Policy**

**Structural Complexity and Reef Function: Evaluating the Linearity of Rugosity-Ecology Relationships for Caribbean Coral Reef Management**

**By**

**Albert Kundrak**

**A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC.**

**10.09.2025**

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## Abstract

Coral reefs are highly biodiverse and structurally complex habitats which contribute greatly to both ecological function and ecosystem services for human populations living in coastal areas. One of the driving factors behind the unique properties of reef habitats is structural complexity. As a result of climate change and other threats facing reef-building coral species, a phenomenon named ‘reef-flattening’ in which reefs slowly lose their structural complexity has been observed over the past 40 years in the Caribbean. Rugosity has emerged within the general literature as the main standard measure of structural complexity in reef survey studies. It has been identified to be associated with many ecological reef health variables such as fish abundance, biomass, biodiversity and coral cover. However, whilst these associations seem to follow a linear trend in most of the globe, conflicting research has emerged from the Caribbean disputing the complete linearity of these trends. Instead, it has been theorised that a rugosity threshold might exist which, once passed, will yield increasingly greater gains of ecological health variables alongside increases in rugosity. Data collection is carried out using SfM photogrammetry surveys for reef rugosity, stereo video system surveys for fish population data and benthic videos for benthic data. Analysis is conducted using ordinary least squares (OLS) linear models and segmented regression models. The results of these analyses showed significant correlation between rugosity and fish abundance, biodiversity and coral cover, but not biomass within the linear models at the transect level. None of the segmented models (breakpoint) provided a better fit than the linear models, implying there was no rugosity threshold within the data at the transect level. This contrasts with the rugosity threshold theory in studies from the Caribbean and aligns closer to globally recorded trends. An important conclusion drawn from the data is that policy makers should focus on implementing rugosity data on a finer level than the standard macro-overview. Furthermore, more research is required using survey data from multiple years and more site locations within the Caribbean, as well as other structural complexity metrics to accompany rugosity.

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# Ethics Declaration

I declare that this thesis:

Structural Complexity and Reef Function: Evaluating the Linearity of Rugosity-Ecology Relationships for Caribbean Coral Reef Management

Did not require ethics approval <input checked="" type="checkbox"/>	Was granted ethics approval <input type="checkbox"/>
Reason(s): No human participants	

Signature:

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# Glossary

<b>Benthic</b>	The bottom substrate of a body of water such as a lake, river or ocean.
<b>Breakpoint (segmented regression)</b>	The estimated value at which the slope showing the relationship of an independent and response variable changes.
<b>Linearity</b>	The extent to which a response variable changes at a constant rate with a predictor.
<b>Rugosity</b>	A structural complexity metric used to describe coral reefs. Consists of the ratio of a reefs 2D to 3D surface area.
<b>Structure from Motion (SfM)</b>	A modelling technique that uses overlapping 2d pictures to construct a 3d model.
<b>Stereo Video System (SVS)</b>	Two calibrated cameras with overlapping FOVs used for fish surveys, allowing for precise length measurements.
<b>Ordinary Least Squares (OLS) Regression</b>	A linear regression method that minimises the sum of squared residuals to estimate linear relationship.
<b>Segmented Regression</b>	A regression method that fits multiple linear models, separated by one or more breakpoints.

## Executive Summary

### **Structural Complexity and Reef Function: Evaluating the Linearity of Rugosity-Ecology Relationships for Caribbean Coral Reef Management**

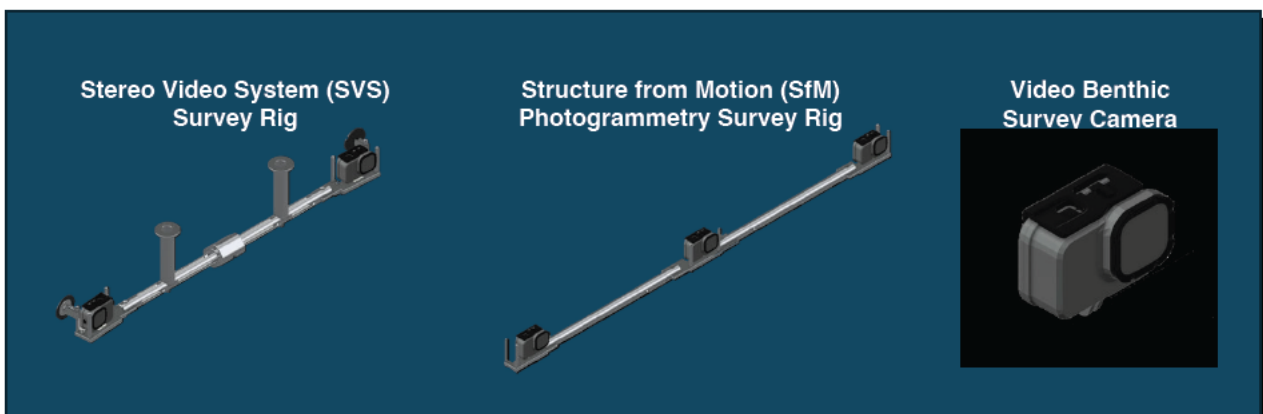
Coral reefs are one of the world’s most biodiverse habitats because of their incredible structural complexity (Knowlton et al., 2010). As a result of climate change pressures, human interference and coral disease, a phenomenon named ‘reef-flattening’ has emerged in the past 40 years, which is characterised as a decline in reef structural complexity (Randazzo-Eisemann et al., 2022). This process has greatly impacted the Mesoamerican reef system in the Caribbean. The primary metric used by researchers to quantify reef structural complexity is rugosity, which is the ratio of a reef section’s three-dimensional surface area to its two-dimensional surface area (McCormick, 1994). Rugosity has strong correlations to reef ecological variables such as fish abundance, biomass, biodiversity and coral cover (McCormick, 1994). Whilst these relationships are well supported by numerous studies, the exact linearity of the correlation is not fully understood. General global trends indicated these relationships to be linear; however, some studies emerging from Caribbean reefs challenge this, claiming the existence of a rugosity threshold (Alvarez-Filip et al., 2011). This potential threshold is described to be a disproportionate increase in ecological benefit as the level of rugosity passes a minimum required complexity. Further understanding of the relationship between structural complexity and ecological condition is critical to reef management and conservation projects.

#### **Thesis Aims:**

To collect coral reef data and quantify the relationship between rugosity and ecological condition in Utila, Honduras. Furthermore, to determine whether a threshold-based model outperforms a linear model for the association with ecological conditions and to determine the reef management implications of the findings.

#### **Data Collection Methods and Analysis:**

Three survey methods were utilised to collect data for this thesis: Stereo video system (SVS), structure from motion (SfM), and benthic video surveys. These survey methods are currently the most novel and accurate for coral reef monitoring, and this study is among the first to use all three simultaneously.

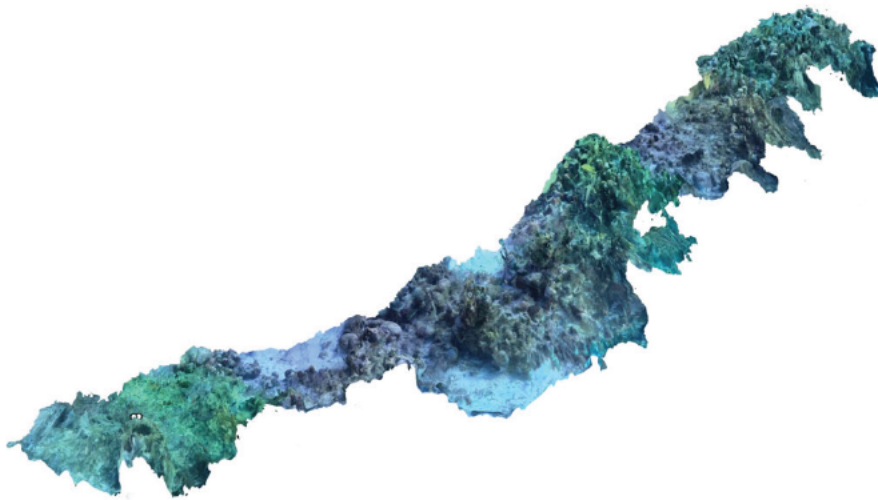


## Executive summary (Page 2)

The SVS rig used for this study is comprised of two calibrated cameras with overlapping FOVs mounted on either end of the rig, which allows the cameras to have ‘depth perception’ in a similar way in which our eyes do. The SVS rig is used to conduct fish surveys and is able to discern fish lengths to the millimetre with a high degree of accuracy. These lengths are used to calculate the accurate biomass of fish populations.

SfM photogrammetry is a recent technological advancement which enables researchers to construct three-dimensional models from overlapping two-dimensional images, as seen in Figure 1. It was first utilised to model coral reefs in 2015, after which it was quickly established as the most accurate method for determining reef rugosity (Burns et al., 2015). The SfM rig used for this study is comprised of three cameras placed at equal distances along the rig.

The benthic survey camera is simply an action camera which is mounted onto a dive handle. It is used to record the ecological composition of the sea floor to be identified later and used to calculate coral cover.



*Figure 1: Example of a three-dimensional render of a reef transect.*

The data collection was performed on reefs around Utila, Honduras. Data was collected at six dive sites: Black Coral Wall (BCW), Coral View (COV), Little Bight (LIB), Light House (LIG), Stingray Point (SRP), and Sturch Bank (STU) as seen in Figure 2. At each site, 50m transects were laid at a depth of 5 meters and 15 meters, 6 at each depth. This resulted in 72 total transects with a cumulative length of 3.6 kilometres. The transects were laid out starting from the buoy anchor in an eastward and westward direction, as seen in Figure 3. Data analysis was carried out using R Studio. OLS linear models were run to determine a ‘baseline’ for any linear correlations present between rugosity and environmental conditions. The four environmental response variables tested against rugosity were fish abundance, biomass, biodiversity and coral cover. Afterwards, segmented regression models were run, which estimated a breakpoint (threshold) within the response variables. Finally, F tests were performed to determine whether the segmented models outperformed the linear models.

Executive summary (Page 3)

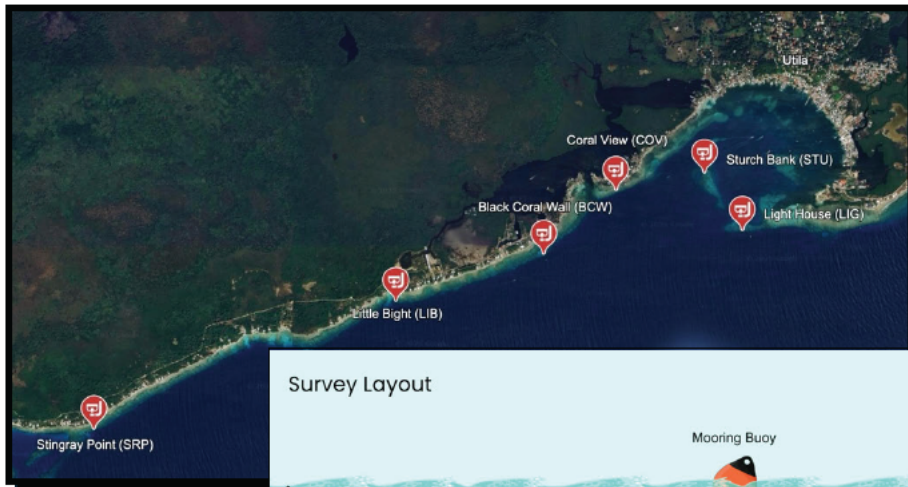


Figure 2: Map of dive sites in Utiia (Google LLC, 2025)

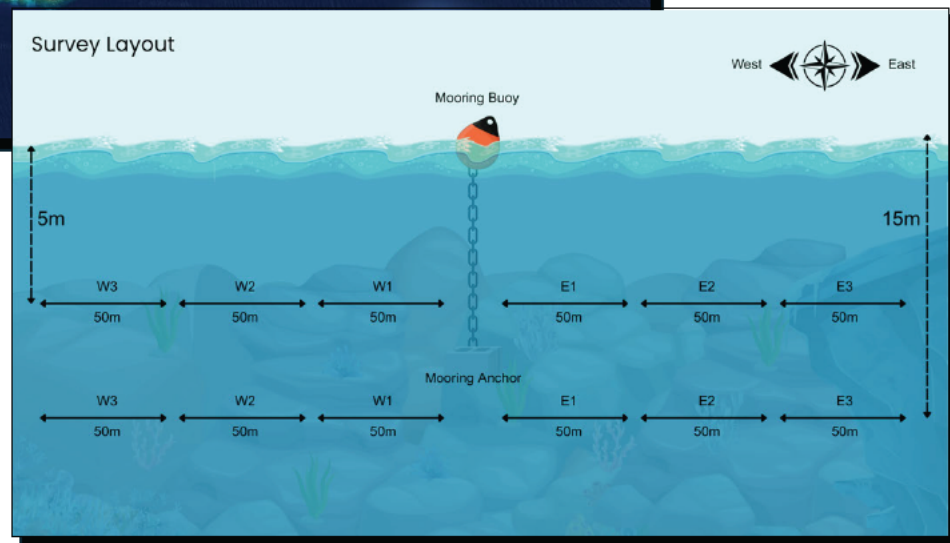


Figure 3: Visual representation of transect layouts used for data collection.

**Results:**

Below are the p-values for the linear and segment models for rugosity and the environmental response variables. The OLS linear models found significant correlations between rugosity and fish abundance, biodiversity and coral cover, but not fish biomass. Meanwhile, the segmented models found no significant breakpoints between rugosity and the environmental responses, concluding that no threshold was detected in the data.

**OLS linear models (rugosity):**

- Fish abundance (P = 0.0021)
- Fish biodiversity (P = 0.0059)
- Coral cover (P = 0.0136)
- Fish biomass (P > 0.05)

**Segmented models (rugosity):**

- Fish abundance (P > 0.05)
- Fish biodiversity (P > 0.05)
- Coral cover (P > 0.05)
- Fish biomass (P > 0.05)

## Executive summary (Page 4)

### Implications:

The results of this study align with the global rugosity trends and contrast with the findings from the Caribbean. Rugosity exhibited a linear relationship with most environmental response variables, whilst no significant thresholds were detected. Furthermore, the linear relationships were present even at the transect level, emphasising the viability of fine-scale monitoring. This supports the notion that site-specific surveys are needed for conservation action to be optimally effective. Furthermore, the association of rugosity and fish abundance at the transect level may qualify rugosity to play a larger role as an environmental predictor in fisheries planning.

### Limitations:

The main limitations of this study were the temporal and geographic constraints. The data used was from a single year, meaning temporal variance couldn't be accounted for. Furthermore, the site was limited to Utila reefs, which makes it uncertain if the trends seen are local or apply to the Caribbean. Transect-level analysis also inflates the risk of a type 1 error. Finally, only rugosity was used as a structural complexity metric, whilst more niche metrics are now also seeing use in other studies.

### Future Research:

Follow-up research is needed to replicate the results using larger-scale data sets that span multiple sites throughout the Caribbean spanning multiple years. Moreover, other structural complexity metrics are required to accompany rugosity to provide more specific results as to which aspect of rugosity is most influential. Finally, most studies do not directly investigate non-linearity and only use linear models for analysis. It is important for future research on reef complexity to incorporate segmented models as well.

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# 1. Introduction

## 1.1 Overview

Coral reefs are amongst the most structurally complex and biodiverse habitats on our planet, often referred to as the rainforests of the sea. (Beukers and Jones, 1998; Knowlton et al., 2010). They serve countless functions which benefit not only marine life but also human populations living near coastal reefs. The structural complexity exhibited by reefs promotes niche partitioning and increases refuge availability, which supports high invertebrate and fish richness (Bellwood et al., 2004). While also stabilising key ecosystem processes such as predation, herbivory, bioerosion and carbonate production, bringing ecological balance to the surrounding marine habitat (Bellwood et al., 2004). Furthermore, reef crests dissipate wave energy and help prevent coastal erosion and flooding, with one meta-analysis study estimating a 97% reduction in wave heights across reef crests (Ferrario et al., 2014; Beck et al., 2018). Coral reefs also have a more direct impact on human populations, serving as a critical source of food and income for millions worldwide, especially among small-scale coastal populations (Cinner et al., 2018).

While coral reefs are heavily relied upon by marine wildlife and human populations, they have faced significant challenges over the last century. One of the most prominent being a process called “reef flattening”, which refers to the long-term loss of reef structural complexity (Randazzo-Eisemann et al., 2022). Characterised by a reduction in branching and tubular forms, lower vertical relief and overall smoother reef surfaces, this pattern has been documented at a regional scale in the Caribbean for numerous decades (Randazzo-Eisemann et al., 2022). Early research indicated that the widespread decline in reef structural complexity began between the 1970s and 1990s (Alvarez-Filip et al., 2015). This has been tightly associated with the decline of the *Acropora* genus of corals, which were historically the primary builders of three-dimensional habitats in the Caribbean (Gladfeiter, 1982; Aronson and Precht, 2001). The population crash of *Acropora* corals and other reef builders occurred as a result of white band disease and numerous bleaching events, which were triggered by rising ocean temperatures (Aronson and Precht, 2001). Furthermore, several other factors have contributed to reef flattening, including the loss of herbivorous fish species and subsequent macroalgal proliferation (Mumby, 2009). Herbivorous fish species keep algal populations in check, and

without them, algal blooms can lead to macroalgae outcompeting coral species for space on reefs (Mumby, 2009). Another significant contributor to reef flattening is climate change, not only in the form of rising water temperatures in the Caribbean, but also as a result of increasingly intense tropical storms that disrupt reefs (Gardner et al., 2005). Whilst tropical storms are a natural part of life for reef ecosystems, with dwindling populations of fast-growing reef-building corals such as *Acropora* and increasingly erratic and severe weather, the damage sustained by a reef during a storm is recovered much more slowly (Gardner et al., 2005). The result of this reef flattening is the inverse of what its complexity provides: lowered ecological balance due to the loss of refuge and niche partitioning, as well as human population impacts such as increased coastal erosion, loss of livelihoods and greater rates of malnutrition in coastal communities (Randazzo-Eisemann et al., 2022; Lester et al., 2020).

As a result of its importance, reef structural complexity has been studied since the 1970s, when the first rugosity index methodology, known as the chain-and-tape rugosity index, was developed (Risk, 1972). Since the 1970s, numerous studies have linked rugosity to ecological patterns, including fish abundance, diversity, biomass, and even benthic composition (McCormick, 1994). As a result, reef complexity metrics have been increasingly utilised in policy making and reef conservation initiatives by both governments and NGOs (Santavy et al., 2022). Often surveyed using more modern methods, these structural complexity metrics, such as rugosity, have started to serve as a key environmental indicator when considering reef conservation frameworks. Despite this increasing usage, many questions remain unanswered regarding the nuances of the positive relationship between rugosity and ecological patterns. One of these understudied areas is how this relationship scales along the rugosity index, specifically whether the correlation is completely linear or if a rugosity threshold exists. Whilst disputed in the literature, some studies have theorised that a rugosity threshold may exist, which, once surpassed, yields an increased positive association with ecological markers such as fish/coral patterns (Alvarez-Filip et al., 2011). However, there has not been enough robust research to prove or disprove such a rugosity trend. A better understanding of the link between rugosities and reef health, as well as the extent to which it follows a linear relationship, is critical information for reef planners and conservation initiatives across the Caribbean. This increased insight is crucial for the efficient allocation of resources for coral reef management and is the centre of this research paper's investigation.

### 1.1.1 Research Questions

1. Are fish abundance, biodiversity and biomass positively associated with rugosity on the transect scale in reefs around Utila, Honduras?
2. Is coral cover positively associated with rugosity on the transect scale in reefs around Utila?
3. Does a threshold-based model provide a better fit for the relationship between rugosity and ecological condition than a linear model in reefs around Utila?

### 1.1.2 Research Aims

This study aims to quantify the association between rugosity and ecological conditions in Utila, and to explore whether a threshold-based model provides a better fit than a linear model.

### 1.1.3 Research Objectives

- a. Collect coral reef ecological data using best-in-field reef survey technology and methodology in Utila, Honduras.
- b. Create transect-level response variables for biomass, abundance, biodiversity and coral cover from co-located surveys.
- c. Fit linear models to the response variables to determine the strength of association.
- d. Fit segmented (piecewise) models to the response variables and compare them to the linear models to determine the existence of a threshold within the data.
- e. Summarise the management implications of findings for coral reef planning and restoration initiatives.

### 1.1.4 Scope

The scope of the quantitative investigation portion of this thesis is limited to data collected from a single year of surveys in Utila, Honduras. Whilst the aim of the primary investigation

of this study is to quantify the linearity of the relationship between rugosity and ecological conditions, the quantitative exploration of the underlying reasons for this relationship is outside of this study's scope. For the qualitative coral reef management section within the discussion chapter of this thesis, conclusions and recommendations will also be drawn using the general literature.

## 2. Literature Review

### 2.1 The Linearity of Rugosity

This initial section of the literature review is dedicated to evaluating the evidence for the linearity and non-linearity of coral reef structural complexity (rugosity) in relation to fish abundance, biomass, biodiversity, and coral cover. The scope encompasses the most influential and relevant peer-reviewed literature spanning the past 30 years on a global scale, with a focus on Caribbean trends that diverge from the global trend. The purpose of this review is to highlight the current knowledge base on coral reef rugosity relationships and identify the knowledge gaps which necessitate the need for this study.

#### 2.1.1 Evidence for Linearity

Numerous studies outline an increase in fish abundance, biomass, biodiversity, and coral cover with an increase in rugosity, and as a result, reef complexity metrics such as rugosity are increasingly being recognised in policy frameworks and NGO conservation projects (Rogers et al., 2014; Castaño et al., 2021; Graham et al., 2013). A 2021 study on the relationships between reef complexity and fish abundance, biomass, and biodiversity found that rugosity and coral cover accounted for 66% of the variance in these variables (Castaño et al., 2021). This illustrates the close relationship between rugosity and reef health. Gratwicke and Speight (2005) investigated the relationship between rugosity and fish abundance/ biodiversity using visual surveys spanning multiple tropical habitats and found strong linear relationships. As seen in Figure 1, both fish abundance and number of species (biodiversity) exhibit highly linear relationships with rugosity, with number of species showing a very strong correlation (Gratwicke and Speight, 2005). Darling *et al.* (2017) provide further evidence of a linear relationship in a large-scale study of reef complexity, spanning 157 reef sites in the Seychelles, Maldives, Chagos, and Great Barrier Reef. Their analysis revealed no evidence of abrupt changes in slope or distribution within their broad datasets, suggesting a completely linear relationship (Darling et al., 2017). Many studies that do not explicitly investigate the linearity of the correlation still exhibit linear data and use linear regression models to convey the correlations found (Agudo-Adriani et al., 2019; Castaño et al., 2021). In summary, many studies investigating the relationship between reef complexity and reef ecology variables

explain their data using linear regression, and some even directly conclude that their data exhibit linearity. However, it is worth noting that the trend of linear rugosity relationships is less prevalent in the literature based on the Caribbean and is more common in other reef systems.

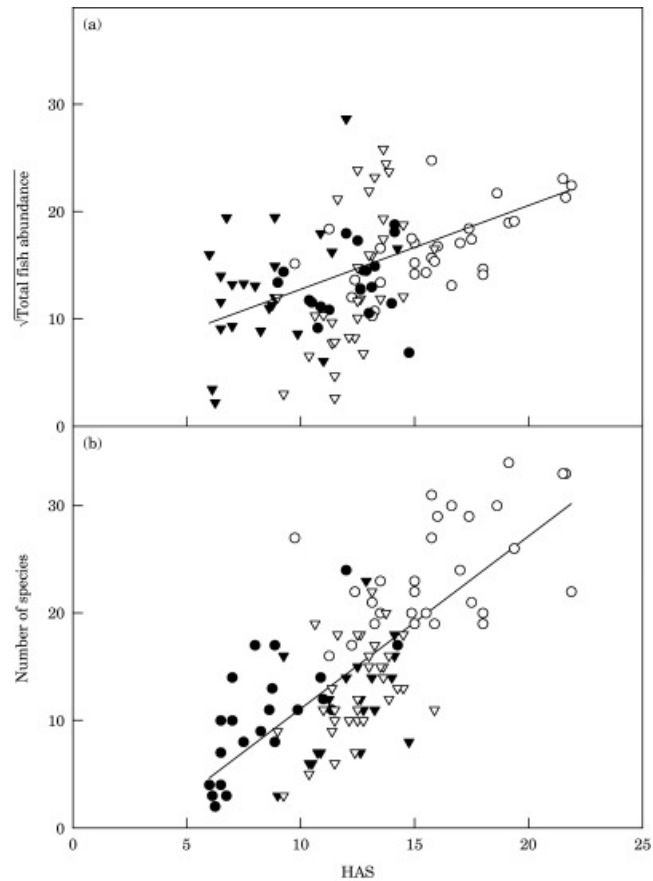


Figure 1: The relationship between the total habitat assessment score (HAS) and (a) total fish abundance and (b) number of species (○ reef, • sand, ▼ algae, ▽ seagrass). (Gratwicke and Speight, 2005).

### 2.1.2 Evidence for Non-Linearity

One of the concepts behind the theory of a non-linear relationship between coral reef rugosity and environmental variables lies within the overall trend of reef flattening itself. Since rugosity has been strongly linked to these environmental variables, a linear model suggests that as the coral reefs have been gradually flattening in the Caribbean, the decline of the ecosystem would also gradually follow (Alvarez-Filip et al., 2009). However, this is not the case as ecosystem habitats surrounding coral reefs undergoing reef flattening have experienced a disproportional, non-linear decline (Alvarez-Filip et al., 2009). This is theorised to be due to reefs falling below

a certain threshold of rugosity, where the habitat can no longer sustain the same fish populations (Alvarez-Filip et al., 2009). This is reinforced by studies such as Rogers *et al.* (2014), which find positive linear relationships between rugosity and environmental variables. However, they also found that rugosity is linked to fish predation risk, which causes nonlinearities in biomass; this finding contributes evidence to the idea that changes in rugosity have disproportionate effects on reef fish biomass (Rogers et al., 2014). Furthermore, the modelling in the study also found that providing sufficient refuges, which is associated with higher rugosity, allowed a much greater number of small fish species to thrive on the reefs (Rogers et al., 2014). Moreover, a conclusion was drawn from the inverse relationship, stating that if a reef fell below a certain complexity, it could trigger a threefold decline in fishery productivity, i.e. fish abundance (Rogers et al., 2014). Shifting the focus to corals, healthy coral reefs often exhibit a strong coupling between live coral and rugosity; however, in the Caribbean, a decoupling of these two variables has begun to emerge (Castaño et al., 2021). Trends have emerged where, once the diversity of ‘reef-building’ coral species on a reef drops below a certain point, an improvement in coral cover might not necessarily yield more rugosity gain (Castaño et al., 2021). This suggests that under certain conditions, the relationship between coral cover and rugosity could be nonlinear.

The cumulative evidence suggests that global and, specifically, Indo-Pacific surveys tend to report more linear relationships between rugosity and fish abundance, biomass, and biodiversity (Gratwicke and Speight, 2005; Darling et al., 2017; Graham et al., 2013). Meanwhile, the literature on the Caribbean is more varied, often reporting disproportionate losses as a result of reef flattening, potentially implying the presence of a threshold (Alvarez-Filip et al., 2009; Rogers et al., 2014). However, there are many gaps in the literature, which means the conclusions drawn from the evidence above may not fully represent the entire picture. A geographic bias is present, as there are significantly fewer studies conducted in the Caribbean investigating thresholds versus linearity compared to the Indo-Pacific region. Furthermore, a wide range of survey methods are used across studies to assess rugosity in the literature, including chain-and-tape, visual, and Structure from Motion (SfM) surveys. Finally, the primary deficit in the literature is the lack of studies directly testing best-fit models on their data, assuming that simple linear models will work best. This creates a lack of robust evidence to draw conclusions from. As a result of these data and study gaps, this thesis aims to address a vital yet understudied topic regarding the relationship between rugosity and environmental variables.

## 2.2 Technological Advancements in Coral Reef Surveys

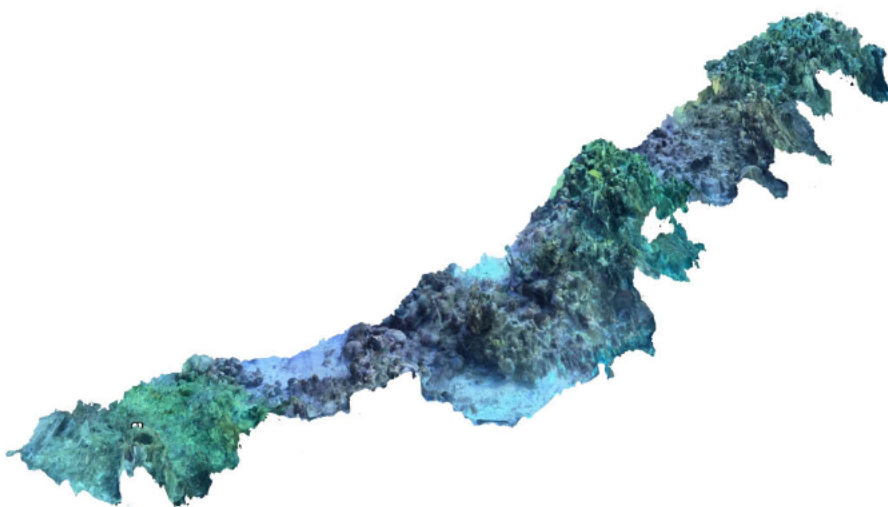
Coral reef survey methodology has evolved rapidly over the past 50 years, undergoing digitalisation as technology has advanced. Newer study designs often bring increased precision but also contain trade-offs to historical techniques; as a result, it is vital to consider all available survey methods. The following section provides a review of all recent and historical reef survey methodologies, along with an analysis of the trade-offs associated with each survey. A more detailed methods justification section, based on this trade-off review, is presented in Chapter 3.2.

### 2.2.1 Stereo Video System (SVS) Survey

Fish community monitoring survey methods have undergone significant changes since their introduction, dating back to the 1950s (Brock, 1954). These initial fish survey methods employed belt-transect and stationary point count surveys, during which the diver manually recorded all fish species present. Whilst effective, this form of survey suffered from significant observer bias with high observational variance between separate divers conducting the surveys. During the late 1990s to early 2000s, Harvey and Shortis (1998) pioneered what would become known as the Stereo-video revolution. These calibrated stereo camera systems now allowed for ‘depth perception’ following a similar concept to our eyes, which enabled researchers to accurately discern the length of a fish from the footage alone. This was a significant breakthrough as not only could these recordings be stored as a permanent record for reproducibility, but accurate biomass measurements could also be made from fish lengths captured. These advancements addressed many of the shortcomings associated with previous survey methods, such as observer bias, and propelled the technology to become mainstream in the years to come. Harvey/Cappo et al. (2007) went on to codify sampling design and analysis, helping to create a standardised methodology for transect-based reef fish surveys. This methodology is widely used today; however, the bulky cameras initially employed have been scaled down to compact action cameras, which have significantly increased ease of use.

### 2.2.2 Structure from Motion Survey

Another reef monitoring survey which was revolutionised by the advent of new technology was the habitat structural complexity survey. Initially pioneered by Risk in 1972, the chain-and-tape rugosity index quickly became the field standard in the 1970s. Skipping forward to the 1980s-1990s, the chain-and-tape methodology was accompanied by coarse visual relief scores (McCormick, 1994). This survey method consisted of a visual assessment of simple categorical “relief” scores from low to high. This new methodology benefited surveys where the use of chains was impractical or many sites had to be assessed very quickly, with the drawback of lower accuracy and greater observer bias than the chain-and-tape method. The most significant breakthrough for coral reef structural complexity surveys since their earliest implementation was the advent of (SfM) photogrammetry. This workflow, comprising of hardware and software innovations, enabled consumer cameras to produce fully scaled 3D models by capturing overlapping images and utilising SfM software as seen in Figure 2. This advancement not only allowed for the most accurate way to quantify rugosity to date, but also enabled the recording of other metrics, such as fractal dimension, vertical relief, and curvature. This new technology was first established in a complete SfM pipeline by Burns et al in 2015, with subsequent studies such as Ferrari et al, 2016 renewing the link to structural complexity through the new methodology. SfM is seeing increased use in coral reef surveys thanks to its high degree of accuracy and versatility; however, both chain-and-tape as well as visual relief scoring are still widely used due to their simplicity and speed. Whilst SfM photogrammetry is more accurate, it can be time-consuming and costly to adopt the system, which often requires custom rig configuration and software operation training.



*Figure 2: Example of a 50m coral reef transect rendered into a 3d model using SfM photogrammetry.*

### 2.2.3 Benthic Surveys

Benthic cover and community composition surveys have also undergone digitalisation since their first appearance in the scientific literature in the 1970s, as seen in studies such as Loya (1972) in the Red Sea. These early methods featured quadrat and line intercept-based methods, which were later developed into a standardised methodology by manuals such as those by English, Wilkinson, and Baker (1997). This survey methodology further evolved to use digital photography instead of diver observation in the early 2000s, which significantly increased accuracy and reproducibility. Despite the digital advancement which accompanied benthic surveys, the manual identification required for this survey method has often been seen as its most significant drawback. Recent advancements in machine learning (ML) have enabled AI-based programs, such as CoralNet, to perform benthic analysis and annotation in an automated/semi-automated workflow. After model training, current leading ML models, such as CoralNet, are able to perform rapid analysis of large quantities of benthic data while achieving near-analyst accuracy. However, the training times for these models can outweigh the benefit of smaller-scale studies, and the analysis format is not compatible with some historically used methods, such as point intercept surveys.

To summarise, all coral reef survey methods have undergone digitalisation in the last 30 years, and the literature is clear regarding the superiority of these updated survey methods for accurate ecological data collection. Rugosity and other structural complexity metrics are now most accurately surveyed using SfM survey methods, which create three-dimensional renders of reef survey areas. Stereo video systems have revolutionised fish population surveys and are now more accessible than ever, thanks to the performance and affordability of modern action cameras. Finally, benthic surveys have also benefited from digitalisation; however, they have also begun to incorporate ML implementations, which show great potential in reducing the time spent on manual benthic analysis. Whilst these survey methods are widely used in different configurations across the globe for coral reef monitoring, there are few robust implementations of all of them simultaneously within the literature.

## 3. Methodology

### 3.1 Overview

The data collection portion of this project was achieved through collaboration with Operation Wallacea (Opwall), an international biodiversity and conservation research organisation. All data collection was conducted at their marine research site in Utila, Honduras, utilising three data collection methods: 3D photogrammetry surveys, stereo video surveys, and benthic video surveys. Data was collected at six dive sites: Black Coral Wall (BCW), Coral View (COV), Little Bight (LIB), Light House (LIG), Stingray Point (SRP), and Sturch Bank (STU) as seen in Figure 3. These dive sites are a part of Opwall’s reef monitoring program and have been under survey since 2012, being used to build a long-term data set to understand changing trends in reef health.

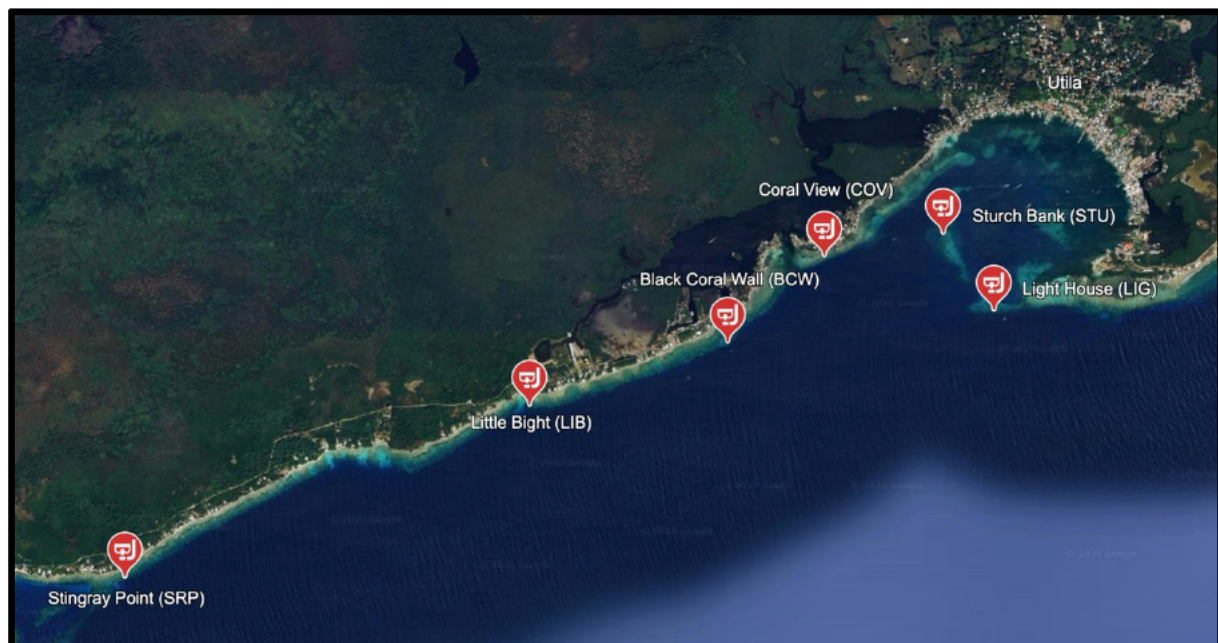


Figure 3: Map of dive site locations in Utila. (BCW: N 16.08305968, W 86.91699554) (COV: N 16.08823274, W 86.91094506) (LIG: N 16.08498, W 86.90032) (LIB: N 16.07926302, W 86.92942222) (SRP: N 16.0689055, W 86.95477948) (STU: N 16.089602, W 86.9035006) (Google LLC, 2025).

For data collection, 50m long transect tapes were placed on the reef to indicate the study area. A total of 12 transects were used on each site, six at a depth of 5m and six more at 15m. The transects were placed relative to the site’s mooring buoy, which is where each dive began. At a depth of 5m, the transects started at the anchor point of the buoy and extended eastward and

westward, with each subsequent transect beginning at the end of the previous one. This resulted in three transects spanning 150m away from the buoy anchor in eastward and westward directions. At 15m, the same method was used; however, as there was no buoy anchor point present at this depth, navigation in a northward direction to the closest suitable spot at a depth of 15m, starting from the buoy anchor, was required. See Figure 4 for a visual representation of the survey layout. As dive limits only allowed for 50-minute dives, 1-2 transects were fully surveyed per dive. As a result, transect laying often started 50 or 100m away from the buoy anchor point. Under these circumstances, pre-measured fin kick lengths were used to travel to the start point of the transect whilst following an east or westward heading.

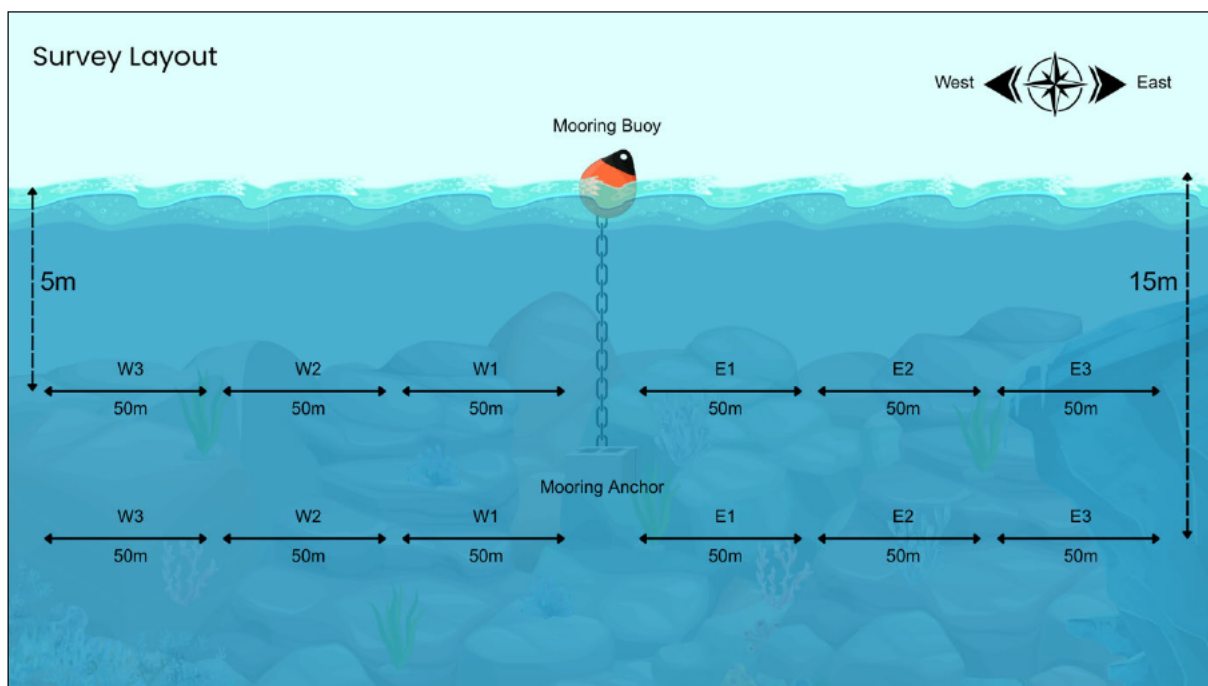


Figure 4: Visual representation of transect layouts used for data collection. 50m transect tapes are laid along the reef at a depth of 5m and 15m. Transects are named after their direction and placement; 'W1', for example, refers to a westward heading transect placed in position one from the buoy anchor.

### 3.2 Study Methods Justification

Opwall's Reef monitoring programme in Utila has been running since 2012, and the survey methodology has undergone several changes as technology and the literature on coral monitoring have advanced. The Utila monitoring programme has been a consistent early adopter of emerging technologies, such as SfM for structural complexity surveys. It was first utilised in Utila in 2017, a mere two years after its debut in the literature (Burns et al., 2015).

The survey design for this study's methodology follows the most robust and accurate survey methodologies currently present in the literature for reef monitoring.

SVS fish population surveys have been shown to produce more precise and consistent fish length estimates for biomass measurement than traditional visual count surveys (Harvey et al., 2001, 2002). Moreover, recent studies comparing SVS and visual surveys further validated the use of SVS, finding no significant discrepancies in species richness or biomass (Grane-Feliu et al., 2019; Juárez-Hernández et al., 2022). In addition to this increased accuracy, the recordings produced in the survey serve as a historical record and are stored for potential future research.

Multiple studies since the emergence of photogrammetry in the reef monitoring literature have definitively shown its superiority in accuracy compared to diver-based measurements (Ferrari et al., 2016; Remmers et al., 2024). Moreover, a recent meta-analysis indicates that SfM surveys are “rapidly emerging as the new standard” due to their ability to record habitat and colony-scale metrics in both two and three dimensions (Remmers et al., 2024). This ability enables researchers to extract and investigate multiple structural complexity metrics, including rugosity, fractal dimension, surface area, slope, volume, shelter volume, and many more (Barrera-Falcón et al., 2025). All of this culminates in SfM being utilised in major reef monitoring projects on the Great Barrier Reef, Pacific atolls, the Indian Ocean, and more (Remmers et al., 2024).

Whilst not having undergone as drastic an evolution as the other two surveys used in this study, photo-quadrat surveys, or in this case, benthic transect surveys, are often shown to have an optimal balance between precision and efficiency (Carneiro et al., 2024). The application of ML-based accelerators for analysing benthic recordings is a promising advancement in survey efficiency. However, for studies on the scale of this investigation, the initial time investment in model training outweighs the benefit in efficiency gained. Even more importantly, the format of data analysis and output of cloud-based platforms such as CoralNet faces compatibility barriers with the historically collected benthic data as a part of Opwall's monitoring in Utila.

In summary, the survey methods used in this study (3d photogrammetry, stereo video systems and digitalised benthic recordings) are optimal for accurate data collection. The literature

leaves no doubt about the effectiveness and applicability of these survey methods in producing precise and robust data sets that reflect reef health to the best of our current capacity.

### 3.3 Stereo Video System Survey

#### 3.3.1 SVS Materials

- 2x GoPro Hero12 Blacks with SD cards
- Stereo video system rig
- 1x dive computer with rig adapter
- 1x compass with rig adapter
- 1-2x double-sided transect tape (50m)
- Minimum 2 divers
- Dive Torch
- Underwater Surveyor software

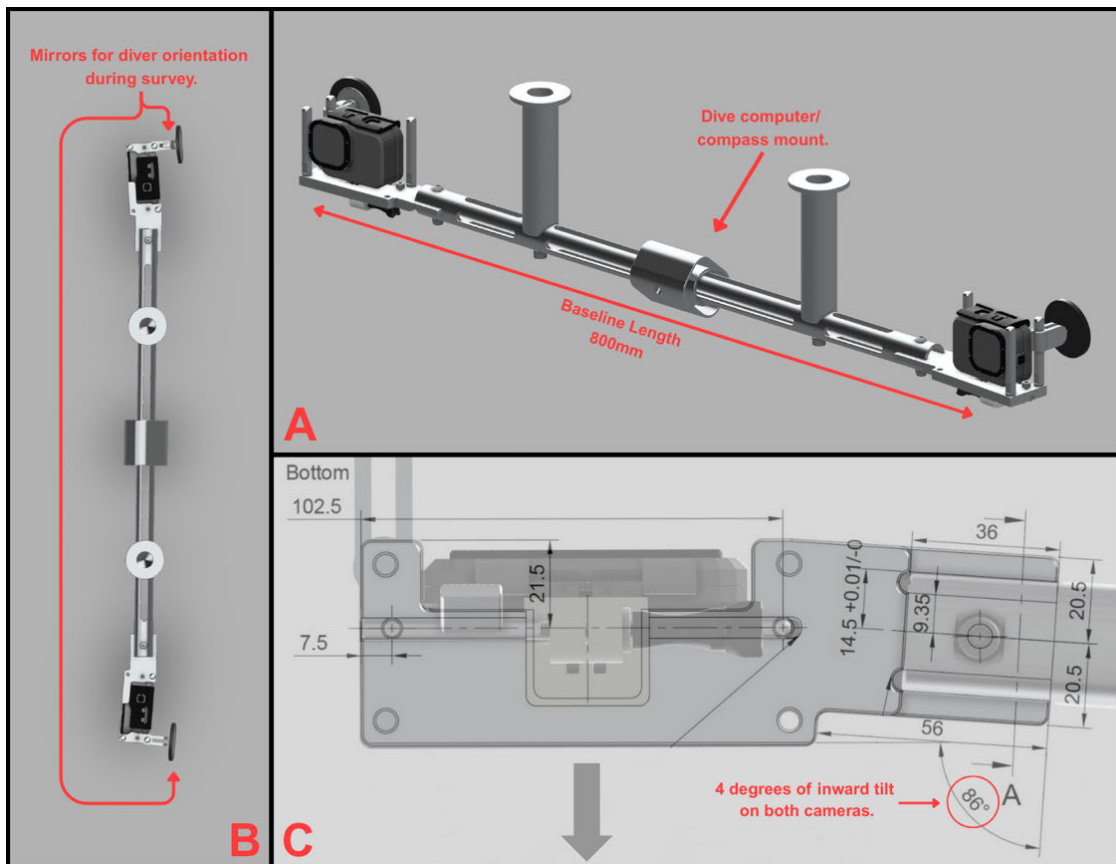


Figure 5: Render of stereo video survey rig. Section A depicts the baseline length of the rig (straight line distance between the optical centres of the left and right cameras) as well as the dive computer/compass mount. Section B shows a top view of the rig and mirror placement. Section C shows the 4-degree inward tilt of the camera.

The stereo video survey rig used for this study was custom-built for reef fish surveying by Toby Haddon, as seen in Figure 5. The design is centred around two GoPro Hero12 Blacks in waterproof housings at either end of the rig. The cameras are both tilted 4 degrees inwards with a baseline length of 800mm between the sensors.

### 3.3.2 Calibration

The setup calibration of the stereo video rig is completed using a CharuCo board. Initially, the two cameras are individually calibrated, after which they are mounted to the rig for stereo calibration. The entire calibration process was completed underwater in a freshwater pool. Furthermore, before starting each stereo video survey, the pre-survey calibration process is carried out. This entails one of the divers holding the rig in a forward-facing position and towards a second diver. The second diver flashes their dive torch towards the SVS rig as seen in Figure 6, making sure the light is visible in both cameras by looking at each GoPro's forward display. The torch is flashed 3 times at the rig.

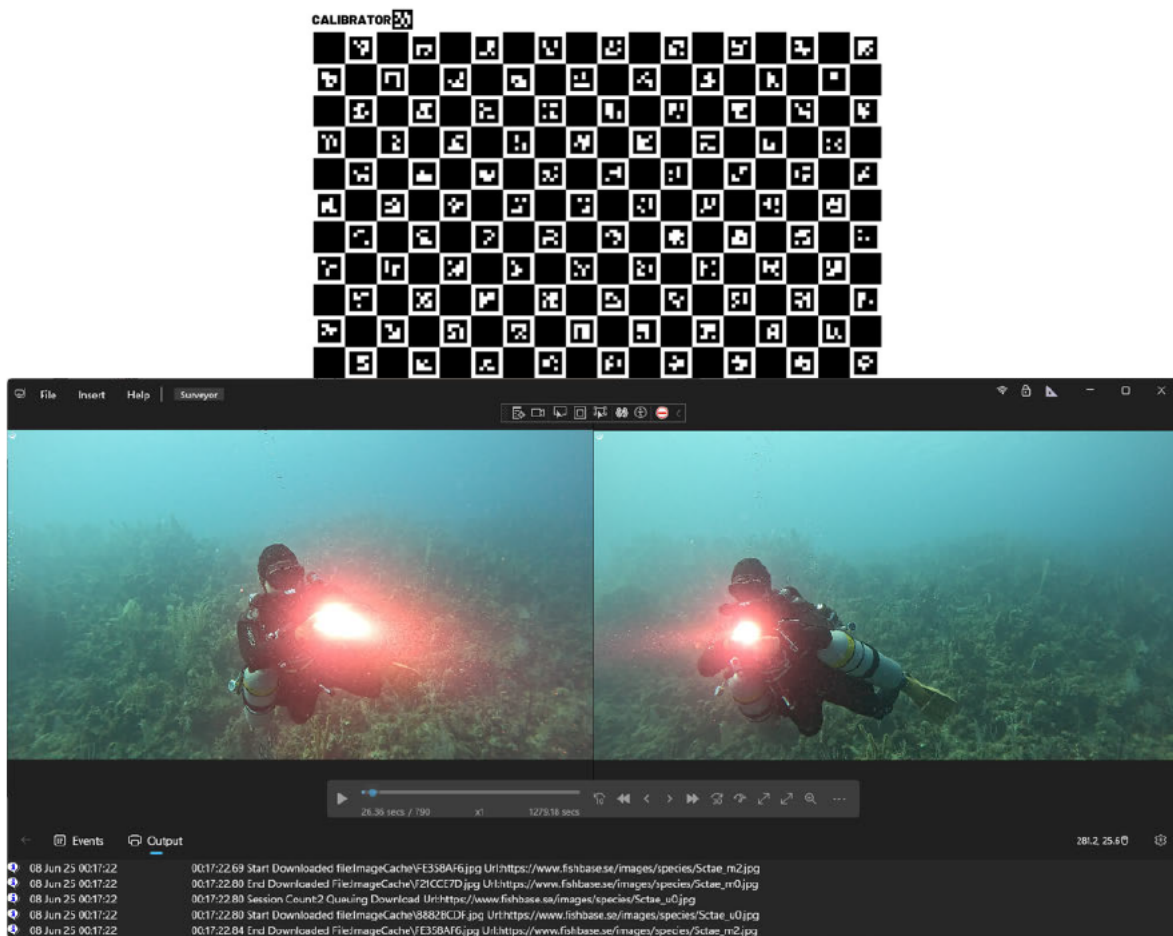


Figure 6: Setup/pre-survey calibration processes. CharuCo Calibration Board 60cmx40cm (Bradski, 2000), Underwater Surveyor stereo video calibration process.

### 3.3.3 Data Collection (3 divers)

To begin the survey, the dive team navigates to the start of the survey transect at either 5m or 15m. This is accomplished with visual orientation via the buoy anchor, and fin kick counting/compass navigation when necessary. Once at the start of the transect, the transect tape is secured to the reef using the string attached to the end of the tape. This end of the tape marks the beginning of the SVS survey. The diver conducting the SVS survey, designated diver 1, shakes the SVS rig. The cameras are preprogrammed to begin recording when shaken, meaning that this action starts both recording simultaneously. Once the recording has begun, diver 1 performs the previously mentioned pre-survey calibration with diver 2. Once the calibration is completed, diver 1 points the rig downwards and swims above the survey start point. Once in place, diver 1 establishes the predetermined heading of the transect (either E or W) using the compass on the SVS rig and points the rig in this direction of travel, making sure to keep it level. See Figure 7 for an example of the SVS survey process.



*Figure 7: SVS survey for illustration, note that during an active SVS survey, the transect line would not yet be laid.*

At this point, the setup is complete, and the survey has begun as diver 1 starts swimming slowly along the bearing. During the survey, diver 1 keeps track of multiple positional factors whilst swimming. Diver 1 maintains adequate buoyancy control to maintain proximity to the bottom

to ensure capturing all of the fish visible, keeping the rig roughly 1m from the reef. If the reef geography resembles a wall with a great drop in depth below, a similar concept is followed; diver 1 stays as close to the wall as possible (within 1m). Furthermore, the survey must be conducted at the predetermined depth, 5m or 15m, meaning the dive computer attached to the rig must be regularly observed. Often, the reef counters in a manner where it is not possible to follow the compass bearing, maintain the correct depth and maintain adequate proximity to the reef simultaneously. In this scenario, diver 1 must prioritise depth consistency and proximity to the reef over following the bearing. Once the end of the 50m survey is reached, diver 1 is notified via fin tug or auditory queue by diver 2. The 50m transect length is accurately obtained by diver 2 laying the transect tape whilst following diver 1's swim path. At the endpoint of the survey, diver 1 points the SVS rig downwards and subsequently ends the recording. If another survey is planned to follow, divers 1 and 2 prepare to repeat the process.

It is important to consider that the presence of divers in the water will inevitably alter the natural behaviour of reef fish, meaning that certain measures are taken to minimise this impact. Firstly, our dive team was always given priority to enter the water first when performing SVS surveys. Moreover, coordination prior to dives with other researchers was necessary to avoid overlap in study areas. Finally, this consideration also mandated that SVS is the first survey performed on each transect.

#### 3.3.4 Data processing

SVS data is captured in the form of 2 recordings per transect, 1 per camera. These recordings are transferred to backup drives and processed using the Underwater Surveyor software. Within the software, the two recordings are imported and synced up using the flashlight pre-calibration as seen in Figure 6. The fish visible in the videos are then identified and measured using the software. Once all the fish in all of the transects are processed, the resulting data are exported for analysis in R to determine fish biomasses.

### 3.4 Benthic Survey

### 3.4.1 Benthic Survey Materials

- 1x GoPro Hero12 Black with SD card
- Benthic Rig
- 1-2x double-sided transect tape (50m)
- Minimum 2 divers

The benthic rig is composed of a single GoPro Hero 12 Black mounted in a waterproof housing on a diving handle. The diving handle attachment is also equipped with a carabiner for easy attachment to the diver when not in use.

### 3.4.2 Data Collection (3 divers)

Continuing from where the SVS data collection methodology ended, the benthic survey follows the SVS survey. Diver 3, who has the benthic rig attached to their BCD, unclips and turns on the camera. The benthic survey can begin once diver 2, who is the transect layer following the SVS survey, has laid at least 5m of transect tape. Diver 3 starts the recording and holds the benthic rig with one hand and the transect tape in the other. Diver 3 points the camera straight down and holds it 30cm above the tape. Diver 3 begins swimming after the transect layer whilst holding onto the tape to ensure the numbers are visible in the recording. In the case that the reef geography resembles a wall and the transect tape is attached to its side, diver 3 records the reef perpendicular to the wall at a distance of 30cm. Once diver 3 reaches the end of the transect, the recording is stopped, and the benthic rig is re-clipped to the diver.

### 3.4.3 Data processing

Benthic data is captured in the form of a single recording per transect. These transect recordings are transferred to backup drives and can be analysed using any video playback software. A video player with slowed playback and single-frame skipping features is recommended. The benthic data is analysed by recording benthic composition at every 25cm of the transect line. This is done by stopping the playback when the camera is directly above the 25cm interval of the transect tape and recording the benthic which intersects the interval on the tape. The result

is recorded in Excel under one of the categories seen in Table 1. Hard corals are recorded to species level and macro algae are recorded to genus level, and others are recorded to their morphology. Once all the analysis is complete, all of the transects are combined and exported for analysis in R.

ANE	Anemone
ASC	Ascidian
BRY	Bryozoan
CCA	Coraline Crustose Algae
CYA	Cyanobacteria
DCA	Dead Coral with Algae
DCO	Dead Coral
HCO	Hard Coral
INV	Other Invertebrate
MAA	Macroalgae
MIL	Millepora
OTH	Other
PEY	Peysonnellia
RBB	Rubble
RCK	Rock
SAN	Sand
SCO	Soft Coral
SGR	Seagrass
SIL	Silt
SPO	Sponge
TAL	Turf Algae
UNK	Unknown
WAT	Water
ZOA	Zooanthid

*Table 1: Benthic Classifications*

### 3.5 3D Photogrammetry Survey

#### 3.5.1 3D Photogrammetry Materials

- 3x GoPro Hero12 Blacks with SD cards
- 3D Photogrammetry SfM Rig
- 1-2x double-sided transect tape (50m)
- Minimum 2 divers
- Minimum 7 3D markers and a carry bag
- Agisoft Metashape & Rhinoceros 8 software

The 3D photogrammetry rig used for this study was also custom-built for reef modelling by Toby Haddon, see Figure 8. The rig is made up of 3 GoPro Hero 12 Blacks mounted in waterproof housings and spaced 60cm apart, facing in the same direction. The cameras are not tilted inwards like the SVS rig.

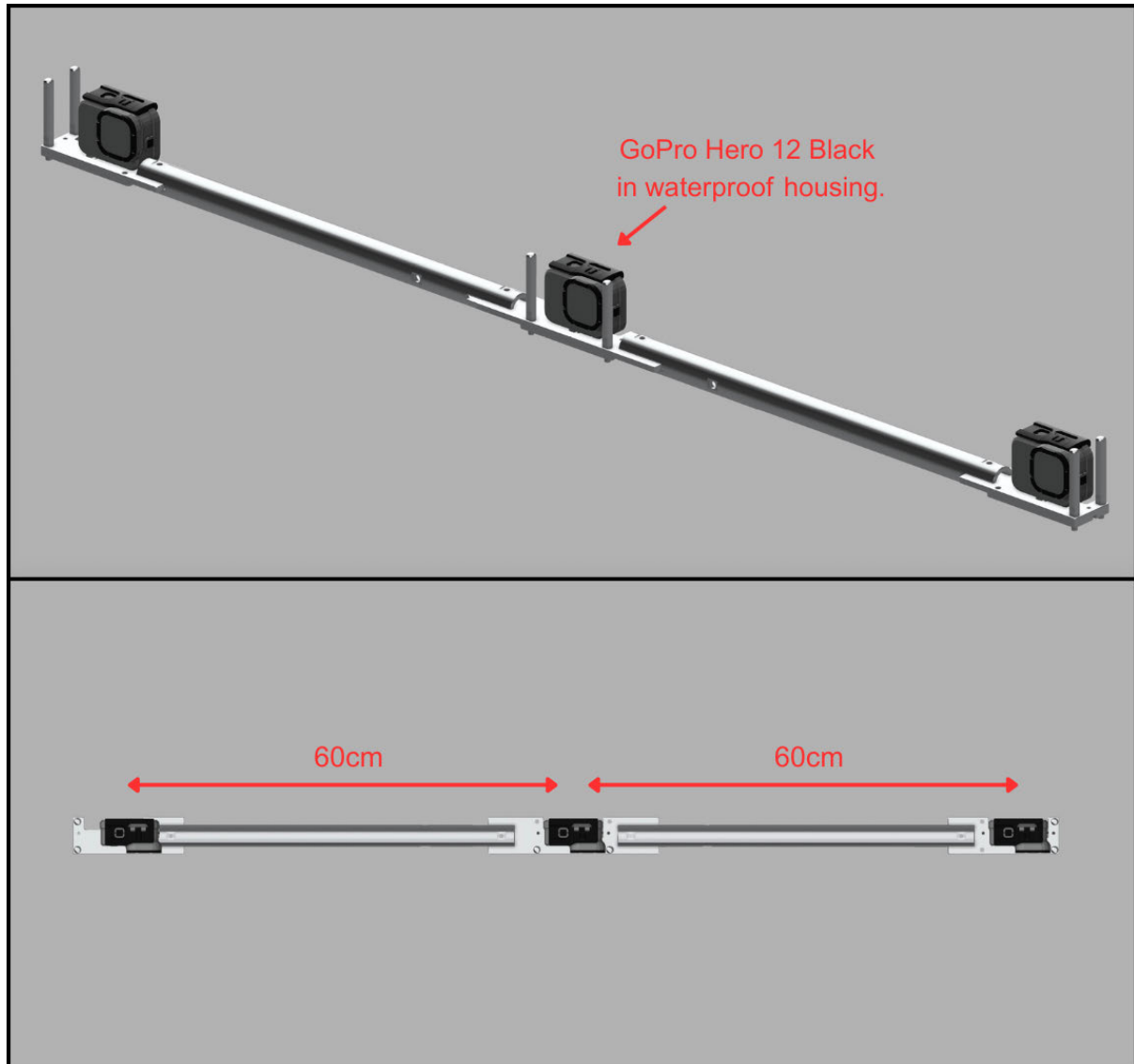
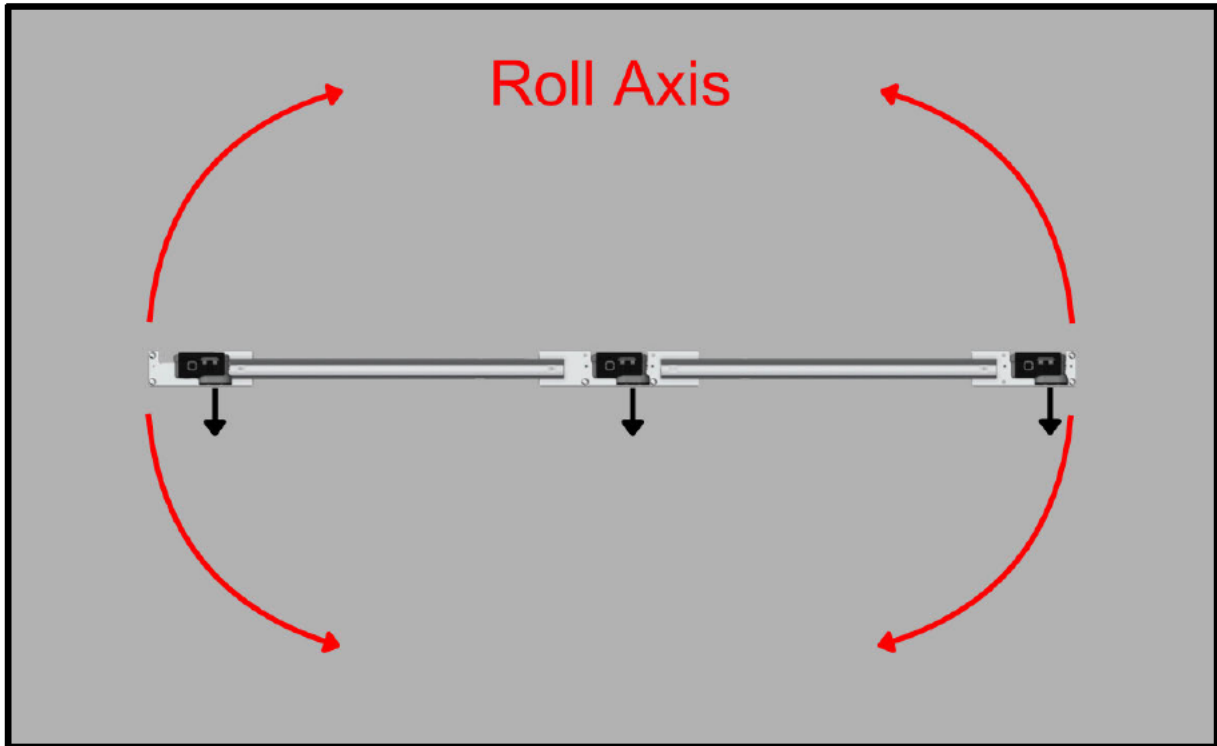


Figure 8: Render of 3D photogrammetry rig. Depicts the spacing between the three cameras on the rig.

### 3.5.2 Data Collection (3 divers)

The 3D photogrammetry survey is conducted following the benthic survey. After completing the benthic survey, diver 3 starts preparing to place 3D markers along the transect tape's path. A total of 7 markers are required per transect, placed at 0m, 10m, 20m, 25m, 30m, 40m, and 50m along the transect. The markers must be placed horizontally along the transect and must be clearly visible without being too far from the transect tape. Amongst the 7 markers, one is painted green; this one is placed at 25m to indicate the halfway point of the survey. It is important to note diver 3 must pick one side of the transect tape to place the markers on and stick to it for the duration of the transect. Before starting marker placement, diver 3 is given the SVS rig by diver 3 whilst diver 2 unclips the 3D rig from the back of diver 1. After diver 3 has placed the first two markers along the transect, diver 1 will turn on and start the recordings on each camera. For this survey, the GoPros are set to time-lapse mode, recording 2 frames per second per camera.

Diver 1 moves into position over the end transect tape, preparing to swim back along the transect. To commence the survey, diver 1 points the camera directly towards the water's surface for 1 second and then back down to face the reef. Diver 1 starts to slowly swim along the transect following diver 3, who is laying the markers. Diver 1 has to ensure correct angling and elevation of the 3d rig at all times. Assuming that the top of the cameras, which is the side of the rig facing the direction of travel (forward) during the survey, is considered the front of the rig during the survey, the roll axis of the rig must be kept as horizontal to the reef as possible. This can be seen in Figure 9. As the contour of the reef changes, the roll angle of the rig must shift with it. Furthermore, the rig should be held around 1.5 m away from the reef at all times. At the end of the transect, diver 1 once again points the camera directly towards the water's surface and subsequently ends the recording. Whilst diver 3 was completing the survey, diver 2 followed behind while reeling in the transect tape and collecting the markers.



*Figure 9: Illustration of the roll axis.*

### 3.5.3 Data processing

3D data is captured in the form of 3 timelapses per transect, 1 per camera. These recordings are transferred to backup drives and analysed using the Agisoft Metashape and Rhino 8. Prior to analysis, the time lapses must be converted to JPEG form, gathering around 200 frames from each time lapse. Once converted, the images are imported into Agisoft, where each transect is rendered into a model and exported. These models are then imported into Rhino, and the data is collected from the transects and saved in Excel as numerical values.

## 4. Analysis

### 4.1 Data Sources

#### 4.1.1 Datasets

After compilation, Opwall provided complete data sets in the form of 3 Excel spreadsheets. The SVS data were recorded in the form of individual observations per fish with counts and estimated biomass. 3D photogrammetry data were recorded per transect in the form of a Rugosity Index. Benthic data were also recorded per transect, in the form of 201 nominal point-intercepts classified by benthic codes.

### 4.2 Data Handling

Site, Depth and Transect keys were joined. Then the data columns between the 3 data sets were renamed to be consistent across all the data in preparation for merging. Per transect data frames were constructed in each stream, followed by the SVS, 3D and benthic being left-joined via the keys. For SVS data, fish abundance was calculated using the sum of individual fish observations present per site. Fish biomass was similarly summed into total biomass per transect. The 'biodiversity score' was calculated by totalling the number of unique fish species present per transect. There was a concern of input mistakes in the data, such as typos inflating unique fish observation counts; however, the Underwater Surveyor software has pre-set fish ID outputs, negating this issue.

Rugosity data were recorded by Opwall in an inverse format, generating rugosity indexes  $< 1$  by calculating the transect planar area/true surface area. Most scientific literature calculates rugosity with this ratio flipped, so all the rugosity values were inverted to produce rugosity indexes  $\geq 1$ . This aligns better with ecological interpretation and prior literature.

For benthic data, the individual observations were converted into percentages per transect for analysis. Firstly, the benthic categories mentioned in the methods (Table 1) were clustered into groups.

Clustered Categories:

- Coral cover: HCO, SCO
- Other benthic inverts: MIL, ZOA, SPO
- Algae: MAA, TAL, PEY, CYA, CCA
- Abiotic: RCK, SAN, RBB, SIL, DCA, DCO, WAT
- Other: all remaining codes

Coral cover was the primary group used for analysis, as it consisted of hard corals and soft corals, which are the most ecologically relevant to the study aims. To calculate percentages, each group's total point count was divided by the total transect point count and multiplied by 100; any groups with no observations were made to zero-fill for the calculations in order to get percentages summing to 100.

### 4.3 Data Cleaning

The individual data frames were merged into a complete transect-level data frame including the new fish biomass, abundance and biodiversity columns as well as rugosity and coral cover percentage columns. As there were missing transects in both the SVS and benthic data, which did not overlap, it was necessary to fill the corresponding observation in the compiled data frame with the NA designation. This allowed for the maximisation of the transect count in each model by dropping rows with NA in the predictor for the specific response variables being analysed. This, in turn, allowed other columns to be NA without affecting the model fit. During the assessment of the data, it became clear that one of the transects (LIG-5m-W2) was an outlier in terms of rugosity index and was skewing the dataset. The transect had a rugosity index approaching 6, which was almost certainly an error produced at the 3D modelling rendering or data extraction process. Consequently, this transect was omitted from all of the models. It is also important to note that not all of the benthic transects had a full 201 observations present; a few had ~195–200 observations. However, displaying the benthic components as percentages inherently normalises for the small differences in observation count.

A log transformation was applied to the biomass and abundance response variables, but not the biodiversity score or coral. This was done using log1p to reduce the right-skewed counts, preserve zeros, and improve homoscedasticity. log1p was used over log so that it wasn't necessary to drop any potential transects with zero abundance and biomass. Biodiversity score and coral cover showed adequate data distributions for linear model fitting after OLS diagnostics, so were left untransformed for easier interpretability.

#### 4.4 Exploratory Analysis

For each of the response variables vs rugosity, a Pearson and Spearman correlation test was performed. Both were performed as the Pearson test aligns with OLS linear model assumptions, and the Spearman test creates a monotonic check, which is less sensitive to scale or any outliers present.

**Table 2: Pearson and Spearman correlations between rugosity and fish biomass, abundance, biodiversity and coral cover.**

Outlier transect removed, showing transformation type for response variables, including log1p. Displaying Pearson's R with two-sided P value as well as Spearman's P with P value. Positive coefficients will indicate higher values with increasing rugosity index. There was no multiple-comparison correction applied to the test ( $\alpha = 0.05$ ).

Response	Transform	Transect Count	Pearson R	Pearson P	Spearman RHO	Spearman P
Biomass (g)	Log1p	66	0.117	0.350	0.068	0.588
Fish abundance (n)	Log1p	66	0.371	0.0021	0.374	0.002
Biodiversity score (n)	None	66	0.335	0.0059	0.343	0.0048
Coral cover (%)	None	64	0.307	0.0136	0.281	0.0245

## 4.5 Modelling

To establish a baseline for comparison with a non-linear model, Ordinary Least Squares (OLS) linear models were run to establish the presence of linear relationships. Furthermore, these models were run to compare the data against trends present in the broader literature, acting as an informal assay for the data. OLS linear models were run on all four response variables against rugosity (Table 3). OLS was chosen over other linear models as the previously mentioned log1p transformation, and other residual diagnostics were suitable for single-predictor inference. Furthermore, OLS models produce easily interpretable effect sizes and a clean null for non-linear comparison ( $\Delta p$ ). Finally, it is also standard practice to use OLS linear models to detect ecological relationships (Zuur et al., 2007)

$$g(y_i) = \beta_0 + \beta_1 x_i + \varepsilon_i$$
$$\varepsilon_i \sim \text{i.i.d. } (0, \sigma^2)$$

*Equation 1: OLS linear model.  $y_i$ : response for transect  $i$  for e.g. fish abundance.  $x_i$ : predictor for transect  $i$  (rugosity index).  $g()$ : response transformation, =  $\log(1+y)$  for biomass and abundance (log1p transformation).  $\beta_0$ : intercept.  $\beta_1$ : slope.  $\varepsilon_i$ : random error term for transect  $i$ .  $\varepsilon_i \sim \mathcal{N}(0, \sigma^2)$ : errors are independent and identically distributed.*

After the linear models, piecewise linear (single breakpoint) models were run to investigate the existence of a threshold in rugosity index in relation to the ecological response variables. For each of the response variables, a segmented regression model with an unknown breakpoint was fit using the segmented R package. Segmented regression modelling was chosen for this analysis as it is shown to effectively identify ecological thresholds (Toms and Lesperance, 2003). Initially, multiple starting values were run, and the fits with the best improvement were retained. The linear and segmented fits were compared by an F-test, which produced a  $\Delta p$  and an estimated break point. The  $\Delta p$  determined whether the fit of the segmented (threshold) model was a statistically better fit than the linear model. Pre and post breakpoint slopes were also calculated; however, inference was centred on the  $\Delta p$  value as the main goal was establishing a potential threshold. It is important to note that if the surveyed range of rugosity is relatively narrow, the segmented analysis is not able to detect thresholds at higher rugosity

indexes. This is important as the global trend of reef flattening may have resulted in Utila's reefs being flatter than historically.

$$g(y_i) = \beta_0 + \beta_1 x_i + \beta_2 (x_i - \psi)_+ + \varepsilon_i.$$

*Equation 2: Single breakpoint piecewise model (segmented).  $\Psi$ : unknown breakpoint.  $y_i$ : response for transect  $i$  for e.g. fish abundance.  $x_i$ : predictor for transect  $i$  (rugosity index).  $g()$ : response transformation, =  $\log(1+y)$  for biomass and abundance ( $\log 1p$  transformation).  $\beta_0$ : intercept.  $\beta_1$ : slope below breakpoint.  $\beta_1 + \beta_2$ : slope above breakpoint.  $\varepsilon_i$ : random error term for transect*

$$F = \frac{(RSS_1 - RSS_2)/(df_1 - df_2)}{RSS_2/df_2},$$

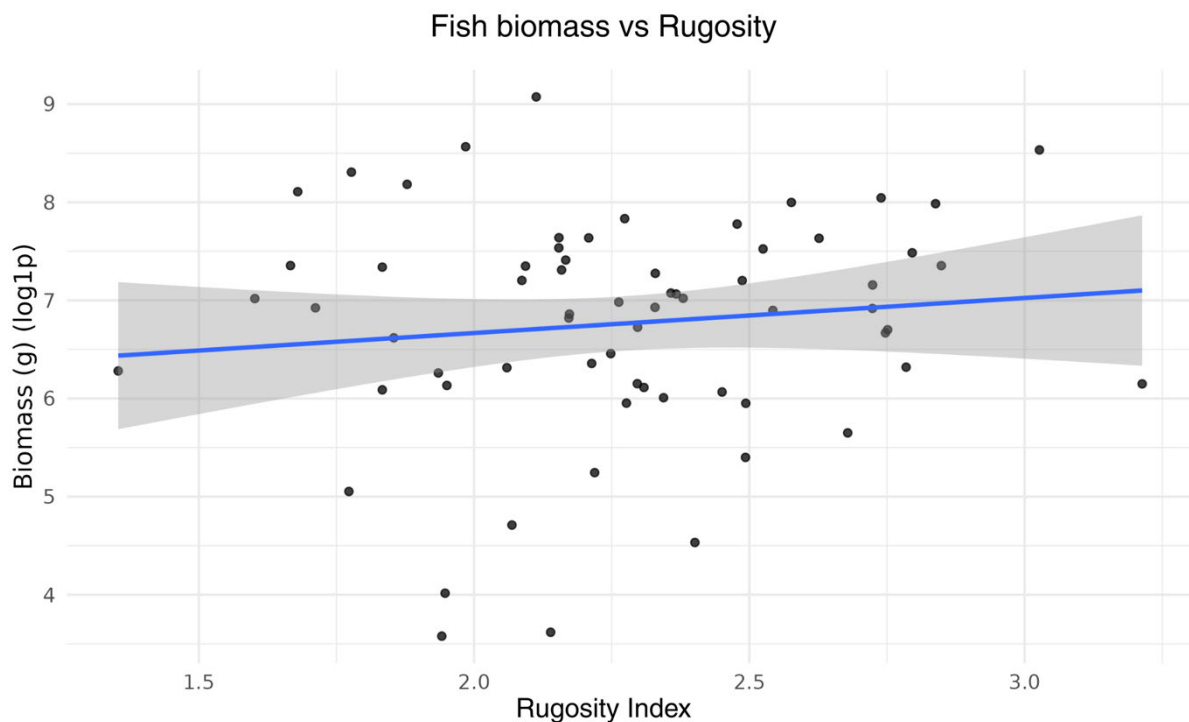
$$\Delta p = \Pr(F_{df_1 - df_2, df_2} \geq F).$$

*Equation 3: F test (linear vs segmented).  $F$ : F value.  $RSS_1$ : residual sum of squares for the OLS model.  $RSS_2$ : residual sum of squares for the segmented model.  $df_1$ : residual degrees of freedom for the OLS model.  $df_2$ : residual degrees of freedom for the segmented model.  $\Delta p$  = change in p value,  $\Delta p < 0.05$  is significant.*

## 5. Results

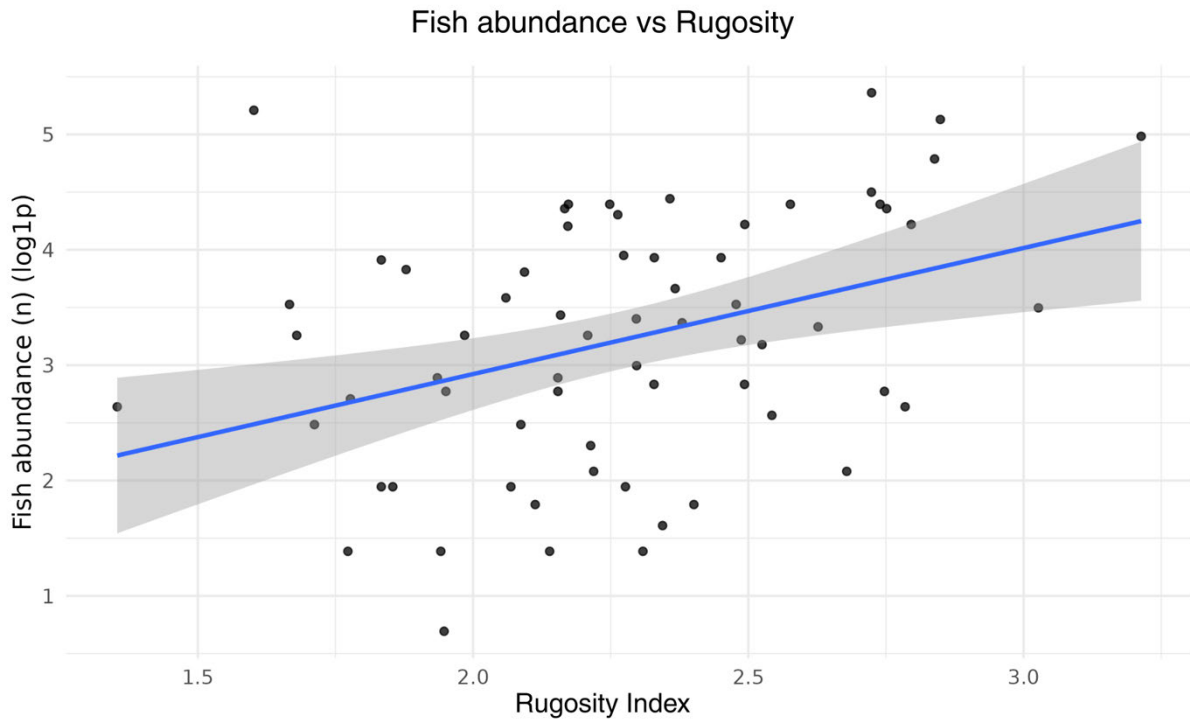
### 5.1 Linear Models

The baseline models showed no correlation between rugosity and fish biomass; however, there were significant correlations between rugosity and fish abundance, diversity and coral cover (Figures 10-13, Table 3).



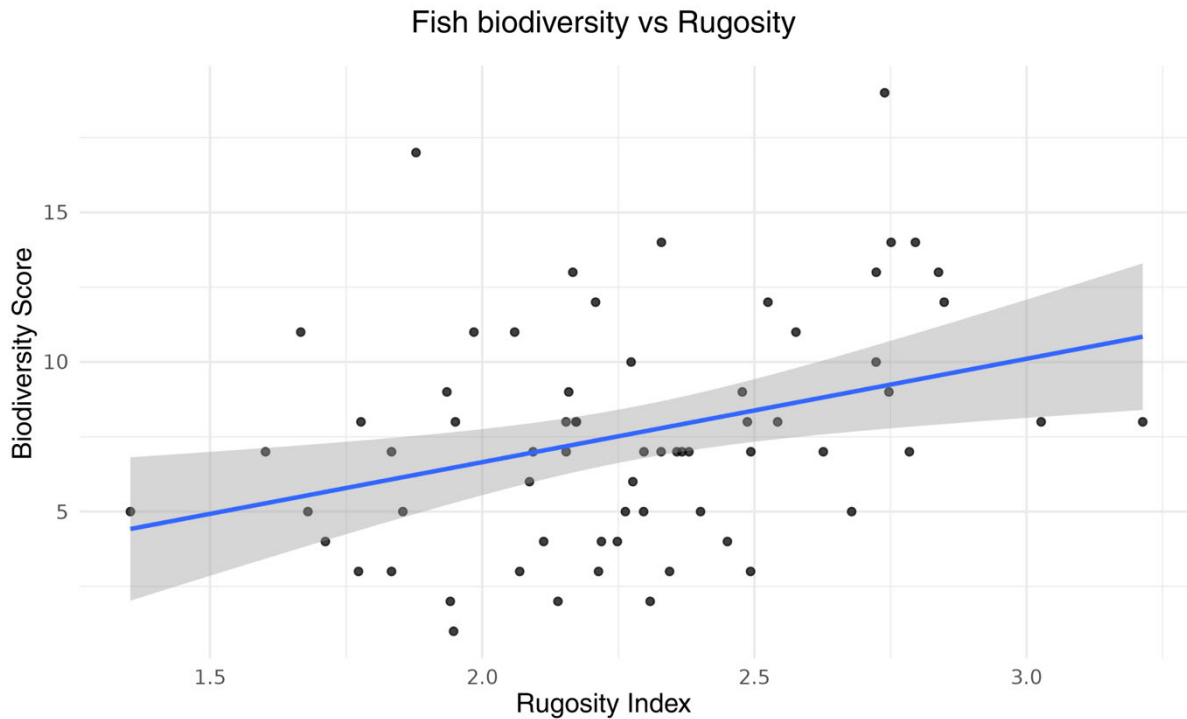
**Figure 10: The relationship between total fish biomass per transect and the transect's rugosity, with the blue line showing OLS fit and 95% CI. Transect (n) = 66.**

The total fish biomass values were log-transformed ( $\log_{1p}$ ) to reduce right-skew and stabilise variance, improving linearity with rugosity while accommodating zeros. Each point on the plot represents an individual transect. Total fish biomass did not show a significant association with rugosity (Table 3).



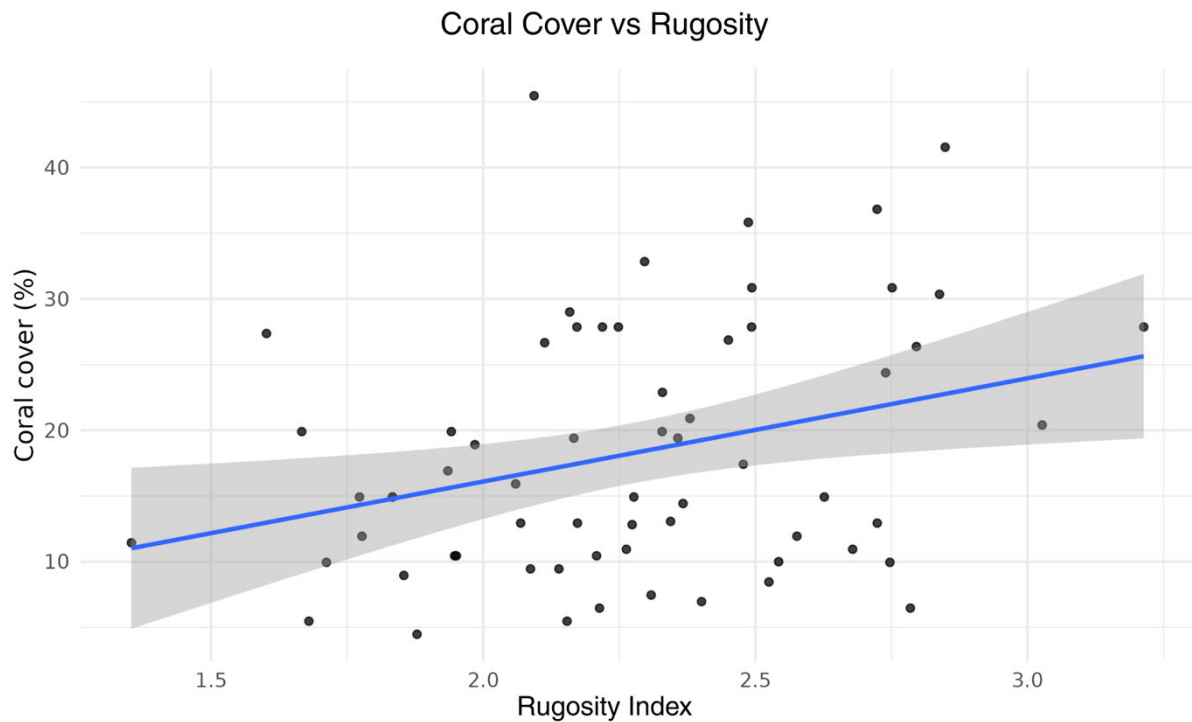
**Figure 11: The relationship between fish abundance per transect and the transect’s rugosity, with the blue line showing OLS fit and 95% CI. Transect (n) = 66.**

Fish abundance is calculated as the total count of unique fish observations collected per transect. Furthermore, fish abundance was log-transformed (log1p) to handle zeros, reduce right-skew, and stabilise variance, improving the linear fit with rugosity. At the transect level, fish abundance exhibited a positive relationship with transect rugosity. The linear model found this positive relationship to be statistically significant (Table 3).



**Figure 12: The relationship between fish biodiversity per transect and the transect’s rugosity, with the blue line showing OLS fit and 95% CI. Transect (n) = 66.**

The fish biodiversity score was calculated as the number of unique species recorded within each transect. At the transect level, fish biodiversity showed a mild positive relationship with transect rugosity. The linear model found this positive relationship to be statistically significant (Table 3).



**Figure 13: The relationship between transect coral cover and the transect’s rugosity, with the blue line showing OLS fit and 95% CI. Transect (n) = 64.**

The percentage of coral cover on each transect was calculated using hard coral and soft coral counts; *Zoanthids* and *Millepora* were not included in this criterion. Coral cover exhibited a positive relationship with rugosity on the transect level. The linear model found this positive relationship to be statistically significant (Table 3).

**Table 3: OLS linear models showing the relationship between transect rugosity and fish biomass, abundance, biodiversity, and coral cover.**

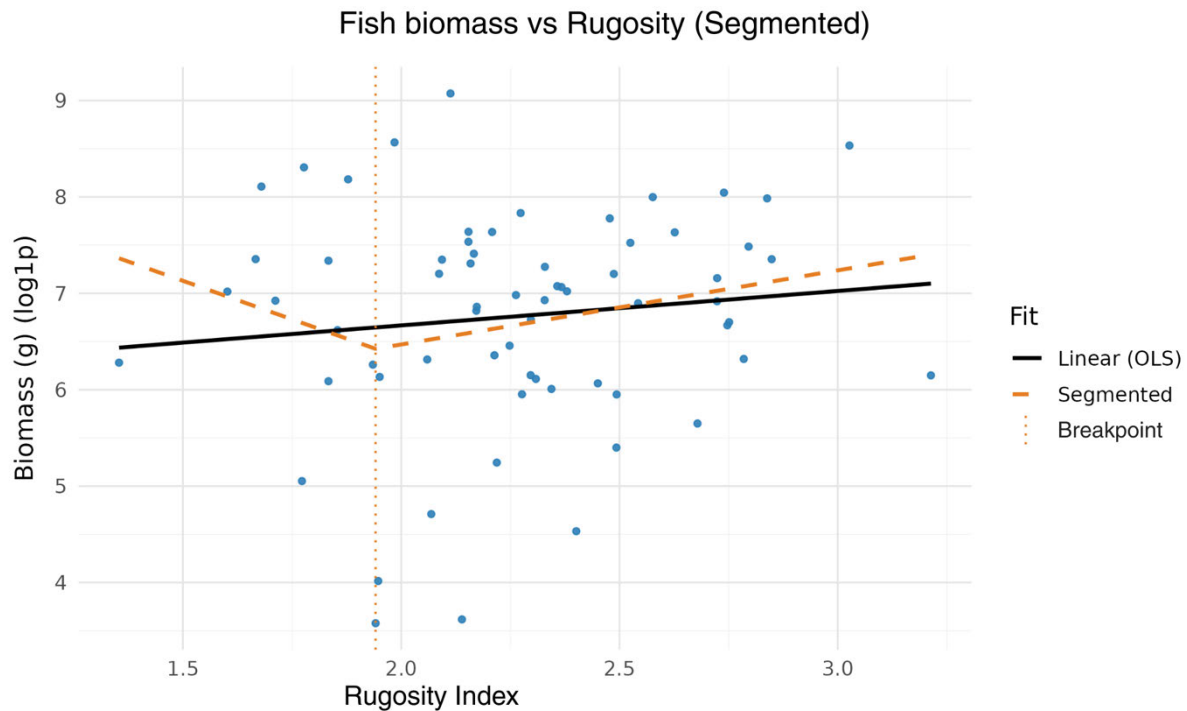
The OLS models used rugosity as the predictor and four responses: log-transformed biomass (log1p(g)), log-transformed abundance (log1p(n)), biodiversity score and coral cover (%). These linear models serve as a baseline for comparison to the segmented models to ascertain if they pose a better fit, implying a threshold. The models for fish biomass, abundance and coral cover found a positive relationship with rugosity,  $P < 0.05$ .

Response	Transformation	Transect Count	Beta	P Value	R <sup>2</sup>	Adjusted R <sup>2</sup>
Biomass (g)	Log1p	66	0.357	0.350	0.0136	-0.0018
Fish abundance (n)	Log1p	66	1.09	0.0021**	0.138	0.124
Biodiversity score (n)	None	66	3.46	0.0059*	0.112	0.0985
Coral cover (%)	None	64	7.86	0.0136*	0.0943	0.0797

P<0.05\*, P<0.005\*\*, P<0.0005\*\*\*

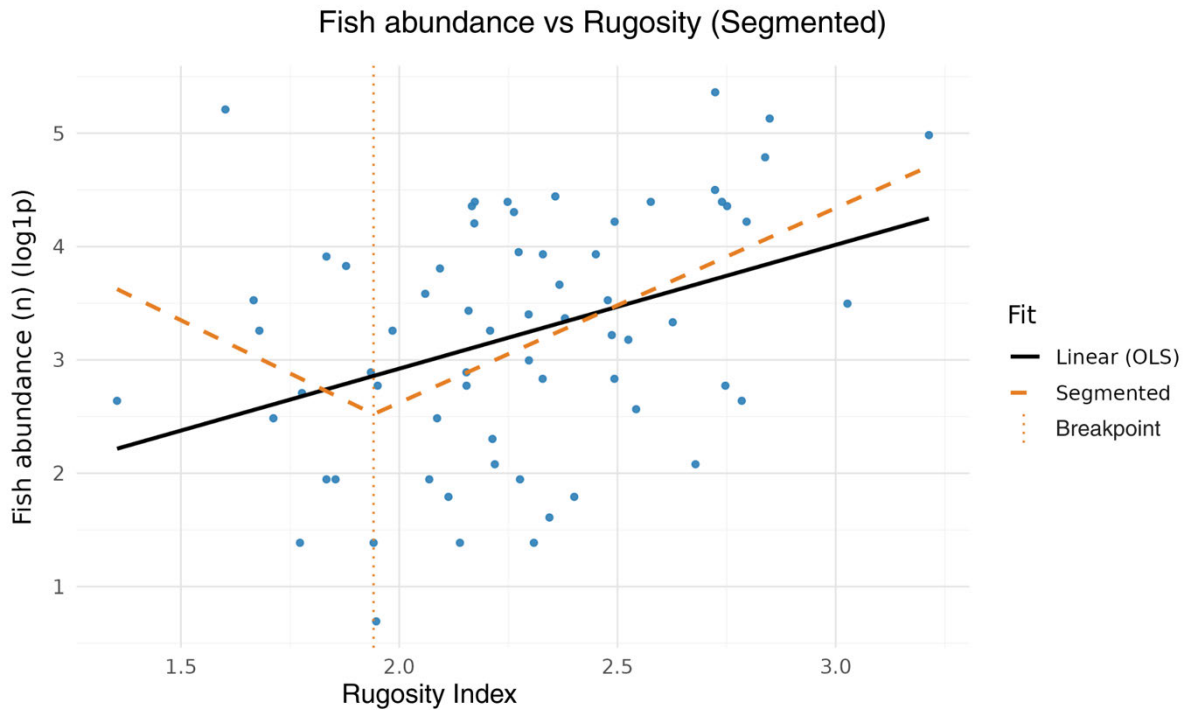
## 5.2 Segmented Models

The segmented models did not provide a better fit in comparison to the linear models. All four of the models produced a non-significant  $\Delta P$  value, implying that all four response variables lack a rugosity threshold (Figure 14-17, Table 4).



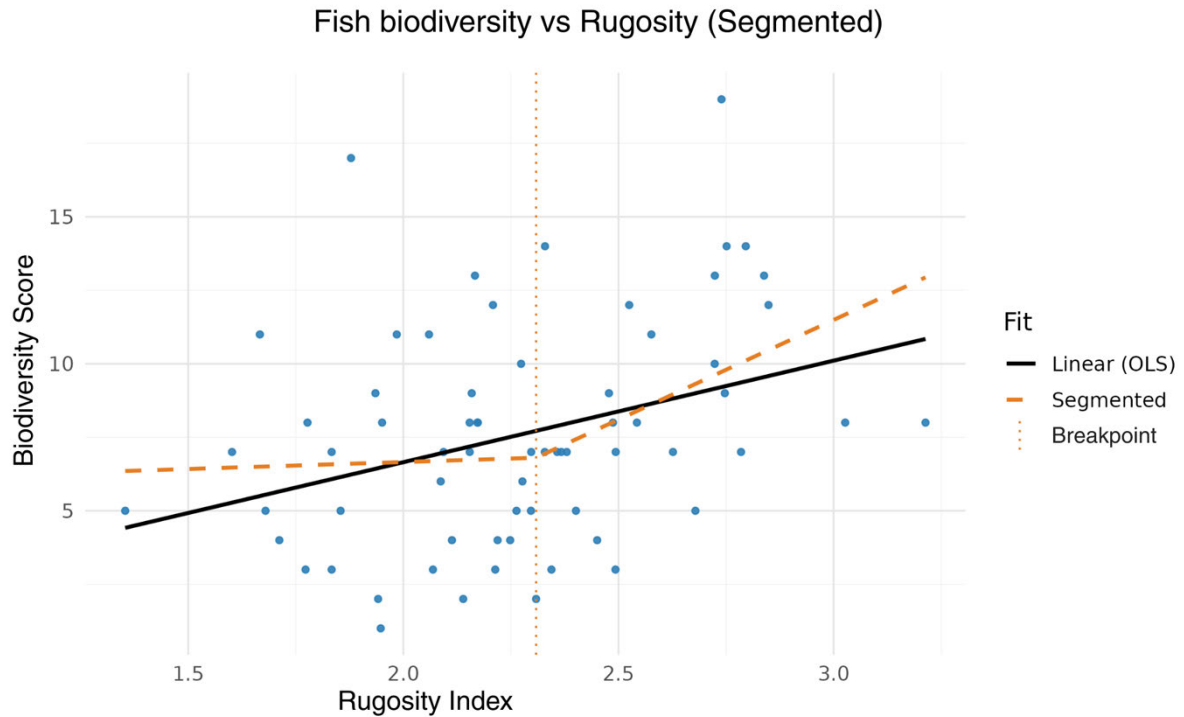
**Figure 14: The relationship between total fish biomass per transect and the transect's rugosity, transect (n) = 66.**

The black line represents the OLS fit, the orange dashed line represents the piecewise (segmented fit), and the vertical orange dotted line represents the estimated breakpoint. Fish biomass was log-transformed for the segmented model, similarly to the linear model. The segmented model identified the most likely breakpoint (threshold) to be at a rugosity index of 1.94. However, the segmented model didn't create a significantly better fit than the linear model with a  $\Delta P$  value of 0.429.



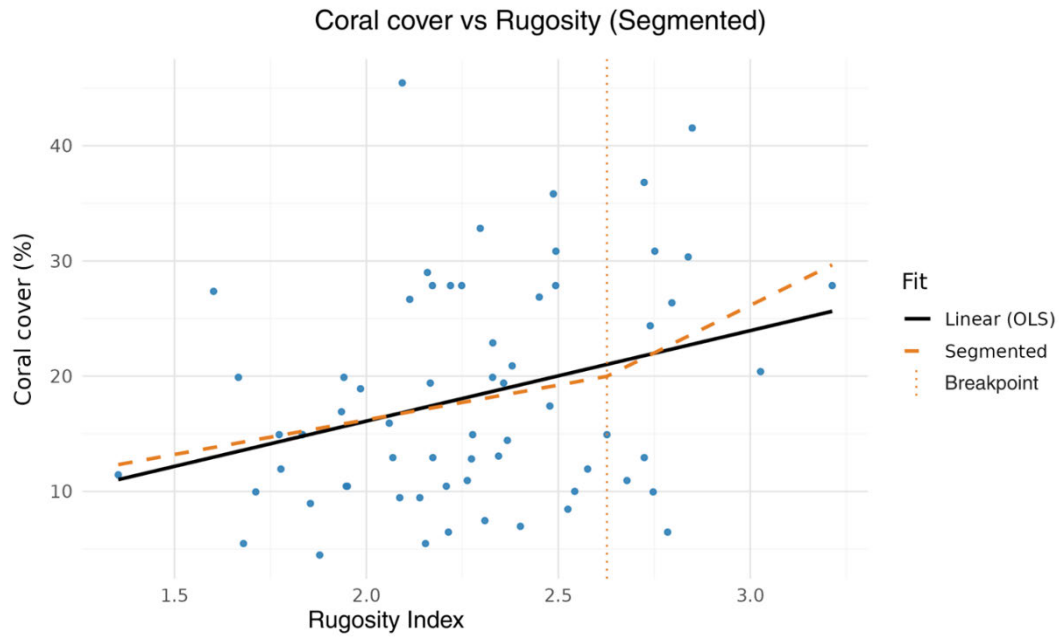
**Figure 15: The relationship between fish abundance per transect and the transect’s rugosity, transect (n) = 66.**

The black line represents the OLS fit, the orange dashed line represents the piecewise (segmented fit), and the vertical orange dotted line represents the estimated breakpoint. Fish abundance was log-transformed for the segmented model, similarly to the linear model. The breakpoint of the segmented model 1.94 for fish abundance was also at a rugosity index of 1.94. The segmented model implies a threshold but did not create a better fit than the linear model with a  $\Delta P$  value of 0.0838. It is of note that there are only 12 pre-break transects, which may skew the results.



**Figure 16: The relationship between fish biodiversity per transect and the transect's rugosity, transect (n) = 66.**

The black line represents the OLS fit, the orange dashed line represents the piecewise (segmented fit), and the vertical orange dotted line represents the estimated breakpoint. The segmented model for biodiversity identified the most likely breakpoint (threshold) to be at a rugosity index of 2.31. The segmented model did not create a better fit than the linear model with a  $\Delta P$  value of 0.289.



**Figure 17: The relationship between total coral cover per transect and the transect’s rugosity, transect (n) = 64.**

The black line represents the OLS fit, the orange dashed line represents the piecewise (segmented fit), and the vertical orange dotted line represents the estimated breakpoint. The segmented model for coral cover identified the most likely breakpoint (threshold) to be at a rugosity index of 2.63. The segmented model did not create a better fit than the linear model with a  $\Delta P$  value of 0.798.

**Table 4: Segmented linear models showing the relationship between transect rugosity and fish biomass, abundance, biodiversity, and coral cover.**

The segmented models also used rugosity as the predictor and four responses: log-transformed biomass ( $\log_{1p}(g)$ ), log-transformed abundance ( $\log_{1p}(n)$ ), biodiversity score and coral cover (%). None of the segmented models provided a significantly better fit than the linear models with a  $\Delta P > 0.5$ .

Response	Transform	Transect Count	Breakpoint	Breakpoint P Value	R <sup>2</sup> Linear
Biomass (g)	Log1p	66	1.94	0.429	0.0136
Fish abundance (n)	Log1p	66	1.94	0.0838	0.138
Biodiversity score (n)	None	66	2.31	0.289	0.112
Coral cover (%)	None	64	2.63	0.798	0.0943

### 5.3 Results Summary:

Across all of the transects surveyed (1 excluded), rugosity shows a modest positive correlation with fish biodiversity, abundance and coral cover, whilst biomass shows no statistically significant relationship. Overall, the effect sizes of the positive correlations are relatively small in power ( $R^2 \approx 0.09-0.16$ ), which suggests that the rugosity index of a transect is only responsible for a limited fraction of the variation in the response variables. The segmented models do not significantly outperform the OLS linear models, indicating that no robust threshold/breakpoint was discovered within the surveyed rugosity range. Therefore, the overall draw from the data is that there is a gradual, positive relationship between rugosity and ecological metrics rather than a sharper threshold trend.

## 5. Discussion

### 5.1 Introduction

Coral reef complexity is understood in the literature to be positively correlated with ecological variables such as fish abundance, biomass, biodiversity and coral cover (Rogers et al., 2014; Castaño et al., 2021; Graham et al., 2013). The results of this study provide mixed evidence on linearity; all linear models, except biomass, showed a positive correlation with rugosity (Figures 10-13, Table 3). Whilst the segmented analysis showed possible thresholds, they were statistically insignificant (Table 4). These results reflect the disparity within the broader debates around the specific patterns of reef structural complexity and ecological status (Alvarez-Filip et al., 2009).

#### 5.1.1 Linear Models

The OLS linear model for fish abundance vs rugosity showed a statistically significant, positive relationship (Figure 11). This aligns with the general literature, which shows that as reef complexity increases, greater fish populations are supported by the increase in refuges and niche partitioning (Wilson et al., 2007; Nash et al., 2014). It is noteworthy that this relationship was significant at the transect level, indicating that local changes in rugosity had a substantial impact on fish abundance. This is important as policy and NGO planning tend to operate on a more macro scale, only considering effects for whole reefs, whilst localised changes in rugosity may also exhibit similar trends. The linear regression model for fish biodiversity and rugosity also revealed a statistically significant positive relationship (Figure 12). This finding also supports the general literature, which shows that increased rugosity drives species sorting and enhances fish biodiversity (Messmer et al., 2011). Biodiversity's sensitivity to rugosity has the potential to serve as an early warning indicator for reef health, as it appears to precede biomass declines.

Coral cover was also correlated with rugosity, with a statistically significant positive relationship (Figure 13). Once again, this aligns with the evidence found in the general literature; however, the directionality of this association is likely to be different from that of the fish metrics. This is due to hard corals being reef builders and major contributors to

rugosity; it's more than likely that the association visible in the data is more bidirectional than seen with the fish metrics. Reef-building coral may contribute to increased structural complexity, whilst the increased structural complexity creates more refuges for coral recruits (Oh et al., 2025). Finally, no statistical relationship was found between fish biomass and rugosity using the linear model (Figure 10). This diverges from the trend seen in the general literature, where fish biomass and rugosity are typically positively associated (Graham et al., 2015). Possible reasons for this occurrence may include the use of a single-year data set, the dominance of smaller fish species in the assemblages, disruption by local factors such as overfishing, or natural variability. It's also possible that there is a time lag present between rugosity shifts and total fish biomass reaction, which would require an investigation into multiyear rugosity shifts and biomass responses.

#### 5.1.2 Non-Linear Models

None of the segmented models found statistically significant breakpoints between rugosity and fish abundance, biomass, biodiversity and coral cover (Table 4). This implies that no evidence of a rugosity threshold was present in the data. Whilst there is debate in the general literature about the existence of a structural complexity threshold, the Caribbean has been the host to the most studies providing evidence for a non-linear relationship (Alvarez-Filip et al., 2011; Bellwood et al., 2004; Graham et al., 2015). The results of this analysis provide evidence against the existence of a threshold at the rugosity indexes surveyed. If a rugosity threshold(s) were present, the conditions under which the surveys were performed could not detect it. It is feasible that with larger data sets spanning more reef systems than Utila, and over multiple years, more signs of non-linearity in structural complexity relationships could be detected. There may also be many unaccounted-for variables which are influencing reef ecosystems and producing the linear trend currently visible in Utila. The non-statistically significant threshold found between rugosity and fish abundance may also respond differently if the surveys were expanded temporally and geographically.

### 5.1.3 Limitations

Whilst this investigation was designed with the most appropriate available survey and analysis methods, like all studies, it has its limitations. Altogether, a cumulative 3.6 kilometres of reef were surveyed for this study; however, this was limited by the low geographical variation, which hinders attempts to explain trends across the Caribbean. Furthermore, with only one year of survey data, any temporal variances resulting from external factors may have caused unanticipated variation in the data. This was also noted by Graham et al. (2007), where it was concluded that long-term monitoring is required to distinguish between true structural changes and short-term variance. Furthermore, one of the transects was removed from the analysis due to unusually high rugosity, which skewed the overall results. Whilst this was necessary as the skew was likely caused due to an error during the data extraction process of the 3d photogrammetry, it still introduces bias to remove such data points. Another limitation was performing analysis on the transect level instead of the wider site level. This was decided during the data exploration. It was concluded that performing the analysis on a site level caused a great loss in statistical power, as there are only 6 sites, meaning transect-level analysis was a better fit for the data. Despite this better fit, this decision does potentially inflate the chance of a type 1 error in the data. This is because ecological processes often overlap boundaries, meaning the transects may not be fully ecologically dependent, creating bias.

Rugosity is often considered the standard for quantifying structural complexity within coral reef survey literature; however, since the advent of SfM photogrammetry, many more structural variables are now available for use (Burns et al., 2015). Whilst it was outside of the scope of this study to make use of complexity variables other than rugosity, it is considered a limitation as more context for the structural complexity relationships could have been derived. Finally, OLS and segmented models were used for the detection of a threshold within the data sets; whilst this is a justified methodology within the literature, it is important to know that these tests are only used to detect a specific type of threshold (Toms and Lesperance, 2003; Zuur et al., 2007). Ecological relationships can often be monotonic and present in a ‘hump-shaped’ distribution, along with many other curve shapes other than linear. Furthermore, the detection of a threshold was limited in this study as there was only a narrow range of rugosity index present within the transects in the Utila data, meaning a potential threshold might exist on more varied reefs.

## 5.2 Policy Implications

Firstly, the resulting positive correlations obtained from the OLS linear models (Table 3) provide further evidence for the well-established link between rugosity and fish abundance, biodiversity and benthic composition. Whilst rugosity is already used by some governments and NGOs for quantitative decision-making for coral reef management and conservation, the results of this study show that these relationships are present even at the transect level. This further highlights the necessity for the incorporation of rugosity into planning, and on a much finer scale than previous macro implementations. Moreover, this implies the need for surveys in individual management zones instead of a ‘one size fits all’ approach, which may generalise reef conditions over multiple areas. Furthermore, no statistically significant breakpoint threshold was found for *Utila*, which is in contradiction with the trend within the literature on Caribbean reef complexity. These results indicate that there isn’t necessarily a threshold target for rugosity which policy makers should aim to reach, but rather a consistent incremental increase in environmental responses as rugosity increases. Although research is needed which incorporates higher rugosity environments, the results suggest that aiming to maximise rugosity should be a priority for policy makers.

Since transect-level relationships between rugosity and ecological factors, including fish abundance, were found in *Utila*, it is important to consider the implications for general fisheries surveys across the Caribbean. If this trend can be replicated across other reefs in the Caribbean, rugosity may play a greater role than expected in fisheries management than expected. However, more research would be needed to confirm if the transect-level relationships can be replicated on a larger scale. Continued research should prioritise utilising all three of the survey methods used in this study within the same transect or quadrat to get the most fine-scale survey data possible. Furthermore, if future research can replicate the transect-level relationships seen in this study, the use of these three survey methods simultaneously has the potential to become a new standard methodology for comprehensive fine-scale reef health monitoring surveys. This would have the potential to reshape the capabilities of reef monitoring for reef conservation and policy making.

## 6. Conclusion

The primary aim of this study was to identify any relationships between rugosity and fish abundance, biomass, biodiversity and coral cover and whether they were better explained by a segmented (threshold) model than linear models. The OLS linear models for rugosity and fish abundance, biodiversity and coral cover all exhibited statistically significant positive correlations ( $P = 0.0021^{**}$ ,  $0.0059^{**}$ ,  $0.0136^{*}$ , Table 3). Fish biomass showed no significant correlation with rugosity ( $P > 0.05$ , Table 3), which goes against the trends seen within other studies (Graham and Nash, 2013; Rogers et al., 2013). This may be due to external factors interfering with results or a time lag effect between rugosity and biomass. However, the segmented models did not outperform any of the linear models ( $\Delta P > 0.05$ , Table 4) at their estimated breakpoint values. These results largely align with the broader global trends in the literature; however, they conflict with the Caribbean literature, which presents evidence for a threshold resulting from reef flattening. Despite this, the results do not show any evidence for a significant breakpoint within the data, which would suggest the existence of a rugosity threshold.

The results of this study faced a few limitations, the main one being the time span and geographical scale limits resulting from the nature of an MSc thesis. Ideally, data collection would take place over several years and varying locations throughout the Caribbean to create a more accurate portrayal of the consequences of Caribbean reef flattening. Furthermore, a greater number of structural complexity metrics collected along with more survey sites may have avoided transect transect-level analysis. Despite this, the data sets collected using SfM photogrammetry, stereo video system surveys, and benthic recording produced robust data for analysis. The results of the analysis provide evidence for a few shifts in the way that coral reef management is currently carried out, namely in the scale and zoning. The transect-level correlations found within this analysis support the need for finer-scale surveys before policy or conservation is carried out, and most importantly, differing policies for different reefs, dependent on the present structural complexity and ecological relationships.

Future research is essential to further develop the link between coral reef structural complexity and ecological status. It is necessary to create a wider-scope survey spanning over many sites in the Caribbean and over the course of multiple years to account for any temporal variance

within the data. Furthermore, more structural complexity variables, which have been shown to correlate with ecological status, need to be included within the survey parameters. Finally, most studies which investigate structural complexity do not make it an objective to explore non-linearity; this must be amended in future research for a more comprehensive analysis. To summarise, the data collected and the resulting analysis showed clear linear relationships between rugosity and fish abundance, biodiversity and coral cover, but no rugosity threshold was detected on the reefs of Utila.

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## 8. Appendix

### Response Summary:

# Research Ethics Application Form - CEP

### Principle Investigator and Student Details (to be completed by all students)

#### Section 1a: Details of Principal Investigator (PI)

For all projects the PI must be employed by Imperial College London or hold an honorary contract. For all student projects, the student's supervisor must be named as PI. Student, co-investigator and collaborator details must be added to Section 13.

**Q2. Supervisor (PI) name (incl. title)**

Dr Zen Makuch

**Q3. Academic position (at Imperial College London)**

Head of Department | Lecturer

**Q4. Faculty**

Faculty of Natural Sciences

**Q5. Division/ School/ Department**

Centre for Environmental Policy

**Q6. PI Email (Imperial College)**

z.makuch@imperial.ac.uk

**Q7. Summary of PI skills (experience relevant to the study and in any procedures to be used) (350 characters max)**

Experience in advising on environmental and regulatory issues including on marine and climate related governance, this is relevant to the policy aspect of the thesis.

#### Section 1b: Student Details

**Q253. Student name**

Albert Kundrak

**Q254. Student email (Imperial College)**

Amk224@ic.ac.uk

#### Section 2: Research Type

**Q9. Is your study considered low risk?**

'Low Risk' includes collecting data from individuals or groups that can give consent, or using secondary data that you have permission to use.

See the Research Term Guidance document for more information and consult with your supervisor.

- Yes

**Q10. Does your study only involve analysis of secondary data which is publicly available, and permission is not required to access the data? This includes extended or systematic literature reviews.**

- Yes

### Section 3: Filter for ICREC and SETREC

**Q13. Is the primary aim of the research answering a human health related question?**

- No

**Q14. Is the primary aim of the research answering a non-health related science, social science, engineering or technology related question?**

- Yes

**Q15. Is the primary aim of the research to answer an educational question?**

- No

### Section 4: Risk level categorisation

This section determines the research risk level and if the application requires full committee review.

Meeting dates and submission deadlines [ICREC/SETREC](#).

**Q18. High risk**

<i>Does the research involve drugs/medication? If yes, please attach the SmPc.</i>	No
<i>Does the research involve genetically modified materials? If yes, please also complete appendix two and attach the GM Safety Committee letter.</i>	No
<i>Will you be recruiting vulnerable participants? i.e. children (15 years or younger), adults (16 years or over) who are unable to consent, people in care, the mentally ill or individuals with learning difficulties?</i>	No
<i>Will participants take part in the study without their explicit consent? i.e. studies involving deception.</i>	No
<i>Will you be recruiting prisoners or young offenders?</i>	No

<b><i>Is there any aspect of the proposed research which could potentially cause harm to the reputation of the College? i.e. could the research be considered controversial or prejudiced?</i></b>	No
<b><i>Could participants disclose any illegal or harmful activity due to the nature of the research?</i></b>	No
<b><i>Will personally sensitive subjects be discussed that have the potential to induce stress, anxiety or negative consequences for the participant?</i></b>	No
<b><i>Will the researcher be in a position of influence or authority over the participants that could give rise to a perceived pressure to participate? i.e. lecturers/teachers and students.</i></b>	No
<b><i>Does the study involve physically intrusive procedures, administration of substances, use of bodily fluids, tissues, DNA or RNA? Use of relevant material must be registered with Imperial College Tissue Bank under the College HTA license.</i></b>	No
<b><i>Does the study involve ultrasound or sources of non-ionizing radiation? i.e. radiation, MRI, or fMRI.</i></b>	No
<b><i>Are there any potential conflicts of interest, or what could be perceived by an outside observer as conflicts of interest?</i></b>	No
<b><i>Will undue incentives for participants be offered? Incentives should be proportionate to the burden imposed and justified by the benefits.</i></b>	No
<b><i>Are you using any medical device in the UK that is CE/UKCA marked but is being used outside its product limitation? Or are you using any non-CE/non-UKCA marked product(s)? For more information on <a href="#">regulating medical devices</a>.</i></b>	No

<b>Does the proposed research raise any ethical issues that are not covered above?</b>	No
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If you have answered **NO TO ALL** of the above questions, your project is considered low risk and you can proceed with the rest of the ethics form.

## Section 5: Project Description

(to be completed by all)

### Q22. Full title of study

Topography of Biodiversity: Quantifying Reef Complexity to Guide Coral Reef Management in the Caribbean

### Q23. P code or cost code and study funder (only if applicable to study)

N/A

### Q24. Lead organisation

*(who has overall responsibility for the study)*

Operation Wallacea

### Q25. List of location(s) where study will be conducted

Utila, Bay Islands, Honduras

### Q26. Proposed start date

*From start of advertising and/or recruitment*

24/06/2025

### Q27. Proposed end date

*To end of data collection*

05/08/2025

## Section 6: Project Summary

Q29. Provide a summary of the project in lay terms, this should include:

- a brief description of reasons for doing the study (justification for the research)
- the aims (research aim/question)
- how data will be disseminated
- any expected benefits to the participant, researchers or others.

*(500 words max)*

The project aims to 3d model coral reefs around Utila in order to derive physical reef structural features which may correlate to ecological health predictors such as fish populations and coral/ algal species. From the 3d models, data such as rugosity, fractal dimension, surface area, curvature and slope can be obtained.

The three data collection and analysis techniques harnessed in this study are highly novel and have been made possible by recent advancements in technology. This is beneficial as the study aims to delve deeper into previously understood reef relationships using these advancements.

The three research questions for this thesis are:

- Whether specific physical reef structural attributes correlate to fish population sizes.
- Whether specific physical reef structural attributes correlate to benthic community health.
- Whether specific physical reef structural attributes are viable to be used as indicators for reef health in conservation planning.

## Section 7: Research Methods

**Q31. What methods will you be using in this study?  
Briefly describe in lay terms:**

- what will happen
- the number of times
- any data collection techniques

*(500 words max)*

The fieldwork portion of the project will be carried out over 5 weeks of data collection in Utila, Honduras, between July 1st and August 5th, 2025. During the data collection period, 2 dives per day, 6 days a week, will be conducted to ensure adequate surveying is done. For each site used for the study, a transect line will be established and marked, which will be used for all of the survey techniques to keep collected data consistent. During data collection, the diver will swim along or right next to the transect line and survey the reef along it. Data collection will be carried out using multiple dive camera rigs capturing photos and videos of the sea floor and surrounding fish. Some of the photographs will be used for the 3d modeling, from which reef complexity data will be derived. The data will then be cleaned and statistically analysed in R.

**Q32.**

## **STUDY OBJECTIVES**

**What are you hoping the study achieves? List the primary, secondary and other study objectives.**

*List the specific research objectives. Again, this can be copied from your research proposal*

The aim of this project is to identify which physical variables of coral reef structural complexity have the strongest correlation to healthy fish populations and benthic communities on coral reefs located around Utila, Honduras. Describing the causation of these relationships is outside the scope of this project, instead, the main objectives are the identification and evaluation of physical reef attributes and their viability to be used as indicators or targets for coral reef conservation efforts.

The three hypotheses are: reef structural complexity metrics correlate to the abundance of locally present fish populations measured using biomass; reef structural complexity metrics correlate to benthic community diversity; reef structural complexity metrics are a viable environmental indicator for reef planning and conservation.

**Q33.**

## **PUBLICATION POLICY**

**The study publication policy should be described in full.**

*In most cases, you should just state that this work is being prepared for publication as an MSc thesis at Imperial College London. If you intend to write a report for some external party or you intend to publish in the academic/peer reviewed literature you should say that too*

This work is being prepared for publication as an MSc thesis at Imperial College London.

**Q34.**

## **STUDY DESIGN**

**Detail how this study will be conducted from advertising to data processing. Make sure your design is explicitly described and appropriately justified. Repeat for each method you use. Include the following bullet points below:**

- Type of study method: survey, interviews, focus groups, simulator study.
- Recruitment methods: how you will recruit participants, use of participant information sheets and consent forms
- Duration of study from advertising and recruitment to end of data collection
- Number of participants. This should be justified.

*This should describe what variables you will be measuring, how you will be measuring them, how often they will be measured (just once, or is there a follow-up or repeat measurement) and whether this will be done through survey, interview, focus group or other means. Describe here how many people you are looking to recruit and how you will recruit them. Any further details about inclusion criteria will be given in the next sections.*

This study will be carried out using a fieldwork-based ecological survey (see details above). Furthermore, a literature review will be performed to discuss and provide background on the thesis. The variables being investigated are the physical reef complexity features against ecological health indicators. Each transect will be captured by photographs and video on one dive.

## Section 8: Participant Recruitment

**Q36. Provide details of methods of recruitment, participant inclusion and exclusion criteria and the number of participants you are aiming to recruit. Please include:**

- Details of any incentives (such as financial reimbursement).
- Recruitment and advertising material (email, poster, social media advert)
- Oral information scripts

**\*The recruitment material (points 2 and 3) needs to be developed in a separate document and sent to your supervisor along with the print out of your ethics form. (1000 words max)**

N/A

**Q37.**

### Pre-recruitment evaluations

**Are there any requirements that a participant must fulfil? E.g., fitness test, allergy test.**

*This will likely be not applicable to most of you – you should just say that there will be no pre-recruitment evaluations*

N/A

**Q38.**

### Inclusion criteria

**Include justifications.**

*This is relevant if you are, for instance, interviewing professionals or members of a particular group. Indicate why you need to speak with these people specifically and how you will know that they meet your specific criteria. For instance, "I will contact the sustainability officers of large multinational companies based on their publicly available LinkedIn profiles. The study requires insights from professionals on [whatever the topic is...]"*

N/A

**Q39.**

### Exclusion Criteria

**Include justifications.**

*If there is a reason why you might exclude someone after you contacted them, you should say this here. Otherwise, you may just reiterate that anyone meeting the inclusion criteria will be considered and there are no specific exclusion criteria. Extending the above example you might be looking for experts, so one of your exclusion criteria might be that if you have identified someone through LinkedIn as a sustainability officer, but it turns out they have less than 1 year experience in the role, you will exclude them*

N/A

## Section 9: Informed Consent

Include details of how you will be obtaining consent.

**Q42. Detail the process for ensuring informed consent of all research participants.**

N/A

**Q43. The withdrawal process(es).**

Describe procedures for

- stopping early
- when can a participant withdraw from the study
- how and who to contact.

Include details of data usage once participant has withdrawn if the data be used once it has been anonymised.

N/A

**Q44. If participants whose first language is not English are to be recruited, state clearly how the details of the study will be explained, and the consent processed.**

N/A

## Section 10: Ethical Summary

**Q46. Has any part of this proposal received prior ethics approval?**

e.g. if project part of a larger project that has already gone through ethics, then an amendment to that ethics approval will need to be sought via College committees – may be lengthy – avoid if possible, unless minor.

- No

**Q47. Is this study subject to local ethics approval to where research is being conducted?**

e.g. through another university or institution

- No

## Section 11: Documentation checklist

**Q53. Do Imperial College's insurers need to be notified about your project?**

If your project is running abroad and is not qualitative or data only, or if your project is interventional and involves pregnant women, children under 5 or more than 5000 participants you may need additional insurance cover. [Insurance for studies](#), email the [insurance team](#) with any insurance enquiries.

*If yes, please provide confirmation that insurance cover has been agreed.*

- Yes

**Q54. Has your research project been independently peer reviewed?**

This can be organised by the [Peer Review Office](#) (within the RGIT). If you answered yes to any questions in section 3, you may be asked to ensure the study is peer reviewed. However, the study does not have to use the RGIT's office for peer review.

- No

**Q55. Are you developing a mobile app?**

See the [mobile app webpage](#) for more information.

- No

**Q56. Have you had a Disclosure and Barring Service (DBS) check carried out? If yes, when (add date).**

For more information about DBS, check [government guidance](#) and the [College website](#).

- No

**Q57. Do you need a contractual agreement in place? For further information, please contact your supervisor in the first instance.**

- No

**Q58. Do you have permissions to use the data in your study? This may be required if you are looking at secondary data.**

Postings on social media may not be considered public for research uses – please check

- Yes

**Q59. Has Imperial College's [Risk Assessment procedure](#) been followed? Contact your departmental administrator for further information.**

- Yes

## **Section 12: Confidentiality and management of personal and other research data**

**Q61. I understand it is the responsibility of the researcher to ensure all research data is securely stored during and after the study in accordance with College Guidelines, Codes of Practice, Policies and Procedures.**

- Yes

**Q62. I confirm that all the processing of personal information related to the study will be in full compliance with the GDPR. Including but not limited to, the creation of all necessary documentation (PIS, Data Protection Impact Assessments, Consent forms etc.)**

- Yes

**Q63. Describe how you will preserve the confidentiality of participants taking part in the study and fulfil transparency requirements under the General Data Protection Regulation.**

Best practice requires that all participants information be entirely anonymised. If you are not doing this please give well-justified reasons for keeping personal and traceable information.

*All data should be stored on a GDPR-compliant service e.g. Imperial College OneDrive or Sharepoint.*

N/A

## **Section 13: Co-investigators/ Collaborators (second supervisor or external collaborators)**

(to be completed by all)

If there are more than four co-investigators (second supervisor or external collaborators), please use a separate sheet and follow the format below.

**Q66. Name of Co-investigator/ Collaborator**

Alex O'Brien

**Q67. Position Incl. organisation, company, institution**

Operation Wallacea | Marine Research and Operations Manager

**Q68. Role in the study (what contributions you will make and relevant experience)**

Supervisor

**Q69. Email (Work, not personal)**

Alex.obrien@opwall.ac.uk

**Q70. Do you have another Co-investigator/ Collaborator (second supervisor or external collaborators)?**

- No

PI Declaration

I declare that:

- I undertake to abide by the ethical principles underlying the Declaration of Helsinki (1964) and subsequent amendments and good practice guidelines on the proper conduct of research.
- I undertake to abide by the Data Protection Act 2018 and General Data Protection Regulation (Europe) and any applicable local laws.
- I undertake to abide by all local laws and regulations for non-UK research.
- I will report any adverse or unforeseen events or protocol violations and deviations which occur to the Ethics and Research Governance Co-ordinator within 24 hours.
- I will provide an [annual progress report](#) of the project until the end of the study.
- If I register my study on a public database, i.e. ClinicalTrials.gov, I will report results on that database within one year of study completion.
- I will provide [notification of the end or early termination](#) of the research project.
- I will provide [notification of amendment](#) to the CEP Ethics Panel if there are any changes to the research protocol or personnel which affect the ethical aspects of the project.
- I will assist the CEP Ethics Panel in any continuing review of the project deemed necessary by the Committee or Faculty Members.
- All information on this form is correct.

**Q90. PI Name (please print)**

Zen Makuch

**Q91. PI Signature: PI must sign and date this section after you have submitted and downloaded the PDF form (Note: PDF copy of form can be downloaded on final page of survey following submission)**

**Q92. Date**

Any attendance required by the CEP Ethics Panel must be made by the PI named in section one. Attendance at the meeting will give you the opportunity to answer any ethics questions raised by the committee.

**Please note, this is the last section of the form. When you press the 'next' button, you will submit your ethics application form. Please ensure you are ready to submit, as you can't go back and amend once you press the 'next' button. Once submitted, all forms should be downloaded using the 'Download PDF' button on the final survey response page and then sent to your supervisor for checking and signing off.**

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**Embedded Data:**

N/A