LINEAR REGRESSION ANALYSIS OF SENTINEL-2 SPECTRAL DATA FOR DETECTION AND MONITORING OF HARMFUL ALGAL BLOOMS IN THE FLORIDA INDIAN RIVER LAGOON & BANANA RIVER LAGOON

by

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ABSTRACT

In the fall of 2020, a harmful algal super bloom event in the Indian River Lagoon, the Banana River Lagoon, and Mosquito Lagoon (FL) triggered a mass aquatic fauna die-off. This event, along with the earlier super blooms in the region, reinvigorated the need for accurate models to watch and warn about coming events in conjunction with water quality sampling. There have been models previously created for this region and calibrated with Landsat imagery data but not for the newer Sentinel-2 satellites. The model was built using water quality chlorophyll-a sample data and Sentinel-2 image data taken during the fall of 2020. In the Indian River Lagoon, the most reliable linear regression model was concluded to be with the band 4/band 3 ratio. However, in the Banana River Lagoon the most reliable linear regression model was found to be with the band 3/band 2 ratio. This study creates a dependable algorithm based on the imagery data from the 2020 bloom to be applied on an ongoing basis to monitor algal blooms.

INTRODUCTION

Bacterial History

As the climate warms, coastal communities become increasingly susceptible to saltwater intrusion, flooding, extreme weather events, erosion, sea level rise, and harmful algal blooms. Harmful algal blooms (HABs) can directly affect human health when humans encounter them through breathing in aerosolized toxins, direct water contact, or ingesting infected seafood. Common HABs are red and brown tide but can be orange, yellow, blue, green, brown, or red. Humans can experience respiratory problems, gastrointestinal illness, neurological disorders, skin irritations, and death in severe cases. HABs can decimate aquatic flora and fauna populations by causing a cascade of effects that create hypoxic and anoxic conditions. These conditions can cause food web collapse in extreme cases. The Indian River Lagoon, the Banana River Lagoon, and the Mosquito Lagoons comprise a part of the longest barrier island complex in the United States and provide sanctuary to thousands of species of aquatic organisms, especially during the first stages of life for many species.

The Indian River Lagoon and Banana River Lagoon have been subject to the consequences of development as the coastal community grew rapidly during the 1960s with the introduction of the Kennedy Space Center in 1962. This development continued in the 1970s and there was an increase in pollutants (like phosphorus) that let to low oxygen levels. To decrease mosquitos, dikes were constructed but, in the process, destroyed mangrove forests which had provided shelter for a variety of fish and birds at the beginning of their lives. The 1996 Indian River Lagoon and Basin Act was enacted to prevent point source pollution from septic tanks and wastewater treatment plants. The conditions in the Indian River Lagoon and basins had continued to decline and resulted in numerous super bloom events (Pepperman, 2018).

Elevated levels of a single species of algae, like toxic *Karenia brevis* which cause red tide or *Aureococcus lagunensis* which cause brown tide, can prompt an exponential population increase of bacteria that feed on the algae. Once this happens and the bacteria have killed the algae, the bacteria use the dissolved oxygen in the water to the point where it can create hypoxic conditions for the other inhabitants like fish and seagrass. These hypoxic and anoxic conditions are what lead to mass die-offs in addition to the toxic conditions created by *K. brevis* and *A. lagunensis*. Certain bacterial species show preferences for consuming specific types of algae, resulting in fluctuations in bacterial populations and dramatic declines in dissolved oxygen levels.

K. brevis has rarely been found in high concentrations in the Indian River Lagoon, Mosquito Lagoon, or Banana River Lagoons but several other diatoms and dinoflagellates have been credited with causing HABs when they have congregated in high concentrations.

Pyrodimium bahamense is a dinoflagellate that typically blooms in the northern Indian River Lagoon between April and October in water bodies that are shallow, brackish and have low flushing rates. *P. bahamense* creates a neurotoxin called saxitoxin that can cause paralytic shellfish poisoning and saxitoxin pufferfish poisoning. *P. bahamense* was found to be present in samples taken in the fall of 2020 in the IRL but the levels were lower than in previous years, so it is unlikely that it caused mass die-offs (Lopez et al., 2021).

Aureoumbra lagunensis, the source of brown tide, has been well documented in the northern Indian River Lagoon, Mosquito Lagoon, and the Banana River Lagoon. It has been credited with causing major ecological shifts in the region and has caused some of the largest fish kills on the east coast. There are no known direct negative impacts on human health.

A novel nano-sized cyanobacterium was detected in August 2020 in the Indian River Lagoon and has been associated with turning the water green. It was found that this cyanobacterium had been present since June 2020 and rose to a concentration of >2 × 108 cells L–1 and spread to all sub-basins until the bloom ended in December 2020. Upon analyzing its rRNA, it was found to share 93.5% of its genetic code with *Prochlorothrix hollandic*a but is a unique and previously unknown cyanobacterium (Lopez et al., 2021).

It was found that the bloom that occurred in 2020 was primarily a combination of *A. lagunensis* and the novel cyanobacteria. When two samples were taken from the Indian River Lagoon on September 10, 2020, it was discovered that the novel cyanobacteria concentrations were between 72- and 173-fold more abundant than *A. lagunensis*. *A. lagunensis* was found to have bloomed in the Northern IRL and Banana River Lagoon from August to September 2020 and in the central IRL from late September to mid-October. A delay in cooling in the fall led to a warmer November than usual and a sustained bloom. The bloom ended in December due to declining water temperatures below 20° C (Lopez et al., 2021).

HABs can be detected by the presence of chlorophyll-a in water through water quality samples and calibrated satellite imagery.

Satellite Imagery

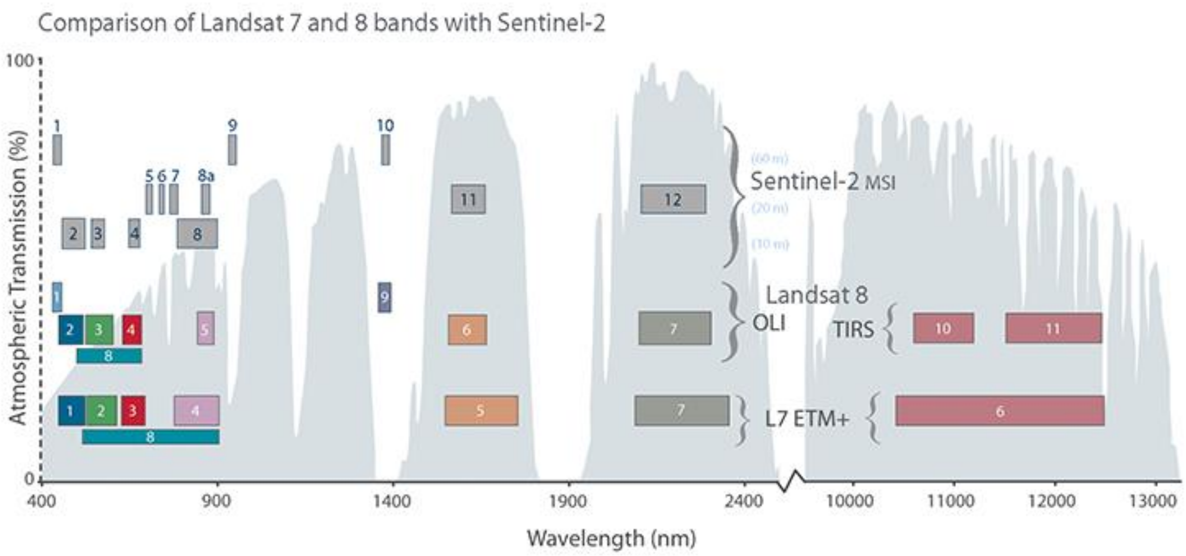
Since the first Landsat satellite was launched in 1973, remote sensing with satellite imagery has continually been refined to monitor algal blooms. The first research was conducted on Lake Michigan and then quickly spread to research sites across the globe. One of the lead researchers using satellite imagery for algal bloom assessment is Richard P. Stumpf. His earliest work was published in 1988 (Stumpf, 1988) and he has continued publishing since. He championed the idea of refining imagery with atmospheric correction algorithms specific to coastal zones (Stumpf, 2001) which are now an integral part of remote sensing imagery analysis. Stumpf's approach to using satellite imagery for monitoring algal blooms provided the framework this study implements in also monitoring regional harmful algal blooms.

Coastal regions present a unique challenge for satellite imagery. They are often synonymous with high turbidity and complex water quality variables. When used properly, remote sensing of coastal waterways can save time and money as well as provide a more exact depiction of current conditions.

Multispectral imaging divides light reflectants into 4 to 36 bands. Landsat and Sentinel-2 both use multispectral imaging. Landsat data is mostly used for water quality assessment with a multispectral imaging medium due to its accessibility and resolution. In the past decade, technological improvements, like the Sentinel-2 from the European Commission's Copernicus project have significantly improved the observational capability of coastal environments (Caballero et al., 2019; Bacques et al., 2020; Caballero et al., 2020; Tapete and Cigna, 2020; Caballero and Navarro, 2021; McKee et al., 2021; Normandeau et al., 2021).

When using multispectral imaging it is also important to consider its limitations. The spectral data must also be calibrated to the local region. The major downside to using multispectral imaging is the short periods that the satellites pass over given areas, typically ranging between 5 to 8 days so information can be missed if conditions rapidly change. Clouds, cloud shadows, and wind can all cause poor data quality (as seen in Appendix Map 2). For both Landsat and Sentinel-2, bands 2 (blue), 3 (green), and 4 (red) are preferred for analysis and closely align as seen in Image 1 and Table 1.

Image 1



Source: https://landsat.gsfc.nasa.gov/wp-content/uploads/2015/06/Landsat.v.Sent…(Public domain)

Table 1

Landsat 8 OLI			Sentinel-2 MSI		
Band	Wavelength range (nm)	Resolution (m)	Band	Wavelength range (nm)	Resolution (m)
1 Coastal aerosol	433 - 453	30	1 Coastal aerosol	433 - 453	60
2 Blue (B)	450 - 515	30	2 Blue (B)	458 - 523	10
3 Green (G)	525 - 600	30	3 Green (G)	543 - 578	10
4 Red (R)	630 - 680	30	4 Red (R)	650 - 680	10
			5 Red edge 1 (RE1)	698 - 713	20
			6 Red edge 2 (RE2)	733 - 748	20
			7 Red edge 3 (RE3)	773 - 793	20
5 Near infrared (NIR)	845 - 885	30	8 Near infrared (NIR)	785 - 900	10
			8a Near infrared narrow (NIRn)	855 - 875	20
			9 Water vapour	935 - 955	60
9 Shortwave infrared / Cirrus	1360 - 1390	30	10 Shortwave infrared / Cirrus	1360 - 1390	60
6 Shortwave infrared 1 (SWIR1)	1560 - 1660	30	11 Shortwave infrared 1 (SWIR1)	1565 - 1655	20
7 Shortwave infrared 2 (SWIR2)	2100 - 2300	30	12 Shortwave infrared 2 (SWIR2)	2100 - 2280	20
8 Panchromatic	500 - 680	15			

(Korhonen, L et al 2017)

Together the three color bands make up the true color index (TCI). Band ratios of band 3/band 2 have been widely used in open ocean studies and have been highly effective across large areas due to the color variability being largely a product of phytoplankton changes (Morel & Prieur, 1977). The blue and green bands are shorter and penetrate water best. The suspended phytoplankton particles absorb, scatter, and reflect electromagnetic waves in proportion to their abundance. However, coastal zones tend to have significantly higher suspended particulate matter, colored dissolved organic matter resulting in a remarkably diverse spectral range in comparison to open water which make analysis difficult (Tran et al., 2023). To combat this issue, red and near infrared band 4 can also be considered in analysis. Algorithms have been developed at the local scale to find and monitor specific areas of concern and are limited in their range of spatial applicability (Tran et al, 2023).

There have been models created for the Indian River Lagoon region using Landsat data but not with Sentinel 2 data. The purpose of this study was to determine a reliable model to detect and monitor algal blooms in each of the lagoons.

METHODS

There were two distinct procedures used to build an algorithm suitable for finding and monitoring future algal blooms in the Indian River Lagoon, the Banana River Lagoon and Mosquito Lagoon. Before any of these procedures could begin, a historical algal bloom had to be found that occurred after Sentinel 2 was launched in June 2015. The bloom used in this study occurred during the late summer into the fall and early winter of 2020. Along with visual confirmation of the bright green water, the water quality samples supported the presence of algal blooms all over the three lagoons when specifically tested for chlorophyll-a.

Data Preparation

The first procedure was to prepare the chlorophyll-a data and spectral data for analysis. The field water quality data was obtained from the Saint John's Water District and organized it by date. Next, water sample site location shapefiles provided by the Saint John's Water District were uploaded to ArcGIS Pro. A 100-meter buffer was added around each sample site location (n = 20) (Map 1).

Band 2, 3, and 4 images from the Sentinel-2A satellite were added to the same ArcGIS Pro file at a resolution of 10-meters. Sentinel-2A was launched in 2015. There is a second Sentinel-2B satellite that was launched in 2017, but to eliminate variables introduced with other instruments only Sentinel 2A was used. Using the "Zonal Statistics as a Table (image analyst)" tool, the buffer zone for each sample was analyzed for both the mean and range. The mean for each sample was then added to the data set alongside the chlorophyll-a values with the date that the image had been taken. Due to none of the water samples being done on the exact date that the spectral image had been taken, linear interpolation was used to estimate the correct cholorophyll-a value for the spectral image date. This was done by counting the number of days between spectral image dates and dividing the difference between the chlorophyll-a values from before and after the spectral image date. Then this number was multiplied by the number dates between the earlier chlorophyll-a sample date and added to the earlier chlorophyll-a value. The resulting values were the linear interpolated chlorophyll-a values that aligned to the true spectral data on those dates.

There were six spectral image dates with complete data sets between the time of 9/1/2020 and 12/31/2020 (Appendix Table 2). These images were chosen due to having cloud cover of less than 30% and because they covered the entire area of interest. To extend the dataset, five other partial images were added within the same date range. Each site was categorized by the lagoon it was found in. Finally, to calculate the band ratios, the spectral values of band 3 were divided by those of band 2, and the spectral values of band 4 were divided by those of band 3, resulting in two separate columns. In addition to the two columns of band ratios, a third column was added with the respective chlorophyll-a interpolated values.

Data Analysis

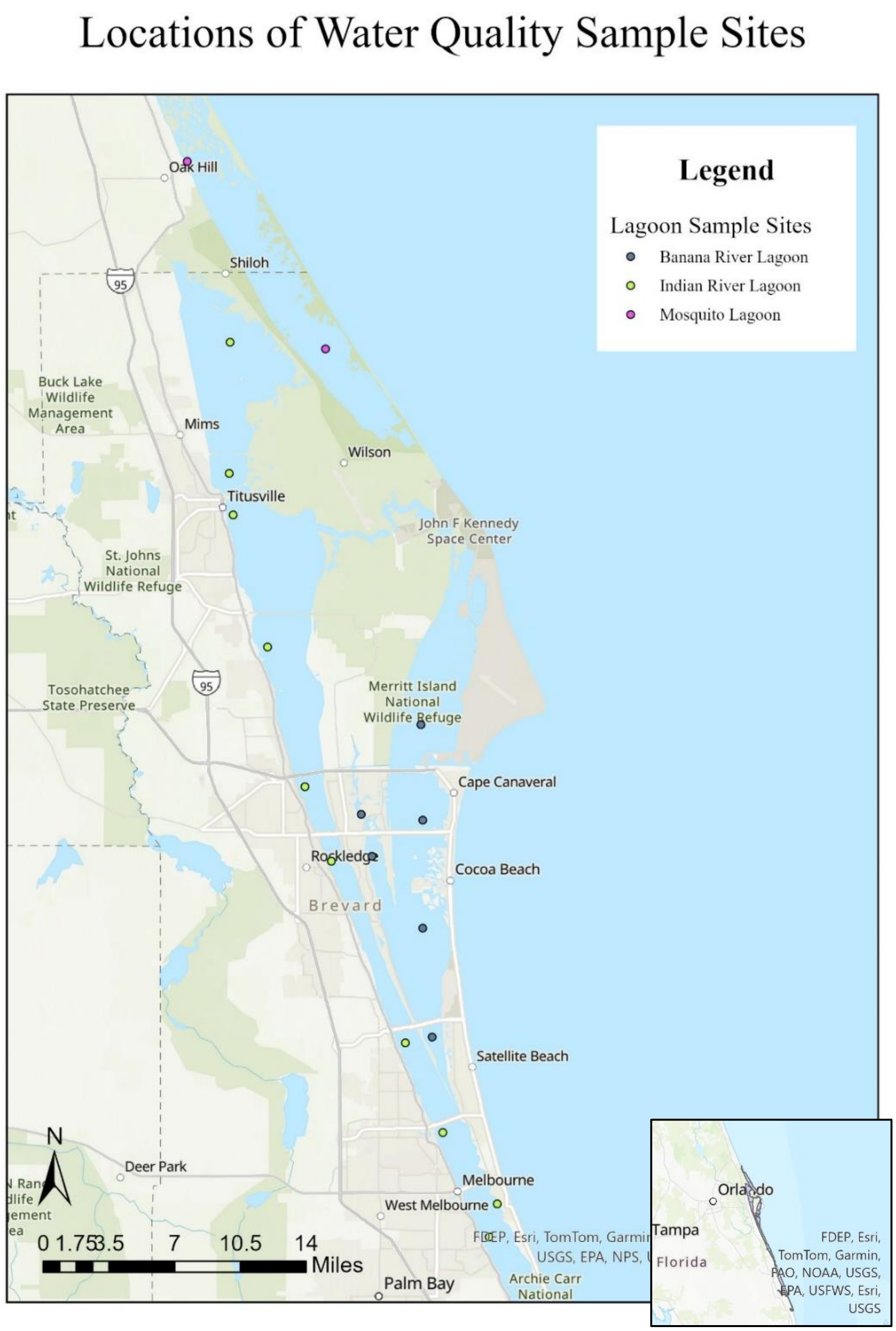
Once the file was prepared with the three columns of data, the process of cleaning the data began. Any buffer zone site for a particular day with a range larger than 400 was investigated for potential issues by looking at the TCI image. At first this zone was set at 500 but this produced problems later. High ranges could be indicative of cloud cover, cloud shadows, wind or the edge of a shoreline. All spectral values were disposed of if they were above this threshold.

With the prepared data, linear regression analyses were performed on each lagoon with R Studio. A variety of dates were tested for their accuracy and ability to corollate the chlorophyll-a values to spectral ratios.

RESULTS

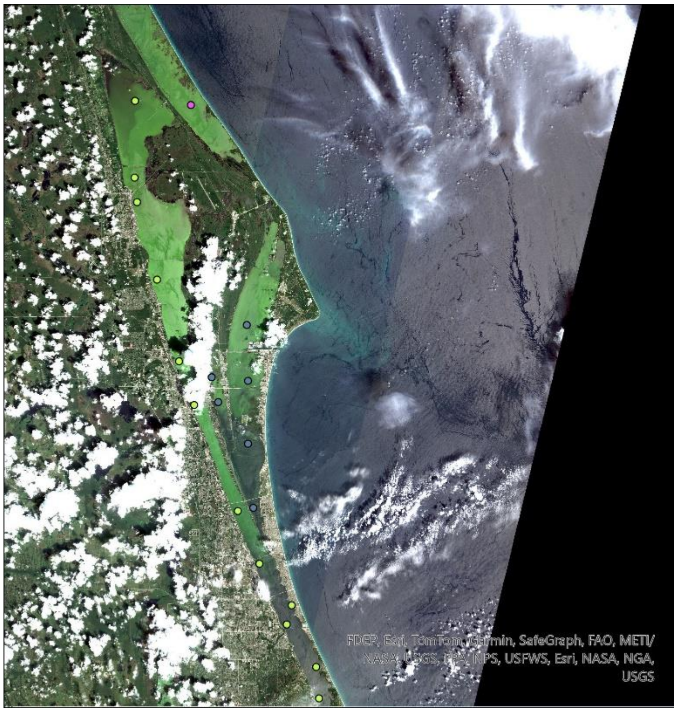
Map 1 displays the location of each of the 20 sample site locations. Map 2 shows true color indices on the four dates that had complete data sets (two complete data sets had to be removed due to wind). The true color indices were used during the process of cleaning the data to prepare for linear regression analysis by investing the range of values in a buffer zone. Map 3 presents the chlorophyll-a concentrations as graduated symbols for each of the sites on the dates with complete data sets. Map 4 displays the band ratios of band 3/band 2. The higher the band 3 (green) value in relation to band 2 (blue) the greener the color on the map. Map 5 shows the band ratios of band 4/band 3. The higher the band 4 (red) value in relation to band 3 (green) the redder the color on the map.

Map 1

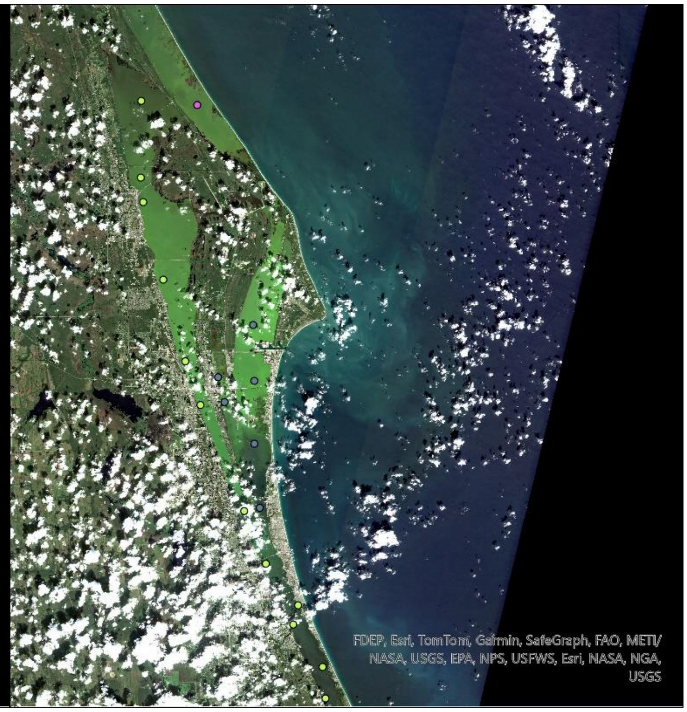


Map 2

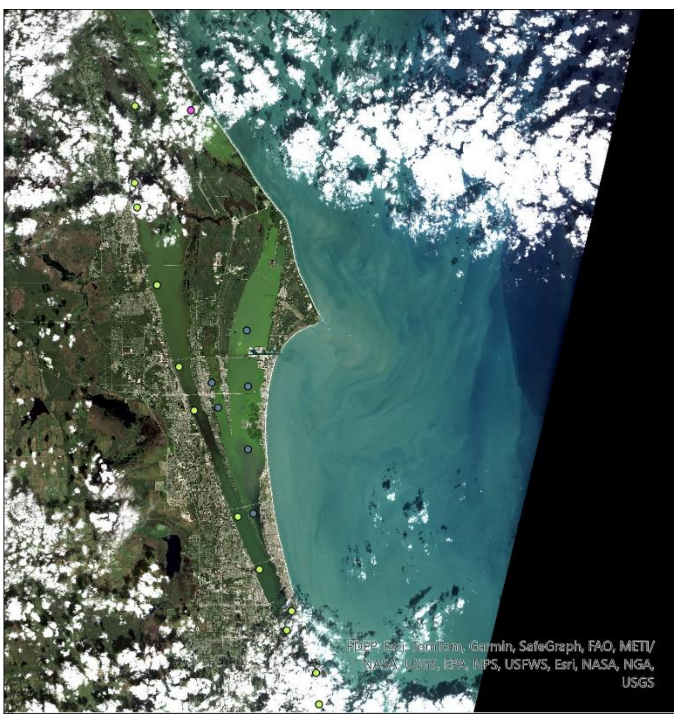
True Color Indexes of Selected Dates with Complete Data Sets



9.5.2020



10.15.2020



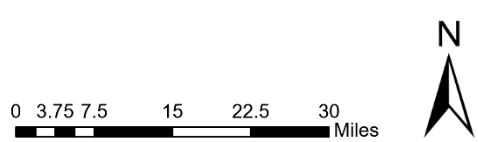
11.24.2020

12.9.2020

Legend

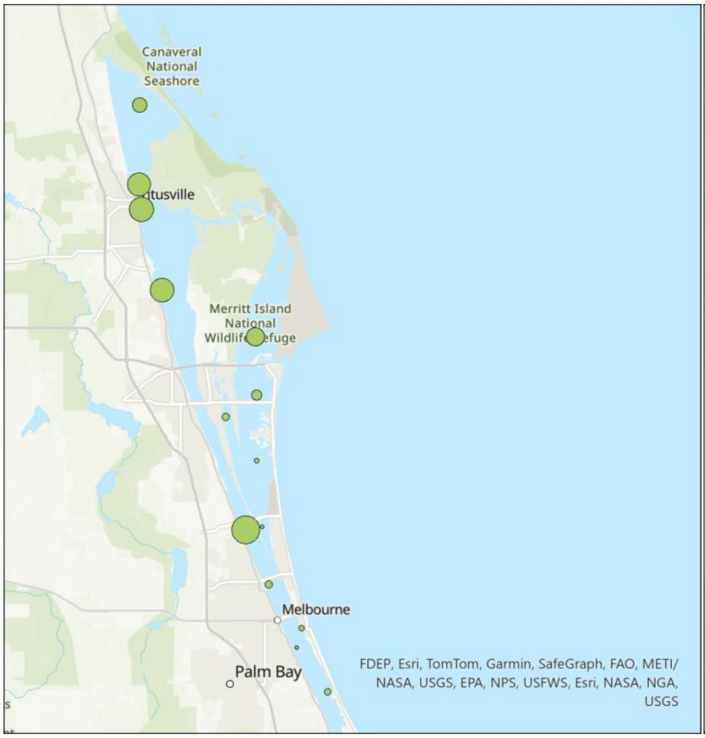
Lagoon Sample Sites

- Banana River Lagoon
- Indian River Lagoon
- Mosquito Lagoon

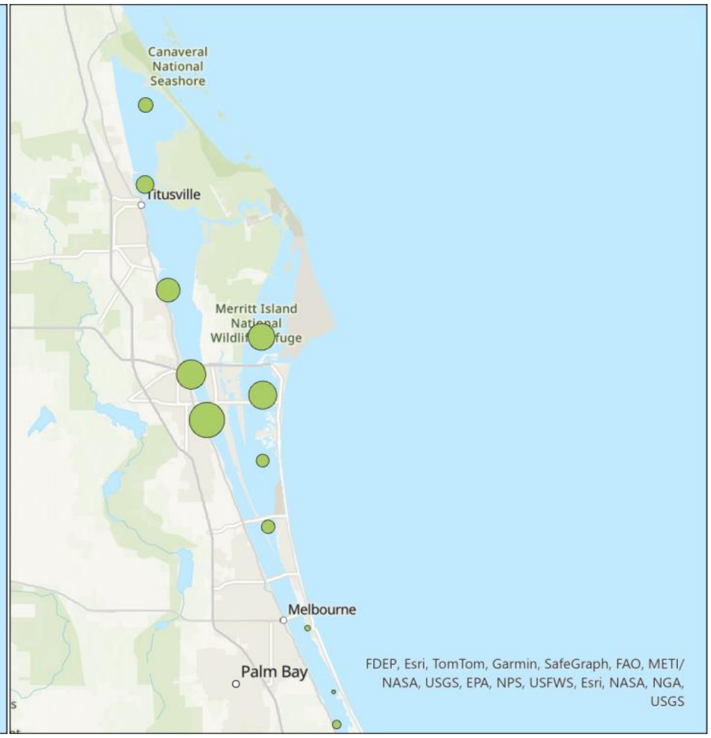


Map 3

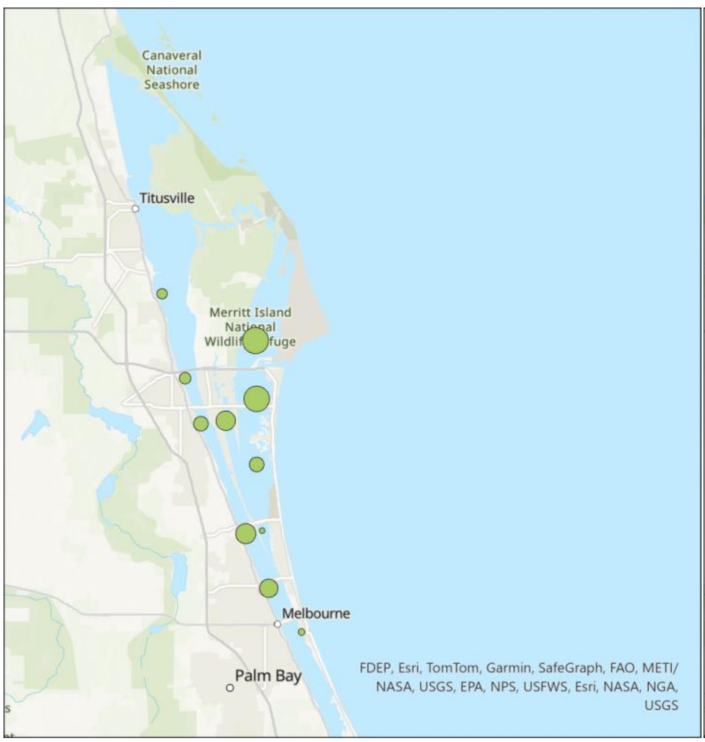
Chlorophyll-a Concentrations (μg/L^{-1}) in the Indian River Lagoon and Banana River Lagoon



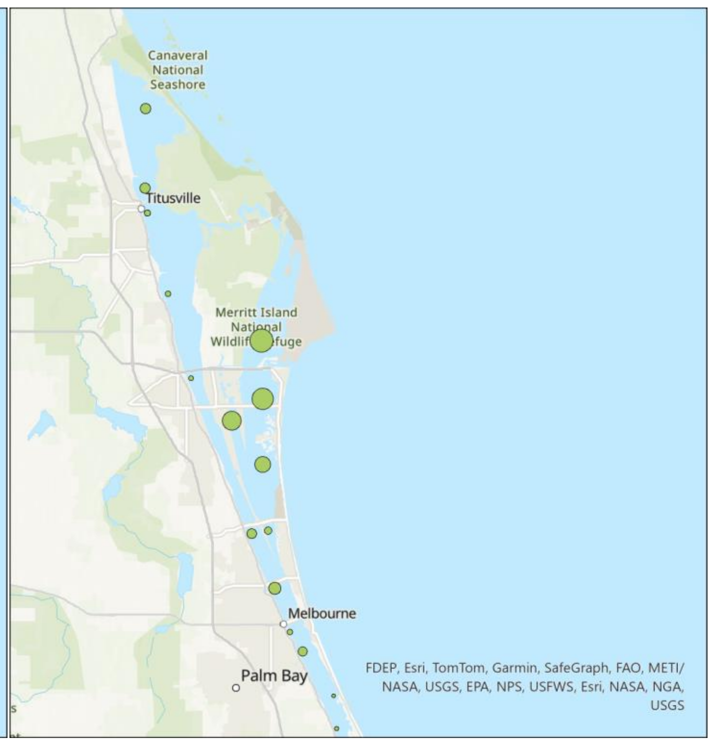
9.5.2020



10.15.2020



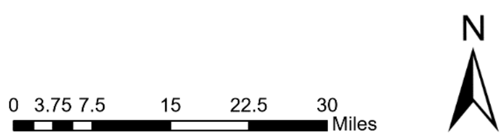
11.24.2020



12.9.2020

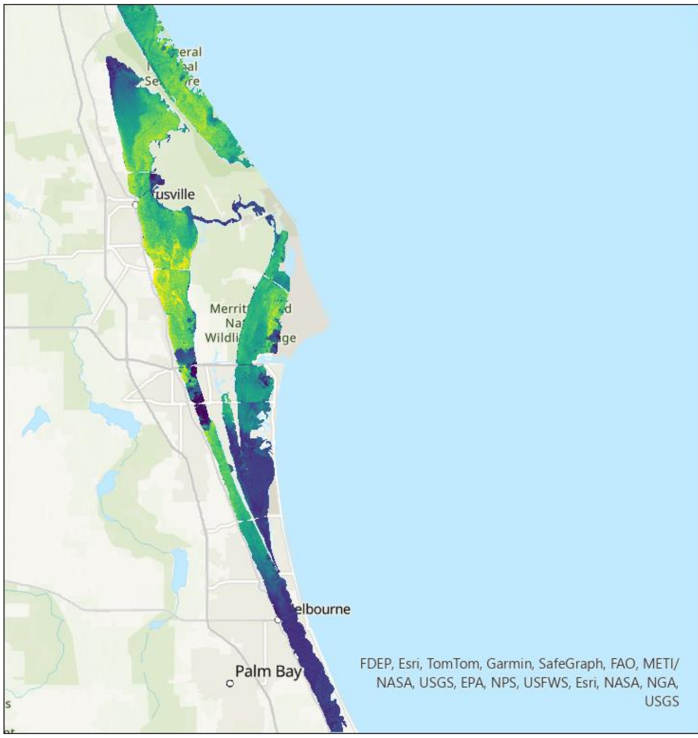
Legend

- 1
- 5
- 10
- 50
- 100

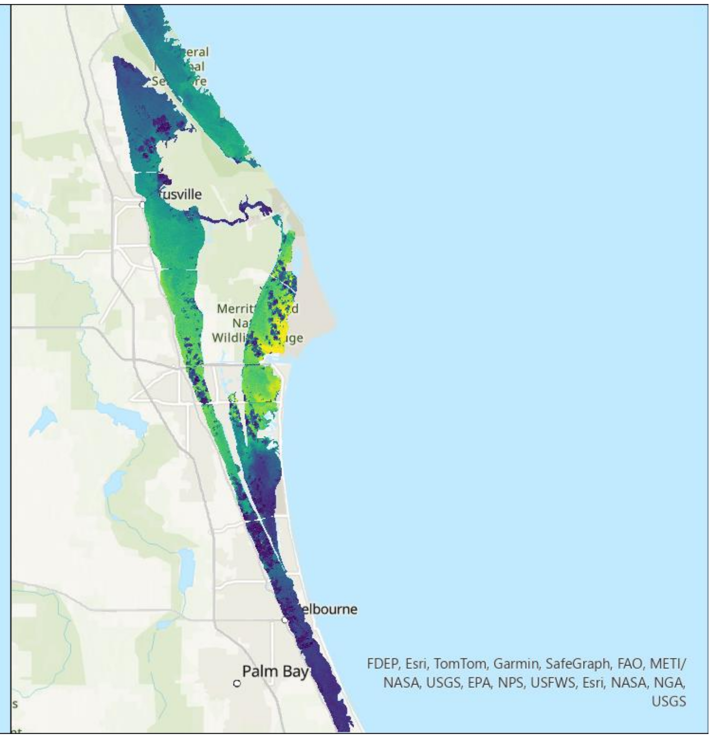


Map 4

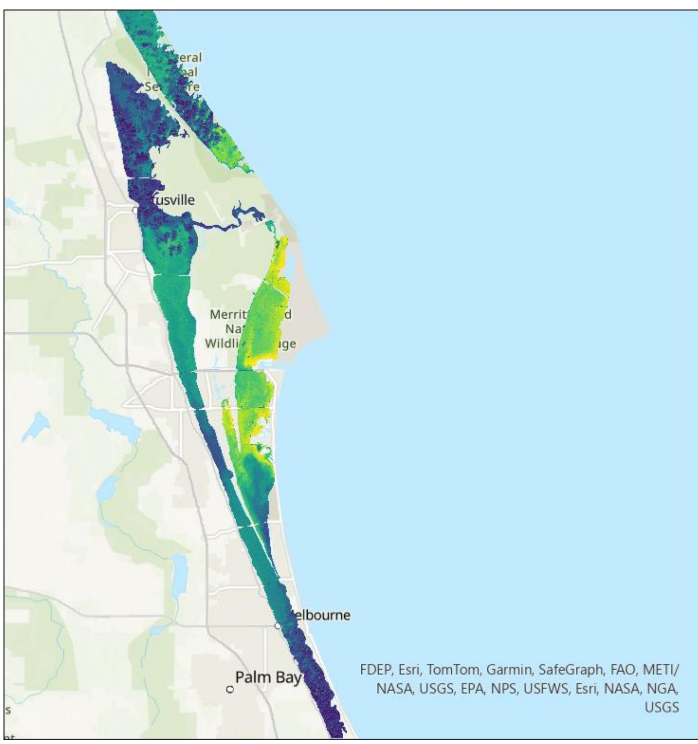
Band 3/Band 2 Spectral Ratio in the Indian River Lagoon & Banana River Lagoon



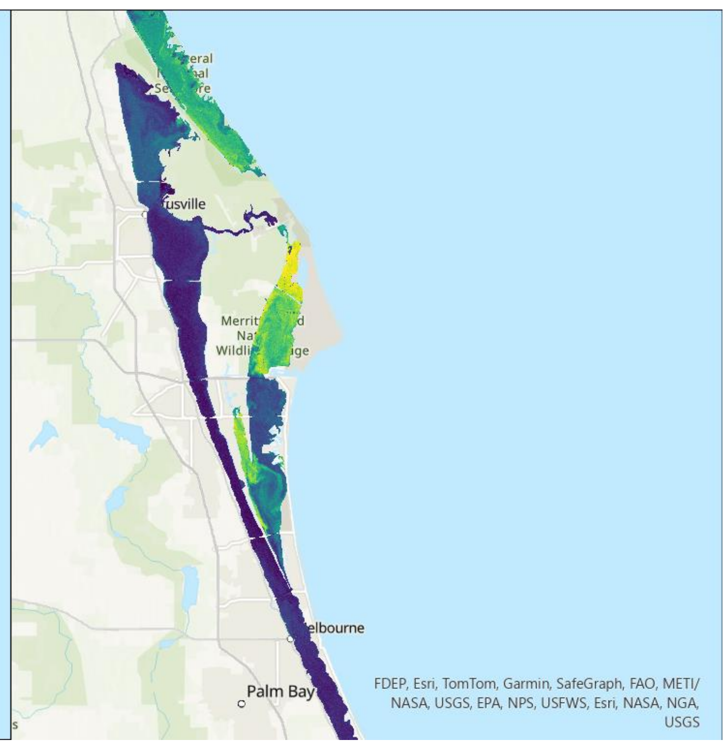
9.5.2020



10.15.2020



11.24.2020



12.9.2020

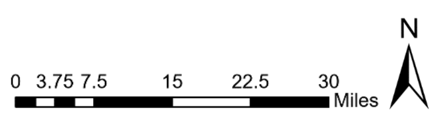
Legend

B3/B2 Spectral Ratio

Value

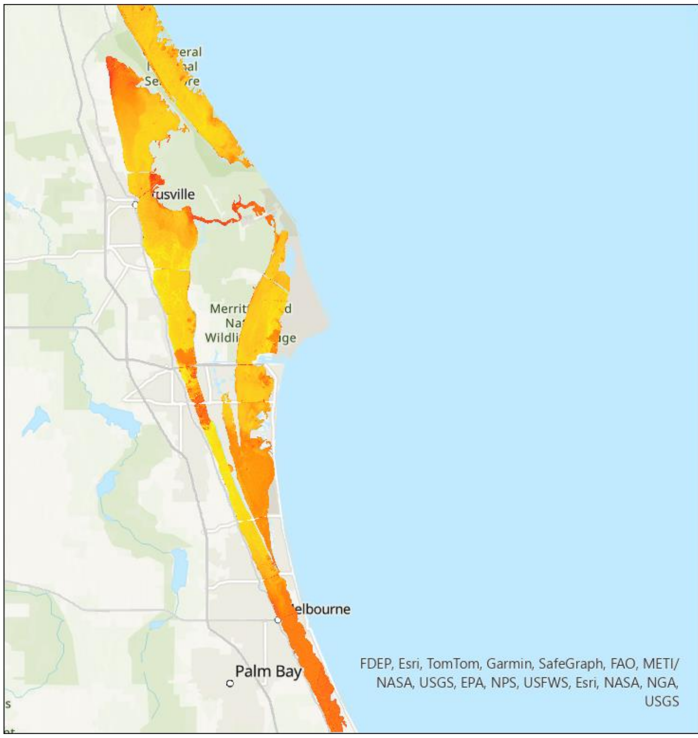
5.35987

0

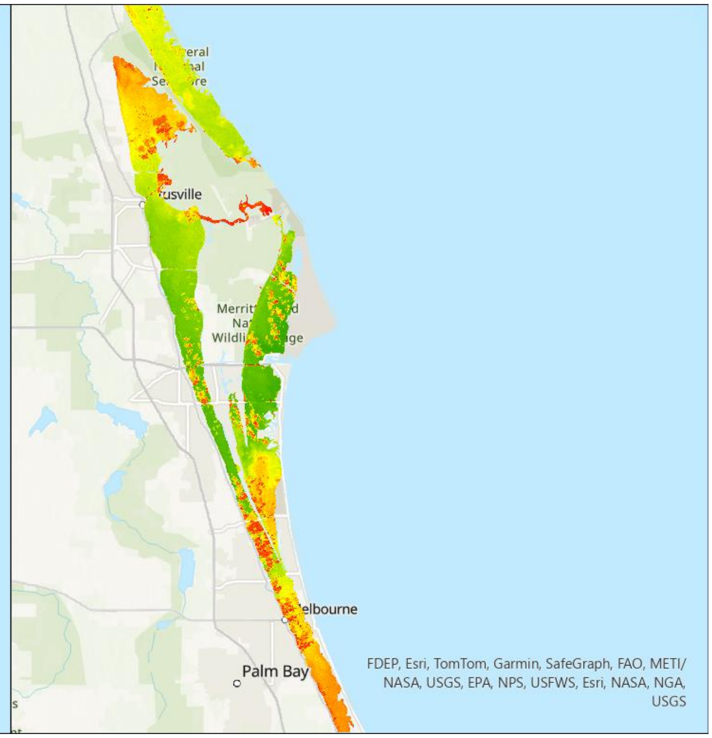


Map 5

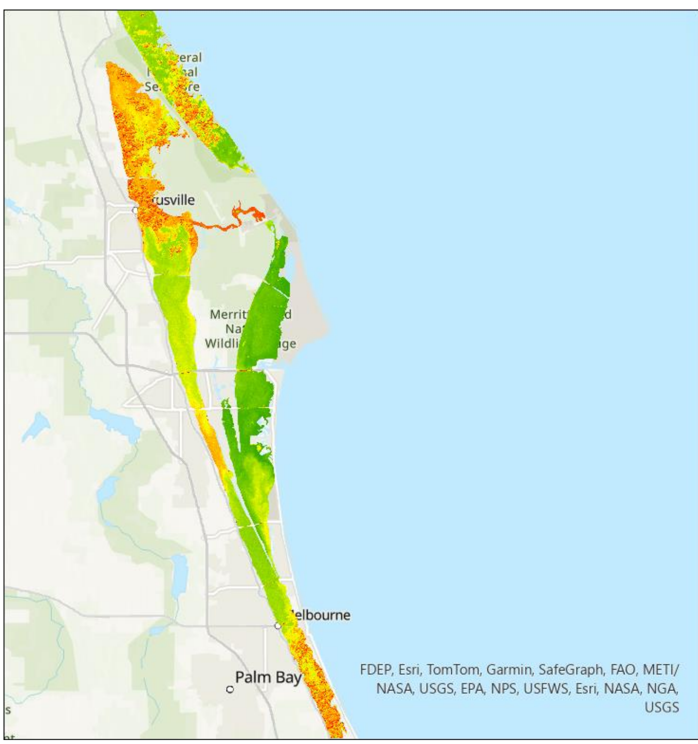
Band 4/Band 3 Spectral Ratio in the Indian River Lagoon & Banana River Lagoon



9.5.2020



10.15.2020



11.24.2020

12.9.2020

Legend

B4/B3 Spectral Ratio

Value

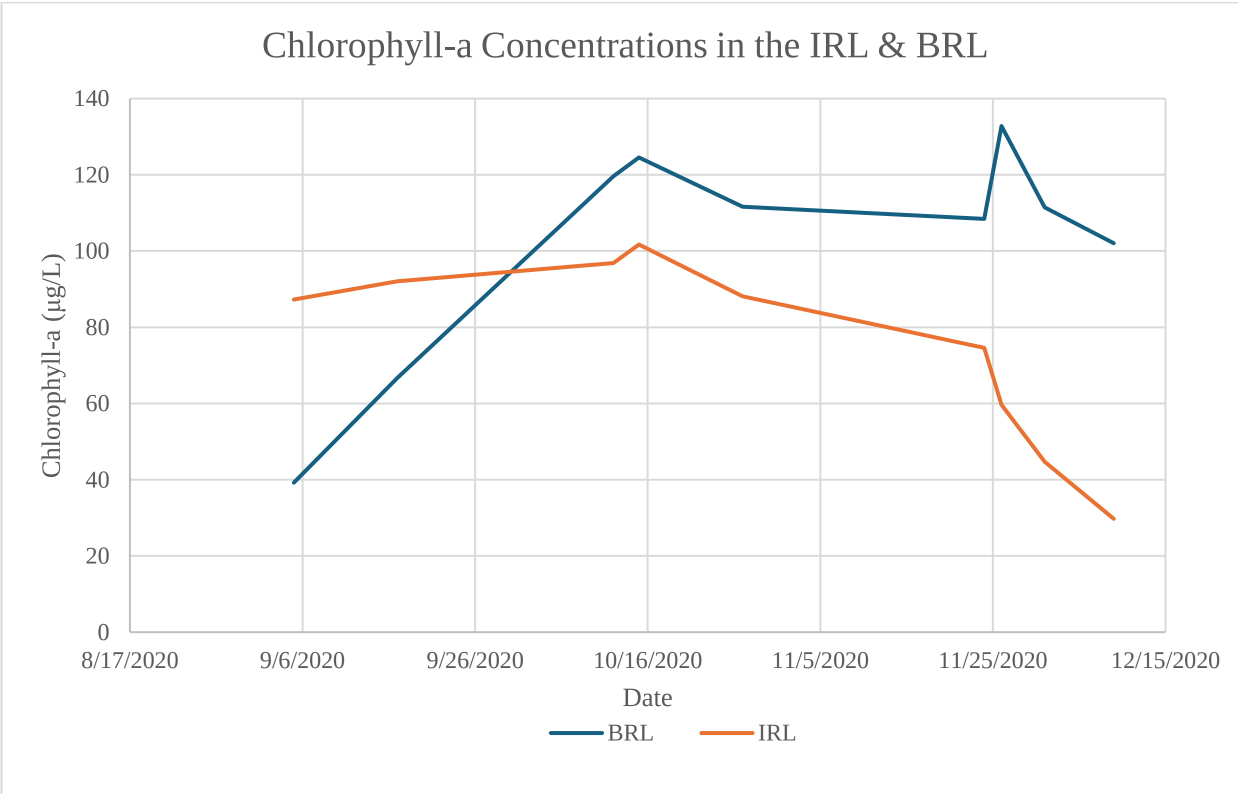
2.468

0

0 3.75 7.5 15 22.5 30 Miles

N

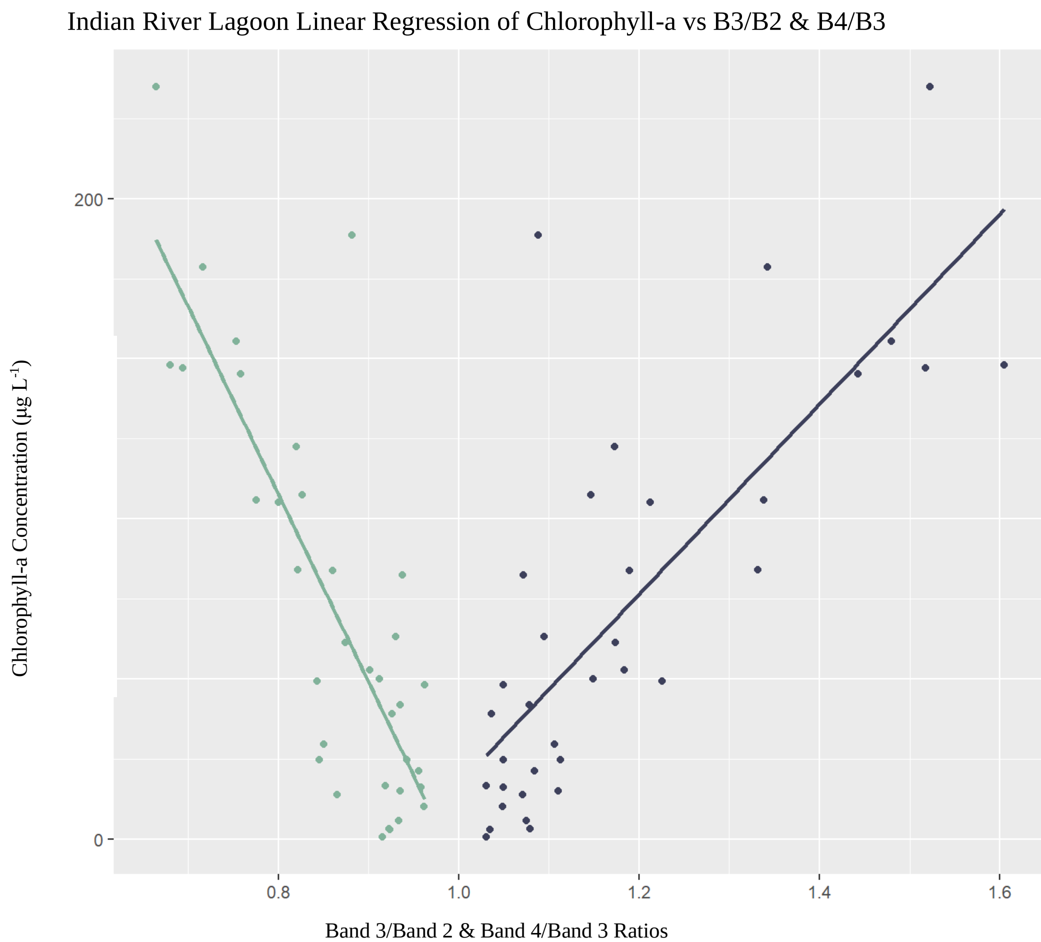
Graph 1:



As Graph 1 displays, the Indian River Lagoon started off with a much higher chlorophyll-a concentration than the Banana River Lagoon. The Indian River Lagoon only marginally increased through mid-October before gradually decreasing until the end of November when it sharply decreased afterwards. The Banana River Lagoon rapidly increased in concentration and surpassed the Indian River Lagoon by the end of September to hold a higher concentration for the remainder of the study. There were two peaks in the Banana River Lagoon, one in mid-October and the other at the end of November.

Linear regression analysis was conducted on three date combinations for each lagoon using R Studio: 1) the original complete data sets (with the exclusion of two windy dates), 2) partial data sets and the original complete sets (with the exclusion of two windy dates), and 3) all data sets, encompassing both the complete and partial sets, including windy dates (See Appendix Table 2 for details).

Indian River Lagoon



Band 3/Band 2

Band 4/Band 3

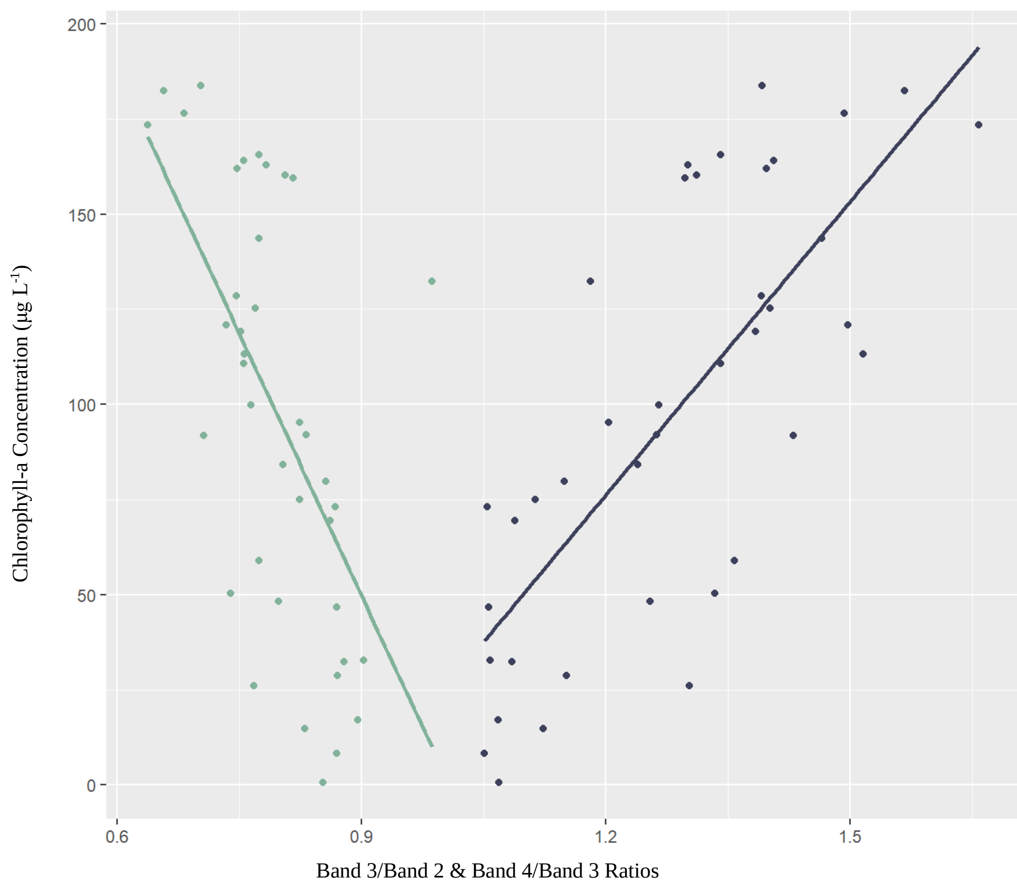
In the Indian River Lagoon, the four original complete data sets were found to have the highest R value.

For model band 3/band 2 the adjusted R value was 0.60 (multiple R value was 0.61) and produced the linear regression model chlorophyll-a = 296.88 * B3/B2 + -279.80.

For model band 4/band 3 the adjusted R value was 0.66 (multiple R value was 0.67). and the linear regression model created was chlorophyll-a = -586.03 * B4/B3 + 576.51.

Banana River Lagoon

Banana River Lagoon Linear Regression of Chlorophyll-a vs B3/B2 & B4/B3



Band 3/Band 2

Band 4/Band 3

The highest R value model in the Banana River Lagoon was found using the four complete data sets (without the two windy dates) and the partial data sets.

For model band 3/band 2 the adjusted R value was 0.54 (multiple R value was 0.55) and the resulting linear regression model was chlorophyll-a = = 256.82 * B3B2 + -231.96.

For model band 4/band 3 the adjected R value was 0.23 (multiple R value was 0.27) and the linear regression model was chlorophyll-a -459.11 * B4B3 + 462.79.

Mosquito Lagoon

There were only two sampling sites and limited chlorophyll-a data from the Mosquito Lagoon so a model could not be created due to a lack of data.

DISCUSSION

The objective of this study was to establish a predictive model of algal blooms in the Indian River Lagoon, Mosquito and Banana River Lagoon. This study succeeded in creating two of the three models.

At first, the data for all three lagoons were combined but upon preliminary analysis it was decided that investigating each lagoon separately would provide better information. Then, complete data sets for the six dates were analyzed. Two dates were excluded from further analysis due to the high ranges within the buffer zone that can be attributed to wind causing unusual reflectance patterns (10/25/2020 and 12/31/2020). The introduction of the partial data sets was helpful to studying the Banana River Lagoon.

In reference to Graph 1, it is important to consider the low number of values in the partial data sets. For the date 10/27/2020 (only included in Banana River Lagoon data), there were only two data points, and they had a range of 129.74 µg L^{-1}. The data does seem to align well with the surrounding values, but the limited number of values could be at risk of skewing the data and displaying an inaccurate overall portrayal. The models may be improved with additional complete data sets. Only having four complete data sets over four months may have contributed to not having higher R values for both lagoons. The partial data sets contained an average of 4.2 data points per day for the Indian River Lagoon while the partial data sets for the Banana River Lagoon Contained an average of 3.8 data points per day.

The strongest model was achieved using the band 4/band 3 model in the Indian River Lagoon with an adjusted R value of 0.6557. Band 4 covers the red spectrum while band 3 includes the green spectrum. This is different from past Landsat models that best fit with band 3/band 2 ratios.

The strongest model in the Banana River Lagoon was created using band 3/band 2 ratios with an adjusted R value of 0.5449. Band 2 includes the blue spectrum.

Another potential area of improvement to the model is refining the buffer size around each sample point. The 100m buffer was based on past successful Landsat models but other buffer areas have not been tested. The buffer area provided an average of spectral values and could be deemed too granular or coarse.

The Indian River Lagoon and Banana River Lagoon are similar in average depths of 1.8 m and 1.7 m respectively (Steward et al., 2005). But they differ in total area – the Banana River Lagoon is about 30,000 acres while the Indian River Lagoon is about 191,180 acres. The Indian River Lagoon tends to be more turbid as it receives inputs from multiple rivers and tributaries, and is more susceptible to agricultural runoff, urbanization, and tidal action. The Banana River Lagoon is more sheltered and has more limited connectivity to external water bodies. This may explain the reason behind why the best linear regression model in the Indian River Lagoon was the band ratio band 4/band 3 which registers more brown and green hues that are often associated with turbidity. In addition, they may provide an explanation for why the best linear regression model for the Banana Lagoon was created using band 3/band 2. As seen in Graph 1, it is of note that the Banana River Lagoon had higher concentrations of chlorophyll-a than the Indian River Lagoon.

In Map 4, the band 3/band 2 spectral ratio visually shows the chlorophyll-a values start off high and gradually decrease in the Indian River Lagoon as the colors transition from bright green to deep blue by the final date. The Banana River Lagoon appears to have a higher degree of variability and the northern portion had a more prevalent bloom.

In Map 5, the band 4/band 3 spectral ratio displays an interesting relationship between the red and green values. On the first date the band 4 values were much higher than the rest of the dates with hardly any green displayed on the map. As time continued, the band 4 values decreased in relation to band 3 and green showed up increasingly strong in the other dates. The final date showed a dramatic difference between band ratios in the northern and southern portions of the Banana River Lagoon to mimic the same pattern as seen on Map 3.

An interesting consideration in this study is the presence of the novel bacterium that was first observed in the Banana River and Northern Indian River Lagoon from early August to December 2020. It could be a contributing variable to the reliability of the linear regression models compared to past models (when *A. lagunensis* was dominant). Further studies will need to be conducted to establish the difference in spectral reflectance data between bacteria species.

In addition to this, future research will need to be conducted on what drives the novel cyanobacterium to thrive if it continues to persist. *Prochlorothrix hollandic*a is only able to assimilate phosphorus and not nitrogen so efforts to control the novel cyanobacterium will likely involve strict control of phosphorus (Pinevich et al., 2012).

CONCLUSION

Two linear regression models were created with reasonable reliability to monitor ongoing algal blooms in the Indian River Lagoon and Banana River Lagoon. The presence of the novel cyanobacterium was an unexpected variable in this study and future research will need to be conducted on how this dominance will affect previous dominant bacteria like *A. lagunensis* and their spectral data fingerprints. As we look to the future, the pressing challenges of climate change and the blossoming coastal population emphasize the critical importance of our efforts to protect aquatic ecosystems from the destruction posed by algal blooms.

APPENDIX

Table 2

Description	All Lagoons - All Dates	All Lagoons - Partial Data with Windy Dates Removed - Range 500	All Lagoons - Complete Data Only	All Lagoons - Partial Data with Windy Dates Removed - Range 400	Indian River Lagoon - All Dates	Indian River Lagoon - Partial Data with Windy Dates Removed	Indian River Lagoon - Complete Data Only	Banana River Lagoon - All Dates	Banana River Lagoon - Partial Data with Windy Dates Removed	Banana River Lagoon - Complete Data Only
Dates Included	9/5/2020, 9/17/2020, 10/12/2020, 10/15/2020, 10/25/2020, 10/27/2020, 11/24/2020, 11/26/2020, 12/1/2020, 12/9/2020, 12/31/2020	9/5/2020, 9/17/2020, 10/12/2020, 10/15/2020, 10/27/2020, 11/24/2020, 11/26/2020, 12/1/2020, 12/9/2020	9/5/2020, 10/15/2020, 11/24/2020, 12/9/2020	9/5/2020, 9/17/2020, 10/12/2020, 10/15/2020, 10/27/2020, 11/24/2020, 11/26/2020, 12/1/2020, 12/9/2020	9/5/2020, 9/17/2020, 10/12/2020, 10/15/2020, 10/25/2020, 10/27/2020, 11/24/2020, 11/26/2020, 12/1/2020, 12/9/2020, 12/31/2020	9/5/2020, 9/17/2020, 10/12/2020, 10/15/2020, 10/27/2020, 11/24/2020, 11/26/2020, 12/1/2020, 12/9/2020	9/5/2020, 10/15/2020, 11/24/2020, 12/9/2020	9/5/2020, 9/17/2020, 10/12/2020, 10/15/2020, 10/25/2020, 10/27/2020, 11/24/2020, 11/26/2020, 12/1/2020, 12/9/2020, 12/31/2020	9/5/2020, 9/17/2020, 10/12/2020, 10/15/2020, 10/27/2020, 11/24/2020, 11/26/2020, 12/1/2020, 12/9/2020	9/5/2020, 10/15/2020, 11/24/2020, 12/9/2020
B3/B2 Multiple R2 Value	0.4658	0.4536	0.5549	0.4698	0.4575	0.4277	0.6105	0.5071	0.5569	0.5211
B3/B2 Adjusted R2 Value	0.4612	0.4478	0.5471	0.4649	0.4482	0.416	0.5983	0.4964	0.5449	0.4994
B4/B3 Multiple R2 Value	0.4839	0.478	0.5009	0.4862	0.5672	0.5602	0.6661	0.3424	0.3537	0.2529
B4/B3 Adjusted R2 Value	0.4793	0.4725	0.4921	0.4815	0.5597	0.5512	0.6557	0.3281	0.3363	0.219
Range limit	500	500	500	400	400	400	400	400	400	400

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