GeoEye-1 multispectral satellite imagery classification: An accurate method for identifying populations of *Acropora* spp. corals prior to a field study

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Abstract

In recent decades Caribbean coral reefs have experienced drastic decline in live coral cover. Some of the main framework-building coral species *Acropora cervicornis, Acropora palmata*, and the new hybrid species *Acropora prolifera* have suffered the greatest collapse. Coral Gardens, Belize is one of the few remaining refugia for abundant, healthy populations of *Acropora* species coral. GeoEye-1 multispectral satellite imagery of a 25 km^2 area near Ambergris Caye was analyzed to identify live *Acropora* spp. cover in the greater Coral Gardens region. A supervised classification was used to predict areas which contained live *Acropora* spp. coral and separate them from other benthic cover such as mixed sand, seagrass, macroalgae, and mixed massive coral species. In the field, classification accuracy was tested by sending snorkelers to the region of suspected live *Acropora* spp. coral to document bottom composition, and as appropriate, species of coral present, approximate live coral cover, depth, orientation of live coral, species of corals present, and height of the tallest live coral. Locations were recorded using a differential GPS unit to map previously undocumented populations of *Acropora* spp. corals. Of the ten predicted areas, eight were dominated by substantial populations of healthy *Acropora* spp. coral. Reference points and newly mapped regions from the field data were used in conjunction with a refined classification technique to improve the accuracy of locating *Acropora* spp. corals within the image. The final classified image successfully separated *Acropora* spp. corals from other benthic cover with an overall accuracy of 89.9%. This technique can be used as a relatively quick, inexpensive species-specific tool for identifying, monitorying, and conserving populations of *Acropora* spp. corals for the future.

Introduction

In recent decades Caribbean coral reefs have experienced significant decline in live coral cover (Gardner et al., 2003; Miller et al., 2009; Eakin et al., 2010). Acroporid species corals have been among the hardest hit of Caribbean scleractinians (Aronson and Precht, 2001). The main framework-building corals, *Acropora* species, have dominated Caribbean reefs through geologic time, but have experienced massive population decline and mortality since the 1980's (Pandolfi and Jackson, 2006; Greenstein et al., 1998). The mortality of *Acropora* spp. corals has been attributed mostly to white band disease (Aronson and Precht, 2001) which has been connected to climate change driven increases in global sea surface temperature (Randall and Woesik, 2015; Bruno, 2015;) supported by evidence in the geological record of climate change driven reef shutdown in the past (Toth et al., 2015). The drastic decline of *Acropora* spp. throughout the Caribbean led to *Acropora cervicornis* and *Acropora palmata* becoming the first two coral species listed as threatened under the Endangered Species Act in 2005 by NOAA's National Marine Fisheries Service (NOAA and NMFS, 2005). The recent decline of *Acropora* spp. corals is particularly important to understand because in addition to being significant Caribbean reef framework builders, the structural complexity and high growth rates of *Acropora* spp. make them ecologically important for Caribbean and Western Atlantic marine ecosystems (Precht and Aronson, 2010; Williams and Miller, 2012).

There are few remaining places where *Acropora* spp. corals are abundant and healthy; however, several studies have documented rare refugia where large populations still thrive. Large *Acropora* spp. populations have been documented in Florida (Vargas-Ángel et al. 2003); Roatan, Honduras (Keck et al., 2005); Belize (Brown et al., 2007; Macintyre and Toscano, 2007; Peckol et al., 2003); Punta Rucia, Dominican Republic (Lirman et al., 2010); and Veracruz, Mexico

(Larson et al., 2014). All of the aforementioned studies, however, relied on snorkelers taking estimating colony size with tape measures, snorkelers swimming with a handheld GPS, divers making simpler estimates of size, or did not even attempt to map area coverage of *Acropora* spp. populations at these sites.

Recent field studies suggest that Coral Gardens, Belize represents one of these few remaining locations in the Caribbean with abundant, healthy populations of *Acropora* spp. coral. Coral Gardens is located south of Ambergris Caye and north of Caye Caulker in the shallow water back reef off of the coast of Belize (*Figure 1*). Anecdotal reports suggest *Acropora* spp. corals have been well established at Coral Gardens in the past, but it is unclear what their past extent has been and whether or not they suffered significant decline in the past (Mattes, Gannon, and Curran pers. comm.). A comprehensive literature search suggests that there have been no long term studies of *Acropora* spp. corals at Coral Gardens, and thus there is no available data about their abundance, extent, or persistence through time. The lack of quantitative information on the spatial extent of endangered *Acropora* spp. corals at Coral Gardens, as well as the other documented refuges of *Acropora* spp. corals in the Caribbean (Vargas-Ángel et al., 2003; Keck et al. 2005; Lirman et al., 2010; Brown et al., 2007; Macintyre and Toscano, 2007; Peckol et al., 2003; Larson et al., 2014), we suggest that an efficient and reliable method that doesn’t necessarily require field work is critical for identifying and mapping the few remaining *Acropora* spp. coral populations for studying, protection, and long term monitoring.

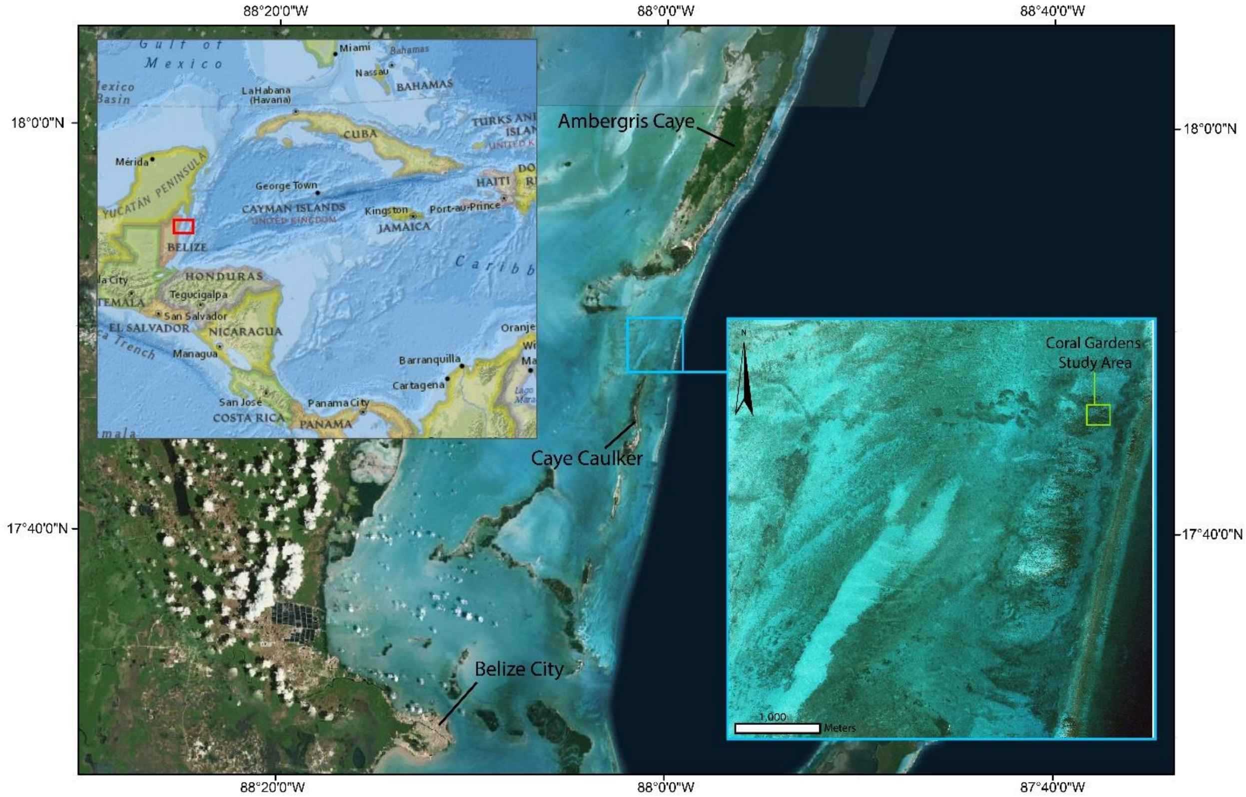

Figure 1: location map of Coral Gardens, Belize and the GeoEye-1 image that was acquired of the area (shown as the image outlined in blue). Basemap imagery courtesy of Esri, DigitalGlobe, GeoEye, i-cubed, Earthstart Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, the GIS User Community, National Geographic, DeLorme, HERE, UNEP-WCMC, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Image classification is the process of extracting informational groupings from images and there are two conventional methods for doing this: a supervised classification, where the operator defines the classes to be identified in the imagery using “training areas,” and an unsupervised classification, where the GIS software automatically defines classes in the image based on statistical relationships of pixel values (Aranoff, 2005). The most common use of image classification is for identifying objects or areas of interest in satellite imagery.

The advent of widely available Landsat satellite imagery was first used for coral reef applications in the early 1970’s (Smith et al., 1975). Since then, a multitude of new sensor platforms have been developed, and the advantages of disadvantages of many of the platforms have been assessed for coral reef specific applications (Mumby et al., 2004). There have been several attempts to identify benthic habitats and coral reef communities using radiance spectrometry (Holden and Ledrew, 1998; Hochberg and Atkinson, 2000; Hochberg et al., 2002; Louchard et al., 2003; Kutser and Jupp, 2006; Suffianidris et al., 2009; Leiper et al., 2012), underwater imagery (Lidz et al., 2008), airborne and space imagery (Rowlands et al., 2005; Mishra et al., 2006; Tamondong et al., 2013; Andréfouët et al., 2001; Mumby and Edwards, 2002; Hochberg and Atkinson, 2002; Andréfouët et al., 2003), combinations of radiance spectrometry and airborne imagery (Leiper et al., 2014), and combinations of spectral modeling and space imagery (Lubin et al., 2001). Because of the significant costs that accompany field work with expensive and complex sensor arrays, airborne and satellite imagery are attractive ways to remotely identify and monitor coral populations.

In considering which satellite or airborne platform to employ for studying corals, there is a significant tradeoff between the spectral resolution, spatial resolution, and cost. For a researcher simply trying to identify and map populations of corals, the most important considerations are likely spatial resolution and cost, because it is important to be able to identify small populations in imagery and funding is often a limiting factor for field studies. However, if the goal of the study is to discern between specific species of coral and map them, the spectral and spatial resolution must both be considered so the chosen sensor has the capability to identify small populations and simultaneously allow the researcher to use conventional methods that can identify one coral species from another.

Very few studies have looked at specifically identifying *Acropora* spp. coral from other species of corals (Collin et al. 2012; Purkis et al., 2006), and the scientific literature provided no previous studies that specifically aimed to do so using an easily replicated methodology with widely available proprietary software and inexpensive imagery. Perhaps the most successful existing method for identifying *Acropora* spp. corals in satellite imagery was identified by Purkis et al. (2006); however, the methodology the researchers outline in the study uses expensive, advanced imagery processing and analysis software and is far from an easily replicable process.

The purpose of this study was to 1). document *Acropora* spp. coral cover and extent near Coral Gardens using GeoEye-1 imagery and ArcGIS® software 2). devise a classification methodology for identifying *Acropora* spp. corals from other benthic cover that is user friendly, time efficient, and inexpensive 3). create an exportable product identifying *Acropora* spp. populations near Coral Gardens that other people can utilize in field studies 4). use the mapped *Acropora* spp. populations to monitor the endangered populations over the long term with an emphasis on facilitating better management practices.

Methods

Initial Image Classification

GeoEye-1 multispectral satellite imagery of a 25 km^2 area near Ambergris Caye was chosen to be analyzed for live *Acropora* coral cover in the greater Coral Gardens region. The GeoEye-1 imagery was chosen for the study because it is relatively inexpensive and has a high spatial resolution of 0.46 m. The spectral resolution consists of three visible light bands (450-690 μm) and one near IR band (780-920 μm). ArcGIS® was chosen to be used exclusively for the imagery analysis because it is one of the most widely available and capable GIS (geographical information systems) programs.

A maximum likelihood supervised classification was first used to identify *Acropora* spp. corals in the image because a large population of healthy, abundant *Acropora* spp. coral had been previously identified and served as an excellent training area for the classification. Ten areas were then selected to visit in the field for having the largest classified populations of live *Acropora* spp. coral in the classified image (*Figure 3*).

The accuracy of the supervised classification was tested in the field using snorkelers to ground-truth the ten identified areas. At each area they made observations about live coral cover, depth, orientation of live coral, species of corals present, and height of the tallest live coral. Locations of newly documented *Acropora* spp. corals were recorded using a Trimble GeoExplorer XT 6000 differential GPS. Additionally, reference locations of other benthic cover such as sandy bottom and seagrass were also recorded to help refine the method of spectrally distinguishing live *Acropora* spp. corals from other benthic cover. The GPS data was post processed using Pathfinder Office® software, and the differential correction was performed using a reference base station in Quintana Roo, Mexico.

Refined Image Classification

Following the accuracy assessment of the supervised classification map in the field, the classification scheme was refined to improve the accuracy of identifying *Acropora* spp. corals from other benthic cover. The initial supervised classification successfully discriminated *Acropora* spp. coral from areas with a sandy bottom, but had incorrectly identified some areas of seagrass and populations of mixed massive corals as *Acropora* spp. coral. Therefore, *Acropora* spp. coral, seagrass (*Thalassia testudinum* and *Syringodium filiforme*), and mixed massive coral cover dominated by *Orvicella* spp., *Siderastraea* spp.. *Agaricia* spp., and *Porites* spp. were identified as the most important benthic units for refining the classification scheme. The spectral signature of each benthic unit was extracted from the image, compared, and examined at representative “reference areas.” The three benthic units were spectrally similar, but there was a unique inverse relationship between the red Band 3 (655-690 µm) and the blue Band 1 (450-510 μm) that was discovered for the *Acropora* spp. coral benthic unit. This inverse relationship was then used as an impetus to carry out a Band 3 to Band 1 ratio. An Iso Cluster unsupervised classification with 50 classes was performed on the Band 3/Band 1 ratio image, and the class which only populated the *Acropora* spp. reference areas was isolated and displayed to yield the distribution map of *Acropora* spp. corals.

Classification Accuracy Assessment

To quantitatively assess the accuracy of the initial supervised classification and refined classification methods, reference points and underwater photography from the field were used to map areas in which one of the types of benthic units were clearly dominant (*Acropora* spp. coral, seagrass, or mixed massive corals). For *Acropora* spp. coral, survey transects that had been placed across the five areas of highest live *A. cervicornis* coral cover to assess percent live coral cover by other researchers were used as reference areas because the amount of live *A. cervicornis* coral was already quantified along the transects using 1 m^2 quadrats and underwater photography (*Figure 2*).

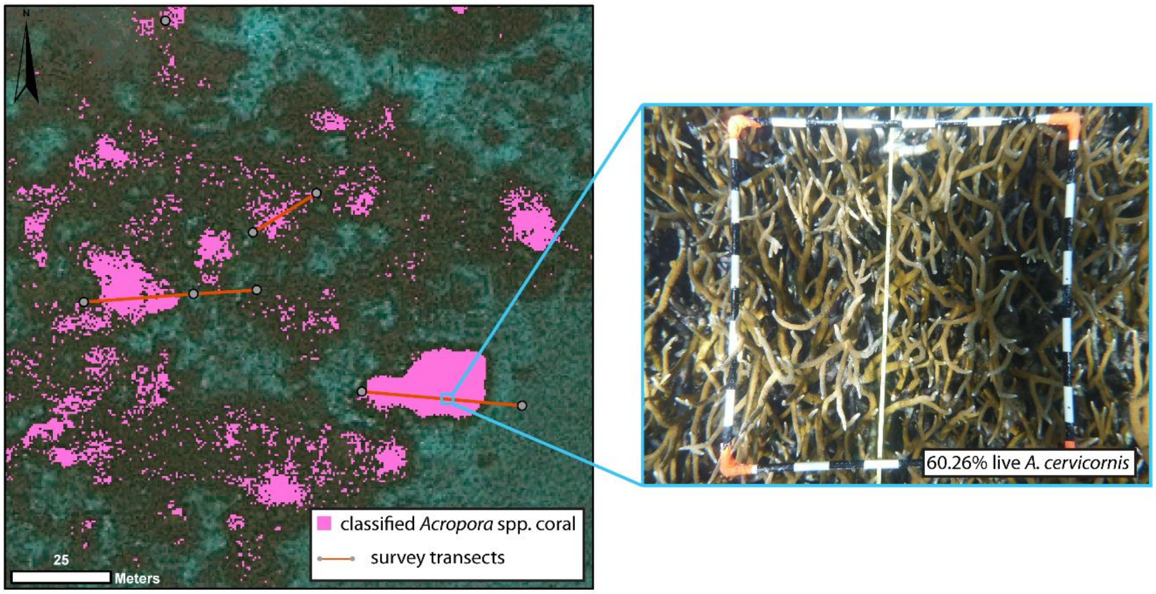

Figure 2: a map of the underwater survey transects with an example of a survey photograph shown with the 1 m^2 quadrat and calculated live coral cover

In each mapped reference area, it was assumed that 100% of the area was comprised of its respective benthic cover. Because the seagrass reference area is significantly larger than the *Acropora* spp. and mixed massive coral reference areas, random points were generated within its extent and converted to a raster with an equivalent area equal to the mean of the *Acropora* spp. and mixed massive coral areas. This was done in order to not skew the final statistics into biasing the larger seagrass reference area.

An error matrix was created for the initial supervised classification and the Band 3:Band 1 ratio unsupervised classification and included calculations of the producer error, consumer error, overall accuracy, and $\hat{k}$ statistic (Jensen, 1996). For the error matrix, the seagrass and mixed massive coral reference areas were combined because the classifications were binary identifications, with choices of either *Acropora* spp. coral or not *Acropora* spp. coral. Therefore, the reference areas had to reflect the same binary classification, with seagrass and mixed massive coral being summed as the two "not *Acropora* spp. coral areas."

A proposed Marine Protected Area was then drawn around the extent of the mapped *Acropora* spp. corals, which were generally located in stands very closely to one another. The extent of the MPA was strategically chosen after an extensive literature search on ideal sizes and designs for MPA's.

Results

The field assessment of the supervised classification led to the discovery of 31 previously undocumented populations of *Acropora* spp. coral (*Table 1*). However, there were large areas of seagrass and stands of mixed massive coral species falsely identified as *Acropora* spp. coral in the image (*Figure 3*).

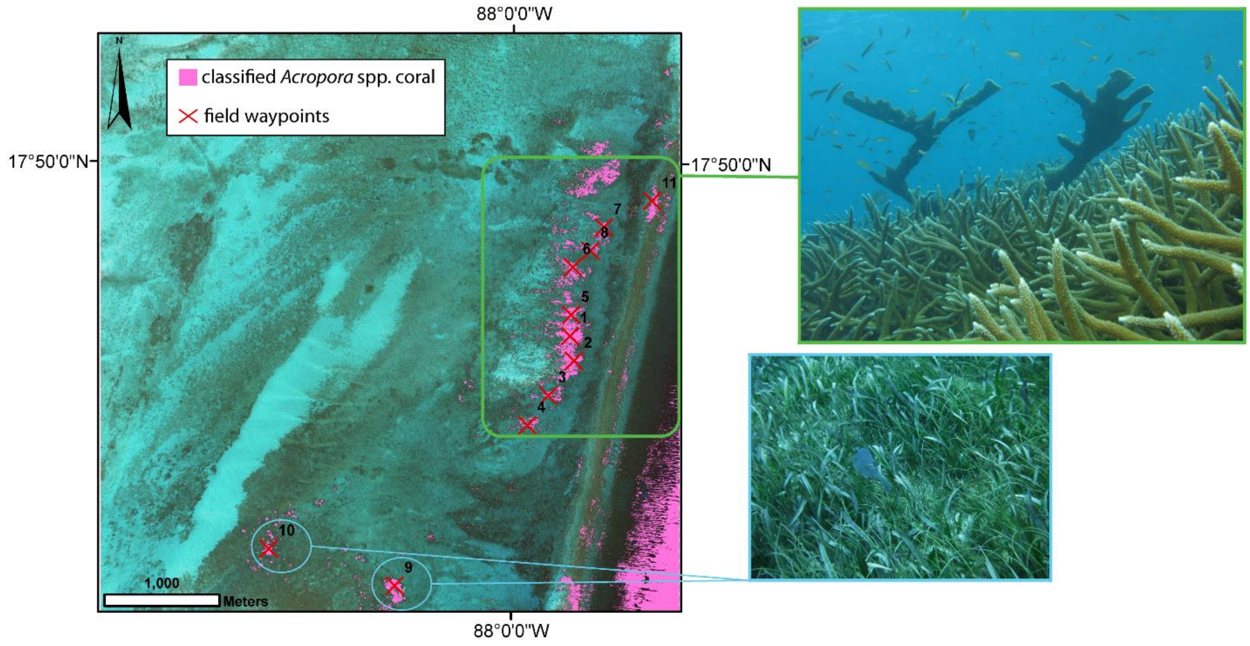

Figure 3: the identified *Acropora* spp. coral from the initial supervised classificaiton. The northern waypoints outlined in green show an example of the *Acropora* spp. dominated areas, and the waypoints circled in blue show an example of the seagrass dominated areas

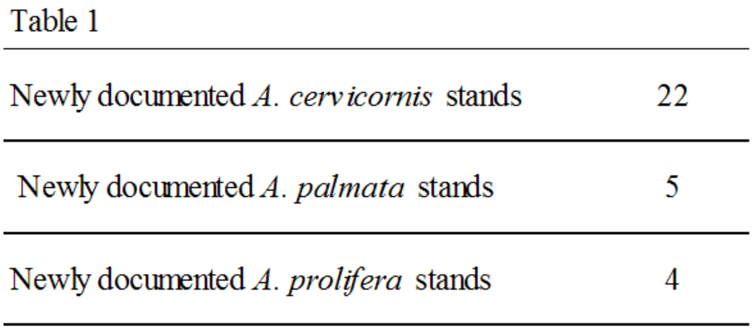

Table 1

Newly documented *A. cervicornis* stands	22
Newly documented *A. palmata* stands	5
Newly documented *A. prolifera* stands	4

Table 1: a summary of the newly documented *Acropora* spp. populations from the field assessment of the initial supervised image. All population locations were documented using differential GPS.

A comparison between the initial supervised classification and the unsupervised classification of the Band 3/Band 1 ratio qualitatively shows that the accuracy of identifying *Acropora* spp. coral from other benthic units increased with the refined classification methodology (*Figure 4*).

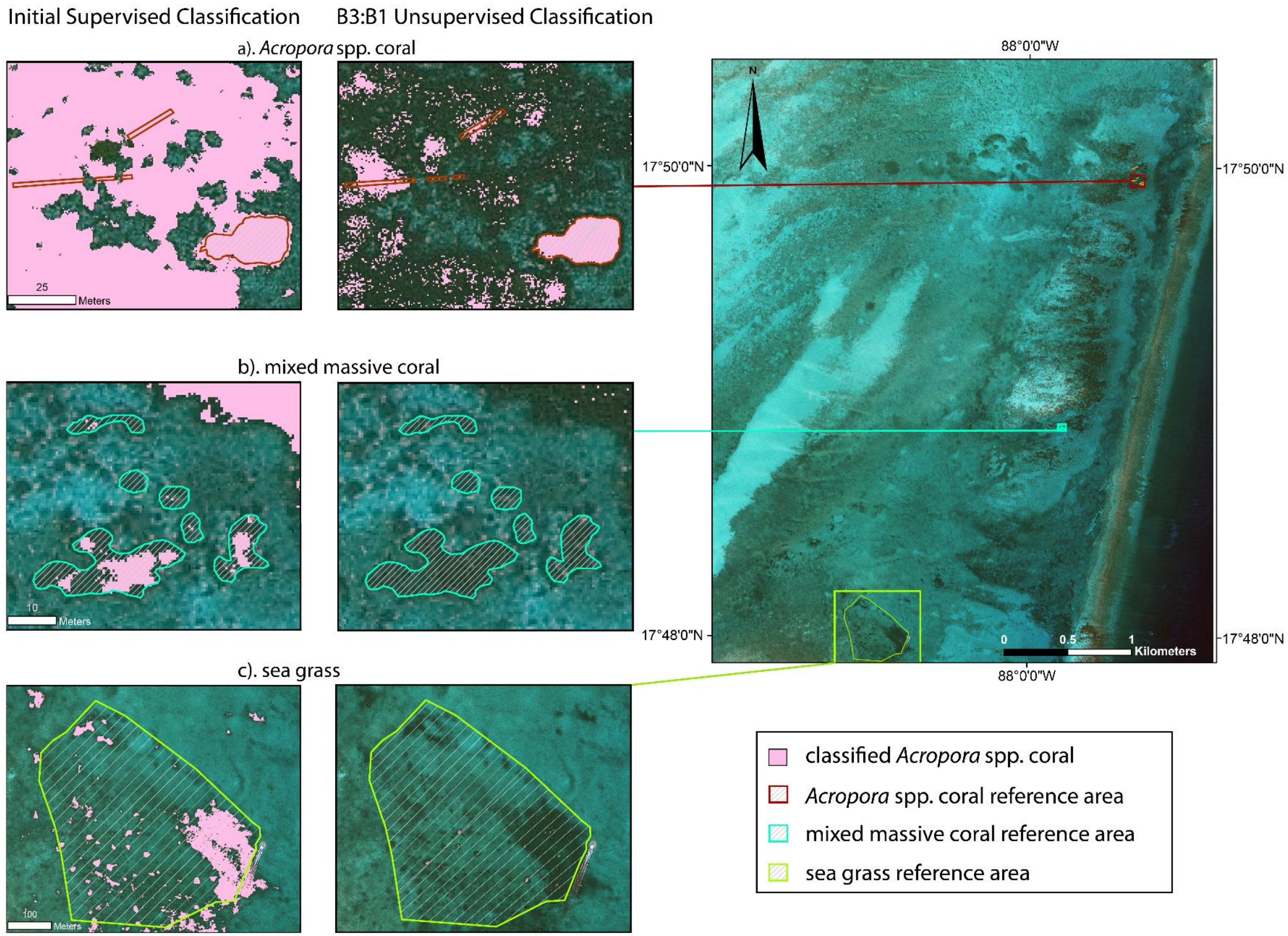

Figure 4: a comparison between the initial supervised classificaiton and the Band 3:Band 1 ratio unsupervised classification of *Acropora* spp. corals at each reference area

The fully mapped *Acropora* spp. populations based on the unsupervised classification of the Band 3/Band 1 ratio shows the *Acropora* spp. corals populate a relatively thin but long stretch of the back reef and lagoonal area around Coral Gardens, Belize (*Figure 5*).

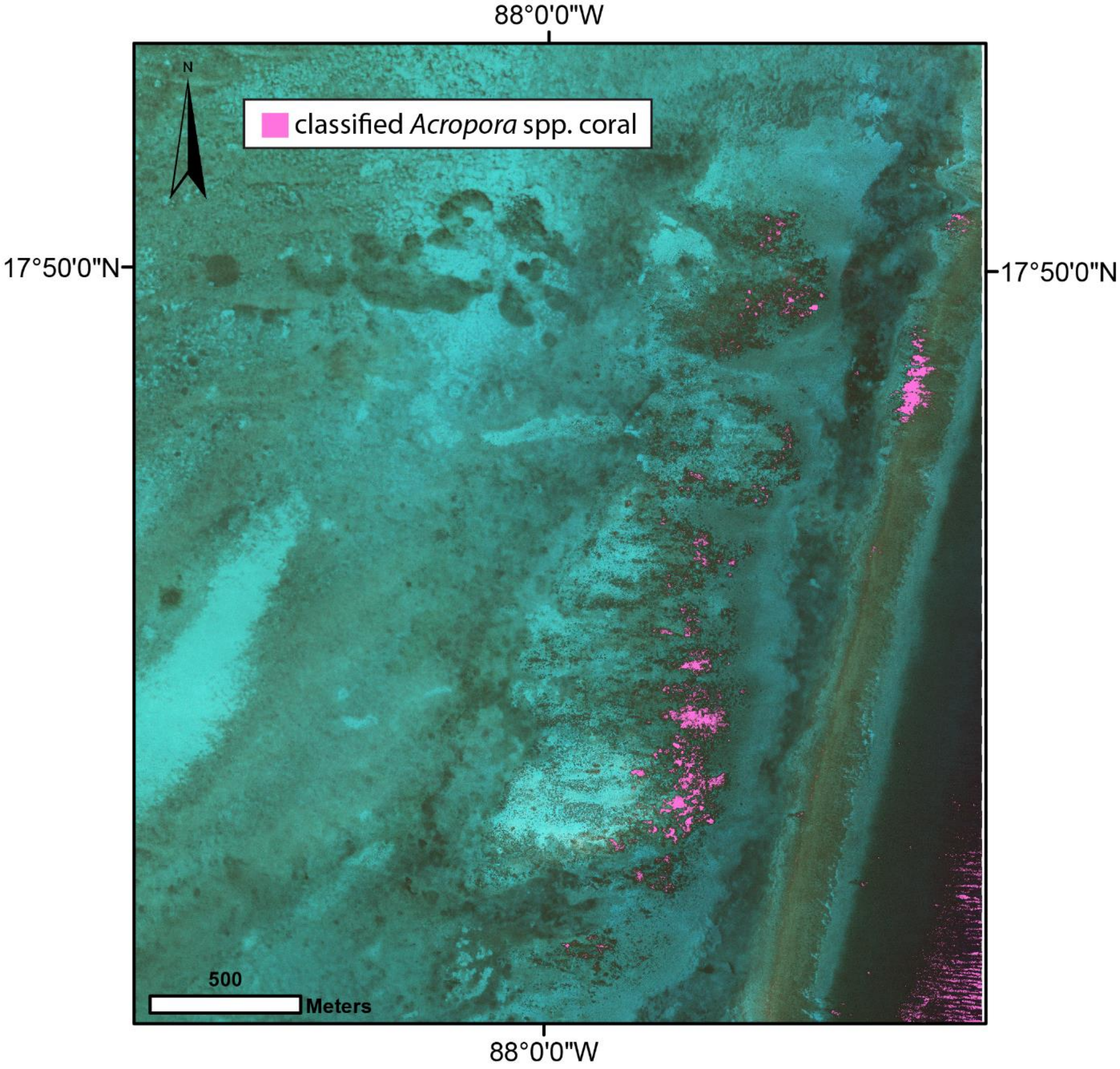

Figure 5: a map of the classified *Acropora* spp. populations from the Band 3:Band 1 ratio unsupervised classification

In the error matrices, consumer error describes the probability that a category on the map will be correct, producer error describes the probability that a reference area was correctly interpreted by the classification, the $\hat{k}$ statistic provides a measure of how accurate the classification is adjusted for the probability that something was identified correctly based purely on chance, and the overall accuracy is simply the overall proportion of correctly classified pixels (Aranoff, 2005). The matrices showed that the Band 3:Band 1 ratio unsupervised classification improved in both overall accuracy and the $\hat{k}$ percentage, but the results were mixed for consumer and producer error (*Tables 2 & 3*). The consumer error for the *Acropora* spp. coral category increased from 75.09% in the initial supervised classification to 99.75% in the Band 3:Band 1 ratio unsupervised classification, meaning that of the *Acropora* spp. coral mapped by the refined classification method in the image, 99.75% was correctly interpreted by the refined classification method. The producer error for the *Acropora* spp. coral category decreased from 97.40% in the initial supervised classification to 73.50% in the Band 3:Band 1 ratio unsupervised classification, meaning that of the actual *Acropora* spp. coral in the image, 73.50% was correctly identified by the refined classification.

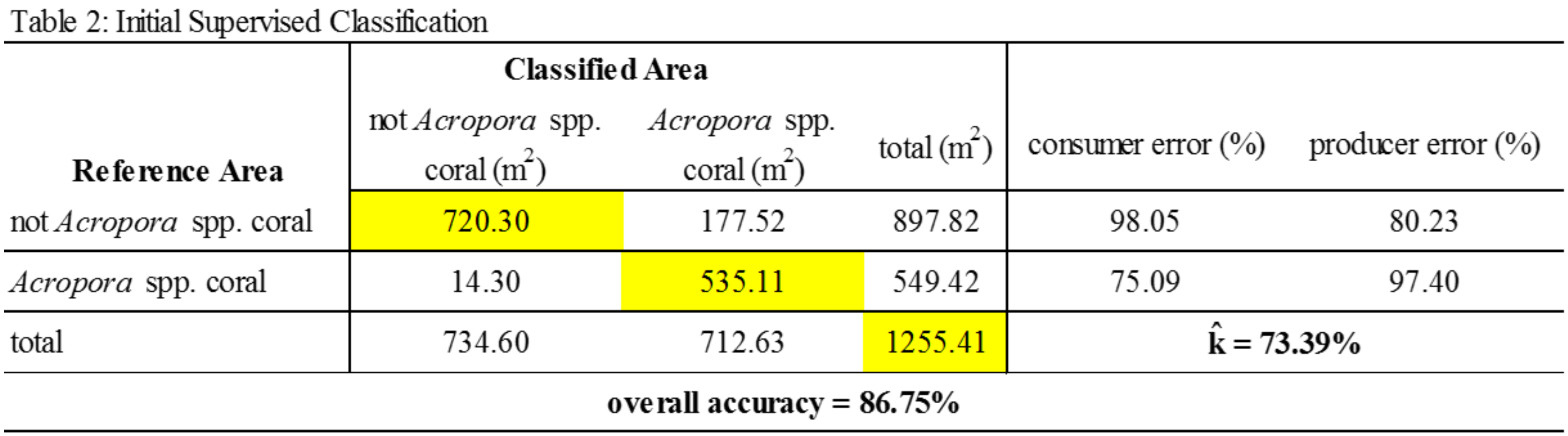

Table 2: Initial Supervised Classification

Reference Area	**Classified Area** not *Acropora* spp. coral (m^2)	Acropora spp. coral (m^2)	total (m^2)	consumer error (%)	producer error (%)
not *Acropora* spp. coral	720.30	177.52	897.82	98.05	80.23
Acropora spp. coral	14.30	535.11	549.42	75.09	97.40
total	734.60	712.63	1255.41	**$\hat{k} = 73.39\%$**	
overall accuracy = 86.75%					

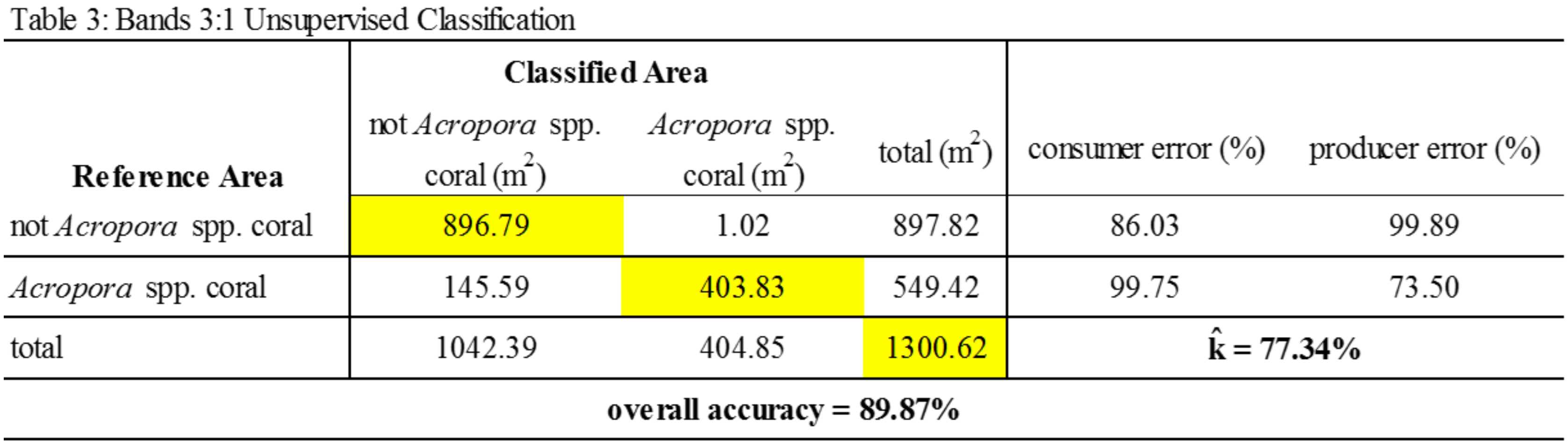

Table 3: Bands 3:1 Unsupervised Classification

Reference Area	**Classified Area** not *Acropora* spp. coral (m^2)	*Acropora* spp. coral (m^2)	total (m^2)	consumer error (%)	producer error (%)
not *Acropora* spp. coral	896.79	1.02	897.82	86.03	99.89
Acropora spp. coral	145.59	403.83	549.42	99.75	73.50
total	1042.39	404.85	1300.62	**$\hat{k} = 77.34\%$**	
overall accuracy = 89.87%					

Tables 2 & 3: error matrices for the initial supervised classification and Band 3:Band 1 ratio unsupervised classification. The yellow boxes indicate the correctly identified area in m^2 for each category.

Discussion

Imagery Classification Techniques

The results from the field assessment found that the initial supervised classification method was successful in identifying populations of *Acropora* spp. coral, but in some instances seagrass and mixed massive coral zones were misidentified as *Acropora* spp. coral (*Figure 3*). The refined classification method that used an unsupervised classification of the Band 3:Band 1 ratio resulted in a significant decrease in the number of false positive classifications of seagrass and mixed massive coral, reflected by the increase in consumer error from 75% to nearly 100% (*Tables 2 & 3*). Additionally, because the refined classification methodology did not falsely identify anything in the mixed massive coral reference area, it successfully separated *Acropora* spp. coral from other coral types.

The results also showed an increase in the number of false negative classification for the refined classification method, reflected by the decrease in producer error from 97% to 74%; however, this may also be a reflection of the inaccuracy of the null hypothesis for the *Acropora* spp. reference area, which was that 100% of the area is live coral cover. Although the reference areas are along transects with documented high density *Acropora* spp. coral cover, high live coral cover is defined as an average of 50% live coral, and some areas along the transects have as low as 14% live coral cover (unpublished data) which one would expect to result in less classified live *Acropora* spp. cover (*Figure 6*). Therefore, the increase in false negatives for the refined classification method may actually be a more accurate reflection of the amount of live *Acropora* spp. cover but it would extremely difficult to assess the accuracy of the classification at such a fine scale.

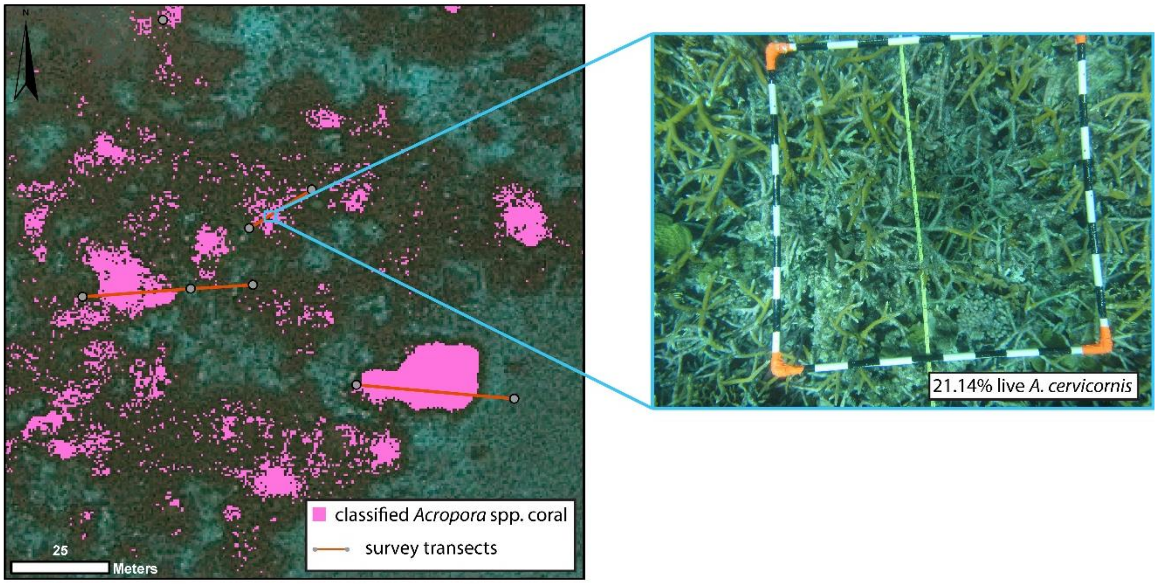

Figure 6: a map of the underwater survey transects with an examply of a survey photograph shown with the 1 m^2 quadrat and calculated live coral cover.

The error matrices also show the tradeoff that is seen between the initial and refined classification methods, with the initial supervised classification identifying more of the *Acropora* spp. coral that is actually in the image and the Band 3:Band 1 unsupervised classification identifying the *Acropora* spp. coral more accurately (*Tables 2 & 3*). It would be up to the individual, but it is more likely that the field researcher would prefer the map to accurately show the *Acropora* spp. coral with a little bit missing rather than have a map with false positive identifications that would lead them to areas without *Acropora* spp. corals and waste valuable time while in the field. Hence, the refined classification method still holds more value to field researchers trying to identify *Acropora* spp. corals prior to a field study.

It should be noted that the accuracy assessment in general is limited because there was only one mixed massive coral reference area, which was representative of the larger mounding corals such as *Orvicella* spp., *Siderastraea* spp.. *Agaricia* spp., and *Porites* spp. This was largely the case because identifying large populations of mixed coral species in the field was not an aim of this study but ideally there would be multiple mixed coral reference areas that could be used to provide a better assessment of the true accuracy of the classification methods.

The improved accuracy of the refined classification method proves it to be a successful tool for identifying populations of *Acropora* spp. corals in a GeoEye-1 image and discerning them from other types of benthic cover, including other types of corals. The method is also relatively easy to employ, inexpensive, and can be utilized by other researchers conducting similar field studies and planning Marine Protected Areas for at-risk *Acropora* spp. populations.

The main drawback to the classification technique is that the location of at least one population of *Acropora* spp. corals has to be known within the image in order to identify which "class" contains the identified *Acropora* spp. coral. A methodology which automatically identifies populations of *Acropora* spp. coral for the researcher in a time efficient and easily replicable method is the ultimate goal.

The purposes of the study were twofold: to create an easily replicated, time efficient, and inexpensive method for identifying *Acropora* spp. corals using remote sensing, and map these endangered corals at Coral Gardens, Belize so they could be monitored remotely over the long term. The methodology that has been devised in ArcGIS® using GeoEye-1 imagery proves to be successful in all of these aspects, with a few minor drawbacks. The most important success of the methodology is its ability to discriminate *Acropora* spp. coral from other types of coral species, and because of the success of the methodology in that respect it was then employed to demonstrate its utility in *Acropora* spp. coral conservation applications, specifically Marine Protected Area planning.

MPA Planning and Conservation Applications

This study is the first to document the extent of *Acropora* spp. corals in Coral Gardens, which is important when considering the creation of a Marine Protected Area in the Coral Gardens area. There is much debate over the effectiveness of MPA's to enhance live coral cover, with some arguing that their success is limited by the quality of planning and implementation of the protected areas (Maypa et al., 2012) and others arguing that amidst increasing global sea surface temperature increases that their effectiveness is negligible (Selig et al., 2012) . Others suggest that MPA's can improve density, biomass, organism size, and species richness of fisheries (Coleman et al., 2013; Christie et al., 2010; Lester et al., 2009; Svensson et al., 2009) and also maintain live coral cover and genetic diversity (Harter et al., 2009; Linares et al., 2010; Linares et al., 2012; Selig and Bruno, 2010; Miller and Ayre, 2008). MPA's have become increasingly popular as an efficient and inexpensive way to maintain and manage fisheries, as well as preserve biodiversity in areas that are particularly prone to damage from anthropogenic factors (Halpern, 2003; Bellwood et al., 2004). At Coral Gardens, both goals would be achieved given the high abundance of *Acropora* spp. coral and their unique branching framework, which provides the three dimensional habitat that many aquatic organisms rely on (*Figure 7*).

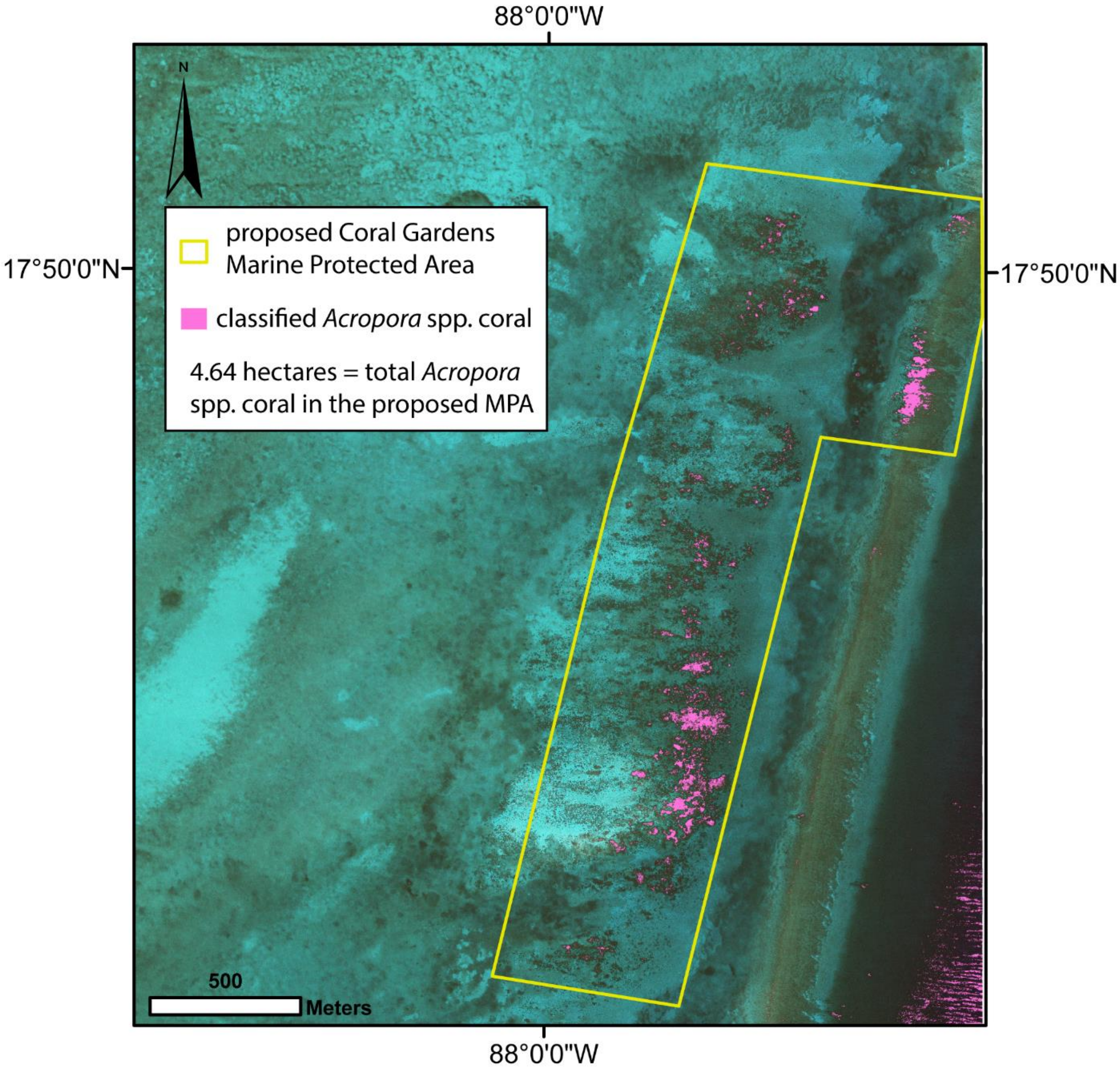

Figure 7: a map of the designed Coral Gardens MPA in relation to the mapped *Acropora* spp. coral populations based on the unsupervised classification of the Band 3:Band 1 ratio.

Two important considerations when planning MPA's are their size and connectivity to other MPA's. The literature suggested that when considering the sustainability of fisheries, which are closely tied to coral reef health in the Caribbean, that MPA's should be large enough so that populations within reserves can sustain themselves, but still small enough so that some larvae produced inside the MPA can be transported to unprotected areas (Almany et al., 2007). As an exercise to demonstrate the utility of our *Acropora* spp. recognition tool, the extent of the

Coral Gardens MPA was chosen to include all regions of identified *Acropora* spp. corals given their threatened status and ecological importance to reef biodiversity. This inclusion made the extent rather large, which would likely cause more resistance from local fisherman; however, when considering connectivity, the Hol Chan MPA is located approximately 0.25 kilometers north of the Coral Gardens MPA, and the Caye Caulker MPA is located approximately 1.5 kilometers south of the Coral Gardens MPA (*Figure 8*). Neither of these well-established MPA's currently house significant populations of *Acropora* spp. corals, yet our study shows that the space between (Coral Gardens) is rich in thriving populations of these now relatively rare corals. The Coral Gardens MPA with its proposed extents would allow connectivity between the Hol Chan and Caye Caulker MPA's, which are currently separated by approximately 5 kilometers of unprotected water that sees heavy boat traffic.

With the addition of the Coral Gardens MPA, the decreased fishing pressure and boat traffic could help optimize larval transport, facilitate the growth of fish populations, promote increased biodiversity within the reserve, and enhance live coral cover.

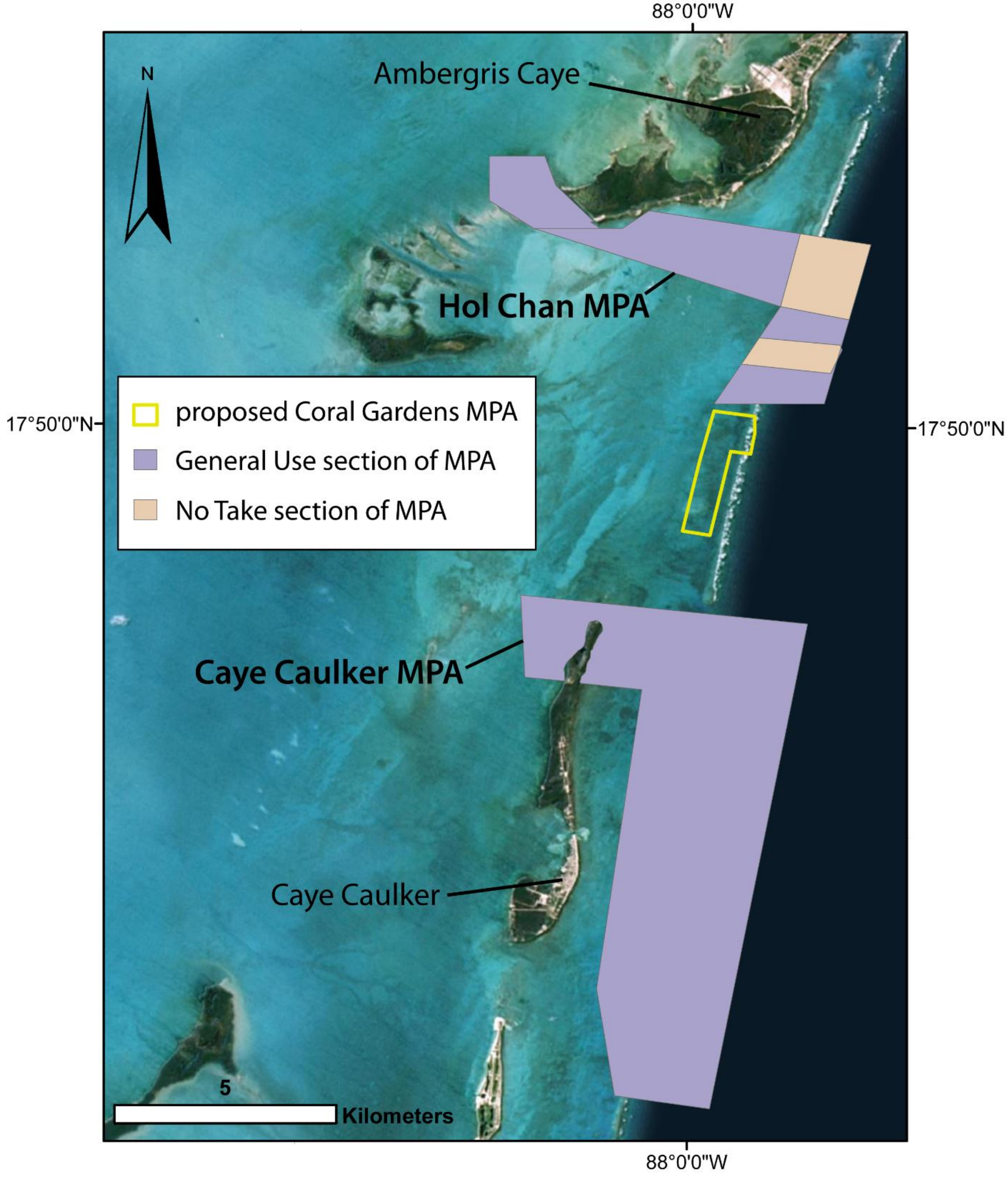

Figure 8: the *proposed* Coral Gardens MPA in relation to the current extents of the Hol Chan MPA and the Caye Caulker MPA. Basemap imagery courtesy of Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Acknowledgments

Thank you to the NSF Keck Geology Consortium grant for funding the research project in Belize, the Washington & Lee Department of Geology for their summer research support, and the R. Preston Hawkins IV Geology Award for funding other parts of the research. Also thank you to Ken and Maurine at the Marine TREC lab for being gracious hosts, Dr. Tom Guilderson for hosting me at the Lawrence Livermore National Laboratory and assisting me with interpreting the radiocarbon data, and Emily Falls for all of her help during the summer.

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