ASSESSING THE IMPACT OF
TERRESTRIAL WATERSHED INPUT
ON COASTAL CORAL REEF COMMUNITIES

by

Paul M. Leingang

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Marine Studies

Fall 2018

© 2018 Paul M. Leingang
All Rights Reserved
ASSESSING THE IMPACT OF
TERRESTRIAL WATERSHED INPUT
ON COASTAL CORAL REEF COMMUNITIES

by

Paul M. Leingang

Approved:

Danielle L. Dixson, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Mark Moline, Ph.D.
Chair of the Department of Marine Science and Policy

Estella Atekwana, Ph.D.
Dean of the College of Earth Ocean and the Environment

Approved:

Douglas J. Doren, Ph.D.
Interim Vice Provost for the Office of Graduate and Professional
Education
ACKNOWLEDGMENTS

There are many people, all over the globe, who I need to thank for helping me get through this program. First, thank you to Dr. Dixson for bringing me into your lab and providing guidance every step along the way. You always pushed me to fulfill my potential and hone my skills as a scientist. Also thank you to my committee members, Dr. Art Trembanis and Dr. Carlos Moffat, who provided valuable guidance and knowledge. Thank you to Luci Coumatos for all the hours you’ve spent pouring over handwritten receipts from Fiji. I want to extend my gratitude to all the administrators here at the University of Delaware for helping make my graduation timeline pass as smoothly as possible as well as the NIH for funding this work.

Everyone in the Dixson Lab, past and present, has made this the best lab group I could have ever hoped for. All other labs pale in comparison to the bond that we’ve formed. I am profoundly lucky to have had such an incredible fieldwork partner as you, Emily. Our memories from Fiji will stay with me forever. To Molly and Rohan, I am so lucky to have gotten to spend time in Fiji with each of you. Thank you to Stephanie Dohner for teaching me how to fly UAVs. I also want to give credit to the help that my Fiji family provided. Brian Patrick, Morgan Wilbur, Kalo Sadrata, Charlie Pace, Eli Turner, Hannah Quigley and all the Murray’s: you’ve helped me more than you know. Thank you to my mom, my brothers, and my sisters for the love and support over the years. And finally, thank you to Meghan for supporting me and toughing out the long separations during all my research trips throughout undergrad and grad school. I dedicate this thesis to my late father, Gary.
<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES ........................................................................................................ vi</td>
</tr>
<tr>
<td>LIST OF FIGURES ...................................................................................................... vii</td>
</tr>
<tr>
<td>ABSTRACT .................................................................................................................. ix</td>
</tr>
<tr>
<td>Chapter</td>
</tr>
<tr>
<td>1 UTILIZING UNMANNED AERIAL VEHICLES TO DELINEATE ISLAND WATERSHEDS .......................................................... 1</td>
</tr>
<tr>
<td>1.1 Introduction ........................................................................................................ 1</td>
</tr>
<tr>
<td>1.2 Methods ............................................................................................................. 3</td>
</tr>
<tr>
<td>1.2.1 Study Site ..................................................................................................... 3</td>
</tr>
<tr>
<td>1.2.2 Unmanned Aerial Vehicles ........................................................................... 4</td>
</tr>
<tr>
<td>1.2.3 Photogrammetry .......................................................................................... 5</td>
</tr>
<tr>
<td>1.2.4 Watershed Delineation ............................................................................... 6</td>
</tr>
<tr>
<td>1.3 Results ............................................................................................................... 8</td>
</tr>
<tr>
<td>1.3.1 RGB (red-green-blue) Quality Report ...................................................... 8</td>
</tr>
<tr>
<td>1.3.2 Watershed Delineation .............................................................................. 10</td>
</tr>
<tr>
<td>1.4 Discussion ....................................................................................................... 12</td>
</tr>
<tr>
<td>2 UTILIZING UNMANNED AERIAL VEHICLES TO ASSESS TERRESTRIAL COMMUNITIES WITHIN ISLAND WATERSHEDS ....... 15</td>
</tr>
<tr>
<td>2.1 Introduction ..................................................................................................... 15</td>
</tr>
<tr>
<td>2.2 Methods ........................................................................................................... 17</td>
</tr>
<tr>
<td>2.2.1 Comparing Vegetation Across Watersheds .............................................. 17</td>
</tr>
<tr>
<td>2.3 Results ............................................................................................................. 18</td>
</tr>
<tr>
<td>2.3.1 Comparing Vegetation Across Watersheds .............................................. 18</td>
</tr>
<tr>
<td>2.4 Discussion ....................................................................................................... 20</td>
</tr>
<tr>
<td>3 DETERMINING THE IMPACT OF WATERSHED COMPOSITION ON CORAL REEF SPECIES ............................................................................................................. 24</td>
</tr>
<tr>
<td>3.1 Introduction ..................................................................................................... 24</td>
</tr>
<tr>
<td>3.2 Methods .......................................................................................................... 25</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1: Area (m$^2$) covered by each watershed and the percentage of the total island covered by that watershed. ................................................................. 10

Table 2: Proportional areas of terrestrial coverage types split by four categories: Coconut, Native Trees/Shrubbery, Grass, Developed. The proportions were calculated by dividing the total area of each coverage type in each watershed by the total area of the watershed. ......................... 19

Table 3: Number of transects conducted (and area surveyed) within in watershed-reef district, separated by depth location. All transects and depth locations were 10m apart................................................................. 27

Table 4: Functional groups used to categorize transect diversity............................... 29

Table 5: Simpson’s Indices of Diversity for each watershed (±SE) at the species level, genus level and comparing the diversity of the functional groupings. ............................................................................. 30

Table 6: Proportional areas of terrestrial coverage types split by three categories: Coconut, Native Vegetation, Developed. The proportions were calculated by dividing the total area of each coverage type in each watershed by the total area of the watershed........................................ 40

Table 7. Quality reports from processed mosaics in Pix4Dmapper Pro (4.2.27). Optimal standards are set by the software............................................. 54
LIST OF FIGURES

Figure 1: Screenshot from the Pix4D Capture flight app showing an example flight path with photographic markers. Flight was conducted with 80% vertical and horizontal overlap along the gridlines. Flights were conducted between 80m and 100m altitude. All flights were conducted with minimal cloud coverage and with constant irradiance..... 5

Figure 2: Resulting mosaic of Tavewa Island from the processed RGB images. .......... 9

Figure 3: Distribution of the watersheds throughout Tavewa Island. ....................... 11

Figure 4: Stacked bar graph depicting the percent coverage by each coverage type within each of the usable watersheds. ..................................................... 20

Figure 5: Theoretical distribution of belt transects throughout any watershed-reef district. Actual locations and number of transects varied depending on size and shape of the coral reef. .............................................................. 27

Figure 6: Non-metric multidimensional scaling (NMDS) plots comparing the fish and benthos communities across the two sides of the island. ................. 32

Figure 7: Benthic community species biodiversity index for Eastern watersheds (±SE). Watersheds that are significantly different from each other are denoted by different letters (ANOVA, $p < 0.05$). ....................... 34

Figure 8: Benthic community genus biodiversity index for Eastern watersheds (±SE). Watersheds that are significantly different from each other are denoted by different letters (ANOVA, $p < 0.05$). ....................... 35

Figure 9: Benthic community functional group diversity index for Eastern watersheds (±SE). Watersheds that are significantly different from each other are denoted by different letters (ANOVA, $p < 0.05$). ............ 36

Figure 10: Average abundances of corals in the genus *Acropora* within Eastern watersheds (±SE). Watersheds that are significantly different from each other are denoted by different letters (Kruskal-Wallis, $p < 0.05$) . 37

Figure 11: Species biodiversity index for fish community within Western watersheds (±SE). Watersheds that are significantly different from each other are denoted by different letters. ............................................. 39

Figure 12: Resulting mosaic of Tavewa Island from the processed near-IR images. .. 59
Figure 13: Resulting color-IR mosaic from the combined RGB and near-IR mosaics. .............................................................. 60

Figure 14: Example of an optimal transect (dashed red line) for conducting salinity profiles. Each black bar is 5m apart and represents locations for taking readings with a CTD. The yellow line represents the reef crest.............. 63

Figure 15: Example mixing curves over time for salinity profiles taken at five different time points. Curves assume baseline salinity for the seawater is 32ppt, while the rainwater salinity is 3ppt................................. 64

Figure 16: Workflow diagram for delineating watersheds within ArcPro. The watershed delineation workflow begins with uploading the Digital Surface Model (DSM) Raster and utilizes raster tools (yellow boxes) located within the Hydrology toolbox. Blue circles are created by the user (DSM Raster created in Pix4D). Green circles are the output results from each tool. ................................................................. 66

Figure 17: Workflow diagram for conducting Object-Based Image Analysis (OBIA) within ArcPro. The OBIA workflow begins with uploading the RGB and near-IR mosaics and utilizes raster functions (yellow boxes). Blue squares are created by the user (RGB and near-IR mosaics created in Pix4D; manually classified training sample created in ArcPro). Green boxes are the output result from the previous raster function. The blue circle is the end product of the workflow. ............... 67
ABSTRACT

Anthropogenic impacts on coastal ecosystems can be pervasive as humans alter the natural environment to suit their needs. A common alteration that coastal communities make to the environment is the removal of native vegetation in order to grow crop plants. The use of fertilizers on these crops can also harm coastal ecosystems through the discharge of non-point source pollution via watershed runoff. Rainwater passes through watersheds and carries a variety of chemicals from the terrestrial systems into aquatic coastal ecosystem. Chemical cues produced by crop plants, such as coconut, have been shown to negatively impact coastal coral reef communities through negative behavioral changes in coral reef fish. This thesis assessed the influence that vegetation community composition within a watershed has on the biodiversity of coastal coral reef ecosystems. First, unmanned aerial vehicles were utilized to map an island in Fiji and delineate the watersheds of the island. Next, machine learning algorithms classified the vegetation communities within those watersheds. This allowed the coverage of vegetation types to be quantified within each watershed. Finally, the coral reefs surrounding the island were separated based on the corresponding upland watershed. The biodiversities of those coral reefs were compared to reveal that watersheds containing coconut (which produces a repulsive chemical cue) did not negatively impact the health of adjacent coral reefs, when those watersheds were also dominated by native vegetation. The findings in this thesis provide evidence that, in the case of negative chemical cues produced by coconut, native vegetation has the potential to overpower the coconut and mitigate any harmful effects. This work furthers the idea that the relationship between land and sea is dynamic, and community-scale approaches should
be utilized when assessing the impacts of terrestrial ecosystems on coastal coral reef communities.
Chapter 1

UTILIZING UNMANNED AERIAL VEHICLES TO DELINEATE ISLAND WATERSHEDS

1.1 Introduction

Historically, societies held the notion that the ocean was a vast space, unable to be affected by human activities. This ideal led to a variety of anthropogenic disturbances to marine ecosystems, such as overfishing (Jackson et al. 2001), hazardous waste dumping (Povinec et al. 2000), and terrestrial runoff (Delavaux et al. 2018). The latter has been studied extensively to assess the impact of terrestrial based activities on coastal marine ecosystems; and over the last few decades, the global framework of coastal management has shifted towards an understanding that terrestrial, anthropogenic activities can produce chronic consequences on marine ecosystems (Salen-Picard et al. 2003, Muniz et al. 2013, Hyndes et al. 2014, Delevaux et al. 2018). Society has begun to understand the mechanisms behind land and sea interactions and how terrestrial inputs may influence the health of coastal ecosystems.

Sources of input do not have to be located directly on the shoreline to influence a coastal ecosystem because of hydrologic flow through watersheds. A watershed is an area of land in which all water flowing through it empties into the same place (Gönenç et al. 2007). As water flows through a watershed towards the sea, it can carry any sediments or chemicals from the land into the sea. Sedimentation and pollution are among the most influential and pervasive terrestrial processes that cause harm to
coastal marine ecosystems. These processes do naturally occur, yet they are often exasperated by anthropogenic changes to the environment.

Both point and nonpoint sources of terrestrial inputs can have severe negative impacts. The Clean Water Act of 2014 (EPA) defines point source pollution as:

“any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural storm water discharges and return flows from irrigated agriculture.” Section 502(14)

Nonpoint source pollution is any source of pollution that does not met the criteria for point source pollution defined above. Common nonpoint sources of pollution include, but are not limited to, fertilizer runoff, urban runoff, and anthropogenic sedimentation (Howarth 2008, Burke et al. 2018). Both point and nonpoint sources of pollution are regulated in the United States, but regulation of nonpoint sources is extremely difficult as their sources of origin are impossible or difficult to locate (Carpenter et al. 1998). Instead, the use of specific harmful agents, such as DDT or excess fertilizer, has been limited on large scales.

Understanding watershed dynamics can provide valuable information when trying to regulate nonpoint sources of pollution. For example, fertilizer runoff from Minnesota flows through various watersheds into the Mississippi River (Turner and Rabalais 2003). These fertilizers make their way south into the Gulf of Mexico, where the increased nutrient load leads to eutrophication and seasonal dead zones (Rabalais et al. 2002). Even though the exact source of pollution (specific farm, for example) may not be identifiable, determining terrestrial flow patterns through watersheds can help management efforts mitigate pollution effects (Sharpley and Meyer 1994).
Coral reefs are often shallow, coastal ecosystems which provide valuable services to coastal human populations, and therefore are tightly linked to anthropogenic activities. Coral reefs provide millions of annual dollars through a variety of ecosystem services ranging from coastal protection, fisheries, and tourism (Barbier et al. 2011). Due to the intricate relationships human communities have developed with coral reefs and their close proximity to large populations, coral reefs are often subjected to heavy anthropogenic influences. Ranging from overfishing, mechanical damage, and to pollution, coral reefs experience pressure from coastal human populations (Hughes et al. 2003, Bellwood et al. 2004, Barbier et al. 2011, Delevaux et al. 2018).

Nonpoint sources of pollution have been shown to negatively impact coral reefs (Singh et al. 2009, Kroon et al. 2016). The objective of this chapter is to assess the locations of the watersheds throughout Tavewa Island, a small island in the Yasawas archipelago of Fiji. This is the first step in understanding how nonpoint sources of pollution on the island may impact the health of the coral reefs below. After knowing where the watersheds are located throughout the island, potential sources of terrestrial impacts on coral reefs can be identified.

1.2 Methods

1.2.1 Study Site

All automated flight surveys were conducted over Tavewa Island, Yasawas, Fiji (-16.925783, 177.359108) using commercially available unmanned aerial vehicles (UAVs). This island was selected because it was small enough to allow for mapping via UAVs. Tavewa Island was surrounded by easily accessible, near-shore, shallow (<
30 m) fringing coral reefs making it ideal for the underwater surveys as described in Chapter 3.

1.2.2 Unmanned Aerial Vehicles

Flights were conducted using a DJI Phantom 4 quadcopter with a 4K red/green/blue (RGB) camera. Thirty-one automated flights were programmed using the Pix4D Capture app with ≥80% vertical and horizontal overlap along the gridlines (Figure 1). Ground control points were not used as the island terrain prevented the placement of markers. All flights were conducted between 13 July and 27 July 2017.
Figure 1: Screenshot from the Pix4D Capture flight app showing an example flight path with photographic markers. Flight was conducted with 80% vertical and horizontal overlap along the gridlines. Flights were conducted between 80m and 100m altitude. All flights were conducted with minimal cloud coverage and with constant irradiance.

1.2.3 Photogrammetry

Photographs collected by UAVs were stitched together to make composite images via a process known as photogrammetry. All photographs were processed using Pix4Dmapper Pro (4.2.27) software. Pix4D stitches the photographs together using tie points (common pixels between photographs) within neighboring photographs, each embedded with GPS coordinates at the moment of capture. The
software then created a mosaic and a digital surface from the stitched together RGB photographs.

### 1.2.4 Watershed Delineation

The digital surface model created from the RGB images was used to separate the island into watersheds utilizing ArcMap (version 10.5.1). The elevations within the digital surface model created from the first surface encountered by the camera. Therefore, tree height influenced pixel elevation. Due to this restriction, the Southwestern half of Tavewa was removed from the analysis, as distinct watershed lines could not be obtained (Figure 3). Ground-truthing revealed that the areas of Tavewa that were utilized for this project have minimal canopy coverage, and therefore any elevation-based watershed delineation is reliable. To account for the elevation of man-made structures, the densified point clouds were edited. For example, the Coralview Island Resort influenced the digital surface model by affecting the relative elevation of that area. The densified point cloud was edited so that the points corresponding to the resort were removed. This created a more accurate digital surface model that was more representative of the island’s true elevation.

The Hydrology toolbox within ArcMap was used to delineate watersheds based on the digital surface model (Appendix D). First, any imperfections were removed from the digital surface model to create a depressionless digital surface model using the **Fill** tool. Next, using the **Flow Direction** tool, a flow direction grid was added. This created a 3x3 grid around each pixel wherein each cell was assigned a numerical value that denoted the direction water entering that cell would travel. The flow direction grid was then further processed with the **Flow Accumulation** tool. This tool
calculated the flow into each cell by accumulating all the upstream cells flowing into it.

The resulting layer was symbolized so that areas of high flow stood out and selected in the next step. A significant amount of adjusting was required in this step. Within the “layer properties” pane, and underneath the “classified” tab, the number of classes was set to “two.” These classes essentially represent either theoretical flow channels or land that drains into those channels. Selecting the button, “classify” next to the classes served to delineate those theoretical flow channels. Within this step, it was necessary to change the “break value.” Determining the break value was a judgment call and eventually set to 1,000. This means that cells having more than 1,000 upstream cells flowing into them will be classified differently than cells having less than 1,000 upstream cells flowing into them. These cells (> 1,000) are classified as the channels within the terrain. This break value required trial and error to achieve, and judgements were made based on reasonable amounts of channels. It was discovered, for example, that a break value < 500 resulted in far too many channels to achieve reasonable delineation, while a break value of > 1,500 resulted in too few.

Cells within those channels and with high flow along the edge of the island were haphazardly selected and added to a new shapefile using the Create Feature function in the editing menu. These cells were then uploaded into the Snap Pour Point tool that removes any human error during placement by snapping to the nearest cell with the highest flow accumulation. Finally, the snapped pour point rasters, along with the flow direction grid, were inputted into the Watershed tool. The Watershed tool was the last step in delineating watersheds based on elevation changes. This tool determines where and how water will flow through the terrain to reach the pour points.
It utilizes the flow direction grid to essentially work backwards from the pour points, flowing up the elevation, and stopping once the elevations shift back downwards. All terrain within that flow direction grid is considered to be one watershed.

1.3 Results

1.3.1 RGB (red-green-blue) Quality Report

Standards for mosaic quality were preset by the Pix4D software (Pix4D Support). The software assessed four areas of processing while determining the quality of the mosaics: calibration percentage, median keypoints and median matches per calibrated image, relative difference between initial and optimized camera parameters, and mean geolocation error across all planes. Images use tie points—common points between images as a result of overlap—to calibrate the images in reference to each other. These tie points were then converted into keypoints and were given (X, Y, Z) coordinates. The software then attempted to match each keypoint a respective keypoint in an adjacent image. Camera optimization corrected for errors of distortion and set standards for heights, widths, and sizes of image pixels. Smaller camera optimization values indicated low image blur (due to flight speeds that are too fast) and constant sun irradiance across flights. Finally, the mean error was calculated between each pixel in each (X, Y, Z) plane.

The RGB mosaic (Figure 2) quality exceeded the standards for keypoints, matches, and geolocation error, while falling slightly short calibrated image and camera parameter percentages (Appendix B). The average ground sampling distance was 5.25 cm between each pixel indicating a high spatial resolution (5.25 cm/px).
Figure 2: Resulting mosaic of Tavewa Island from the processed RGB images.
1.3.2 Watershed Delineation

A digital surface model was generated in Pix4Dmapper Pro (4.2.27) from the RGB processing. The watershed delineation revealed seven distinct watersheds throughout the northern half of Tavewa Island (Figure 3): three on the western side (facing open ocean), three on the eastern side (facing nearby islands), and one on the northern most tip (facing nearby islands). The usable portion of the island encompassed 0.665km$^2$ (41% of the total island), while the unusable portion encompassed 0.959km$^2$ (59% of the total island). The watersheds vary in size and ranged from 0.061km$^2$ to 0.148km$^2$ (Table 2).

Table 1: Area (m$^2$) covered by each watershed and the percentage of the total island covered by that watershed.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (m$^2$)</th>
<th>Percent of total island</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>91,000</td>
<td>5.62%</td>
</tr>
<tr>
<td>West A</td>
<td>90,000</td>
<td>5.56%</td>
</tr>
<tr>
<td>West B</td>
<td>128,000</td>
<td>7.89%</td>
</tr>
<tr>
<td>West C</td>
<td>70,000</td>
<td>4.35%</td>
</tr>
<tr>
<td>East C</td>
<td>74,000</td>
<td>4.57%</td>
</tr>
<tr>
<td>East B</td>
<td>60,000</td>
<td>3.70%</td>
</tr>
<tr>
<td>East A</td>
<td>147,000</td>
<td>9.07%</td>
</tr>
<tr>
<td>Unused</td>
<td>959,000</td>
<td>59.24%</td>
</tr>
</tbody>
</table>
Figure 3: Distribution of the watersheds throughout Tavewa Island.
1.4 Discussion

The photogrammetry and post-processing revealed seven useful watersheds on the northern half of Tavewa Island (Figure 3). Not being able to utilize the southern half was acceptable for our purposes as the distinct elevation changes in the northern half resulted in highly accurate delineation from the digital surface model. As the watersheds were also split into three groups based on external factors—draining west (towards open ocean), draining east (towards neighboring islands), and draining north (towards neighboring islands)—future analyses will need to factor in these directionalities when assessing their influences on coastal coral reefs. Underwater currents, surface wave actions, and potential differences in rainfall due to the island effect may confound comparisons between groups. The East A watershed also has the distinction of being occupied by a resort. While resort runoff/sedimentation is not the focus of this project, anthropogenic construction does influence watershed vegetation compositions.

There are two main types of terrestrial water discharge that may influence the nearshore coral reefs: watershed runoff and groundwater discharge. To our knowledge, there is no known documented information about the groundwater system of Tavewa Island; however, underwater aquifers are utilized by island residents for household water needs.

Tavewa is a volcanic island, and therefore is composed of porous, volcanic rock. Due to the nature of the island’s substrate, some rainfall within each watershed will be absorbed through the ground and become groundwater. As ground water mixes into the island aquifer, excess water flows outward and drains into the ocean. Groundwater influence may impact coral reef health, as chemicals can become absorbed into the groundwater and runoff into ocean systems (Stoate et al. 2001).
However, volcanic island systems tend to experience heavy rainfalls and extreme storm events due to the effect of island elevation. Storm systems can become trapped by the extinct volcano’s peaks in elevation. This island effect results in high levels of precipitation during prolonged storm events. Therefore, while groundwater discharge may disperse any absorbed chemicals, it is likely that rain runoff carries more absorbed chemicals into the surface waters of nearshore coral reef ecosystems. Also, within the confines of this study, it is not possible to know where exactly Tavewa Island’s groundwater discharges. It is possible that the groundwater discharges past the end point of nearshore coral reefs. For the purposes of this study, we operated under the likely assumption that if a groundwater influence does exist, it is overshadowed and less influential than rainwater runoff.

Rainwater runoff has a direct and immediate interaction with terrestrial influence before draining into the nearshore coral reef ecosystems. In order to understand the impact of the island’s terrestrial system on coral reefs, the watersheds needed to first be identified. As a watershed is an area of land where all water drains into the same place (Gönenç et al. 2007), it is reasonable to assume that ubiquity exists within each watershed. For example, the runoff from a resort will impact the entire drainage area. Therefore, simply understanding the locations and extents of the watersheds provides valuable information that can guide future endeavors.

These considerations become increasingly important when debating management and policy decisions. Legislation exists within the USA to regulate and limit pollution into coral reefs (EPA). The Clean Water Act has been extended to protect coral reefs from both point source and nonpoint source pollution that occur in watersheds that drain into coral reefs. Nonpoint sources, such as nutrient runoff from
farming communities in Florida were shown to negatively affect the coastal communities within the respective drainage basins. In 2005, Fiji passed the Environment Management Act (EMA), which brought about strict policies and penalties for point source pollution (Madraiwiwi 2005). However, we could find no language that regulated nonpoint source pollution, such as chemicals absorbed through rainwater falling within a watershed. Delineating the watersheds within Tavewa Island will allow for a better understanding of how watershed composition can affect coral reef health through nonpoint source influences.

In this chapter, unmanned aerial vehicles were utilized to successfully delineate seven watersheds on Tavewa Island. Using these methods, we can move forward and assess each watershed’s nonpoint sources’ influence on coral reef ecosystems and inform management decisions. As Fiji’s EMA does not account for these types of impacts on coral reefs, it is critically important to link the watershed’s influence with the health of the coral reefs within its drainage basin. The next two chapters will fill that knowledge gap by furthering the understanding of land-sea interactions from a watershed basis.
Chapter 2

UTILIZING UNMANNED AERIAL VEHICLES TO ASSESS TERRESTRIAL COMMUNITIES WITHIN ISLAND WATERSHEDS

2.1 Introduction

It is critically important to gain a better understanding of the influence terrestrial watersheds may have on coral reef ecosystems. Currently most literature focuses on the detrimental effects of terrestrial systems, namely excess sediment and nutrient run-off. In Papua New Guinea, the practice of clear-cutting islands for palm oil crops was found to cause significant degradation in over 60% of the adjacent coral reefs (Tulloch et al. 2016). Models constructed demonstrated that if palm oil was sustainably planted, rather than clear-cutting, only a slight improvement in coral reef health was predicted due to the run-off contaminated with pollutants from the plantations (Tulloch et al. 2016). Chemical compounds used in crop plantations can significantly reduce the health of near-shore coral reefs when rainwater carries them into the ocean (Oliver et al. 2011, Linan-Cabello et al. 2016). In light of this and other data highlighting the negative impact of terrestrial runoff, management strategies tend to only consider the negative impacts of terrestrial systems on the marine environment.

Although anthropogenic changes to watersheds usually have a negative influence on aquatic environments, not all terrestrial influences have a negative impact. Riparian zones can provide positive ecological services through nutrient sequestration and storm protection (Hession et al. 2000). Management efforts that focused on restoring riparian zones back to their natural states increased the health and biodiversity of downstream aquatic ecosystems (Lyons et al. 2000). Conversely, transitioning from native to crop vegetation within riparian zones in Papua New Guinea resulted in a loss of storm protection and a decrease in the biodiversity of
downstream coral reefs. Corporate and small family plantations replaced native trees with palm oil within riparian zones on various islands.

Native vegetation within watersheds provides more than protection from storms and excess nutrient runoff. Native vegetation provides critical chemical cues that, when washed into coral reefs, are utilized by coral reef fish. Most coral reef organisms have a dispersal pelagic larval phase in which newly hatched larvae leave the reef to undergo development (Thorson 1950, Jones et al. 1999). This dispersal phase can last from weeks to months, depending on the species (Almany et al. 2007, Munday et al. 2009). Once development is complete, the settlement stage larvae must relocate to a suitable reef to reside on during the juvenile and adult stage (Leis 2007). Settlement-stage fish use their highly developed olfactory systems to gauge whether a reef will improve its chances for survival (Atema et al. 2002, Gerlach et al. 2007, Lara 2008). Larval reef fish exhibit an innate response to olfactory cues from natal island vegetation while seeking out suitable reef habitats (Dixson et al. 2008, Dixson et al. 2014). The anemonefish, *Amphiprion percula*, have been found to positively respond to the chemical cues from at least five native, near-shore plants (Dixson et al. 2008, Dixson et al. 2014). These findings are significant because as coral reefs begin to decline in health, and transition towards algal dominated systems (Hughes et al. 2010), larval coral reef fish may come to rely more heavily on cues originating from terrestrial systems for finding suitable habitat.

One explanation behind terrestrial cues playing an important role in recruitment is because coral reef fish larvae are phototactic and thus remain near the surface while migrating from the pelagic environment to the coral reef (Kamler 1992). In the Indo-Pacific, the recruitment season for larval coral reef fish coincides with the
rainy season: October to April (Srinivasan and Jones 2006). Here, they are expected to encounter rainwater runoff as it flushes off the island over the reef. Therefore, terrestrial cues from the near-shore vegetation could provide vital signals to larval coral reef fish during recruitment. The cues can play a role in guiding the fish towards suitable settlement habitats. However, this also means that as terrestrial environments are changing, the cues that larval coral reef fish use will for navigation also change.

Unpublished data reveals that some recruiting coral reef fish exhibit a strong repulsion towards crop plants that are common in the Fijian regions (coconut and mahogany--Dixson, personal communication). The fish actively avoid water containing chemical cues from those crop plants while being attracted towards water containing chemical cues from native island vegetation. Since rainwater that passes through watersheds will absorb the chemical cues from inhabiting vegetation and wash leaf litter into the marine system, the vegetation composition of a watershed can have a direct impact on the behavior of recruiting coral reef fish. This chapter aims to determine the vegetation composition of Tavewa Island so that watersheds may be assessed for the risk or benefit they pose towards coral reefs.

2.2 Methods

2.2.1 Comparing Vegetation Across Watersheds

Once the watersheds were delineated, the vegetation types and densities located in each usable watershed were assessed. Coverage types were manually classified by creating polygons within ArcPro (version 2.2.1) over each coverage class (coconut, native trees/shrubbery, developed area, and grass) and within each
watershed. 100% of land within each watershed was classified into one of the four coverage types.

Using the *Calculate Geometry* tool, ArcPro calculated the area (m$^2$) of each polygon. The area of all polygons of the same coverage types and within the same watershed were then added together. The sum of those areas was divided by the sum of all polygons within a single watershed to achieve the percent of coverage for each coverage type. For example:

$$\% \text{ coverage of coconut within Watershed East} = \frac{\Sigma (\text{area of all polygons for coconut within Watershed East})}{\Sigma (\text{area of all polygons for all coverage types within Watershed East})} \times 100\%$$

### 2.3 Results

Due to the issues associated with identifying watershed locations on the Southern half of Tavewa Island, only vegetation within the usable watersheds were identified. Locals report that a variety of crop plants are grown on the island, including coconut, breadfruit, mango, papaya, and taro root. However, none are grown within the watersheds that are used in this study except coconut. Therefore, only coconut plants were identified during this study, and all other vegetation types were categorized as either grass, native shrubbery, or native hardwood tree.

#### 2.3.1 Comparing Vegetation Across Watersheds

Within ArcPro, the proportion of area occupied by each coverage type was recorded (Figure 4, Table 3). The proportions were used rather than absolute area coverage to account for the different sizes in the watersheds. The North watershed was left out of analysis due to two main factors: 1) It is the only watershed facing north; therefore, no other watersheds exist to compare and, 2) The underwater currents
occurring in the coral reef adjacent to North’s watershed were too strong and prevented underwater belt transects (described in Chapter 3) from being conducted.

The eastern watersheds (East A, East B, and East C) were all dominated by native trees/shrubbery (between 72.7% and 88.9%). The East C watershed has 1.7 times more proportional coconut coverage than the East B watershed and 2.43 times that of the East A watershed. It also has 3.15 times more proportional grass coverage of the East B watershed and 3.27 that of the East A watershed. There was a small amount of developed area in each of the three watersheds, with East A having the largest (a resort).

The western watersheds (West C, West B, and West A) have a variety of coverage proportions. Neither the West A nor the West B watersheds have coconut and no Western watershed has any developed area. The West C watershed is over 95% grass and has very little native trees/shrubbery, yet the West B watershed is about 53% native trees/shrubbery and 47% grass. The West A watershed is also dominated by native trees/shrubbery (92.2%) and is the only Western watershed to have coconut.

Table 2: Proportional areas of terrestrial coverage types split by four categories: Coconut, Native Trees/Shrubbery, Grass, Developed. The proportions were calculated by dividing the total area of each coverage type in each watershed by the total area of the watershed.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Coconut</th>
<th>Native Trees/Shrubbery</th>
<th>Developed</th>
<th>Grass</th>
</tr>
</thead>
<tbody>
<tr>
<td>East A</td>
<td>0.7%</td>
<td>81%</td>
<td>9.9%</td>
<td>7.8%</td>
</tr>
<tr>
<td>East B</td>
<td>1%</td>
<td>88.9%</td>
<td>2%</td>
<td>8.1%</td>
</tr>
<tr>
<td>East C</td>
<td>1.7%</td>
<td>72.7%</td>
<td>0.06%</td>
<td>25.5%</td>
</tr>
<tr>
<td>West A</td>
<td>2.7%</td>
<td>92.2%</td>
<td>0</td>
<td>2.5%</td>
</tr>
<tr>
<td>West B</td>
<td>0</td>
<td>52.8%</td>
<td>0</td>
<td>47.2%</td>
</tr>
<tr>
<td>West C</td>
<td>0</td>
<td>5%</td>
<td>0</td>
<td>95%</td>
</tr>
</tbody>
</table>
2.4 Discussion

Exactly what influence vegetation may have on the near-shore coral reef ecosystems cannot be determined by simply identifying vegetation types within different watersheds. However, understanding the geographic locations and the coverage types within those watersheds provides information on where to focus efforts moving forward. If correlated to reef health (investigated in Chapter 3), vegetation coverage types could also be used to make predictions on coral reef biodiversity and health.

Most coral reef animals have a bipartite life cycle wherein they develop in pelagic waters and then migrate back to coral reefs once reaching the settlement-stage. These fish utilize chemical cues from the environment to orient themselves and seek
out suitable habitat. The chemical cues can be from the benthic coral community such as corals but could also originate from the terrestrial landscape.

Because of the influence that terrestrial vegetation can exhibit on coral reef animal behavior, it is now important to look at a watershed and the adjacent coral reef as a single unit. Hereafter we will refer to these units as “watershed-reef districts,” defined as a terrestrial watershed and the area of a coral reef that received runoff from that watershed. Thinking of watersheds and coral reefs as a single system can provide valuable information about the factors that influence the coral reefs.

Each of the usable watersheds surrounding Tavewa Island provides its adjacent coral reef with a distinct mixture of chemical cues from terrestrial vegetation. Understanding the vegetation composition of the watersheds helps guide the questions to ask when assessing the coral reef communities. As the usable watersheds were split into two groups based on external factors—draining west (towards open ocean) and draining east (towards neighboring islands) and draining north (towards neighboring islands)—future analyses will need to factor in these directionalities when assessing their influences on coastal coral reefs. Underwater currents, surface wave actions, and potential differences in rainfall due to the island effect may confound comparisons between groups.

The western watersheds had very interesting differences in the coverage patterns and percentages. For example, the West B watershed was the only western watershed containing coconut trees, yet also had the highest proportion of native trees/shrubbery. Also, while 95% of the West C watershed is covered by grasses, the West A watershed was almost an even split of native trees/shrubbery and grasses. Does the large coverage of native trees/shrubbery (attractive chemical cues) outweigh
the influence of the coconut (repulsive chemical cues) in the West B watershed? How does the influence of a watershed that is dominated by grasses while lacking native tree/shrubbery and coconut compare to a watershed also lacking coconut but containing even amounts of native trees/shrubbery and grasses? As these grass species were not assessed for their chemical cues use in fish settlement (Dixson, personal communication), comparing these watershed-reef districts may point to whether grass provide attractive, repulsive, or neutral chemical cues.

It is unknown whether the grass species on Tavewa Island is native or non-native. In order for the grass to be non-native, there would have to have been a vector for dispersal of an invading grass species. One possible dispersal vector is the large goat population (>100 individuals) that inhabit Tavewa Island. Goats are extremely adept at dispersing seeds through their waste, and the introduction of goats to island systems have resulted in numerous invasions of plant species (Treitler et al. 2017). Historically, goats have been introduced to islands across the globe by explorers to serve as food sources during their travels (Atkinson 1989, Hannon and Bradshaw 2000). Locals on Tavewa Island report goats living on the island for at least 50 years, though it is likely they’ve been present for longer. Therefore, it is unknown whether the grass present on Tavewa Island is a native species or was introduced via the goat population.

An equally interesting pattern of coconut coverage is present within the eastern watersheds, wherein the largest coverage of coconut coincides with the largest proportion of grass and the lowest proportion of developed land—the East C watershed. However, unlike the western watersheds, all eastern watersheds contain some coconut coverage while all being dominated by native trees/shrubbery. Also, all
Eastern watersheds contain some percentage of developed land, with the East A watershed having the largest percentage due to a resort located at the base of the watershed.

In Chapter 1, we were able to identify the watersheds found on Tavewa island. Due to restrictions in our equipment (not being able to confidently identify the southern watersheds on the island) and known physical differences in the watershed location (those found facing eastern, western or northern), we have successfully created two independent replicate groups consisting of three watersheds within each replicate for comparative purposes. Here, in Chapter 2, we were able to identify the vegetation type within each of the usable watershed replicates. Lastly, to successfully understand the impact terrestrial vegetation has on the adjacent coral reef, the coral reefs must be surveyed and correlations between vegetation type and the adjacent reef community must be made; this is the primary focus of Chapter 3.
Chapter 3

DETERMINING THE IMPACT OF WATERSHED COMPOSITION ON CORAL REEF SPECIES

3.1 Introduction

Biodiversity is critically important as higher diversities result in ecosystems being more robust to intermediate disturbance events. From reducing the negative impacts of natural disasters to reducing the proliferation of invasive species, diverse ecosystems are more apt to survive throughout time (Hobbs and Huenneke 1992, Barbier et al. 2011). Biodiversity becomes especially important when considering the future implications of natural communities in the face of climate change. Coral reefs, for example, are experiencing a loss of biodiversity as climate change shifts the community structure to those species that are more resilient to increasing temperature and acidification (Hughes et al. 2003). However, the homogenization towards those species leads to a decrease in resilience due to an unbalanced trophic pyramid resulting in trophic cascades, problematic species outbreaks, extreme nutrient loading, and storm events (Bellwood et al. 2004).

High coral reef biodiversity is commonly correlated with coral reef health (Jones et al. 2004). Assessing the marine communities, with an emphasis on coral species and coral reef fish, can provide information on the state of a coral reef. A diverse assemblage of corals can lead to a complex community of associated reef organisms (Tews et al. 2004). High populations of diverse coral reef fish in turn can also impact the biodiversity of the benthic community and can also indicate a high quality coral reef, because recruiting fish tend to seek out the most favorable settlement habitat (Atema et al. 2002, McCormick et al. 2010, Dixson et al. 2014).

24
Coral reefs are not only diverse in the species compositions, but also have high levels of functional group diversity (Bellwood et al. 2004). Functional groups consist of a variety of species that perform similar roles regardless of their taxonomic relationships (Steneck and Dethier 1994), for example acanthurids (tangs), many echinoderms species and scarids (parrotfish) are all functionally redundant herbivores. Functional group diversity is especially important in coral reef ecosystems that are influenced by human activities, such as fishing pressure. The inclusion of functional redundancy allows one species to go extinct, without the collapse of the system as other species within the same functional group can continue to fulfill the role (Bellwood et al. 2004).

This chapter brings the results of Chapter 1 and Chapter 2 together within the context of biodiversity to answer the overarching question of this thesis: *Does terrestrial vegetation influence the health of adjacent coral reefs?*

### 3.2 Methods

#### 3.2.1 Watershed-Reef Districts

The reefs around Tavewa Island were split into sections based on an extension of the upland watershed. These segments have been referred to as watershed-reef districts. A watershed-reef district was defined as an area of coral reef that receives rainwater runoff from the adjacent upland watershed.

#### 3.2.2 Underwater Surveys

Underwater belt-transect surveys provide reliable information on the population of organisms within a coral reef (Beck et al. 2014), transects were used here to determine the community composition of associated coral reefs in identified
watershed-reef districts. Conducting belt transect surveys within watershed-reef districts provided species richness, species abundance and species diversity data for both benthic and free-swimming organisms.

Transects were conducted throughout all the Eastern (East A, East B, and East C) and Western (West A, West B, West C) watershed-reef districts. Ideally, fifteen 25m transects within each watershed-reef district were conducted; however, if watershed-reef districts were small or oddly shaped, the number of transects were altered to achieve approximately 25% of the reef surveyed (Table 4). To account for spatial differences in the reef community, transects within each watershed district were conducted at three different distances from shore, 1) along the reef crest, 2) 10m inshore of the reef crest and 10m offshore of the reef crest (Figure 5). All transects were conducted with 10m of un-surveyed reef between each other transect replicate.
Figure 5: Theoretical distribution of belt transects throughout any watershed-reef district. Actual locations and number of transects varied depending on size and shape of the coral reef.

Table 3: Number of transects conducted (and area surveyed) within in watershed-reef district, separated by depth location. All transects and depth locations were 10m apart

<table>
<thead>
<tr>
<th>Watershed-reef district</th>
<th>Shallow</th>
<th>Middle</th>
<th>Deep</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>West A</td>
<td>6 (300m²)</td>
<td>6 (300m²)</td>
<td>7 (350m²)</td>
<td>18 (950m²)</td>
</tr>
<tr>
<td>West B</td>
<td>2 (100m²)</td>
<td>2 (100m²)</td>
<td>4 (200m²)</td>
<td>8 (400m²)</td>
</tr>
<tr>
<td>West C</td>
<td>5 (250m²)</td>
<td>4 (200m²)</td>
<td>4 (200m²)</td>
<td>13 (650m²)</td>
</tr>
<tr>
<td>East C</td>
<td>5 (250m²)</td>
<td>5 (250m²)</td>
<td>5 (250m²)</td>
<td>15 (750m²)</td>
</tr>
<tr>
<td>East B</td>
<td>3 (150m²)</td>
<td>3 (150m²)</td>
<td>2 (100m²)</td>
<td>8 (400m²)</td>
</tr>
<tr>
<td>East A</td>
<td>5 (250m²)</td>
<td>5 (250m²)</td>
<td>5 (250m²)</td>
<td>15 (750m²)</td>
</tr>
</tbody>
</table>

All fish within 1 m of either side of the transect tape were identified to the lowest taxonomic level. Benthic cover was quantified using 50 haphazardly, pre-placed points on the transect tape (Jones et al. 2004, Roberts et al. 2016). Benthic
species under each point were recorded to lowest taxonomic level; those that could not be identified in situ were identified using a photograph. All benthic components were inspected for crypto benthic species living within the substrate.

3.2.3 Simpson’s Index of Diversity

Diversity indices were calculated based on Simpson’s index of diversity, a common measurement to assess the diversity of natural communities (Simpson 1949, Lande 1996, Easson et al. 2015). Three sets of diversity indices were calculated for both the fish and benthic communities within each watershed: true biodiversity encompassing all species (as well as rubble, sand, and algae for benthic surveys), biodiversity of those communities when assessed at the genus level (as well as rubble, sand, and algae for benthic surveys), and diversity of communities based on functional group (Table 5). For fish species, preferred diet was used to separate functional groups. While many species can act omnivorous when a preferred food source is unavailable, or accidently consume something in the process of the consumption of a preferred source (e.g. consuming small crustaceans living within algal diet), the preferred target prey was used as the categorical variable. Simpson’s index of diversity (\( p_i \)) was calculated for each transect using the following equation, where \( S \) is the abundance of that species, genus, or functional group:

\[
p_i = 1 - \lambda, \quad \text{where} \quad \lambda = \frac{\sum [(S_1 * (S_1 - 1)) + (S_2 * (S_2 - 1)) + (S_i * (S_i - 1))]}{[\sum (S_1 + S_2 + S_i)] * [(\sum (S_1 + S_2 + S_i)) - 1]}
\]
All three sets of diversity indices were calculated for each fish and benthic community within each transect. The average diversity index with standard errors for fish and benthic communities were calculated for all usable watersheds.

Table 4: Functional groups used to categorize transect diversity

<table>
<thead>
<tr>
<th>Benthos</th>
<th>Fish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubble</td>
<td>Predator</td>
</tr>
<tr>
<td>Sand</td>
<td>Herbivore</td>
</tr>
<tr>
<td>Branching coral</td>
<td>Omnivore</td>
</tr>
<tr>
<td>Brain coral</td>
<td>Spongivore</td>
</tr>
<tr>
<td>Mounding Coral</td>
<td>Corallivore</td>
</tr>
<tr>
<td>Cabbage coral</td>
<td>Planktivore</td>
</tr>
<tr>
<td>Plate coral</td>
<td>Detritivore</td>
</tr>
<tr>
<td>Fan Coral</td>
<td>Lepidophagivore</td>
</tr>
<tr>
<td>Soft coral</td>
<td></td>
</tr>
<tr>
<td>Algae</td>
<td></td>
</tr>
</tbody>
</table>

3.2.4 Comparing Watershed-Reef Districts Based on Terrestrial Composition

Diversity indices from each transect was uploaded into RStudio (3.4.4 - “Someone to lean on”). ANOVAs, with Tukey post-hoc tests when appropriate, were conducted to determine the difference if the variation within each diversity index was explained by the variation within each watershed composition. Shapiro-Wilk tests were conducted to confirm the data were normally distributed. For those data sets that were not normally distributed, the non-parametric Kruskal-Wallis test was conducted with Dunn post-hoc tests where appropriate.
3.3 Results

3.3.1 Simpson’s Index of Diversity

Throughout all surveyed watershed-reef districts, 192 different fish species were identified spanning across 89 genera; and 85 different coral species were identified spanning across 32 genera. Three versions of Simpson’s Indices of Diversity were calculated with one standard error for all watersheds based on species, genera, and functional groups (Table 6).

Table 5: Simpson’s Indices of Diversity for each watershed (±SE) at the species level, genus level and comparing the diversity of the functional groupings.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Biodiversity (species)</th>
<th>Biodiversity (genus)</th>
<th>Functional diversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>East A</td>
<td>0.880 ± 0.011</td>
<td>0.856 ± 0.013</td>
<td>0.667 ± 0.022</td>
</tr>
<tr>
<td></td>
<td>0.365 ± 0.071</td>
<td>0.334 ± 0.061</td>
<td>0.342 ± 0.062</td>
</tr>
<tr>
<td>East B</td>
<td>0.892 ± 0.011</td>
<td>0.844 ± 0.013</td>
<td>0.611 ± 0.022</td>
</tr>
<tr>
<td></td>
<td>0.611 ± 0.042</td>
<td>0.580 ± 0.044</td>
<td>0.580 ± 0.044</td>
</tr>
<tr>
<td>East C</td>
<td>0.874 ± 0.013</td>
<td>0.831 ± 0.014</td>
<td>0.573 ± 0.034</td>
</tr>
<tr>
<td></td>
<td>0.479 ± 0.051</td>
<td>0.464 ± 0.047</td>
<td>0.464 ± 0.051</td>
</tr>
<tr>
<td>West A</td>
<td>0.890 ± 0.012</td>
<td>0.850 ± 0.015</td>
<td>0.669 ± 0.016</td>
</tr>
<tr>
<td></td>
<td>0.714 ± 0.035</td>
<td>0.706 ± 0.034</td>
<td>0.684 ± 0.024</td>
</tr>
<tr>
<td>West B</td>
<td>0.882 ± 0.009</td>
<td>0.871 ± 0.008</td>
<td>0.695 ± 0.016</td>
</tr>
<tr>
<td></td>
<td>0.683 ± 0.043</td>
<td>0.680 ± 0.042</td>
<td>0.665 ± 0.042</td>
</tr>
<tr>
<td>West C</td>
<td>0.922 ± 0.005</td>
<td>0.873 ± 0.009</td>
<td>0.650 ± 0.017</td>
</tr>
<tr>
<td></td>
<td>0.723 ± 0.018</td>
<td>0.712 ± 0.017</td>
<td>0.648 ± 0.025</td>
</tr>
</tbody>
</table>

3.3.2 Comparing Watershed-Reef Districts Based on Simpson’s Diversity Index

As noted in Chapters 1 and 2, each side of the island (East vs West) was assessed separately in respect to the Simpson’s Diversity Index. To confirm that side of the island was a critically important factor, both the fish and benthos transect data
were plotted on-metric multidimensional scaling plots (Figure 6). The plots were created from standardized and square-root transformed Bray-Curtis similarities. There were significant differences in both the fish and benthos communities when compared across the sides of the island (Figure 6)
Figure 6: Non-metric multidimensional scaling (NMDS) plots comparing the fish and benthos communities across the two sides of the island.
3.3.2.1 Diversity Indices for Eastern Watershed Districts

Species diversity indices that were calculated for both the fish and benthic communities (as well as rubble, sand, and algae for benthic surveys) were compared by watershed-reef districts to assess if watershed vegetation composition influenced biodiversity within the Eastern watershed-reef districts. Watershed East A’s benthic community species diversity was significantly lower than the benthic community species diversity found in watershed district East B (ANOVA, $p < 0.05$, Figure 7). No other differences were detected between watershed-reef districts and the benthic community species diversity observed (ANOVA, $p > 0.05$ for all other comparisons). Nor was there any difference in the fish community species diversities between the all Eastern watershed districts (ANOVA, $p > 0.05$).
Figure 7: Benthic community species biodiversity index for Eastern watersheds (±SE). Watersheds that are significantly different from each other are denoted by different letters (ANOVA, $p < 0.05$).

Watershed district East A had a significantly lower genus level benthic community biodiversity than watershed district East B (ANOVA, $p < 0.05$, Figure 8). No other differences were detected between watershed districts and the benthic genus diversity observed (ANOVA, $p > 0.05$ for all other comparisons). Nor was there any difference in the genus level fish diversities between the all Eastern watershed districts (ANOVA, $p > 0.05$).
When comparing differences found between the functional classifications (Table 5) of benthic organisms, watershed district East A was found to have significantly lower functional diversity than watershed district East B (ANOVA, $p < 0.05$).
0.05, Figure 9). No other differences were detected between watershed districts and the benthic functional group diversity observed (ANOVA, \( p > 0.05 \) for all other comparisons). Nor was there any difference in the functional group fish diversities between the all Eastern watershed districts (ANOVA, \( p > 0.05 \)).

![Figure 9: Benthic community functional group diversity index for Eastern watersheds (±SE). Watersheds that are significantly different from each other are denoted by different letters (ANOVA, \( p < 0.05 \)).](image-url)
Separate analyses were also conducted to assess whether the abundance of corals in the genus *Acropora* differed across the Eastern watersheds. The abundances of *Acropora spp.* within East A and East B were both significantly greater than the abundances of *Acropora spp.* within East C (Kruskal-Wallis, $p < 0.05$, Figure 10). However, East A and East B did not differ from each other in their abundances of *Acropora spp.* (Kruskal-Wallis, $p > 0.05$, Figure 9).

Figure 10: Average abundances of corals in the genus *Acropora* within Eastern watersheds (±SE). Watersheds that are significantly different from each other are denoted by different letters (Kruskal-Wallis, $p < 0.05$).
3.3.2.2 Diversity Indices for Western Watershed Districts

Species diversity indices that were calculated for both the fish and benthic communities (as well as rubble, sand, and algae for benthic surveys) were compared by watershed-reef district to assess if watershed vegetation composition influenced biodiversity within the Western watershed reef-districts. There was no significant difference in the species diversity indices for the benthic communities among any of the Western watershed districts (Kruskal-Wallis, \( p > 0.05 \)). The West C district did have a species diversity index for the fish communities that was significantly higher than both the West A and West B districts (Kruskal-Wallis, \( p < 0.05 \), Figure 9). Yet there was no difference in the species diversity indices for the fish communities between the West A and West B districts (Kruskal-Wallis, \( p > 0.05 \), Figure 11).

There was no significant difference in the genus level benthic community diversity indices among any of the Western watershed districts (Kruskal-Wallis, \( p > 0.05 \)). Nor was there any significant difference in the genus level fish community diversity indices among any of the Western watershed districts (ANOVA, \( p > 0.05 \)).

When comparing differences found between the functional classifications (Table 5) of benthic organisms, there was no difference in the benthic functional diversity among any of the Western watershed districts (Kruskal-Wallis, \( p > 0.05 \)). Nor were there any differences between Western watershed districts and the fish functional group diversity (ANOVA, \( p > 0.05 \)).
3.3.2.3 Recategorizing Grass Coverage

The two watersheds with the highest proportional coverage of grass—East C and West C—did not show significantly lower biodiversities of fish or benthic communities in relation to the other respective districts, which have markedly lower proportional coverages of grass. The West C district, which is 95% grass, even had significantly higher fish species biodiversity than the other two Western watershed-reef districts. And since the West C watershed is mostly composed of grass and is
more biodiverse in its fish communities, it is reasonable to say the grass, at the very least, is not providing a negative chemical cue to coral reefs. These results suggest that the grass species on Tavewa Island provides a similar chemical cue to native vegetation. Also, as stated in Chapter 2, the grass on Tavewa Island would need to have been transported in the digestive tract of goats (Treitler et al. 2017) in order to be a non-native species.

It is therefore sensible to treat the grass on Tavewa Island as native when categorizing the coverage types. A new coverage type table was created by adding the previous categories of “Native Trees/Shrubbery” and “Grass” into a single category, “Native Vegetation” (Table 9).

Table 6: Proportional areas of terrestrial coverage types split by three categories: Coconut, Native Vegetation, Developed. The proportions were calculated by dividing the total area of each coverage type in each watershed by the total area of the watershed.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Coconut</th>
<th>Native Vegetation</th>
<th>Developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>East A</td>
<td>0.7%</td>
<td>88.8%</td>
<td>9.9%</td>
</tr>
<tr>
<td>East B</td>
<td>1%</td>
<td>97%</td>
<td>2%</td>
</tr>
<tr>
<td>East C</td>
<td>1.7%</td>
<td>98.2%</td>
<td>0.06%</td>
</tr>
<tr>
<td>West A</td>
<td>2.7%</td>
<td>94.7%</td>
<td>0</td>
</tr>
<tr>
<td>West B</td>
<td>0</td>
<td>100%</td>
<td>0</td>
</tr>
<tr>
<td>West C</td>
<td>0</td>
<td>100%</td>
<td>0</td>
</tr>
</tbody>
</table>

3.4 Discussion

Now that the watersheds have been delineated, the terrestrial vegetation coverage has been quantified, and the coral reef diversity indices calculated, the overarching question of this thesis can be addressed: Does terrestrial vegetation influence the health of adjacent coral reefs?
Answering this question by breaking up the island into watershed-reef districts (as defined in Chapter 2) provides two main benefits: First, because the watersheds were delineated, we could quantify the different terrestrial vegetation groupings present within specific watersheds. As a watershed is an area of land where all water drains into the same place (Gönenç et al. 2007), it is reasonable to assume that ubiquity exists within each watershed. Therefore, we can assume that rainwater running off of the East A watershed into its adjacent coral reef is comprised of 0.7% coconut, 81% native trees/shrubbery, 9.9% developed land, and 7.8% grass (Table 3). Operating under this assumption allows us to treat each vegetation composition as a factor unique to that specific watershed-reef district. Secondly, since vegetation compositions were treated as unique factors, the variance in the diversity indices could be compared based on this factor. Our results showed that there was no significant difference in the fish diversities (species, genus or functional groups) within the Eastern watershed-reef districts. And the only difference among the benthic diversities of the Eastern watershed-reef districts occurred between East A and East B. Also, no significant difference was detected in the benthic diversities (species, genus or functional groups) within the Western watershed-reef districts. And the only difference among the fish diversities of the Western watershed-reef districts was West C having a higher species diversity than the other two. It is worth noting that 1) East A has lower proportional coverage of coconut, native trees/shrubbery, and grass than East B and 2) West C has the highest proportional coverage of grass.

At first glance, these results were surprising due to the known behavioral response of larval coral reef fish to the chemical cues of native and crop terrestrial vegetation (attraction and repulsion, respectively—Dixson personal communication,
Dixson et al. 2008, Munday et al. 2009). As coral reef diversity is a metric of the health of a reef system (Jones et al. 2004), we would expect to see lower diversities of fish communities in watershed-reef districts with higher proportional coverage of coconut and higher diversities in those with higher proportional coverage of native trees/shrubbery.

Behavioral trials will need to be conducted to look at the response of settlement stage larvae towards the vegetation compositions found within these watershed districts. The behavioral trials conducted by Dixson (personal communication) assessed the preference or repulsion of coral reef fish towards vegetation when tested separately. The findings of this project suggest that either large coverage of native trees/shrubbery or combinations of different vegetation types can reduce the negative effect of coconut chemical signals.

Also, though there is no a priori information about how the chemical cues produced by the grass on Tavewa Island might impact coral reefs, the grass is likely to be producing a positive cue. If grass was producing a blank or negative cue, we would expect West C (which is 95% grass and only 5% native trees/shrubbery with 0% coconut) to have significantly lower benthic and/or fish biodiversity than West B (which is approximately 53% native trees/shrubbery and 47% grass with 0% coconut). However, as this is not the case—and West C actually has higher species diversity of fish communities—the percentage of coverage across the watersheds was expressed per Table 9, with native trees/shrubbery and grass combined into one category: native vegetation.

Based on these new proportions of coverage types, a new conclusion can be drawn about the Western watershed-reef districts. As there is no developed area within
any of these watersheds, the only influences on the watershed-reef districts are native vegetation or coconut. Also, as no significant differences exist in the benthic community diversities among any of the Western watersheds and no significant difference exists in the fish community diversities between the West A and West B watershed districts, there is either not enough coconut to negatively impact the coral reef, or the negative influence of the coconut is being overshadowed by the positive benefit of the native vegetation.

We would also expect to see a lower diversity of fish communities when benthic diversity is lower. However, the East A reef district does not have significantly lower fish diversity from East B, despite it having significantly lower coral diversity. One explanation for the fish diversity not being affected by the benthic diversity in East A is that the East A coral reef is the only Marine Protected Area (MPA) and, therefore, no fishing occurs within its bounds. This MPA has been established for over 15 years (Nacula Ratu, personal communication).

Another explanation is that low benthic biodiversity may not necessarily indicate a less healthy reef system. East A had high abundances of *Acropora spp.* corals (Figure 8), which provide structural complexity to corals reefs as well as important habitat for reef organisms (Jones et al. 1994, Graham and Nash 2013, Suchley and Alvarez-Filip 2017). In other words, high amounts of corals (thus lower biodiversity) in the genus *Acropora* can indicate a healthy reef because they are keystone species and ecosystem engineers for most coral reefs (Wild et al. 2011). Acroporid corals are responsible for much of the topographic complexity that leads to high abundances and diversity of fish species in the Indo-Pacific (Jones et al. 2004, Mumby and Steneck 2008). The combined effect of the MPA, the large coverage of
*Acropora spp.* corals, and the large proportion of native vegetation potentially overpowering the negative influence of coconut, would explain the lack of significant difference in the fish diversities among the Eastern watersheds.

The results of this project suggest that while coconut has been shown to produce repulsive chemical cues towards recruiting coral reef fish (Dixson, personal communication), this repulsive cue may lose influence when combined with large amounts of attractive cues from native vegetation (Dixson et al. 2008).

An argument can be made to treat coconut vegetation as non-point source pollution (as defined in Chapter 1) because of its agricultural nature and the direct, negative impact of the associating chemical cues on the behavior of recruiting coral reef fish. The results of this project provide a potential path for the mitigation of the effect of this pollutant on coral reef diversity. First, locate the watershed(s) that contain the coconut plants and calculate the coverage of coconut within each watershed. Then, to mitigate the effect of the coconut trees, alter the vegetation coverage so that native vegetation dominates the watershed. Future studies will be needed to determine the ratios necessary for this mitigation, as the lowest ratio across all usable watersheds on Tavewa Island was 35: 1 (native: coconut). However, the same findings may not be true for other invasive or crop plant species. Plants such as mahogany, which are rapidly replacing native hard woods in Fiji, produce a significant amount of tannins. Behavioral assays reflect that a much stronger repulsion occurs by coral reef fishes towards the chemical cues of mahogany than chemical cues of coconut. Therefore, the inclusion of native plants into a watershed that is dominated or contains a portion of mahogany may not yield the same result.
Land use impacts on coral reefs continue to be discovered. As long as coastal human communities rely on coral reefs for ecosystem services such as storm protection, fisheries, and tourism (Barbier et al. 2011), management efforts need to consider ways to mitigate harmful anthropogenic effects. Utilizing a watershed-based approach that factors in agricultural runoff (Sharpley and Meyer 1994, Rabalais et al. 2002, Turner and Rabalais 2003, Delavaux et al. 2018), the crops themselves (Oliver et al. 2011, Linan-Cabello et al. 2016, Tulloch et al. 2016), and the effects they have on the coral reefs (Dixson personal communication, Atema et al. 2002, Munday et al. 2009) in their drainage basin is the best approach to paint a truly complete picture of the influence that terrestrial vegetation may have on coral reef health. This framework provides a new, holistic integration of coastal coral reef communities and near-shore terrestrial ecosystems.
REFERENCES


Appendix A

STATEMENT OF ETHICS

All research conducted in this thesis was within the guidelines of the Institutional Animal Care and Use Committee (IACUC). This committee is constituted according to the Public Health Service Policy on Humane Care and Use of Laboratory Animals. As the grant under which this project was funded included multiple universities, approval was obtained from both the University of Delaware (AUP number: 1305) and Georgia Institute of Technology (protocol number: A16112). Additionally, research was conducted within the guidelines of the Fijian government. A binding memorandum of understanding (MOU) was obtained through the Ministry of Agriculture, Fisheries, and Forests stating conditions for the proposed work.
Table 7. Quality reports from processed mosaics in Pix4Dmapper Pro (4.2.27).
Optimal standards are set by the software.

<table>
<thead>
<tr>
<th></th>
<th>RGB</th>
<th>Near-IR</th>
<th>Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of images calibrated</td>
<td>93%</td>
<td>85%</td>
<td>≥ 95%</td>
</tr>
<tr>
<td>Median keypoints per calibrated image</td>
<td>52,684</td>
<td>20,022</td>
<td>≥ 10,000</td>
</tr>
<tr>
<td>Median matches per calibrated image</td>
<td>4,220.23</td>
<td>2,518.66</td>
<td>≥ 1,000</td>
</tr>
<tr>
<td>Relative difference between initial and optimized camera parameters</td>
<td>8.18%</td>
<td>0.80%</td>
<td>≤ 5%</td>
</tr>
<tr>
<td>Mean X geolocation error between pixels</td>
<td>0.29 cm</td>
<td>0.44 cm</td>
<td>≤ 1 cm</td>
</tr>
<tr>
<td>Mean Y geolocation error between pixels</td>
<td>0.039 cm</td>
<td>0.18 cm</td>
<td>≤ 1 cm</td>
</tr>
<tr>
<td>Mean Z geolocation error between pixels</td>
<td>0.83 cm</td>
<td>0.34 cm</td>
<td>≤ 1 cm</td>
</tr>
</tbody>
</table>
Appendix C

RECOMMENDATIONS FOR FUTURE WORK

The work conducted in this study was constrained by time and funding. Therefore, there were certain steps that could not be taken due the limitations inherent in a Master’s project. This appendix will serve as a recommendation for two changes to the methodologies involved with the unmanned aerial vehicles (UAVs), which will lead to a better interpretation of the data, as well as another set of data that could be collected to strengthen the findings.

A.1 Watershed delineation

Highly accurate and precise watershed delineation requires a bare earth digital elevation model (DEM). A bare earth DEM depicts the true elevation of a surface without the influence of structures such as trees, shrubs, or buildings. This differs from the digital surface model (DSM) utilized in Chapter 1, wherein the elevation was influenced by structures on the ground. A consumer grade UAV with a standard 4K RGB camera does not have the ability to penetrate vegetation and, therefore, does not have the ability to produce a DEM. This resulted in the southern half of Tavewa Island not being delineated (Figure 3).

In order to penetrate dense canopy coverage and produce a bare earth DEM, flights should be conducted with LIDAR (Light Detection and Ranging) technology. LIDAR laser beams are able to pass through vegetation and measure the elevation of a surface (Zaidi et al. 2018). At the start of this project, LIDAR systems were extremely expensive to mount onto a commercial grade UAV. However, the technology has evolved greatly over the last year, and small-scale LIDAR systems are available for less than $1,000. If a future study incorporates LIDAR technologies, follows the
methods listed in Chapter 1.2.4, and utilizes the produced DEM rather than the listed DSM, then that study will not be constrained by thick canopy coverage.

A.2 Object-Based Image Analysis

Classifying and quantifying vegetation and building coverage was originally attempted by using object-based image analysis, a machine learning program commonly used for vegetation classification (Heumann 2011, Juel et al. 2015). The following sections were written “as if” they were used, followed by the issues encountered and recommendations for going forward.

A.2.1 Near-IR Image Analysis and Photogrammetry

While conducting the programmed flights from Chapter 1, the UAV was also taking near-infrared (near-IR) photographs using a near-IR camera, which does not operate within flight programming software. Instead, the near-IR camera is factory-programmed to take photographs entirely via GPS signals. Once the UAV reaches an altitude of 15 m, the near-IR camera fires at a rate in order to achieve 30% overlap between photographs. Therefore, the near-IR photographs obtained 30% vertical overlap and ≥80% horizontal overlap (the horizontal overlap is set by the flight path in the Pix4D Capture app).

As described in Chapter 1, all photographs were processed using Pix4D MapperPro software (4.2.27). Pix4D MapperPro stitched the photographs together using tie points within neighboring photographs, each embedded with GPS coordinates at the moment of capture. The software then created a single band mosaic from the near-IR photographs.
A.2.2 Object-Based Image Analysis Methods

By using both the RGB and near-IR mosaics, different plant species were identified using object based image analysis tools in ArcPro (Appendix D). Object based image analysis is a machine learning technique commonly used in terrestrial vegetation analysis (Pena-Barragan et al. 2011, Husson et al. 2016, Cao et al. 2018), wherein a training sample was used to teach the program how to identify vegetation based on set characteristics.

Object based image analysis required the RGB and near-IR mosaics to be combined into one image. They were combined to create a color-infrared (color-IR) mosaic using a process called pansharpening. Pansharpening took a single band, or panchromatic, image (the near-IR mosaic) and merged it with a multiband image (the RGB mosaic) by replacing the blue color band with the near-IR band. The resulting color-IR mosaic was comprised of green, red, and near-IR color bands and then utilized for identifying vegetation with object based image analysis.

The identification of vegetation types by a programed computer requires a training sample to be created; however, pixels are first removed from the color-IR mosaic to create a single object in a process known as segmentation. Then a supervised classification approach was conducted to train computer software on the correct identification of terrestrial vegetation based on the spectral signature received from the plant. In the training sample, known plant species were manually identified as either coconut, native hardwood trees, native shrubbery, native grasses, bare earth, rock, artificial structure, or water. This method allowed the machine’s learning algorithm to contain a pre-set representation of coverage types. Once the training sample was fully classified, it was loaded into a Random Forest Classifier. This technique selected random subsets within the training sample and created decision
trees based on those subsets. These decision trees formed the basis that all objects outside the training sample were classified. After the completion of the Random Forest Classifier, a final raster layer was produced revealing the location and densities of identified coverage types. This raster layer was converted into a shapefile so that the coverage area could be calculated.

A.3 Near-IR and Color-Infrared Mosaics Results

A.3.1 Near-IR Quality Report

Standards for mosaic quality were preset by the Pix4D software (Pix4D Support). The software assessed four areas of processing while determining the quality of the mosaics: calibration percentage, median keypoints and median matches per calibrated image, relative difference between initial and optimized camera parameters, and mean geolocation error across all planes. Images used tie points—common points between images as a result of overlap—to calibrate the images in reference to each other. These tie points were then converted into keypoints and given \((X, Y, Z)\) coordinates. The software then matched each keypoint a respective keypoint in an adjacent image. Camera optimization corrected for errors of distortion and set the standards for heights, widths, and sizes of image pixels. Smaller camera optimization values indicated low image blur (due to flight speeds that are too fast) and constant sun irradiance across flights. Finally, the mean error was calculated between each pixel in each \((X, Y, Z)\) plane.

The near-IR mosaic (Figure 12) quality exceeded the standards for keypoints, matches, camera parameter percentages, and geolocation error, while falling short for
calibrated images (Appendix B). The average ground sampling distance was 11.84 cm between each pixel (11.84 cm/px).

Figure 12: Resulting mosaic of Tavewa Island from the processed near-IR images.
A.3.2 Color-Infrared Mosaic

The near-IR and RGB mosaics were combined into a single color-IR mosaic that is comprised of the green, red, and near-IR color bands (Figure 13).

Figure 13: Resulting color-IR mosaic from the combined RGB and near-IR mosaics.
A.4 Issues Encountered with Object-Based Image Analysis and Future Recommendations

The previous sections describe the ideal processes for classifying vegetation and building coverages throughout Tavewa Island. If these steps were completed satisfactorily, then quantification of coverage types’ areas would follow the same methods listed in Chapter 2.2.1.

When the methods for the object-based image analysis were completed, the results were incredibly inaccurate and unprecise. Ground-truthing the classifier revealed that most of the vegetation coverages were classified incorrectly and only the training sample set was correct. I believe the main reason for this is due to the drastic difference in the resolutions between the RGB and near-IR mosaics (5.25 cm/px and 11.84 cm/px, respectively).

The differences in resolution is likely due to the differences in overlap between the RGB and near-IR images along the flight paths, as is reflected in the differences in calibrated images (93% RGB, 85% near-IR). It was believed, at the time, that the near-IR vertical overlap could not be manually adjusted and was automatically set at 30% by the factory. However, I have since learned that the near-IR camera can be programmed so that the overlap is increased. The following steps will all users to manually adjust the overlap between near-IR images along the flight path:

1. Remove the MicroSD card from the Sentera near-IR camera and insert it into a PC.

2. Browse to the file in the MicroSD card labeled “UserSettings.txt”

3. Scroll to the line reading “#---- GPS Overlap Trigger Options (Mode 5 and 6 ----------”

4. Change the setting “OverlapPercent=30” to “OverlapPercent=80”
5. Save the changes, eject the MicroSD card, and reinsert into the Sentera near-IR camera.

I believe that this change will result in more calibrated images and, therefore, a much higher resolution within the near-IR mosaic.

Because of the differences in resolution between the RGB and near-IR mosaics, the resulting color-IR mosaic was of poor quality. The color-IR mosaic is produced by replacing the blue color band in the RGB mosaic with the near-IR band. Therefore, stark differences in resolution between the RGB and near-IR mosaics led to inaccurate merging and a fuzzy color-IR mosaic. The color-IR mosaic also appeared to have “shadows,” which were also a result of inaccurate merging.

Ground control points (GCPs) are markers that are manually set throughout the surveyed area. The exact coordinates of the GCPs can be determined by using a hand-held GPS device (such as a Garmin or a Trimble). As the UAV conducts its automated flights, the GCPs will appear in a majority of the photographs. They serve to increase the accuracy during the stitching process and increase the spatial resolution because they act as manual tie points with known coordinates. Utilizing GCPs would also help reduce those issues encountered when creating the color-IR mosaic.

Changing the overlap for the near-IR images as well as implementing GCPs during the flight surveys will likely allow for vegetation coverages to be correctly classified using object-based image analysis.

A.5 Salinity Profiles

The last recommendation for future work would be to conduct profiles of salinity changes nearshore, following a rain storm. The salinity profiles will act as a proxy for freshwater runoff and rainwater mixing into the coral reef seawater. As
rainwater flows through the watershed and out to sea, the freshwater and seawater will stratify creating salinity differences with depth.

Ideally, these profiles would occur immediately following a rainstorm. Measurements would be taken every 5m from shore (perpendicular to the shore) and up to 10m past the reef crest (Figure 14).

Figure 14: Example of an optimal transect (dashed red line) for conducting salinity profiles. Each black bar is 5m apart and represents locations for taking readings with a CTD. The yellow line represents the reef crest.

The profiles could be attained via the utilization of a handheld connectivity, depth, and temperature (CTD) probe, which measures those variables at a constant rate as it is lowered through the water column. Salinity can then be calculated from the
connectivity values based on water temperature. How often the readings need to be taken will depend on how long it takes the freshwater to mix in with the seawater. The salinity profiles will have to be analyzed \textit{in situ} to assess whether complete mixing has occurred at each time frame. Figure 15 depicts what a mixing curve over time could resemble.

![Figure 15: Example mixing curves over time for salinity profiles taken at five different time points. Curves assume baseline salinity for the seawater is 32ppt, while the rainwater salinity is 3ppt.](image-url)
Through the course of this thesis, I attempted to conduct salinity profiles within the watershed-reef districts surrounding Tavewa Island. I used a portable CTD probe, which was lowered into the ocean from the side of a small boat. The CTD was slowly lowered until reaching the sea floor (ranging from < 1m to ~20m). However, due to the remote nature of our field site, I did not have access to safe boating conditions immediately following a rainstorm. Winds were always too high, causing too rough of seas, and preventing the safe acquisition of the CTD data. Once the winds calmed to a safe speed (typically about 6 hours post storm), the freshwater had completely mixed and there was no stratification.

Going forward, if safely possible, collecting salinity profile will help to strengthen the argument that chemical cues from watersheds interact with the coral reef. Because rainwater carries chemical cues into the ocean, showing that water mixing into the seawater surrounding coral reefs will provide the final link between land and sea.
Figure 16: Workflow diagram for delineating watersheds within ArcPro. The watershed delineation workflow begins with uploading the Digital Surface Model (DSM) Raster and utilizes raster tools (yellow boxes) located within the Hydrology toolbox. Blue circles are created by the user (DSM Raster created in Pix4D). Green circles are the output results from each tool.
A.7 OBJECT BASED IMAGE ANALYSIS

Figure 17: Workflow diagram for conducting Object-Based Image Analysis (OBIA) within ArcPro. The OBIA workflow begins with uploading the RGB and near-IR mosaics and utilizes raster functions (yellow boxes). Blue squares are created by the user (RGB and near-IR mosaics created in Pix4D; manually classified training sample created in ArcPro). Green boxes are the output result from the previous raster function. The blue circle is the end product of the workflow.