Connecting Land Cover to Benthic Cover Within the Watershed: Quantifying Impacts of Terrigenous Sediment on Coral Reef Health and Morphology Using Remote Sensing and Machine Learning

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Abstract:
Erosion, with associated sedimentation of reefs and loss of habitat for marine and coastal species, is one of the most pressing environmental challenges in Hawaii. Identifying hotspots of soil erosion guides management on land, but limited work has been done connecting land cover to coral reef health and morphology. Current reef survey methods overgeneralize the spatial variation of benthic cover and this has been reflected in incorrect Geographic Information System (GIS) layers of the reef. We propose a novel and more holistic approach to improve accuracy by connecting sedimentation from source to sink using Unmanned Aerial Vehicles (UAVs), Unmanned Surface Vehicles (USVs), local knowledge, and machine learning. UAVs can capture images to create 3-D orthomosaics of the terrestrial system while USVs can be used to create 3-D coral reef models. As a result, we will be able to identify the effects of different land management practices on coral reef health.

Keywords: Terrigenous Sedimentation, Marine Remote Sensing, Machine Learning

1. Introduction

The south shore of Molokai is home to the longest continuous fringing reef in the United States (Field et al. 2008). This fringing reef provides key ecosystem services to the community such as protection from large tidal events and food security. This protection and food security is at risk to being lost due to sediment runoff events occurring within the watershed (Bothner et al. 2006, Field et al. 2008, Risk, M. J., & Edinger, E. 2011).

Communities along the south shore of Molokai depend upon resources found throughout the watershed. Traditionally, the south shore of Molokai was a place of abundance and a “bread basket” for the island for native Hawaiians. This abundance was due to the indigenous mariculture practice of raising fish in fishponds. Traditional fishponds are located near freshwater springs or at the mouths of rivers providing a brackish environment that young fish could grow. Growth was also accelerated due to the absence of large predators within the pond’s rock walls. Herbivorous fish were sustained on the algae growing on benthic surfaces. Many of these rock walls have fallen into misuse and the fishponds became sediment sinks in the community. Community members are now actively working to revitalize these ponds but the challenges associated with sediment deposition and invasive species represents a significant roadblock in their success.

The watersheds of Molokai are affected by grazing of non-native ungulates such as cows, goats, and axis deer, invasive plants, and short-sighted approaches to land management by land owners or land leases (Jokiel, P. L. et al. 2014) Unfortunately, the majority of management decisions result in the removal of traditional land cover and place the land at a higher risk for sediment loss. Sediment loss happens when rainfall is not absorbed into the system causing it to gather loose sediment and material as it gains momentum moving from the top of the watershed and depositing at the bottom (Stock, J. D. 2011).

Terrigenous sediment deposition is a major stressor on coral reefs and one of the biggest potential sources of reef degradation, but it is currently unknown how variable factors exhibited in terrestrial systems translate to degradation of coral reefs in the marine system (Jones, R. et al. 2019, Larsen, M. C., & Webb, R. M. T. 2009, Ouyang, W. et al. 2010). The marine system exhibits signs of being affected by poorly managed lands and this is one of the reasons that coastal zones are priority regions for NASA research (NASA Earth Science 2020). We seek to advance the knowledge and explore the interactions between the ocean and terrestrial processes to understand and predict the consequences of change, thus aligning with the Earth Science Research and Applied Sciences Program's strategic objective.

Land cover mapping is crucial for assessing changes in ecological communities (Solaimani, K. 2009). Changes at the ecosystem level can be mapped using observational methods or by utilizing a remote sensing approach. Remote sensing approaches utilize high resolution imagery acquired by a satellite sensor or a sensor mounted on an unmanned aerial vehicle (UAV). The type of platform and sensor used is dependant upon the type of change that is being measured. For land cover changes across a large spatial extent, satellite imagery is preferred. When measuring land cover or vegetative species cover changes within a watershed or a farm it is preferable to use a UAV. The advantages of using a UAV include the ability to gather data at any time, the low cost to operate and acquire imagery, and the high temporal resolution that can be achieved when wanting to resample an area. Advances in UAV technology has also allowed for heavier payload capability, improved sensor quality, and multispectral sensors all to be used on the UAV system. Multispectral sensors mounted on a UAV system are of particular interest because this provides the opportunity for data collection of high-resolution multispectral imagery. High-resolution multispectral imagery facilitates the creation of maps displaying indices like the normalized difference vegetation index (NDVI) which highlights areas of healthier vegetation across the landscape. Measuring change and vegetative cover on the land is a straightforward process that stands in stark contrast with remote sensing of coral reefs.

Underwater remote sensing remains a field that faces challenges with image acquisition. Water and its associated effects related to diffraction challenge the efficacy of UAV systems gathering imagery above the water. Water is also subject to glint which could render images captured by a UAV useless. Technologies like unmanned surface vehicles (USV) seek to fill this gap by performing autonomous data collection using stereo cameras that are set within a waterproof housing and immersed underwater (Burns et al. 2015, Raber, G. & Schill. S. 2019). Cameras that are immersed underwater are no longer subject to sun glint along the surface and with a portion of the USV being above water it is still able to be controlled in a similar manner to a UAV.

Both the UAV and USV are capable of performing pre-programmed missions within a defined area, capturing images at equal intervals. These images can then be used to create 3-d orthomosaic models. These models can be classified using machine learning techniques to quantify land cover, benthic cover, and highlight areas that are of high risk to erosion or terrigenous sediment deposition. Such models can help when making decisions regarding future land management plans and are of particular use to land managers and community members.

Native Hawaiians are the primary stakeholders because they represent the people that have been most heavily impacted by a changing system. These community members have observed changes to the community throughout their whole life. There is a growing trend to include expert knowledge from community members and local land users when creating land management plans and refining the accuracy of remote sensed data. Remotely sensed data represents the landscape at a specific point in time while community knowledge provides insights across a larger temporal resolution. Utilizing community knowledge land managers and other stakeholders can better understand patterns of erosion and the effects of terrigenous sediment deposition on coral reefs after major storm events. Tension between scientific methods of research and traditional knowledge are known hinderances to collaboration. Overcoming hinderances takes time and community outreach. Community outreach between scientists and groups within the community, namely community members, land users, and students, provides a foundation of understanding and acknowledgement between all groups.

Our goal is to understand the impacts of non-native ungulates, invasive plants, and different land management practices on erosion susceptibility of an area within the watershed. To achieve this goal we pursued three specific aims: 1) Characterize erosional patterns of an overgrazed and poorly managed watershed compared to an alternative management practice with reduced grazing and road infrastructure 2) Characterize terrigenous sediment deposition patterns on a coral reef and 3) Provide community outreach and engagement through interviews and workshops. Connecting the changes on land to changes in the water will provide a holistic view of the watershed that will benefit community members dependant upon the resources provided by the land and ocean.

2. Methods

Study Area

The study was performed in the watershed of Kaʻamola, Molokai, Hawaiʻi. This watershed is owned by Kamehameha Schools and is leased to various groups for purposes ranging from cattle grazing and educational outreach. The non-governmental organization (NGO) ʻĀina Momona operates a K-6 school serving the Native Hawaiian population and is also restoring a Native Hawaiian fishpond. 345 hectares

Image Acquisition

A DJI Phantom Multispectral drone that is real time kinetic (RTK) enabled was used in the data collection on land. This drone uses a FC6360 camera that captures visible light images (RGB) as well as capturing along the Green, Blue, Red, Red Edge, and Near Infrared (NIR) spectral bands. The built-in RTK system allows for centimeter level accuracy of georeferenced images.

Mission planning was performed in the DJI GS Pro application. The 345 acre watershed was split into 15 sections within the app. Within each section we set our front and side overlap at 80% between individual images and between sections we aimed for 10-15% overlap in coverage redundancy.

Image acquisition was done in the morning hours between 8am-11am. There was some variation within these times due to unfavorable weather conditions. We were unable to fly the UAV after 11am due to elevated wind speeds and frequent afternoon rain showers.

Image Processing

3-d orthomosaics were created using the Pix4D program. Tie points were automatically generated within the software and then a point cloud and triangle mesh were generated after the images were stitched together. Processing was done on a Dell desktop running the Windows 10 Enterprise operating system. This machine utilized an Intel Core i7-7700 CPU @ 3.60 GHz with 64GB of RAM.

Due to processing restraints related to computer hardware we processed smaller the watershed in groups of three to six sections at a given time.

Community Outreach

Outreach within the community was split between outreach at the local school Rooted and informal interviews with community members and local land users.

The local school Rooted serves students in K-6 from the local comunity. A two-part 20 minute workshop series was shared with the students. The first part of the workshop focused on providing exposure to UAVs and remote sensing technology in a classroom setting. Students learned about the utility of UAVs and were provided with scenarios in which UAVs would help optimize the solving of various problems. The second part of the workshop was held outside where students were able to see the UAVs and RTK system in action. UAVs were sent on preprogrammed missions and the students watched the drone fly across the sky while also being able to view the live feed of what the UAV was remotely sensing.

Informal interviews were performed by asking interviewees the following two questions: what changes have they observed in the landscape and what changes do they hope to see in the future. Answers were recorded as notes and in some cases audio recordings were taken.

3. Results

The entire watershed was mapped over the course of four days. A point cloud was created after the images were stitched together (Fig. 1-3).

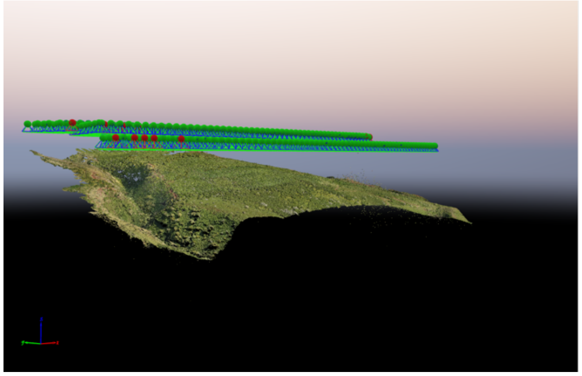

Figure 1. Side view of the 3-d orthomosaic created from the top third of the Ka‘amola watershed.

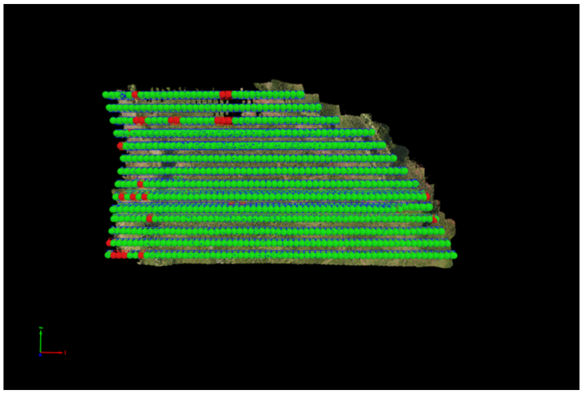

Figure 2. Top down view of the point cloud mesh for the top third of the Ka‘amola watershed. Each sphere represents the exact location where the UAV captured an image.

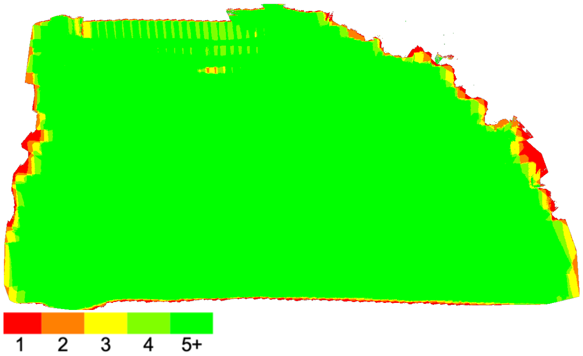

Figure 3. A 2-d simplification of the point cloud mesh for the top third of the Ka‘amola watershed. Colors are related to the number of overlapping images of a given area, scaled according to the legend above.

A digital surface model (DSM) was created of the watershed (Fig. 4) with GSDs ranging from 7.7cm to 8.9cm.

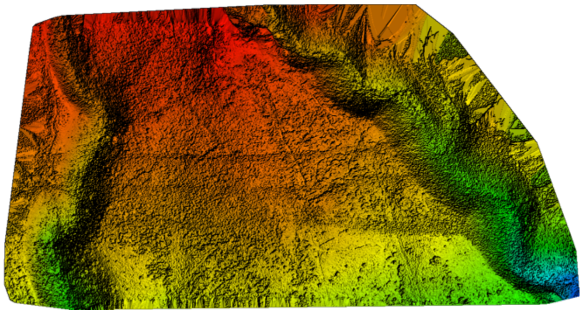

Figure 4. The DSM created from the point cloud mesh for the top third of the Ka‘amola watershed. This DSM has a GSD of 7.7cm.

Imagery collected along the Blue, Green, Red, Red Edge, and NIR spectral bands were individually stitched together (Fig. 5) and then run through an index calculator to create a NDVI map.

Figure 5. Stitched images from the five spectral bands for the top third of the Ka‘amola watershed. From top to bottom: Blue, Green, Red, Red Edge, NIR.

Geolocation error was calculated as the difference between the initial image position at the time of capture and the computed image position. Absolute geolocation variance is shown in the table below for the top third of the Ka‘amola watershed (Table 1). The percent of images that were within +/- 0.85m of their calculated location is 99.56% of images along the x axis, 100% along the y axis, and 99.48% along the z axis.

Min Error (m)	Max Error (m)	Geolocation Error X (%)	Geolocation Error Y (%)	Geolocation Error Z (%)
-2.55	-1.70	0.00	0.00	0.10
-1.70	-0.85	0.00	0.00	0.33
-0.85	0.00	50.19	53.22	50.79
0.00	0.85	49.37	46.78	48.69
0.85	1.70	0.16	0.00	0.09
1.70	2.55	0.28	0.00	0.00
Mean (m)		0.006092	0.00647	-0.034795
RMS Error (m)		0.214492	0.021546	0.165864

Table 1. This table shows the geolocation error for the X, Y, and Z axes between predefined error ranges that are measured in meters. The mean and RMS errors for each axis are shown at the bottom of the table.

4. Discussion

Throughout our DSM and 3-d orthomosaics we are seeing consistently high resolution data products. Achieving a GSD below 9cm allows for the reasonable extraction of objects as small as 18cm. At this high of a resolution we anticipate being able to classify vegetative species based on visual characteristics and then use in-situ data alongside NDVI maps to increase accuracy. Such high resolution DSMs also open the door to the creation of topographic maps that have at least 1 foot contour intervals. These topographic maps will be highly useful for the land managers when planning strategies to mitigate erosion along known areas that are of high risk. In the red and NIR orthomosaics we can see a clear distinction between vegetative areas and areas of bare ground. This is because vegetation tends to absorb light in the red band while it reflects light from the NIR band. Using the NIR, red, and green bands we can create a false-color composite that will allow us to better differentiate between bare ground, vegetation, man-made structures, and rock.

The usage of a RTK system greatly improved spatial accuracy of our data outputs. This is beneficial for land planners to better define specific areas in need of restoration as well as helping future researchers understand changes over time when re-surveying the area. Sub 1-meter level spatial accuracy without the use of ground control points (GCPs) is a great testament to the efficacy of an integrated RTK system.

In future analyses we will adjust the minimum number of key points needed between images. Adjusting the minimum number should increase the accuracy of measurements we can take from the models. These measurements include length, height of features, and volume.

The edges of the 3-d orthomosaics tend to be the areas with the least amount of overlapping images and also present possible areas of concern when performing future analyses. It must be taken into consideration that a buffer zone should be made around the study area to account for the associated edge effects.

We have completed the primary terrestrial imagery acquisition and have now moved into the imagery processing stage in Pix4D. We anticipate the supervised object based classification and analysis to conclude by July 2021.

The marine component of this research is projected to undergo testing and the initial rounds of data collection mid to late summer 2021. Delays in the shipping of key components made it so that the USV was not ready at the initial time of travel. Testing of individual components for the USV are optimistic and when integrated should perform as needed for our purposes. We are collaborating with Dr. Joshua Magelson's lab in electrical and computer engineering at BYU on the final steps of USV design and deployment.

Outreach efforts at the local K-6 school was extremely promising. By engaging these students at a young age and providing exposure to new technologies it breaks down preconceived barriers and can inspire a new generation of community members that reconcile indigenous knowledge and Western technology. The students and teachers were constantly engaged in the learning process, asking questions and making comments about UAVs and their experience with them in the community.

When performing the informal interviews with members of the community we have learned that it is much more important to listen and allow them to talk freely. Audio recordings will be taken and transcripts will be made for future interviews.

5. Conclusion

Our initial data collection and the processing performed up to this point shows great promise in completing our first specific aim of characterizing erosional patterns of an overgrazed and poorly managed watershed. High spatial resolution coupled with a high level of spatial accuracy is a great start for creating accurate and precise land cover maps. From a brief visual interpretation of the orthomosaics we are able to see patterns between different land management practices, the presence vs absence of livestock, as well as the difference between types of roads that traverse the watershed.

There was an immense amount of data collected during this initial trip and will continue to grow during subsequent trips to the watershed. After the remotely sensed and in-situ data collection stages have been completed future trips will focus on tracking change between time periods and evaluating the efficacy of land management projects.

The Kaʻamola watershed can serve as a model system of the effects of poor land management practices on sediment delivery to marine ecosystems. The approach taken in this watershed is widely applicable to other watersheds throughout the Pacific and we anticipate that our future findings about the effects of livestock grazing, invasive ungulates, and various land management practices will serve to better inform land managers that are seeking to conserve the entire watershed, from the mountains to the reefs.

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