QUANTIFYING SARGASSUM ON EASTERN AND WESTERN WALLS OF THE GULF STREAM PROTRUDING NEAR CAPE HATTERAS INTO SARGASSO SEA BERMUDA/AZORES

ABSTRACT

The Sargasso Sea has been a marine life habitat for millions of years. located in the North Atlantic Subtropical Gyre with the western limit formed by the north and the north-eastern flowing, powerful 'Gulf stream. The importance of the Sargasso Sea is recognized for the role of this current-system providing shelter and protection for marine animals such as fish and sea turtles. Two species of *Sargassum natans* and *S. fluitans* are highly branched with thalluses with numerous pneumatcyst that contain oxygen, nitrogen, and carbon dioxide to give buoyancy to the brownish algae. Sea surface winds cause *Sargassum* aggregate and form lengthy windrowed rafts to propagate. As the pneumatcyst lose their gasses, *Sargassum* can reach 100 meters below the sea's surface or even accumulate on the sea floor. Accurate mapping of the boundary in the local area of the Gulf Stream near the coast of Cape Hatteras extending to Bermuda area has yet to be conducted using Earth observing Landsat satellites. Detection of these scattered aggregations of floating *Sargassum* suggests that this brown algae form small raft-like sea surface features In relativity to the resolution of Landsat series and Moderate Resolution Imaging Spectroradiometer (MODIS) atmospheric instruments have been found to have difficulty due to lack of spatial resolution, coverage, recurring observance, and algorithm limitations to identify pelagic species of *Sargassum*. *Sargassum* rafts, when identified, tend to be elongated and curved in the direction of the wind, and warmer than the surrounding ocean surface. Satellite data utilizing simple ocean color indexes such as the Floating Algae Index (FAI) has shown

advantages over the traditional NDVI and Enhanced Vegetation Index (EVI) because FAI is less sensitive to changes in environmental and observing conditions (aerosol type and thickness, solar/viewing geometry, and sun glint) and calculated from optical and infrared measurements made through thin clouds. The baseline subtraction method provides a simple yet effective means for atmospheric correction. The FIA and NDVI index algorithms assisted in identifying the boundary area of the Sargasso Sea and the path of this floating Alga past Cape Hatteras into the Atlantic Ocean. The goal of this research was to identify seasonal patterns of the *Sargassos* boundary in the area near the Cape Hatteras coast out to Bermuda for protection and regulation. Similar spectral bands used in previous research applications of FIA are available on many existing and planned satellite sensors such as the Landsat series of Earth observation satellites, the NDVI and FIA concept was utilized to establish a long-term record of vegetation in the Gulf Stream near Cape Hatteras coast extending out to Bermuda. Once a base procedure for mapping locations where *Sargassum* occur, a new approach, possibly using drone, will be recommended to estimate accurate biomass of algal floating patches.

DEDICATION

This thesis is dedicated to my mother & father for supporting my chosen pathway in life and giving me great examples of character and self-esteem. To our Brave men and women who Sacrifice so that work like this can be conducted. To Dr. Hayden for challenging me to strive higher than a Bachelor's degree, as well as challenging me to mentor and be a role model for my peers on how professional research is conducted. To all, I hope to become the best of what I can be in this world thanks to your investments. I hope to provide the wisdom, knowledge, and compassion you have shown me.

ACKNOWLEDGEMENTS

I am truly grateful to Dr. Malcolm LeCompte for his training on how to manipulate Landsat images so that I was prepared to succeed in my Thesis endeavor. I want to express sincere gratitude to The Math and Science department faculty and the amazing team of mathematics professors'. Thank you for the instruction at this institution of Higher learning. Deep appreciation for Dr. George for Introducing me to the study of the Sargasso Sea which has challenged my computer science, mathematics, and Science skills to gain an understanding of this broad focus. Most importantly Dr. Linda B. Hayden for uplifting me and guiding me these past five years to be a professional in the field of Remote Sensing through her program at Elizabeth City State Universities' Center of Excellence in Remote Sensing and Education through Internships, professional conferences, and mentorship.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

Background

Sargasso Sea

The famous *Sargasso* Sea, located geographically in the legendary "Bermuda Triangle" or more accurately in the so-called North Atlantic Subtropical Gyre with the western wall formed by the north and the north-eastern flowing powerful 'Gulf stream (George, 2010). Columbus was the first to observed the floating weeds in the Atlantic on his voyage to the New World. 'Sarga' means grape in Portuguese and the sailors from Portugal compared the round air bladders of *Sargassum* to sea grapes (George, 2010). Spanish historian Oviedo came up with the first name the Sargasso Sea in 1514 for the vast surface covered by these floating weeds. There was a controversy about where *Sargassum* weed came from. Some believed that it grew on the sea floor below and floated to the surface. German botanist Meyen in 1834 was the first to prove that *Sargassum* continues to grow as it floats in the sea. In 1852 Major James Rennell was the first to prove that *Sargassum* was bcarried in from the Gulf of Mexico by the Gulf Stream to the Sargasso Sea (George, 2010). Over the years of human exploration, curiosity has sparked researchers to begin the documentation of crude first-hand accounts of the vast phenomenon.

3.5 million Years ago, befor the formation of the Isthmus of Panama separating the Atlantic ocean from the pacific ocean, Sargasso evolved 40 million years ago just around the time of the last Basilosaurus ("king lizard") that lived. First fossil of the Basilosaurus was discovered in the United States and was initially perceived to be a reptile but was later found to be a marine animal. Two species occur in the *Sargassum* Sea are S.fluitans with large lanceolate leaves and S. natans with fine, delicate leaf structure (see figure 1) (George, 2010).

Sargassum includes benthic and pelagic species that occur near or at the bottom of the ocean and living or growing at or near the surface of the ocean far from land (Webster, 2016) (USGS, 2016). S.natans and S. fluitans became highly branched with thalluses with numerous pneumatcyst that contain oxygen, nitrogen, and carbon dioxide to give buoyancy to the brownish algae (see image 2). Sea surface winds cause *Sargassum* aggregate and form lengthy windrows. As the gasses in the pneumatcyst lose their gasses, *Sargassum* can reach 100 meters below the sea's surface or even the sea floor (George, 2010) .

The Sargasso Sea is a vast area that is located east of Cape Hatteras, North Carolina, north of the Caribbean islands, includes the Bermuda Triangle as well as the Tropic of Cancer, and extends far east into the North Atlantic Ocean (George, 2010). The sea is named for the *Sargassum*, a genus of macro algae, that blankets the surface, stretching for “miles and miles”, prominent during late spring into early August (George, 2010). Four currents act on the Sargasso Sea, manipulating its outward extension: the Gulf Stream on the West, the North Atlantic current on the North, the Canary current on the East, and the North Equatorial current on the South (see figure 3).

Mid-ocean Sargasso Sea is between several currents such as The Gulf Stream on the west, North Atlantic Drift to the north, Azores- Anticyclonic current to the Northeast, Southward-flowing Canary Current to the east, and the wet-ward flowing North Equatorial Current to the south (George, 2010).

Unfortunately, the many benthic and pelagic species that inhabit *Sargassum* are under threat of harvesting due to its apparent use as a natural resource in the no man’s sea: for using it as fertilizer, cattle feed, and renewable oil. Fisheries Management Council established Maximum Sustainable Yield (MSY) and declared that *Sargassum* would be protected within the international waters. There are even plans to accelerate the growth rate in orderto be able to exploit and maximize the allowed MSY for industries such as medical use to explore antibiotic compounds (George, 2010).

Figure 1. A windrow of floating Sargassum in the Gulf Stream.

The illegal, unregulated, or unreported fishing by foreign fleets from other nations such as Spain and Russia at large seamounts could disrupt the entire food chain, which can forwarn of an ecosystem collapse (George, 2010).

NOAA National Marine Fisheries Service (NMFS) has developed management tools to mitigate the influence of fishing practices on Vulnerable Marine Ecosystems (VMEs) such as deep-water coral habitats by designating these offshore areas as Federal Fisheries management zones (FFMZ), Essential Fish Habitats, Habitat Areas of Particular Concern (HAPC), National Monuments, and National Maine Sanctuaries (MPAs). The Magnuson-Stevens Fishery Conservation and Management Act stipulates that the regional fishery management council (SAFMC has the responsibility to identify, describe, conserve, enhance and minimize the adverse impact of fishing in the designated conservation area (George, 2010).

There is much difference of opinion, for if protection areas are hampering the local economy. Many who fish these areas have the idea of "freedom to fish" which precludes any concept of disallowing fishing in any ocean zone, especially in the high seas (George, 2010).

With the ability to understand that every biome has an effect on another, the idea of protecting an ocean's ecosystem calls for protecting not just the sea floor, but the surface ecosystem above. Since the Atlantic Ocean is on huge ecological unit, this idea is attracting support(George, 2010).

The importance of the Sargasso Sea is it provides shelter and protection for marine animals such as fish and sea turtles. Migratory fish such as swordfish, billfish, alfonsino, sharks

Figure 2. Sargasso Pneumatcyst and branched thalluses.

Figure 3. Currents acting upon the Sargasso Sea

and tuna use this corridor of seamounts in their transatlantic migration. The sea also serves as a breeding ground for both the European and American eels and feeding grounds as well as nurseries for migrating fish (George, 2010). On top of the *Sargassum* canopy, a unique species of shrimp, crab, and fish are inhabitants.

Considering the effect of strong winds and currents (i.e. hurricanes), these elements combined with the Sargasso Sea have led to significant changes in the ecosystem of the area (George, 2010). To be specific, the sea serves as a pelagic habitat for phytoplankton, varying species of fish.

On the beaches the smell and the amount of work required to remove *Sargassum* out of public areas is imminse (figure 5). (George, 2010). Many of the commercial fishing fleets target these seamounts. Pauly and Myers and Worms caution that fishing at the top of the trophic pyramid could disrupt the ecosystems. (George, 2010)

Sargassum also plays a role in defining ocean productivity and (climate change) carbon flux (Hu et al, 2010) and is now considered a critical protected marine habitat and its harvesting in some ocean regions is regulated to protect the associated marine species at the south Atlantic Fishery Management Council, 2002 (Powers, 2015). Some species of floating algae can also be used for human food and phycocolloid production. Conversely, an excessive amount of floating algae in coastal oceans can cause significant adverse impact on local environments and economy. Dead algae washed onto the beaches must be physically removed in a prompt fashion, and represents an economic burden to local management in the Gulf of Mexico.

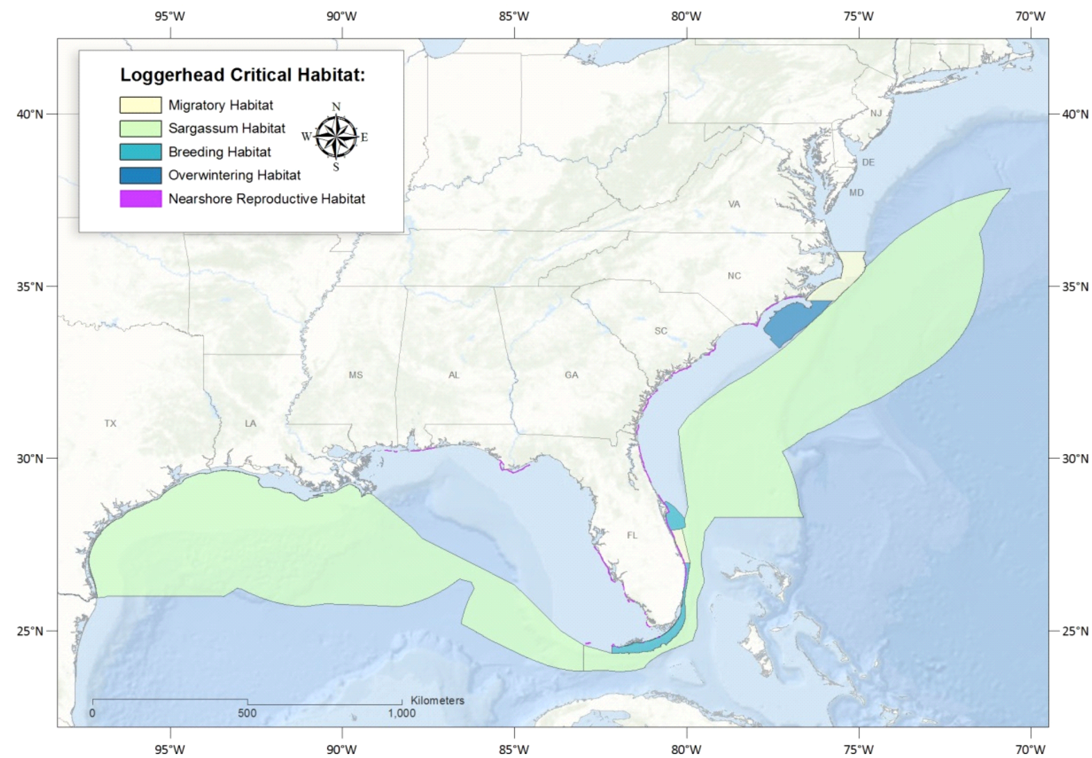

Figure 4. *Sargassum* Habitat from the Gulf of Mexico to the Sargasso Sea off the coast of Cape Hatteras

Figure 5. Sargassum washed ashore on the coast of the Gulf of Mexico

Statement of Purpose

The purpose of this research endeavor is to utilize Landsat satellite imagery to detect amounts of Sargassum floating on the sea surface in the Area between Cape Hatteras and Bermuda to establish methods and techniques to map and monitor Sargassum's seasonal trends to evaluate if areas along the Cape Hatteras coast have need for protection, conservation, and calculation of quantitative biomass.

Methods and Procedures

Area of Interest

The areas of interest are between Cape Hatteras and the Bermuda since this is the last segment of its travels into the Atlantic. Within this region, quantification of the boundary area and biomass of the “Sargasso jet” along the Gulf Stream.

Image Acquisition

Satellite imagery used in this research was obtained from an online database, provided by the United States Geological Survey (USGS, 2016). Images were obtained from Landsat satellite 7 between the months of August and January from 2003- 2015. The primary purpose of the Landsat program was to acquire and broadcast satellite images of the east coast of United States from Space’s perspective to aid in detecting and mapping seasonal and environmental conditions with its 30 m resolution imagery. The satellites collect images with various instruments on-board the satellites payload. The instrument on board Landsat 7 was equipped with the Enhanced Thematic <mapper plus (ETM+). As of February 2013, Landsat 8 was the newest satellite introduced to the Landsat series of satellites to achieve orbit from the NASA Landsat series.

Table I Landsat 7 ETM+ Description

Band Number	Spectral Range Wavelength (µm)	Resolution (m)
1	(.441 - .514 µm) Blue	30 m
2	(.519 - .601 µm) Green	30 m
3	(.631 - .692 µm) Red	30 m
4	(0.772 to 0.898 µm) NIR	30 m
5	(1.547 – 1.749 µm) SWIR-1	30 m
6	(10.31 – 12.50 µm) TIR	60 m
7	(2.08 to 2.35 µm) SWIR-2	15 m
8	(0.515 – 0.896 µm) Pancromatic	15 m

Table II IKONOS Band-dependent Parameters

Band	Spectral Range wavelength (µm)	Spatial Resolution
1	(0.45-0.52 µm) Blue	4 m
2	(0.51-0.52 µm) Green	4 m
3	(0.63-0.70 µm) Red	4 m
4	(0.76-0.85 µm) Near Infrared	4 m
5	(0.45-0.9 µm) Panchromatic	1 m

Data Processing

Satellite imagery downloaded from USGS Landsat archive require corrected atmospheric radiance and combined to produce the aforementioned vegetation index products FIA and NDVI (see index). ENVI software provided the ability for analysis and visualization of scientific data and imagery (ENVI, 2009). After unzipping the files of the individual bandwidth channels,the satellite images were loaded into the program. With the Bandwith images loaded into ENVI software, atmospheric correction is performed to convert reflectance values into radiance. Next was to combine the bandwidths into the Index formulas NDVI and FIA to produce a combined bandwidth channel GeoTIFF products of the combined imagery. the created imagery enhancements????? to the product with color pallets to have positive values color coded by the intensity of the value. Multiple displays can be linked together for comparison of different products in the same areas of the image.

CHAPTER II REVIEW OF LITERATURE

Characteristics of Invasive Sargassum Species

There are various types of *Sargassum* in the open waters of the earth, mainly. S.natans and S. fluitans and S. muticum require several years to build up sufficient breeding stock to allow for rapid expansion (D.B Harris). Known to grow in densely floating structures which if not regulated could create significant economic damages in the aquaculture industry. *Sargassum* has a large tolerance for conditions of reduced salinity, although growth rate and reproduction are impaired and unable to reproduce if salinity is consistently <15ppt and may be unable to compete effectively if salinity is <25ppt (Haries, 2007).

Sargassum beds contribute to the marine environment by stabilizing bottom sediments and maintaining coastal water quality and clarity. Many important species spawn in the beds such as sea urchins, turban shells, balaos, cuttlefish. Their larvae and juveniles use the beds as a nursery ground. In a way, they serve as an important habitat for marine animals and support biodiversity (Komatsu, 2007). Sometimes floating canopy's over 3 m tall can show high vegetative activity and is also observed to attach itself to stone, wood, mooring lines and wharves (Curiel, 1998). *Sargassum* is capable self-propagation in open sea water due to the average photosynthetic efficiency being higher than that of terrestrial plants (Li, 2012).

Sargassum is a pelagic brown alga that represents an oasis of structure in the open ocean and supports a large and diverse assemblage of marine turtles, fish, and invertebrates. Located in the north-central Gulf of Mexico and Atlantic Ocean, *Sargassum* is almost exclusively composed of two species, *Sargassum* natans, and S. fluitants. Unlike the other species S. muticum that is found in locations such as Scotland and Japan, are holopelagic. Meaning they are typically considered as a single complex organism (Li, 2012). *Sargassum* is a ubiquitous feature where it occurs in three configurations depending on meteorological and *in situ* oceanic conditions: Scattered clumps surfing high winds, small and mesoscale (1m – 10 km's) convergence lines, and larger circular mats. It fulfills a unique position in the open ocean as the only naturally occurring biogenic habitat (Powers, 2015).

Industrial Production Applications on Sargassum species for Bioenergy, Bio-oil, and Antioxidative.

With the depletion of non-renewable fossil energy sources and environmental deterioration, the exploitation of renewable and environmentally friendly energy resources is urgent and significant. Bioenergy is one of the renewable energy sources that have attracted more interest. Biomass can serve as an excellent alternative source to meet fuel needs (Guo, 2012). Various techniques have been developed to utilize this biomass by Fermentation, direct combustion, gasification, pyrolysis and hydrothermal liquefaction. Hydrothermal liquefaction is environmentally friendly and requires no drying of the biomass (Li, 2012).

Out of 13 species of *Sargassum* found in coastal waters, S. siliquastrum has the strongest antioxidant activity. Epidemiological studies have found that intake of antioxidants such as vitamin E and vitamin C reduced the risk of coronary heart disease, stroke, and cancer. An antioxidant is an inhibitor of lipid peroxidation (Lim, 2002). Therefore, production of antioxidants has a large potential to grow the economic potentials of *Sargassum* harvesting.

Besides being a possible indicator of reef degradation in some areas, *Sargassum* harvesting in some areas in the world has occurred for a source of alginate and feed, a component sometimes exported as “kelp powder” (Li, 2012). In French Polynesia, biotechnological research has shown that the brown algae T. ornate and S. mangarevense could be used in cosmetic industries (Li, 2012). The macrophytes have the potential to provide income for heavy Leiden Island countries and a way to control algae proliferation on the coast (Turner, 2005).

Since *Sargassum* photosynthetic efficiency is greater than terrestrial plants, easy to harvest, and capable of self-propagation in open sea water many believe this is a meaningful use of the algae as an energy resource from the viewpoint that this resource has lower breeding cost and algae farming has no negative impact on the marine environment (Li, 2012).

Environmental and Economic Impacts of Sargassum on Beaches

The pelagic brown alga, *Sargassum* fluitans, and S.natans constitute significant quantities of disposits on beach shores annually from May to August. *Sargassum* smells bad and hurts Tourism. Coastal managers are confronted with the difficult choice of cleaning it off the beaches or leave it alone and financially suffer.

Masses of *sargassum* may span over hundreds of meters across and are deposited by marine currents and winds on coastlines around the world (Williams, 2010). Common maintenance practice is beach raking in which a tractor equipped with a rake is used to remove the wrack line of *Sargassum* and other marine deposits off of the beach (Williams, 2010). Large piles of *Sargassum* restrict human access to the beach and water. *Sargassum* traps material such as seeds, animals, decaying matter and anthropogenic litter from the water column, which then end up on the beach (Li, 2012). Furthermore, trash entangled in the mix is considered unsightly.

As a consequence of not removing *Sargassum* from the beaches is poor Tourism business. On the other hand leaving *Sargassum* on the beach preserves the natural wrack environment. It provides a valuable habitat for foraging shorebirds and beach scavengers. When on the beach *Sargassum* acts like a sponge during daily events and hurricanes by absorbing wave energy that protects the sand from wave and wind erosion (Williams, 2010).

In this study, greenhouse experiments are used for this article and results states that the accumulation of sand around patches of *Sargassum* help build small embryonic dunes that stabilize the beach (Williams, 2010). They tested 72 samples and assigned random treatment groups and replanted them in 40 oz individual plastic pots. Over the 15-week period, the change in total vegetative length was calculated for each plant. Each species was subjected to a control treatment that was grown without *Sargassum* as “conditions” and “frequency” treatments respectively (Williams, 2010).

This study indicated that *Sargassum* is a naturally occuring fertilizer, distributing the *Sargassum* that washes ashore along the sand dune line, rather than enormous smelly unpleasant piles and would assist in stabilizing the dune systems. With this improvement in coastal management practices, this method has the potential to help maintain attractive recreational areas for tourists. All in all, most plants responded positively to some form of *Sargassum* treatment (Williams, 2010).

Mapping Sargassum with Imagery from Aerial and Space-Borne Instruments

Observations of *Sargassum* from ships, like Dr. George (George, 2010) has performed, provide a firsthand experience that has been impeded by the large and Variable area over which *Sargassum* is dispersed by either Sea winds or bounding currents, which make it difficult to estimate the biomass. And the ability to visualize the seasonal pattern in which *Sargassum* originates at the Gulf of Mexico on its path via the Gulf stream up past Cape Hatteras at the "*Sargassum* jet," then end North East of the Bahamas in the coming February (Hu et al, 2010).

Free-floating pelagic species of *Sargassum* have been recorded since the 1500's (George, 2010) only recently been detected in satellite images. To be detected, *Sargassum* must be dense enough and cover enough area to be detected on the resolution of the satellites instrument (Hu, 2008).

Mapping of *Sargasso* is crucial for management; conservation of ecosystems and sustainable fisheries in coastal waters (Komatsu, 2007) one is the direct method by visual observation and the other is indirect utilizing remote sensing equipment. There are optical and hydroacoustic methods. Indirect methods require sea truth, an onsite classification of the resulting anomaly, by direct methods. Optical methods are conducted by aerial photography or satellite imagery which are effective at mapping extensive areas yet limited to shallow waters due to light attenuation in waters. Hydro-acoustic methods such as an echo sounder and side scan sonar have no limitation and provide vertical density and height measurements of floating patches of *Sargassum* (Komatsu, 2007).

Direct methods are not efficient yet are highly accurate. More time, manpower, and resources are needed to perform field surveys that cover even a small percentage of what indirect methods can cover. Consequently direct or *in situ* methods are required for Aerial and space Mounted sensor calibration (Komatsu, 2007).

Aerial photographs can provide more detailed data for studying sea surface distribution of *Sargassum* over long-term change and biomass. Satellite imagery is efficient where dense *Sargassum* is identified on a grand scale, yet cannot always be successful to map or estimate the biomass. Low density, small patches, turbid water, and submerged patches are variables, which cause low chances of visibility (Komatsu, 2007).

Acoustic methods are very expensive and difficult to process surface maps of the distribution of floating mats from the position of the boat, but it succeeds in distinguishing *Sargassum* mats ranging only 50 to 500 meters. The echo sounders are a low cost and easy to manipulate. It provides a continuous measurement of biomass distributions and topographies of the floating mats canopy below (Komatsu, 2007).

Attempts have been made in the past to estimate biomass of pelagic *Sargassum* from the surface to satellite images to provide useful new data (Gower, 2006). In several cases, ecological mapping was a prelude to estimate the vegetation of biomass (Gower, 2006). Remote sensing is used to estimate biomasses that cover large areas avoiding destruction of Area of Interest (AOI), costly time spent continuity of data, etc. Utilizing satellite data is effective, because of its large coverage area. satellite data provides a frequency of coverage, so differences over time in an area can be observed at the same positions, therefore providing measurement data continuity. Such approaches could help estimate the quality and changes in *Sargassum* floating beds that span many oceans due to wind and sea currents (Turner, 2005).

In the late 1990s drawbacks of coarse spatial resolution from Landsat data were hampering the endeavor to conduct benthic mapping (Turner, 2005). This challenge for *Sargassum* mapping and estimation is presented since targeted vegetation doesn't dominate in the spectral signal. New sensors such as IKONOS and Quick Bird with 4 to 2m meters respectively. However, the limited spectral capacities may still be a limitation for vegetation mapping (see table 2) (Turner, 2005).

Rouse's 1973 [24] concept of Normalized Difference Vegetation Index (NDVI) using Multispectral scanner data from Landsat was defined as

$$\text{NDVI} = (\text{Rnir} - \text{Rred}) / (\text{Rnir} + \text{Rred})$$

Where Rnir and Rred are the spectral reflectance measured in the near- infrared (NIR) and Visible Red bands, The difference between the R_{NIR} and the Rred band's spectral reflectance divided by the sum of the two serves as an index with values between positive and negative one. The sum of NIR and Rred can partially remove the atmospheric effects from different measurements. Since the visual contrast between *Sargassum* and nearby waters make it difficult to implement routine applications on passes in one area of the open ocean at different spatial times (Hu, 2008).

Floating Algae Index (FIA) is introduced for mapping floating algae such as *Sargassum* in various aquatic environments, (Coastal, Ocean, and Lakes) and can be applied to several existing and planned satellite instruments, such as MODIS and Landsat, advantages of the FAI concept were exemplified in application over the yellow, East china sea (Hu, 2008).

RED-NIR-SWIR (shortwave infrared) wavelengths strongly absorb light on water sources in contrast to land surfaces. Thus, the FAI is defined as the difference between reflectance in the NIR (R_{NIR}) and a corrected reflectance of this band by the red and the SWIR bands. Water is opaque or "black" in SWIR wavelengths even in most turbid environments, which provides the ability to correct for the atmospheric effects (Hu, 2008).

$$FAI = R_{rc,nir} - R'_{rc,nir}$$

$$R_{rc,nir} = R_{rc,nir} + (R_{rc,swir} - R_{rc,red}) * (\lambda_{nir} - \lambda_{red}) / (\lambda_{swir} - \lambda_{red})$$

This Vegetation index visualized the floating algae in the yellow sea, which shows the main difference between NDVI and FIA is the amount of Atmospheric obstruction that could be an issue when dealing with high cloud days on the Atlantic coast.

The FAI concept can be applied to any satellite sensor that is equipped with three spectral bands in the Red, NIR, and SWIR. These wavelengths of the Algorithms are used to calibrate any satellites or instruments equipped with these bandwidth channels. Data comparison in the previous studies shows that FAI is more advantageous than the traditional NDVI due to its lower sensitivity to changes in the atmosphere (Hu, 2008).

To estimate the biomass and comprehend the *Sargassum* ecosystem, a conversion of the shading grades of *Sargassum* on echograms above the sea surface. Then biomass-based quadrant samplings classified as *Sargassum* beds are to be seperated along transects into four groups described by canopy height on echograms (Komatsu, 2007). Understanding that imagery from the surface is good data, but knowledge of the depths that *Sargassum* reaches from the surface would provide better quantification of the biomass.

CHAPTER III METHODOLOGY

The region selected to search for and evaluate *Sargassum* is in the Gulf Stream located between the coast of Cape Hatteras to Bermuda close to the Sargasso Sea. This region was selected due to the observed migration of the Sargasso population between the Gulf and the Sargasso Sea between the months July and August where it travels along the Gulf Stream past the North Carolina Outer Banks. The areas of interest are primary between Cape Hatteras and the Bermuda Triangle since this is the last segment of its travels into the Atlantic. Quantifying the current amount of *Sargassum* using Landsat image data, the following Band wavelengths must be used in the algorithm (eqn.1) to compute the quantity designated as '*Landsat FIA*.' (See Table 1)

$$\text{Landsat FIA} = B4 - (B3 + (B5 - B3)*(B4 - B3)/(B5 - B3) \quad \text{eqn.1.}$$

From July to August is when *Sargassum* is exchanged between the Gulf of Mexico and the *Sargasso* Sea via the Gulf Stream.

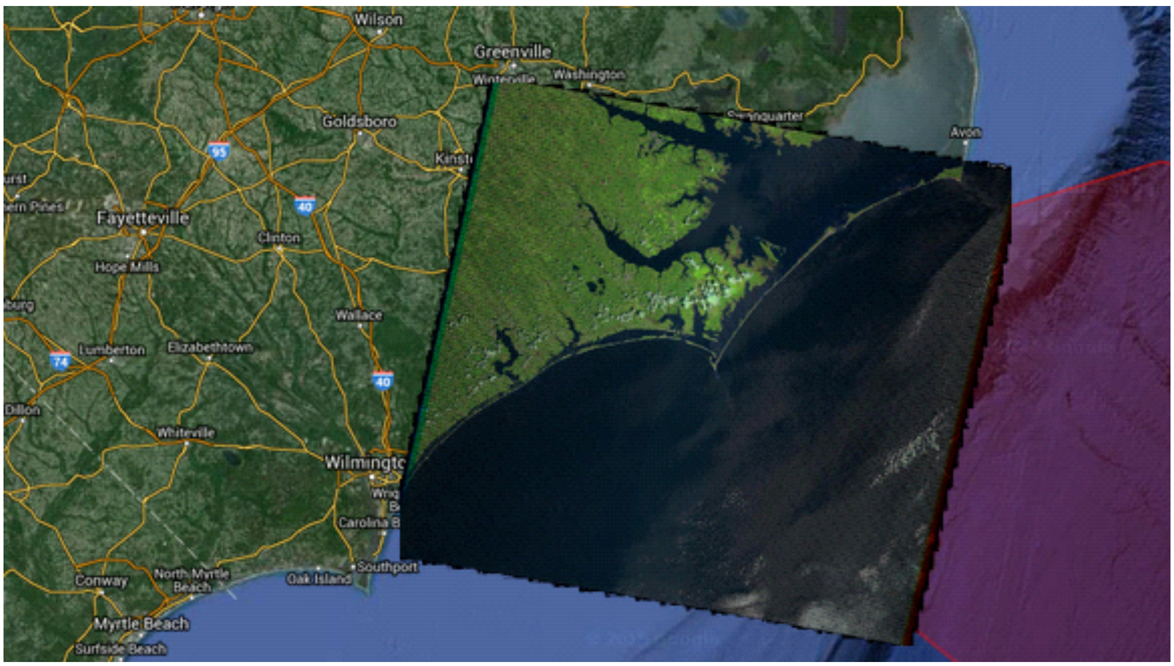

Figure 5. USGS AOI imagery preview of located at Cape Lookout

Data selection

A large quantity of the data obtained was provided by the United States Geological Survey (USGS) and consists of imagery from the Landsat 7. The Area of Interest (AOI) off the coast of Cape Hatteras extending to the Bermuda within the July to August timeframe. Data was obtained from July 2013 through to August 2015. Imagery that was selected from the Landsat satellites needed to meet several requirements for processing. The crucial requirement is a minimum amount of cloud coverage. Images that contain large amounts of cloud coverage or light cloud coverage loosely covering a vast area are simply not possible to be analyzed. Clouds obstruct the view of the sea surface. Among other prerequisites for Landsat imagery to be applicable to the research is for the images to have been taken within the July - August timeframe, as well as, within the boundaries of the area of interest around the Sargasso Sea (see table x).

Table III of Processed Landsat 7 Images

Path	Row	Date
13	36	11th August 2015
15	38	9th August 2015
15	37	9th August 2015
14	36	2nd August 2015
13	36	26th July 2015
14	36	17th July 2015
14	36	31st August 2014
13	36	24th August 2014
15	37	22nd August 2014
14	36	15th August 2014
15	37	5th August 2014
14	36	30th July 2014
13	38	21st August 2013
13	36	21st August 2013

When Searching the Landsat archived images, a filter was placed on the data set search parameters to only display imagery with less than or 30% cloud cover. Since most of the earth's evaporation occurs off the coast, it makes our AOI a cloud-producing factory.

Image processing

Processing and examination of the image files that were downloaded and expanded were accomplished by using ENVI geospatial technology software. Importing the Bandwidth channels 1-5 and 7 from the expanded Landsat files, these bands were then loaded as geo-tiffs into a coherent data stack listed as available bands from descending to ascending order. This data stack must be corrected for radiance. First, an RGB is created of the imagery bandwidths by importing band 3 for red, band channel 2 for green, and band channel 1 for blue. This will help deceiver ??? between clouds and sea surface features found in the imagery.

Appling the vegetation indexes FIA and NDVI the algorithms are imported into the "Band Math" processor of ENVI. The raw data received from the USGS database is in the

GeoTIFF format, which is reflective and must be corrected for radiance. If this is not done, the index band combinations will be incorrect. ENVI software has incorporated a widget to correct for Radiance in their imagery program. The bands that need recalibration are Red, Nir, and Swir bands utilized in NDVI and FAI indexes. To do this ENVI software has a preprocessing application for Landsat images to conduct atmospheric correction for reflectance and radiance values.

Before the creation of the Index's, the individual bands had to be corrected for radiance. To correct the imagery for radiance ENVI software application has a pre-processing application to change from reflectance to radiance. The bands that needed to be preprocessed were Rred, Rnir, and SWIR (Landsat bands 3, 4, and 6) are used for NDVI and FIA respectively.

Then the Basic Band math was used to input the Index's algorithms and apply the bands to the applicable variable with its corrected radiance. With the bands configured and the indexes produced, the new products were loaded into three separate display windows, an RGB for color was produced to distinguish between land, cloud, and open water, and two bands for the Vegetation Index and Floating Algae Index. This NDVI filtered image is compared to a red, green and blue (RGB) render of the same area in order to help identify *Sargassum* and differentiate it from different environmental factors such as clouds and land.

Processing methods

NDVI proved to be the most successful method with which processing was accomplished within ENVI. It is likely this is due to the built-in nature of the NDVI equation that is used to process the imagery.

$$NDVI = (Rnir - Rred)/(Rnir + Rred) \qquad (1)$$

In 'Equation 1' R_{nir} and R_{red} represent the reflectance in the near infrared (NIR) and red bands. In the case of Landsat series satellites, these are the 3rd and 4th bands of the multispectral imagery. Due to it being a built-in function of the ENVI software, it was moderately simple to process the imagery using this function.

This implies the scale of the heat map was reversed using this equation within ENVI.

$$FAI = R_{rc,nir} - R'_{rc,nir}$$

$$R_{rc,nir} = R_{rc,nir} + (R_{rc,swir} - R_{rc,red}) * (\lambda_{nir} - \lambda_{red}) / (\lambda_{swir} - \lambda_{red})$$

Within this equation, the variables λ_{RED}, λ_{NIR}, and λ_{SWIR} refer to 645, 859, and 1240 nm wavelengths respectively. For context in Landsat 4-5, this refers to the 3rd, 4th, and 5th bands.

Identifying Sargassum

Identifying *Sargassum* is accomplished by comparing the NDVI filtered image with an RGB version of the same image. With the displays of RGB, NDVI, FAI linked together the imagery values are scanned for positive values in the index's which are bright wisps in the otherwise dark water. Mostly elongated by winds and curled in its direction is what are target anomaly's description. The area is then compared to the RGB display to ensure the positive values of NDVI and FIA area are not a piece of land, a sandbar or other atmospheric obstructions such has high or low clouds.

CHAPTER IV RESULTS

Identifying *Sargassum* is a very rigorous feat, to find Index values on an anomaly that is believed to be either a large plume of *Sargassum* by comparing the NDVI filtered image with an RGB version of the same image. The NDVI images were scanned for positive values in the sea surface of the AOI that would be concluded as *Sargassum* patches off the coast of Cape Hatteras. Any areas with high NDVI and FIA values (0.0000001 to 0.0000002) are then compared to an area displayed within the RGB. results are high cloud, low clouds, or shadow of clouds. Even on clear days, no brownish Sargassum is seen on RGB product. Large barge ships are able to be seen as the smallest anomaly's in the AOI, so either the water is dark enough to mask the brownish color of *Sargassum* due to the oceans depth. FIA values are in the positive realm when near the coast in shallow waters. Either this is due to the shallowness of the water or the propagation of algae in this area. I would not classify these values as Sargassum because it (1) is not seen as a positive value on the NDVI index, (2) is not seen on the RGB as brown patches.

FAI was implemented successfully within the ENVI software. First, attempts at creating this data product came short of producing an index. The error was due to using the wrong band number as the Swir. When tested using ENVI and the multispectral imagery provided by Landsat models the FAI processing even with Radiance corrected Spectral bands failed to remove cloud coverage from the images as well, but it did remove any thin clouds found in the imagery. FIA also returned results are consistent with provided examples of what FAI was intended to return compared to the NDVI index of vegetation located on land. To decipher between the FIA values an Enhancement color palette was selected so that intensity of the FIA index values can be seen. This helped to identify areas whose values look like clouds or actual vegetation (such as the anomaly's seen from the shallow areas of the outer banks.

The imagery of areas located farther from the coast contained more clouds than coastal imagery. Due to most positive values of FIA as the edge of clouds, and any low negative NDVI values are assumed to be low clouds or shadows of clouds. This hampers detection of *Sargassum* s. Not many Images from the center area of the AOI are found in the database with cloud cover less than 30% since evaporation occurs in the open ocean. With this data, it is very difficult to determine areas needed for regulation and Biomass estimation.

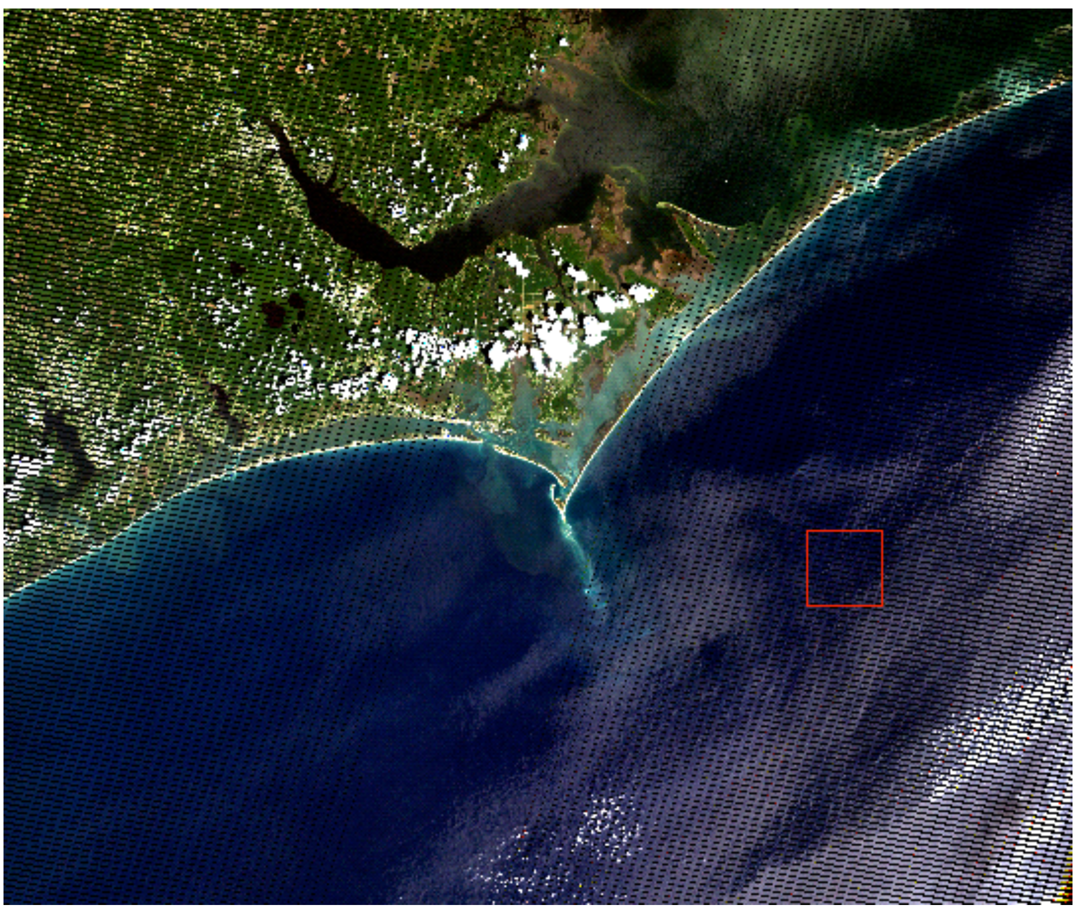

Figure 6. RGB off the Coast of Cape Lookout July 17th, 2015

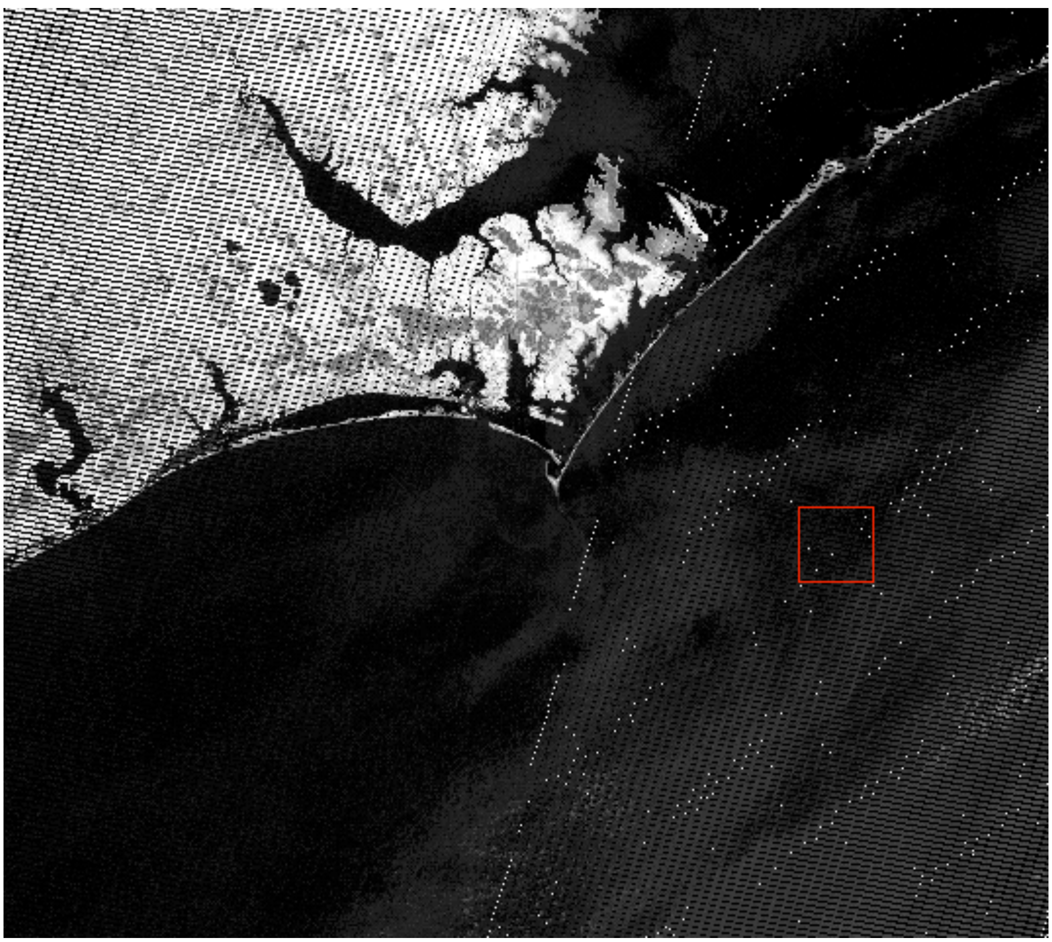

Figure 7. NDVI off the Coast of Cape Lookout July 17th, 2015

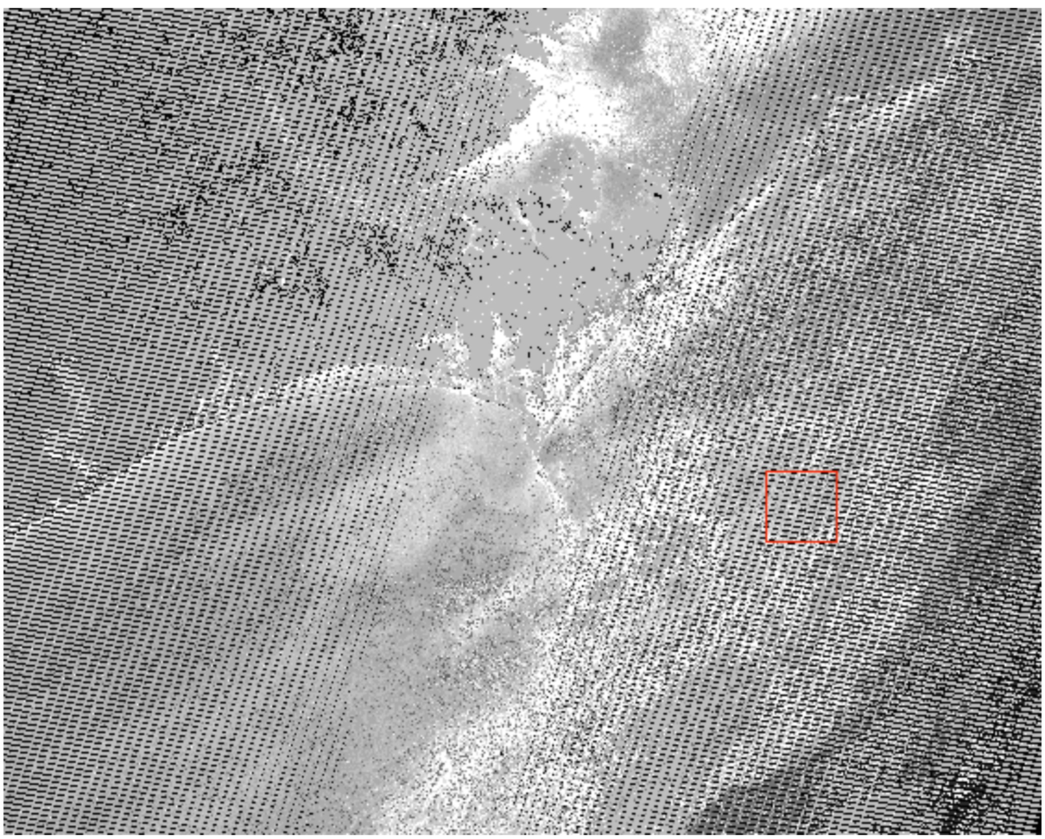

Figure 8. FIA off the Coast of Cape Lookout July 17th, 2015

CHAPTER V DISCUSSION

The satellite covers only so much of the earth each day and at different times. To compare the amount *Sargassum* over the years in the same time frame in the same specific location is next to impossible using Landsat data. Further useful observations were reduced by frequent cloud, sun glint, and data gaps in the images. The usable passes from USGS data library amount to two passes in a month at the same location with cloud covers less than 30%. *Sargassum* that is evenly distributed over 1 km^2 may not be detected unless it is “aggregated” in concentrated windrows about 15 to 30m^2. Due to the amount of clouds, which hamper the view of the sea surface, most imagery of the coast is from the Landsat series. The *Sargasso Sea* is an immense borderless feature, and its detection should be relevantly obvious in the AOI. Unless it's traveling on the Gulf Stream. The floating *Sargassum* must be scattered and in thin strands smaller than 15 meters thick, according to the resolution of the Landsat data results.

As a portion of the AOI is directly off the coast, some benthic vegetation and coral reefs in shallow water may cause false positive with a very low NDVI index as seen in figure 14. These can be ruled out because the shape of the anomaly shown in th figures is not an elongated windrow with a curl toward the winds direction.

With the lack of sufficient ground truth or *in situ* recordings of GPS locations where larger patches of *Sargassum* are present, it is difficult to classify these sea surface anomalies through the NDVI index because values for items which were believed not to be clouds or low clouds have negative index values simmular to the low clouds in the area. A targeted approach is missing, which would help pinpoint times and locations to target immediately reported *Sargassum* in the area.

Previous studies suggest that *Sargassum* amounts are regularly greater in the Gulf of Mexico than in the Atlantic (Hu et al, 2010) 250-meter resolution. MODIS multispectral imagery is capable of detecting thin algae lines 4 to 5 meters in width once they form long slicks greater than 500 meters in length. However, it cannot capture small-scale *Sargassum* patches and slicks. Landsat series provides less frequent coverage days for the same location, but can be used to detect and identify slick widths of estimated 2-meter.

A better system to monitor and map the Sargasso Sea is needed if a clearer understanding of how much *Sargassum* travels past Cape Hatteras and the size of the boundary area out to Bermuda in order to determine regulations if need in this AOI. A monitoring system is required to have high Spatial and temporal resolution that's cloud free and unaffected by atmospheric conditions so *Sargassum* can be detected.

Utilizing a Quad copter UAV and Buoy system to map and estimate the biomass of the large sea surface pelagic organism can do this better and more efficiently with added bonuses.

Since cloud cover is a significant issue for multispectral imagery, a system must be established to collect imagery underneath the clouds. A quadcopter drone can climb to cloud's altitude and record spectral data from that position. The question of where this quad copter would take off and land is answered by utilizing a buoy system in the open ocean, where the buoy is designed to Charge and position the un-maned device. The buoy will act as a carrier and transmitter for the drone's data and for longevity at sea. Because of heavy salt in the water, this buoy must be designed to encase the drone when it's not being operated as to protect the rotors and sensors from moisture or heavy storms. The buoy would also keep the drones location in its study area keeping the array of drones in their proper place to ensure that changes over time can be evaluated. The buoy will also need to provide itself and the drone the power it needs to stay in the location, transmit data, and power the drone's flights. This system will help to complement satellite data by providing real-time ground truth onsite evaluations. Also, good photographic images would be an advantageous as to make record sea life in real time as they interact with *Sargassum.* More opportunities such as estimating floating *Sargassum's* locations over periods of time is possible as more recorded sightings become available. For example, if a large patch of floating S*argassum* is headed toward a popular tourist attraction, the data can provide information for any industries which process beached species of *Sargassum* to plan for its arrival and easily manage a situation before it overwhelms a coastal area.

The addition of remote sensing techniques with Quadcopter drones would supplement satellite data . Also, echograms can be equipped with the buoy system to help with mapping beneath the sea surface to aid in the quantification of its overall biomass.

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