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Osa Peninsula Water Resources III

Evaluating Potential Sites for Coral Reef Rehabilitation in the Golfo Dulce, Costa Rica Based on Turbidity and Sea Surface Temperature

DEVELOP Technical Report

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1. Abstract

The Osa Peninsula, located in the southern region of Costa Rica's Pacific coast, is one of the most biologically diverse places on Earth. NASA DEVELOP partnered with Osa Conservation to analyze the impact of human activity on its vital water resources, with a focus on determining suitable locations for coral reef restoration in the Golfo Dulce. Coral reefs play a crucial role as a habitat provider, an ecosystem stabilizer, and as food security for marine and terrestrial communities; however, they are highly sensitive to changes in aquatic conditions, which can lead to bleaching and to slowed reef accretion. This project used Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI), and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery to investigate turbidity and Sea Surface Temperature (SST). These data were compiled into time series maps to assess variability within a season and over the years. The variability data were used to evaluate sites for coral restoration, and provide insight into the connections between land use, river health, and fluctuations in water quality within the gulf.

Keywords
Landsat, Google Earth Engine, turbidity, coral, MODIS, sea surface temperature

2. Introduction

2.1 Background Information

National Geographic has called the Osa Peninsula in Costa Rica (Figure 1), "the most biologically intense place on Earth"— despite its small size, it houses 2.5% of the world's biodiversity and contains the most significant mangrove forest in Central America ("About the Osa", 2017). The forest on the peninsula serves numerous roles, including providing wildlife habitat, stabilizing the landscape, storing carbon, improving air quality, providing hydrological services and recovering degraded land (Algeet-Abarquero, Sañchez-Azofeifa, Bonatti, & Marchamalo, 2015). Without these ecosystem services, the health of local lands and waters are jeopardized. Costa Rica has lost 80% of its forests since 1943 (Zahawi, Duran, & Kormann, 2015), and even with protected reserves and parks, urban development and agricultural land use have caused pollution, habitat fragmentation, and biodiversity loss in the surrounding areas (Sanchez-Azofeifa, Rivard, Calvo, & Moorthy, 2002).

These effects are particularly consequential in riparian areas where deforestation destabilizes river banks, causing erosion, increased sedimentation and pollutant accumulation (Villablos, 1998). The Osa Peninsula surrounds one of the four tropical fjords on the planet ("About the Osa", 2017), the Golfo Dulce, which is over 200 m deep and is protected from the Pacific Ocean by a shallow sill (Hebbeln, Beese, & Cortes, 1996) (Figure 1). Rivers on the peninsula and mainland transport pollutant accumulation runoff from these land use practices directly into the gulf, endangering endemic aquatic species like coral (Palmer et al., 2009). Thus, the consequences of land use change in Costa Rica affect marine, terrestrial and riverine ecosystems. Forest Law 7575 of 1996 was introduced to mitigate these detrimental effects by creating incentives to prevent future deforestation, encourage reforestation (Algeet-Abarquero et al., 2015) and designate riparian corridors as protected land (Lorian & Kennedy, 2009).

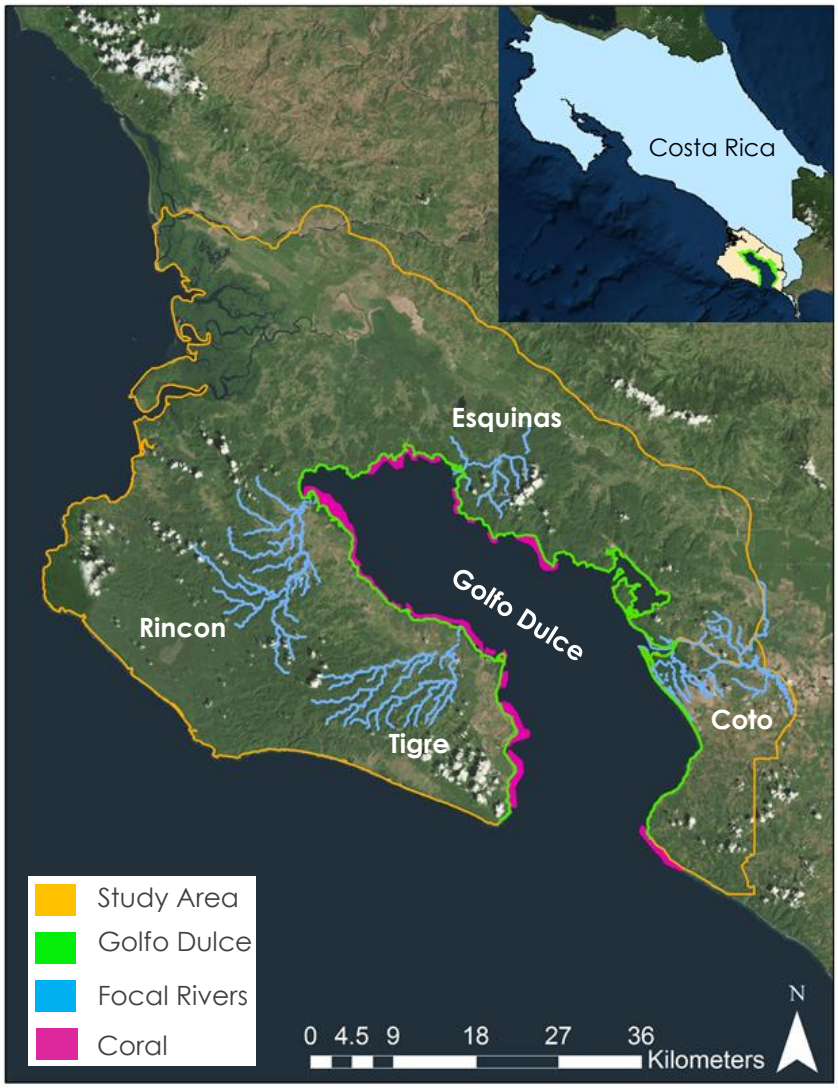

Figure 1. Study area of the Osa region

Coral reefs are significant to the Osa region because they provide key ecosystem services such as marine habitat, shoreline protection and human food security. However in the Golfo Dulce, they have been dying at an alarming rate since before 1990 (Guzmán, 1991). This reef degradation has occurred because of El Niño/Southern Oscillation (ENSO) events (Guzmán & Cortés, 2001), natural disasters and increased pollution from land use changes in Costa Rica (Cortés, 1990).

Because coral reefs are sensitive to these fluctuations in water characteristics (Guan, Hohn, & Merico, 2015), there is a need to understand the nature of the gulf waters. Deforestation and urbanization adversely affect coral by increasing turbidity in surrounding waters, and in turn, changing the distribution of healthy coral communities (Neil, Orpin, Ridd, & Yu, 2002). Additionally, only coral species that are tolerant or adaptable to rising sea surface temperatures survive (Maina, Venus, Mcclanahan, & Ateweberhan, 2008). Osa Conservation is currently assessing suitable coral restoration areas and prioritizing locations with minimal fluxes in water characteristics. Because corals are endemic and variable, restoration efforts require regional, empirical research to conclude findings. Unfortunately, the current lack of current empirical research in the Osa region has impeded restoration efforts.

The Osa Peninsula Water Resources research project has gone through three iterations. Term I investigated changes in vegetation type and abundance as a result of Forest Law 7575 of 1996. They did this through Normalized Difference Vegetation Index (NDVI) and land cover classification time series maps that were created for the years 1987, 1999 and 2017. The results concluded a 10.69% increase in forest cover and 48.58% decrease in grassland cover across the Osa Peninsula.

Term II used the difference in NDVI and Enhanced Vegetation Index (EVI) between 1987 and 2017 to show a net total increase in vegetation cover on the Osa Peninsula. They also measured carbon sequestration from 2012 to 2017, determining GPP was 3.06% higher in the Osa's protected areas than in unprotected areas. The Soil Water Assessment Tool (SWAT) was used to predict the impact of riparian restoration in watersheds through sediment yield analysis across two sub-basin regions. Composite NDVI and EVI maps showed no change for mangrove forest, an increase in palm and forest cover and a decrease in grassland cover.

For Term III, NASA DEVELOP partnered with Osa Conservation to understand the effects of local land use change on the Golfo Dulce and to assess potential locations for coral reef restoration. We used NASA Earth observations to analyze turbidity and sea surface temperature changes in the gulf between February 1, 1986 and April 30, 2018. . We determined variability in water characteristics over this time period to identify optimal restoration areas with minimal fluctuation.

2.2 Project Partners & Objectives

Osa Conservation is a nonprofit organization dedicated to conserving and protecting the wealth of biodiversity on the Osa Peninsula and in the adjacent Golfo Dulce. Through their Marine Conservation Program and partnerships with local universities as part of the Save Our Seas Program, they plan to restore the region's coastal reefs that have been damaged by sedimentation, pollution, warming and natural disasters. They are also interested in the impacts of land use change on reef health pre and post implementation of Forest Law 7575.

Osa Conservation currently uses ground observation techniques to observe reef health. However, there is a shortage in recent and robust research on these local reefs. Using remote sensing for this project can benefit the organization by allowing them to better prioritize and identify suitable locations to allocate reef rehabilitation and new artificial reef formation efforts within the gulf. The organization can use the end-product maps and data analyses to determine areas in the Golfo Dulce with stable water parameters for coral viability. The objectives of this project are to: 1) analyze historical trends in gulf turbidity, 2) create maps of seasonal fluctuations in SST and turbidity, 3) connect gulf stability with land use change by analyzing turbidity in key river deltas, and 4) create a coral rehabilitation suitability map based on stability over time.

Connecting the results of Osa Peninsula Water Resources III with the results from the previous two NASA DEVELOP terms, Osa Conservation can use the turbidity analyses to investigate the impact of land use changes on reef health. The partner can use and share results of this project to the National System of Conservation Areas (SINAC), Ministry of Environment and Energy (MINAE), and local communities to inform land management decisions, policy enforcement, education and outreach initiatives and watershed restoration and monitorin

3. Methodology

3.1 Data Acquisition

Our team used Google Earth Engine (GEE) API to collect and process Surface Reflectance Tier 1 Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) data. Additionally, we acquired level 3 Aqua Moderate Resolution Imaging

Spectroradiometer (MODIS) data processed by Earth Observing System Data and Information System (EOSDIS). Collectively, we used these sensors to investigate turbidity and sea surface temperature (Figure 2). We used Landsat 8 to look closely at a major river delta that contributes to water quality changes in the gulf. We downloaded major rivers and administrative boundaries from DIVA-GIS, a free computer program for mapping and analysis, into Esri ArcMap 10.5. Osa Conservation provided additional river shapefiles.

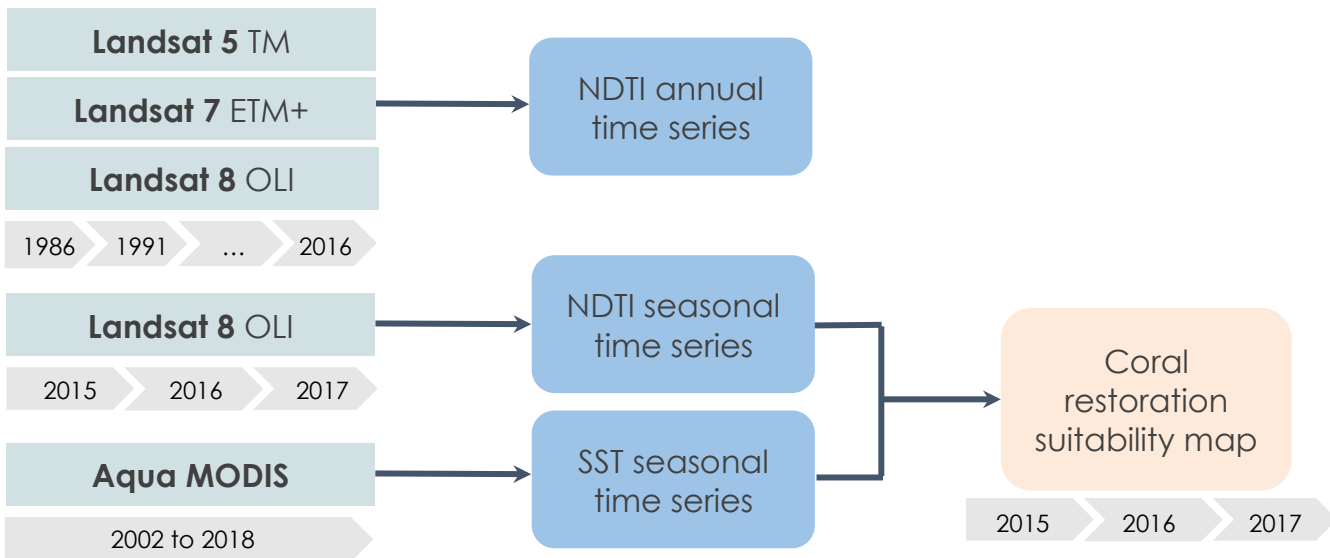

Figure 2. Overview of project methodology.

3.2 Data Processing

Landsat 5 and 7 Tier 1 bands bands 2 (0.52-0.60 µm) and 3 (30.63-0.69 µm) and Landsat 8 Tier 1 bands 3 (0.52-0.60 µm) and 4 (30.63-0.69 µm) were selected for every 5 years between 1986 and 2016, separated into image collections by selection year. Using the quality assurance band (pixel_qa), clouded images were masked out by selecting pixels with values classified as 'clear' or 'water'. The two bands were used to calculate Normalized Difference Turbidity Index (NDTI) medians and fluctuations. The sea surface temperature band was acquired from Ocean Color MSI Standard Mapped Image MODIS Aqua Data, a Level 3 dataset initially processed by EOSDIS. Both composites were clipped to the region of interest.

Costa Rica has two seasons: a dry season from January to June and a wet season from July to December. The most intense months within these seasons are February to May for the dry season and August to November for the wet season. To conduct water characteristic fluctuation studies, we created seasonal composites for the years 2015, 2016, and 2017 using the same periods of highest intensity. This supplied water condition information to assess coral restoration areas.

3.3 Data Analysis

To analyze turbidity in the Golfo Dulce, we calculated NDTI using equation (1). NDTI maps were created from 1986 to 2016 in five years intervals (1986, 1991, 1996, 2001, 2006, 2011 and 2016). Five years intervals were considered in order to distinguish years with significant Eastern Pacific warming due to ENSO, such as the 2015 through 2016 event (Barnard et al., 2017). NDTI quantifies turbidity levels and reclassifies the results to a range from -1 to 1. Values closer to 1 represent areas of the gulf with higher turbidity levels, and values closer to -1 represent areas of the gulf with lower turbidity levels. Comparisons to the natural color image were conducted to verify results (Appendix A).

$$\mathrm{NDTI} = \frac{\varrho_{red} - \varrho_{green}}{\varrho_{red} + \varrho_{green}} \qquad (1)$$

To account for variability between wet and dry seasons, Osa Conservation also wanted to distinguish seasonal turbidity fluctuations over the last few years. To do this, we performed a time series analysis by season for 2015, 2016, and 2017. Medians, minimum and maximum for each season were calculated. The difference was then represented on a color scaled map for each dry and wet season pair.

An interactive mapping tool was created using Sea Surface Temperature (SST) level 3 data collected by Aqua MODIS. This map charts fluctuations in SST for a certain point in the gulf for 2008 through 2018 and 2002 through 2007. These are in separate tools because of limitations in GEE data processing. The chart and corresponding data are then downloadable as a CSV file for further data analysis or as a PNG file for communication of results.

Furthermore, we overlaid our seasonal 2015 through 2017 NDTI results from Landsat 8 with level 3 SST data collected by Aqua MODIS to create a suitability map that assessed water parameter fluctuations. Results for suitability analysis were then displayed using a bivariate key (Figure 3), with two axes (SST and turbidity). Color thresholds were determined statistically using percentile ranges. For each parameter, the lightest color contains values up to the 40th percentile, with the second color containing values between the 40th and 70th percentile, and the darkest color containing values higher than the 70th percentile. Areas of white represent low turbidity and SST, areas of blue represent high turbidity and low SST. Areas of red represent areas of low turbidity and high SST, and areas of purple represent areas of high turbidity and high SST. Black pixels indicate areas that lack enough data to generate a complete pixel. 2015, 2016 and 2017 map fluctuations were averaged to create an average turbidity map. A correlation chart was also created to investigate the relationship between NDTI and SST. We plotted NDTI and SST averages from our seasonal 2015 through 2017 data to show the strength of correlation between these two water parameters. Trends for both parameters were also assessed over time.

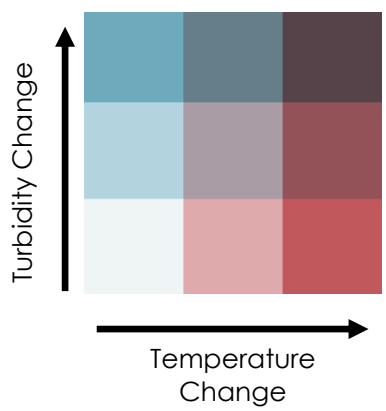

Figure 3. Bivariate key for coral restoration location suitability analysis

4. Results & Discussion

4.1 Analysis of Results

Our SST maps showed an overall increase in median SST throughout the gulf from 2002 to 2018. Temperatures ranged within each season by several degrees with the wet season being consistently colder than the dry season. However, the median temperatures for both seasons also increased over time. This upward trend in temperature was evident in charts produced using our SST tool for points throughout the gulf (Figure 4). Year-round temperatures ranged from 26 to 34℃, peaking in 2015 and 2016. This is consistent with evidence of ENSO warming in the same years. The maps also showed that temperatures are colder closer to the mouth of the gulf (Figure 5).

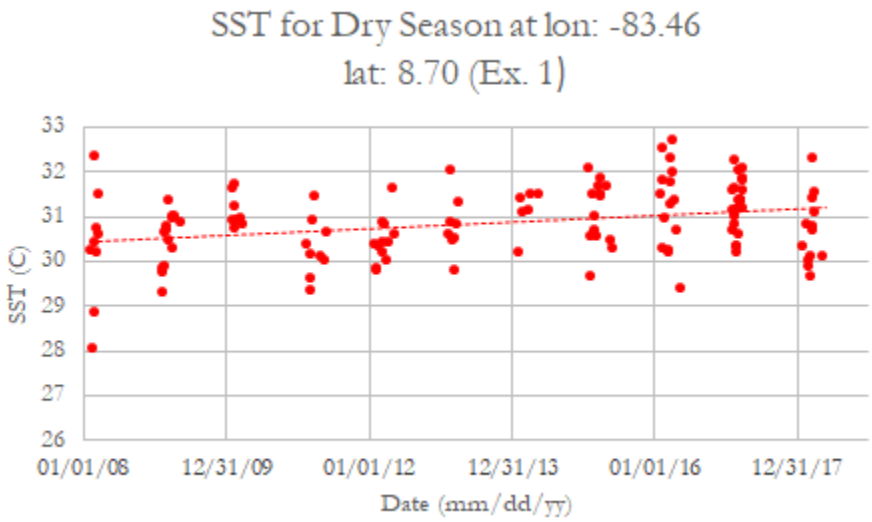

Figure 4. Chart of SST from 2008 through 2018 for a location on the western coast of the gulf (see Appendix E for reference)

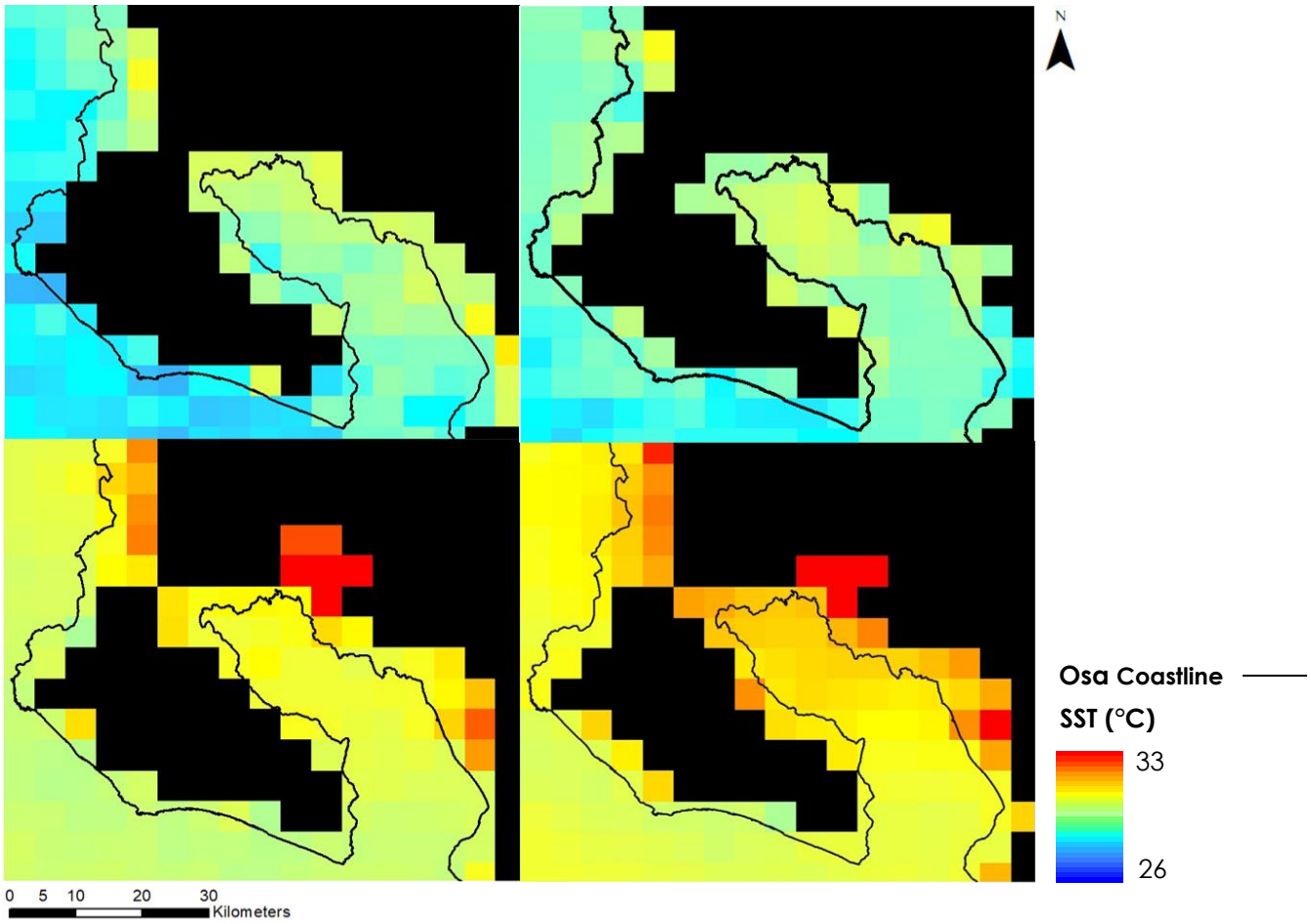

Figure 5. Map of median ST for both dry and wet seasons in 2003 and 2017. (Clockwise from the top left: 2003 wet season, 2017 wet season, 2017 dry season, 2003 dry season)

Further analyses are limited by data availability for the region. Aqua MODIS SST data lacks spatial precision because it collects at a 500 m resolution. Temperature readings may be distorted for coastline pixels because the data collected is a matrix of both land and water temperatures. In addition, there were fewer wet season temporal data points for analysis than the dry season because of cloud cover interference during data collection. Therefore, confidence in our wet season analysis is lower because of a lack in available data points.

Our NDTI maps showed higher turbidity levels in the river deltas and coastlines than in other parts of the gulf. Turbidity decreased from 1986 to 2016 in most areas of the gulf, particularly in the inner fjord and along eastern coastlines near Piedras Blancas National Park and Golfito National Wildlife Refuge where up to a 300% decrease was observed (Figure 6). However, for the focal river deltas (Coto, Rincon, Esquinas, and Tigre) and the southeastern and northern parts of the gulf, NDTI is nearly constant (Appendix B). Río Coto's delta, the largest in the gulf, showed high NDTI values across time but with variable fluctuation magnitudes (Figure 7). For instance, in 1991, turbidity levels were very high, despite lower levels in preceding and subsequent years. This abnormal reading is confirmed by historical accounts of the largest earthquake in Costa Rican history, which hit the Osa Region in April 1991 with a magnitude of 7.7 on the Richter Scale (Suarez et al. 1995). Overall, the 30 year reduction in NDTI could have resulted from the reforestation incentives enacted by the 1996 Forest Law 7575. This is further evidenced with a comparison of difference

maps from 1986 to 1996 and from 1996 to 2016 (Figure 8). Turbidity increased in the ten years prior to the passing of this forest law and greatly decreased in the 20 years following

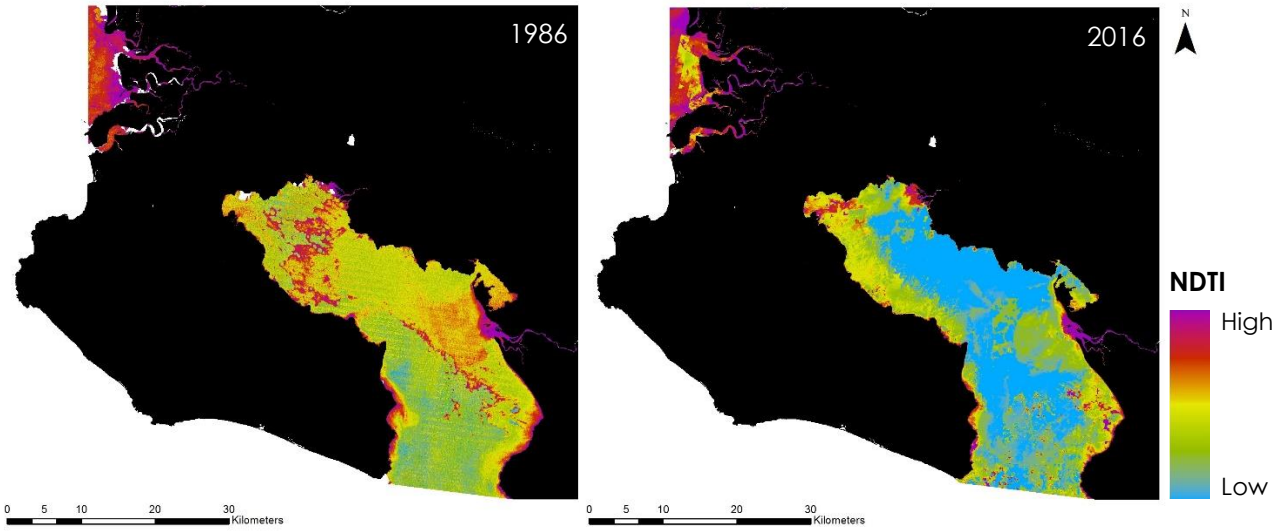

Figure 6. Median annual NDTI maps for 1986 (left) and 2016 (right)

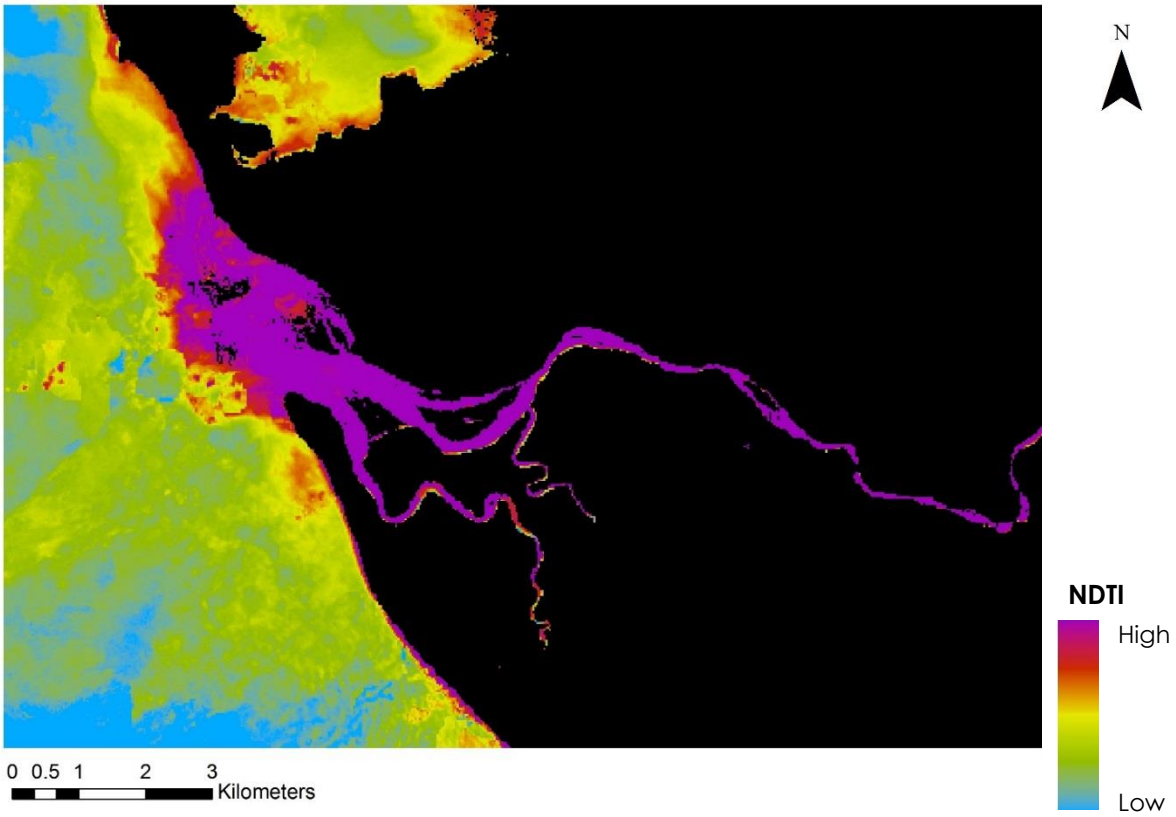

Figure 7. Median NDTI map over the Coto delta in 2016

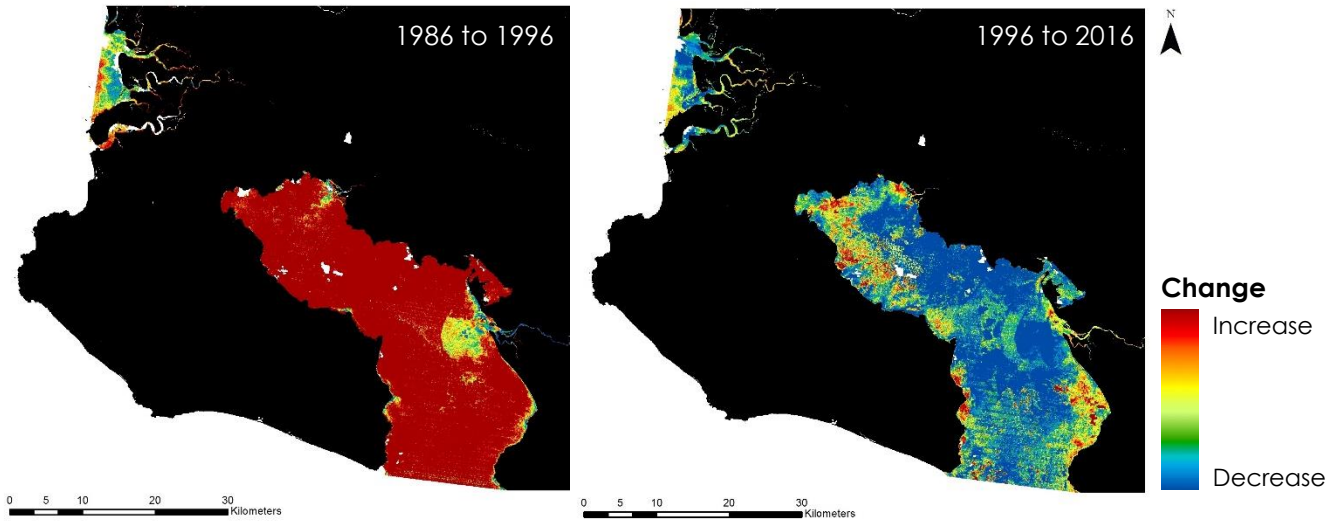

Figure 8. NDTI Change between 1986 to 1996 (left) and 1996 to 2016 (right)

Limited available data made it difficult to retrieve complete image collections of the gulf. There was a failure in the Scan-line Corrector (SLC) of the Landsat 7 ETM+ sensor causing 22% of the pixels in captured images to appear as no data stripes (Chen, Zhu, Vogelmann, Gao, & Jin, 2011), which was prominent in our 2006 and 2011 maps. In 2001, there were pixels without data for the northern and southern regions of the gulf because of cloud cover. In addition to the lack of spatial data, cloud cover interference caused temporal limitations for data retrieval, especially during the wet season, resulting in years with no available data.

Ocean waters are masked since we were not able to calculate ocean turbidity for the Osa region. There are different algorithms for calculating NDTI in inland and ocean waters. For ocean waters, bands from the blue and green regions of the electromagnetic spectrum are used, whereas inland water calculations use bands from red and green regions. In general, blue bands are most impeded by atmospheric scattering. For inland waters, blue wavelengths are also more often absorbed by suspended, dissolved matter rather than reflected by it (Watanabe et al., 2017), driving the need to utilize two different formulas to calculate the index.

Coral thrive in areas with lower and constant turbidity (Bessell-Brown et al., 2017) and temperature, between 21.7 and 29.6°C (Guan et al., 2015). Our bivariate maps identified locations with minimal fluctuations in both SST and NDTI (Figure 9), which indicate potential sites for coral restoration. The northwest region of the gulf showed minimal fluctuations in SST and NDTI, but showed moderate SST, around 29.6°C, and low NDTI, around -0.5. Areas within the Golfito in the Eastern region, as well as several pixels west of it, also showed minimal fluctuations. The Golfito region showed low NDTI, around -0.5, but we could not confirm SST values since the degree of the pixel overlap with land was high. Other areas were also determined to be potential coral restoration locations, but could not be validated because of this overlapping. Our bivariate maps also identified locations with highly variable SST and NDTI. Areas near the largest river delta, the delta of Río Coto, exhibited high fluctuations for both SST and NDTI between the wet and dry seasons, as well as high temperatures and NDTI values.

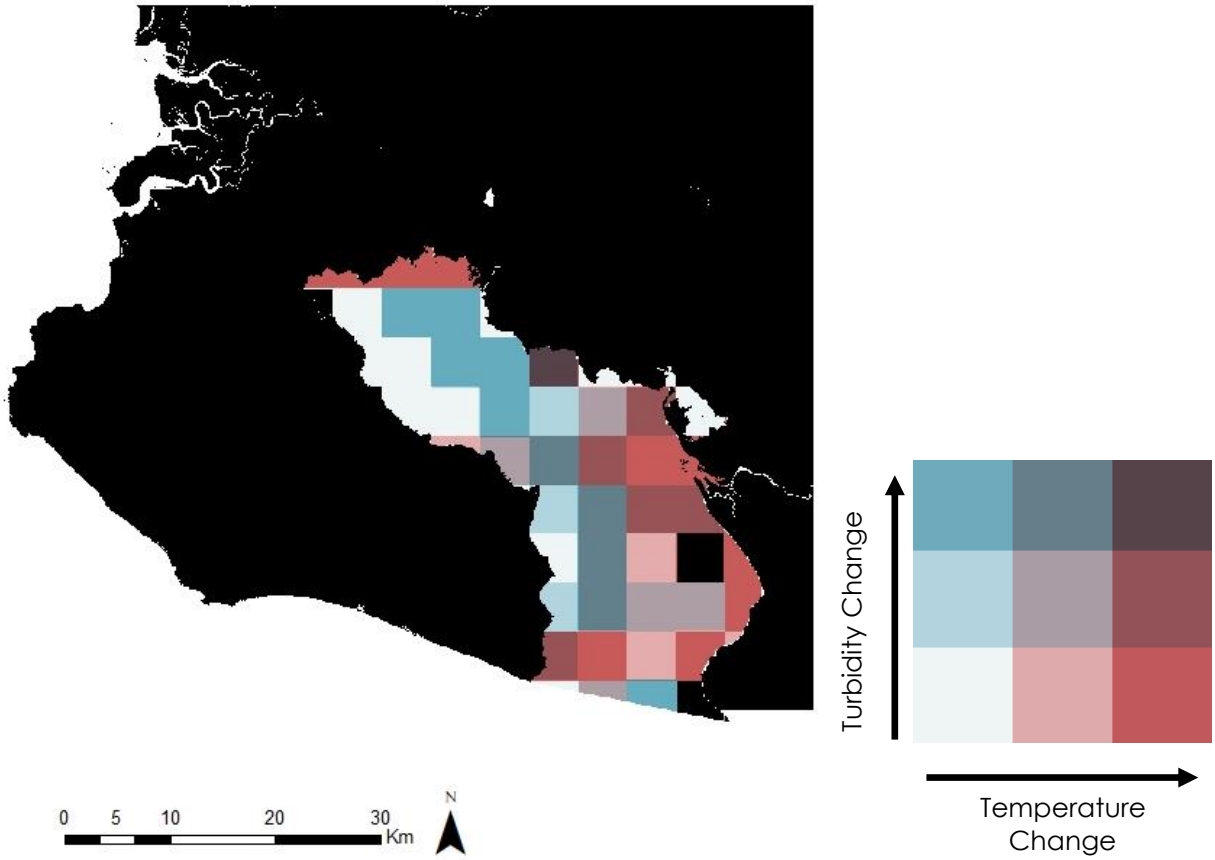

Figure 9. Bivariate map created from average SST and NDTI fluctuations for 2015 through 2017

When analyzing SST and NDTI over time, the trends from 2003 to present are opposite (Figure 10). Over time, median SST in the gulf increased, with a total increase of about 0.5°C (from 29.4 to 29.9°C), while the median NDTI decreased with a change of -0.15 for the same period. SST and NDTI changes in the wet seasons of 2003 and 2017 were 0.7°C and -0.18, respectively. However, we cannot deduce that these variables have a strong correlation. Charting NDTI against SST for different points in time, where both data points (SST and NDTI) are available, yielded no obvious patterns (Appendix D).

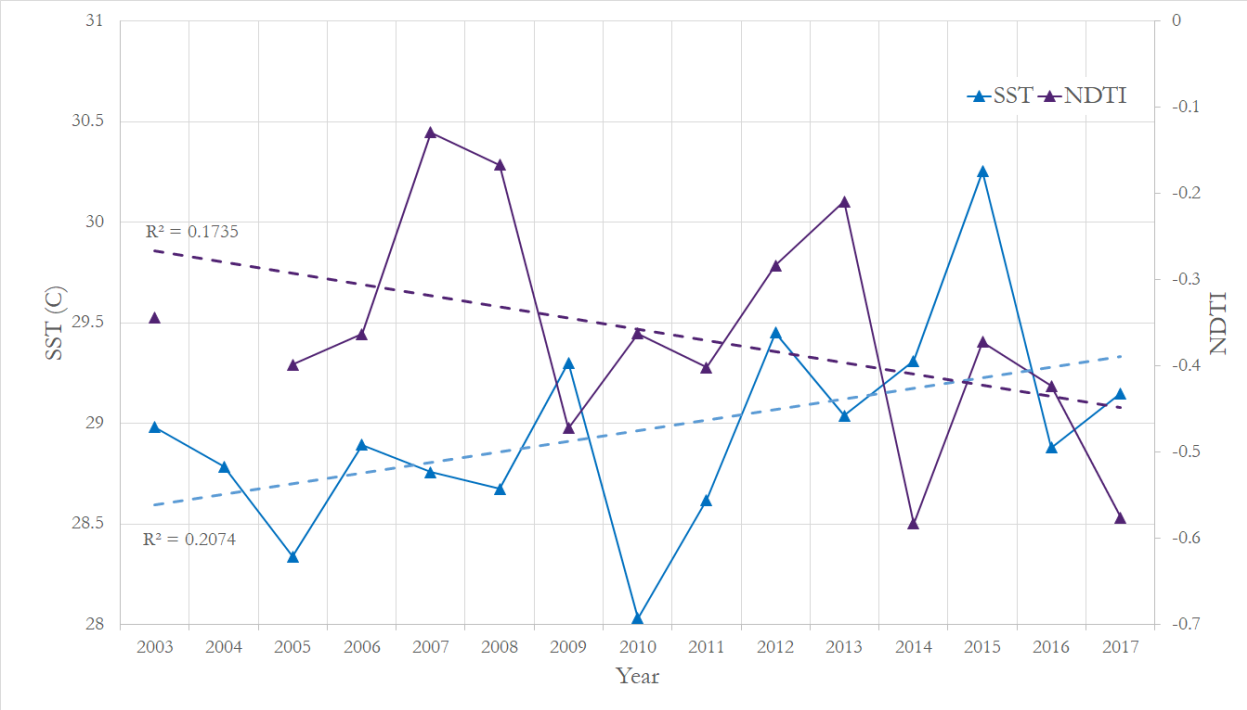

Figure 10. Median SST and NDTI during the wet season over time

Comparing our results to those of the past two terms of Osa Water Resources, we observed similar trends and conclusions. Term I analyzed land cover changes from 1987 to 2017 and found significant increases in forest, wetland, water, and negra forests and decreases in urban areas, palm plantations, and grasslands. These trends coincide with the turbidity decrease we observed over our study period of 1986 to 2016 since increased forest cover could reduce runoff that contributes to gulf turbidity. Similar to Term I, we cannot conclude that these changes were a direct cause of the enactment of Forest Law 7575 since other concurrent socioeconomic and environmental changes may have also contributed.

The second term also investigated watershed health in relation to land use change and found a decrease in sediment pollution within a case study river. This aligns with our results that demonstrated a decrease in turbidity in the gulf from 1996 to present. However, the rate of reforestation occurring before 1997 seems to be higher than the period after, but these results have not been confirmed. Because different satellites and sensors were used across projects, the study period and selected key years differ due to availability of cloud-free images in the region.

4.2 Future Work

Considering the larger scale and finer spatial resolution required for analyzing NDTI over river deltas, PlanetScope and Sentinel-2 MSI data could be used to analyze further river deltas within the Golfo Dulce. These would provide data with resolutions of 3 m and 10 m respectively. Terra ASTER-TIR bands 10-14 could also provide finer spatial resolution for our SST study with a resolution of 90 m. This analysis of river deltas could be expanded further upstream to consider regional watershed health more generally as well as its connection to gulf parameters. Since coral is also sensitive to salinity fluctuations, other satellites and sensors could be explored to analyze this parameter in the gulf. Based on the breadth of initial questions posed by the partner organization, future work could also examine the connection between changes in water parameters and mangrove population health in the gulf.

Additional work could be done by building upon the information we acquired this term. With the procurement of ground truth points, we could devise empirical formulas to calculate absolute turbidity and chlorophyll-a (Chl-a) concentration estimates. Because Chl-a is also being detected by Landsat 8 OLI band 3, the green band used in our calculations of NDTI, inorganic and organic suspended matter is not distinguishable. *In-situ* data for Chl-a would allow us to differentiate between the two and derive absolute water color values for turbidity (Watanabe et al., 2017).

5. Conclusions

A noticeable decrease in NDTI can be seen over the gulf from 1986 to 2016 potentially due to incentives for reforestation efforts after Forest Law 7575 was enacted. NDTI increased from 1986 to 1996 over almost the entire gulf, except for Río Coto and Río Esquinas deltas and some coastlines in the southern part of the gulf. NDTI then decreased from 1996 to 2016, particularly in central parts of the gulf and some eastern coastlines. The net NDTI change from 1986 to 2016 is negative, indicating that the turbidity decrease after 1996 was larger than the increase from 1986 to 1996. Overall, the turbidity over the coastlines and deltas have smaller fluctuations between seasons. Although Río Coto's delta is turbid, it has shown little fluctuation in NDTI over the past 20 years. In contrast to NDTI, SST increased over the gulf from 2003 to 2016 by about 0.5°C, exhibiting higher fluctuations during the wet season (about 0.7°C). Together, NDTI and SST show opposing trends, but we cannot conclude strong correlations between the two. When looking at the overlay of these two parameters for our bivariate map, minimal fluctuations are seen in the northwest region of the gulf. With the sensitive nature of coral, and confirmation that this area has suitable temperatures and low turbidity, this area is one possible location for restoration.

Not only can Osa Conservation use this work, produced using NASA Earth Observations, to determine potential coral restoration sites, but they can also use this information to aid in localizing and finding the root causes of turbidity fluctuations from upstream pollutants. This can inform decision makers on best methods for protecting the area's coastal marine environment. Furthermore, by conducting detailed field analyses in conjunction with results from all three terms, the organization can continue to assess the conditions of the Osa Peninsula and the Golfo Dulce.

6. Acknowledgments

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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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7. Glossary

Biodiversity – the variety of species in a concentrated area
Earth observations – satellites and sensors that collect information about the Earth's physical, chemical, and biological systems over space and time
ENSO (El Niño/Southern Oscillation) – the interaction between atmosphere and ocean that results in fluctuating sea surface temperature and precipitation abnormalities in the tropical Pacific
Enhanced Vegetation Index (EVI) – a measurement of vegetation density and health that corrects for some distortions in the atmosphere and on the ground surface; it is also more sensitive to differences in heavily vegetated areas
Ground Truth Data – data that is collected on location and allows image data to be compared to real features and verify image analysis
MODIS – MODerate resolution Imaging Spectroradiometer
Normalized Difference Turbidity Index (NDTI) – a measurement of water turbidity

$$NDTI = \frac{\rho_{red} - \rho_{green}}{\rho_{red} + \rho_{green}}$$

Normalized Difference Vegetation Index (NDVI) – a measurement of vegetation density and health

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$$

PlanetScope – a constellation of satellites that provide high spatial resolution data and daily coverage
Riparian Zones – the interface area between land and a river or stream
Watershed – the area of land where all of the water that falls in it and drains off it goes to a common outlet

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9. Appendices

Appendix A.

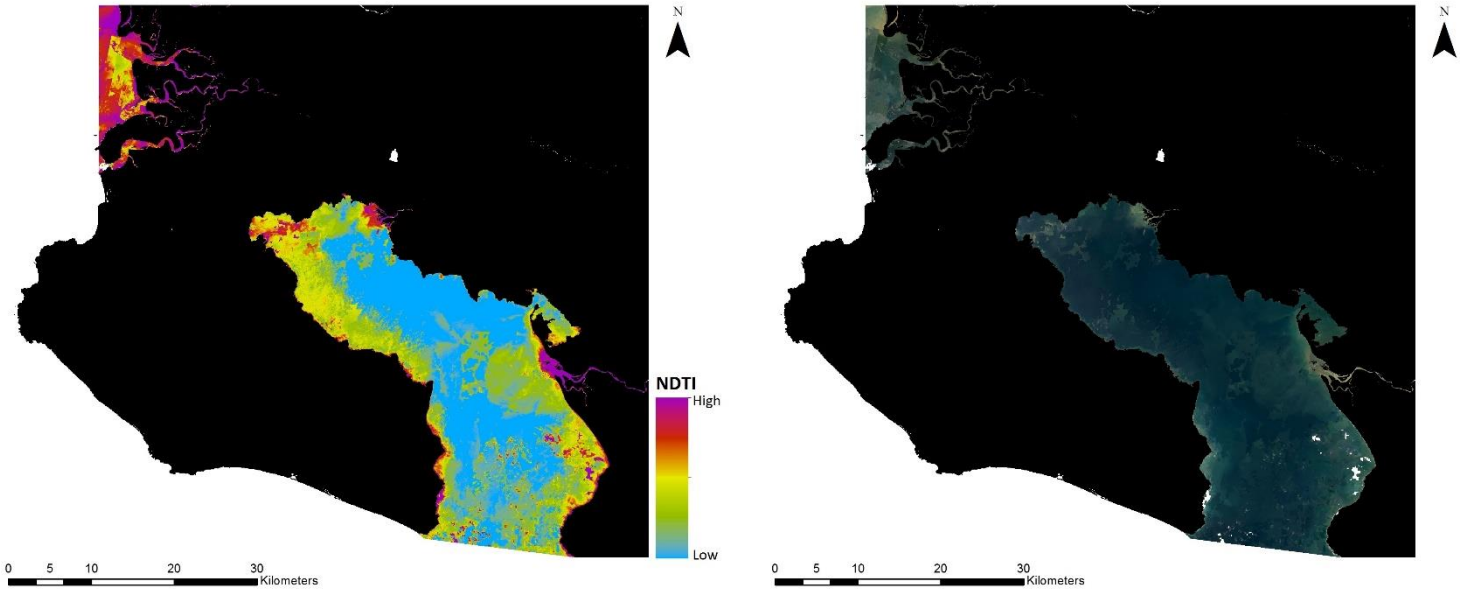

Figure A1. Median turbidity and true color map comparison over Golfo Dulce in 2016

Appendix B. Turbidity in the focal river deltas

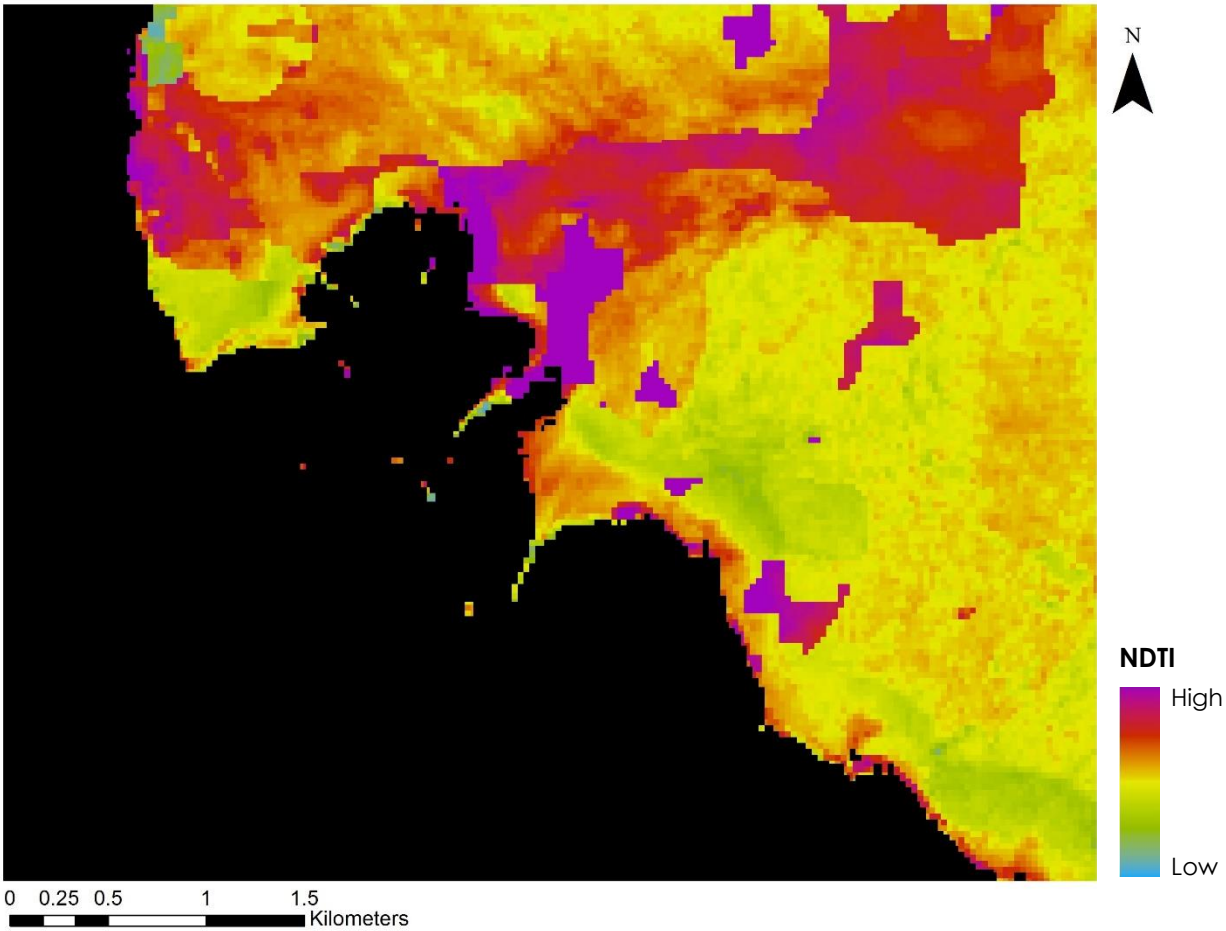

Figure B1. Median NDTI map over Rincon delta in 2016

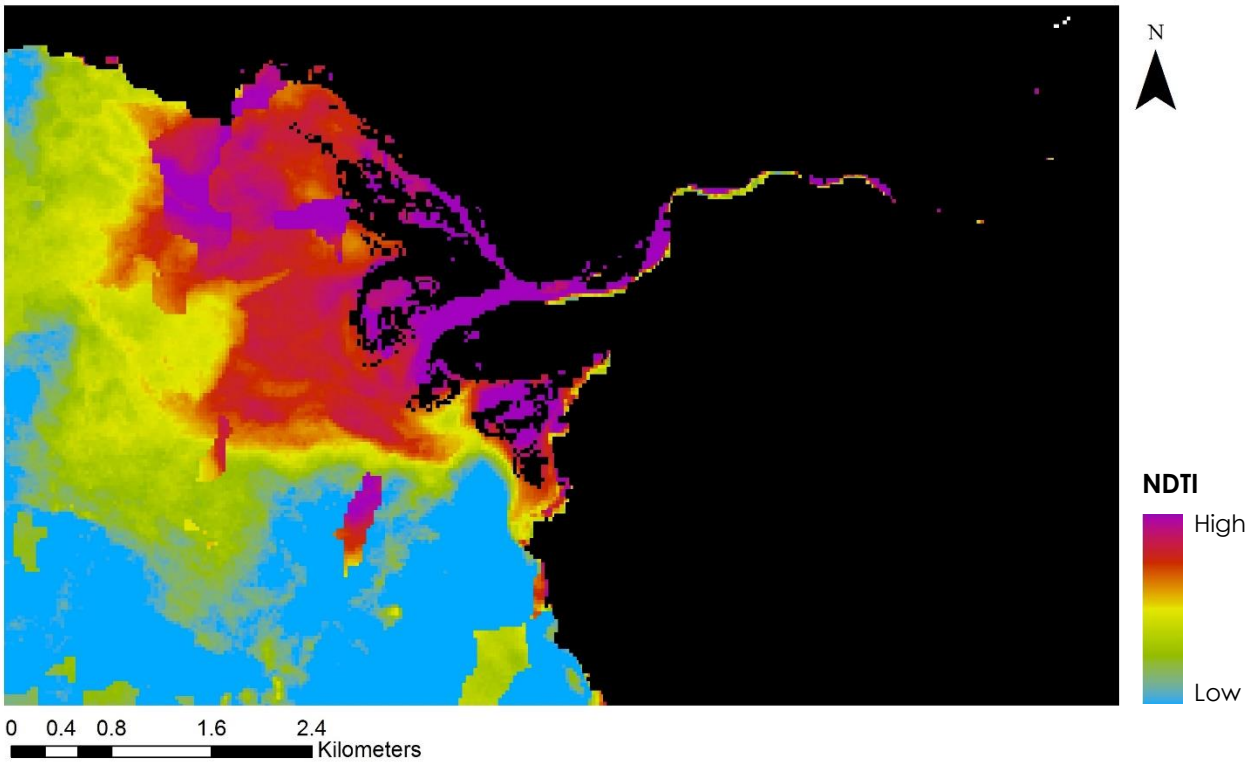

Figure B2. Median NDTI map over Esquinas delta in 2016

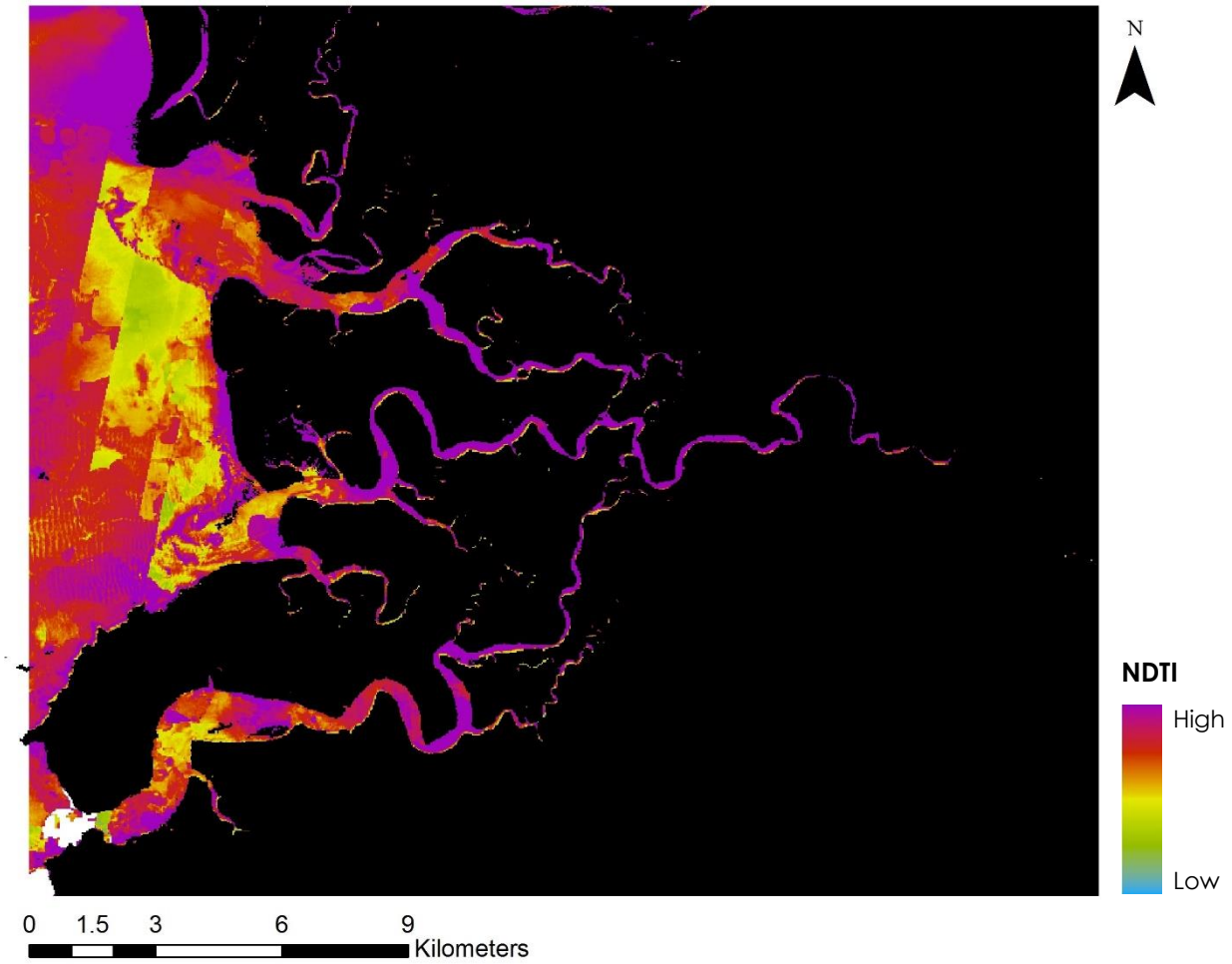

Figure B3. Median NDTI map over Terraba delta in 2016

Appendix C. NDTI and SST Trends

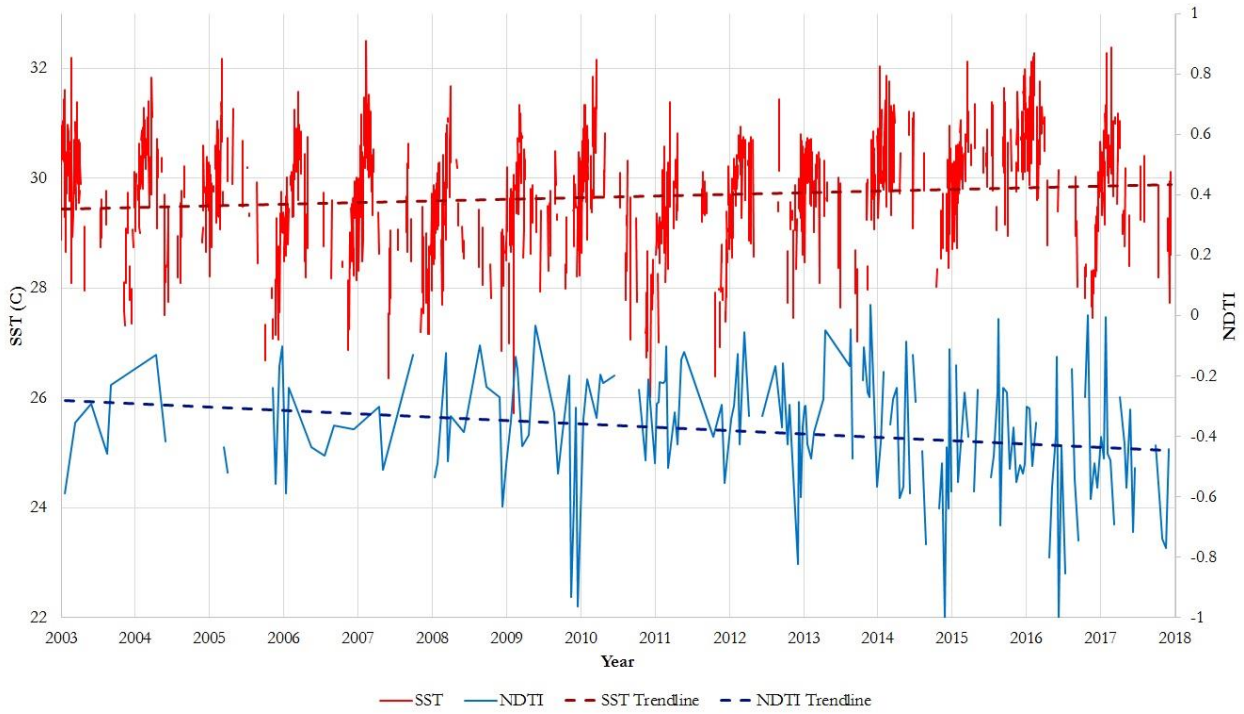

Figure C1. Median SST (red) and NDTI (blue) time series over Golfo Dulce from 2003 to 2017

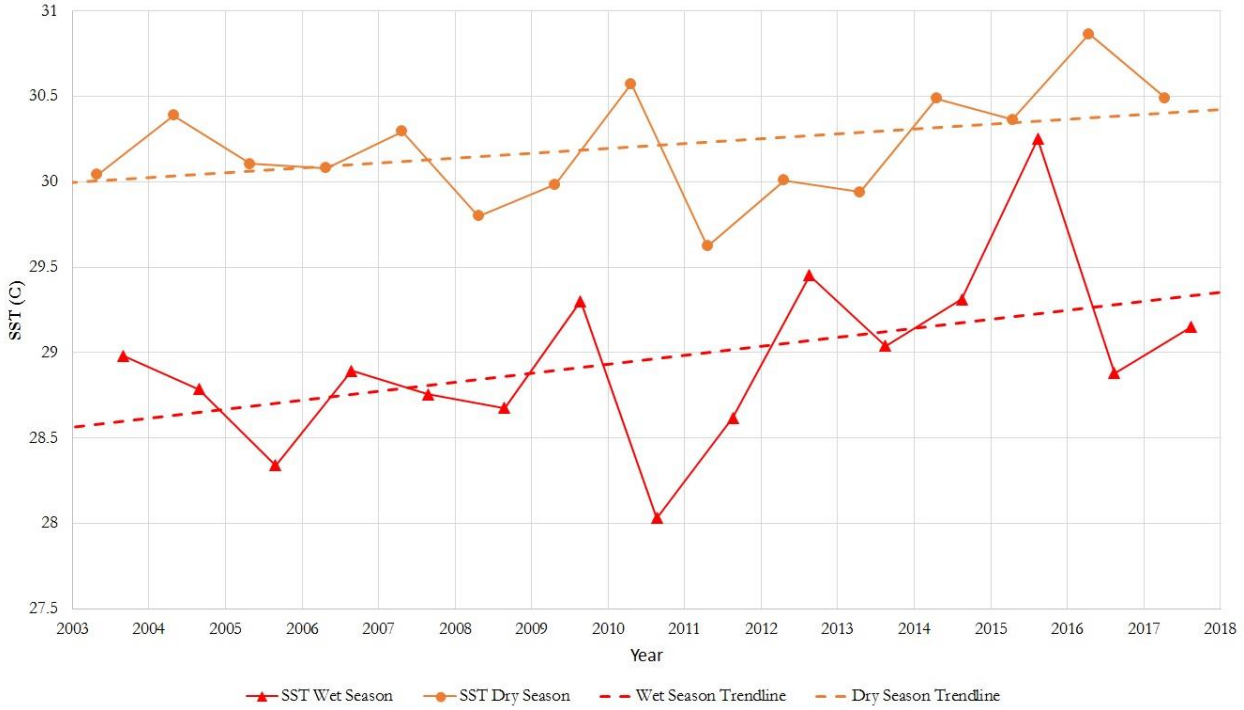

Figure C2. Median SST for wet seasons (red triangles) and dry season (orange circles) time series over Golfo Dulce from 2003 to 2017

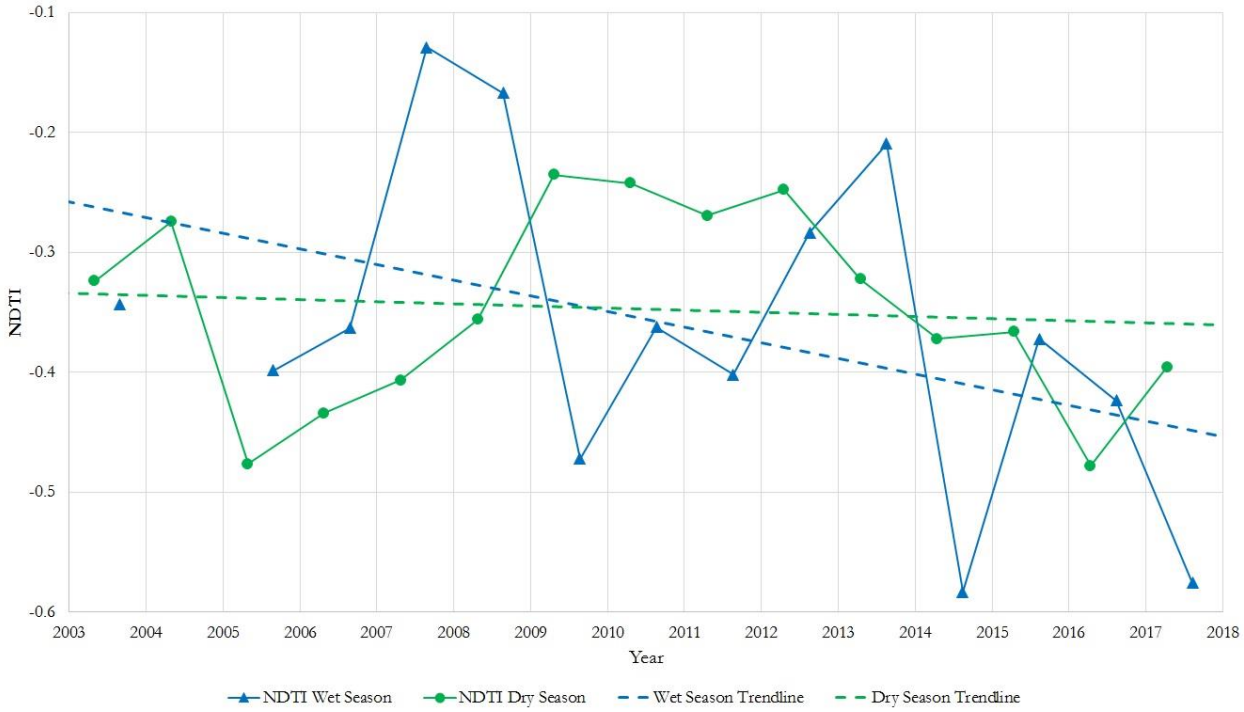

Figure C3. Median NDTI for wet seasons (blue triangles) and dry season (green circles) time series over Golfo Dulce from 2003 to 2017

Appendix D. NDTI and SST Correlation

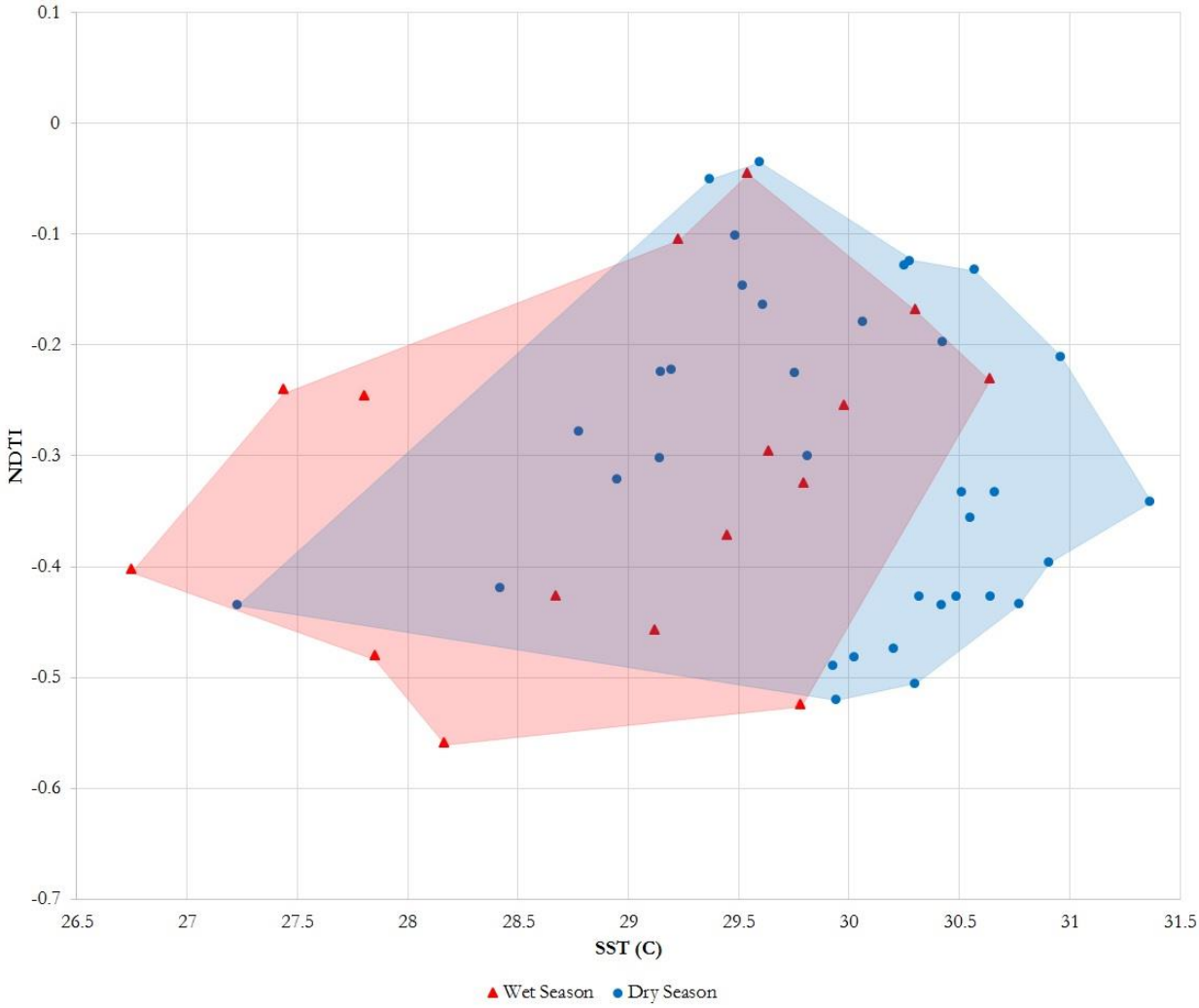

Figure D1. SST and NDTI correlation chart for wet seasons (red triangles) and dry season (blue circles) over Golfo Dulce from 2003 to 2017

Appendix E. Example SST Charts

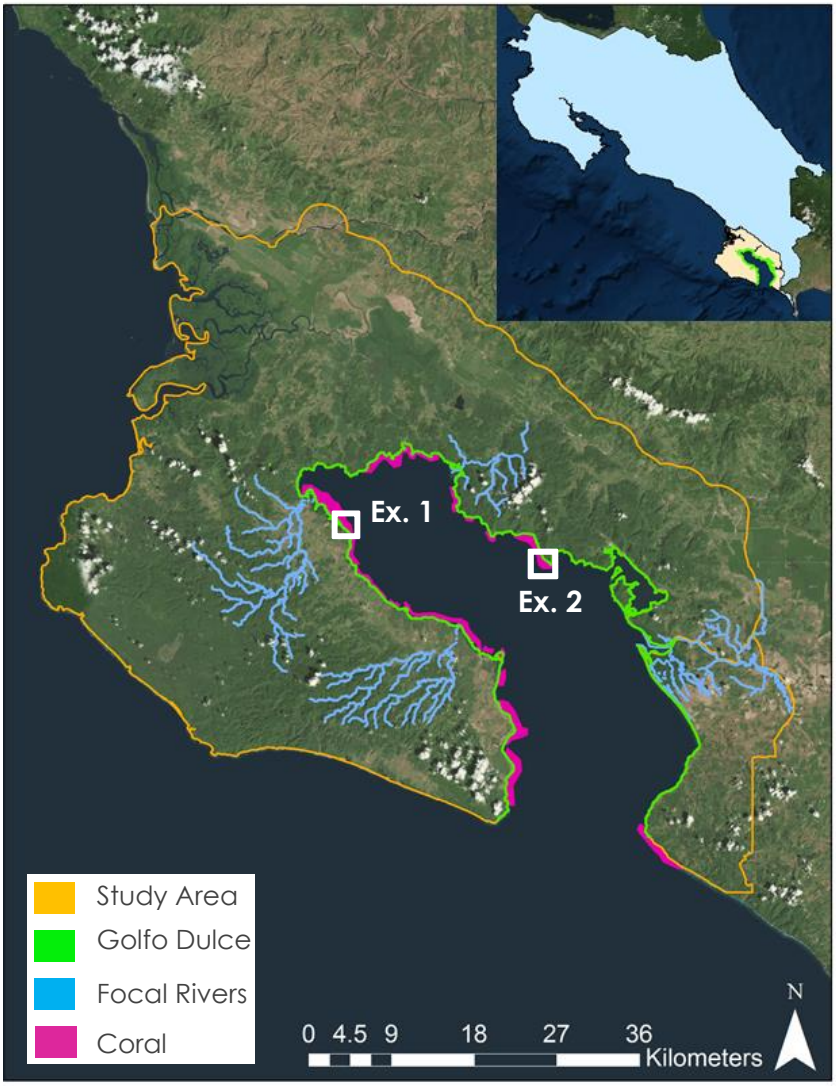

Figure E1. Study area with example locations for SST charts highlighted

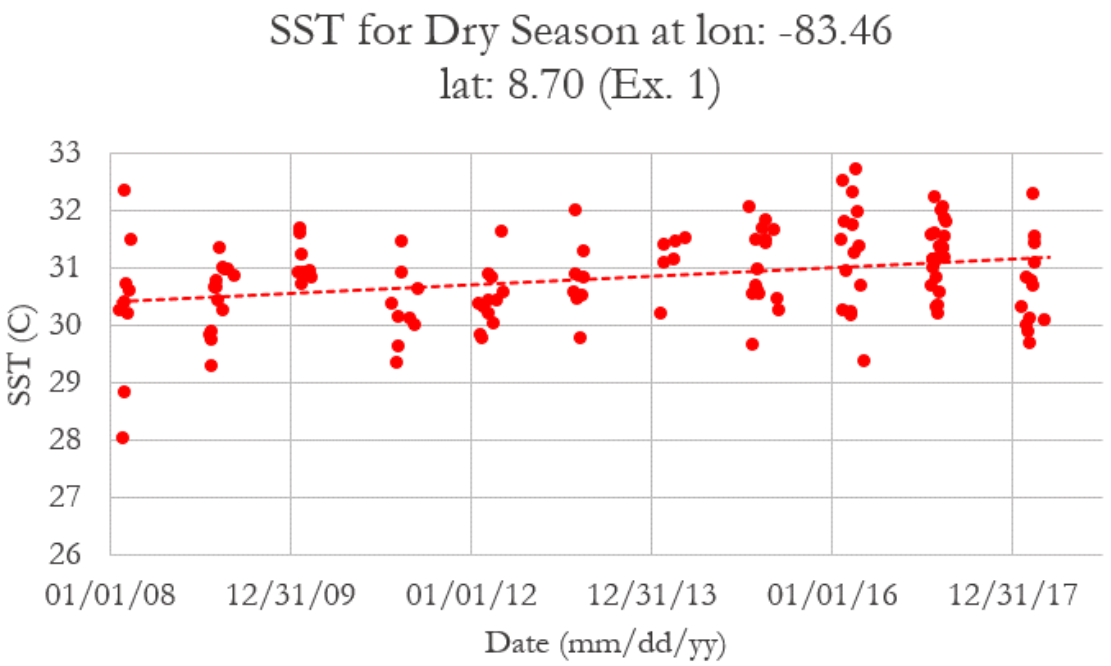

Figure E2. Chart of median SST for the dry season (February-May) from 2008 to 2018 at example location 1

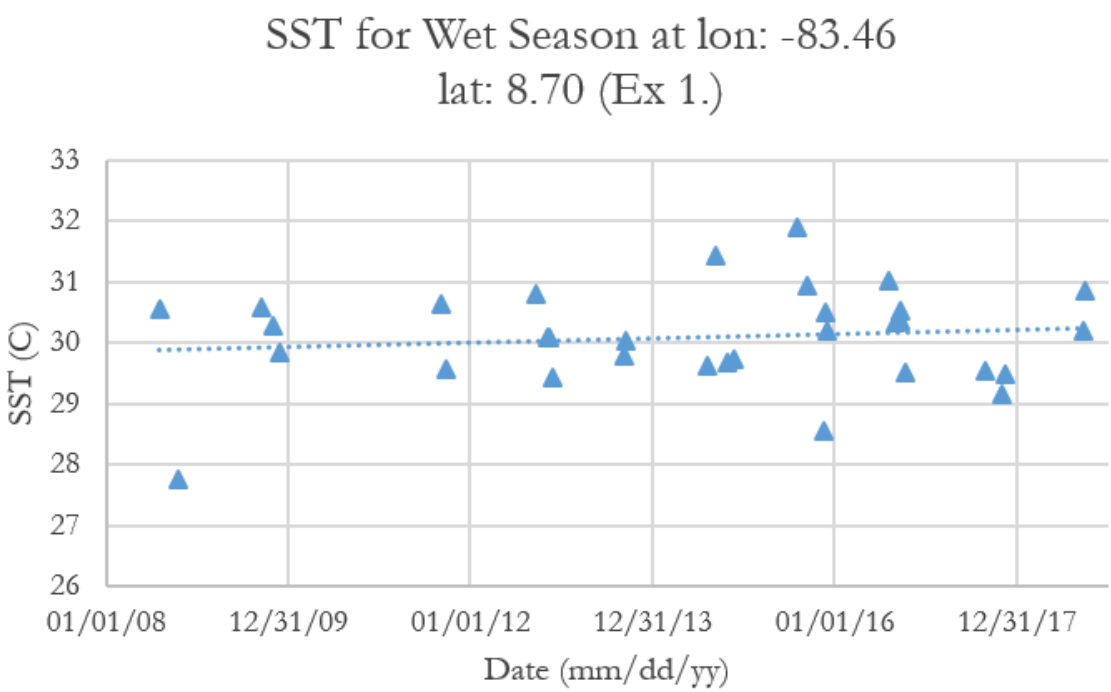

Figure E3. Chart of median SST for the wet season (August-November) from 2008 to 2018 for example location 1

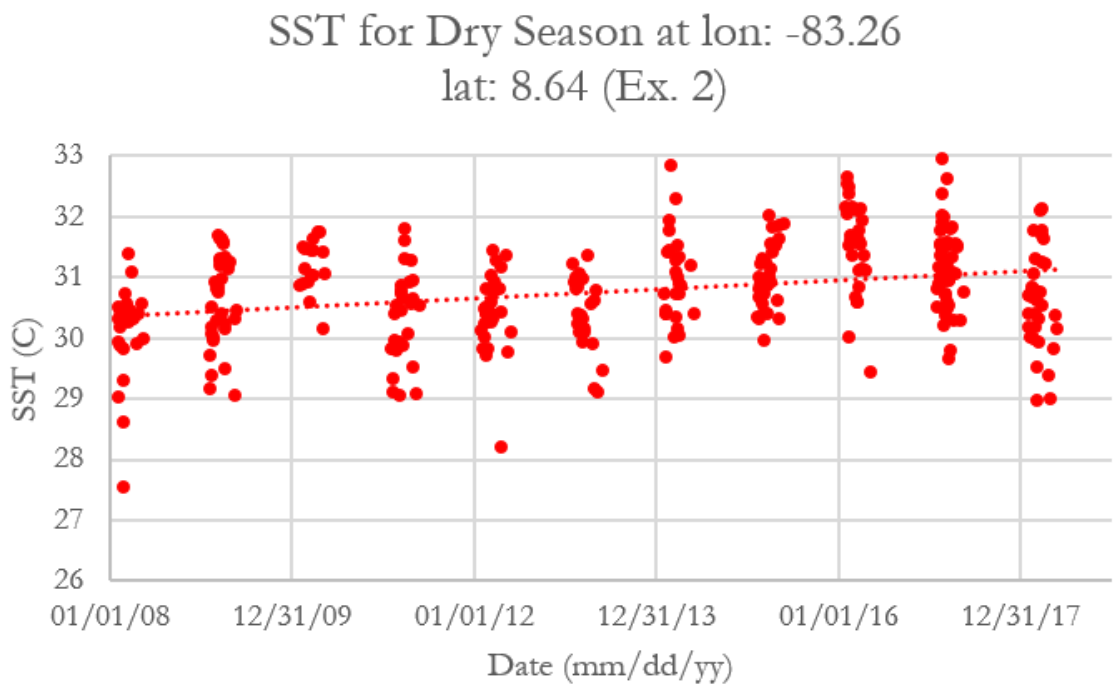

Figure E4. Chart of median SST for the dry season (February-May) from 2008 to 2018 at example location 2

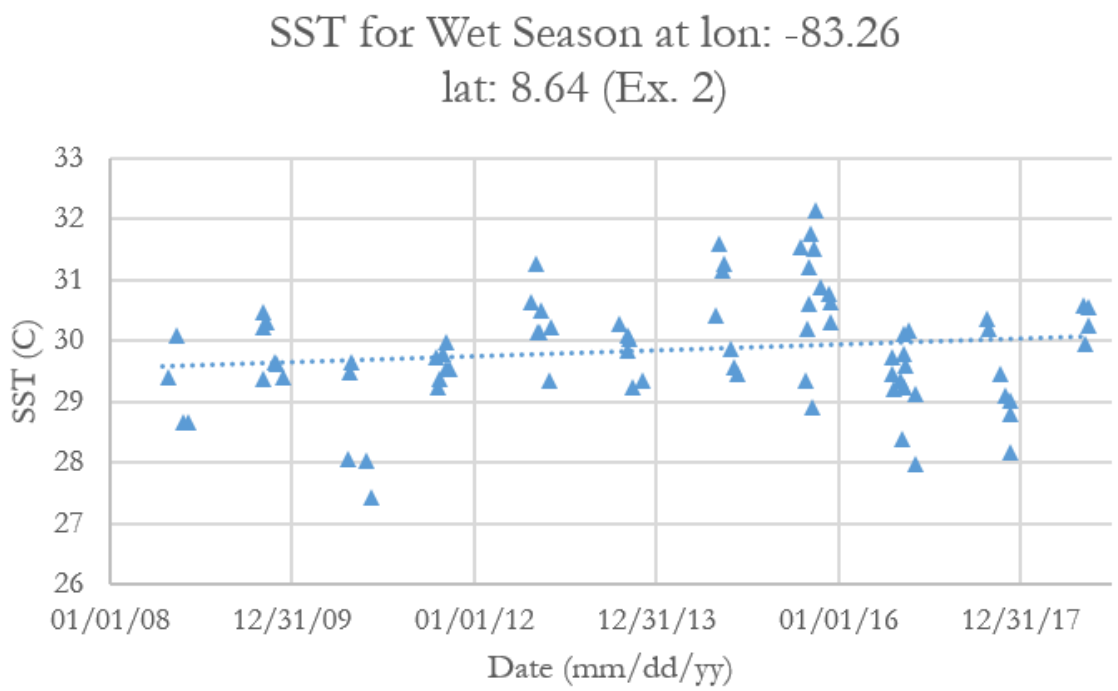

Figure E5. Chart of median SST for the wet season (August-November) from 2008 to 2018 for example location 2

Appendix F. Additional Bivariate Maps

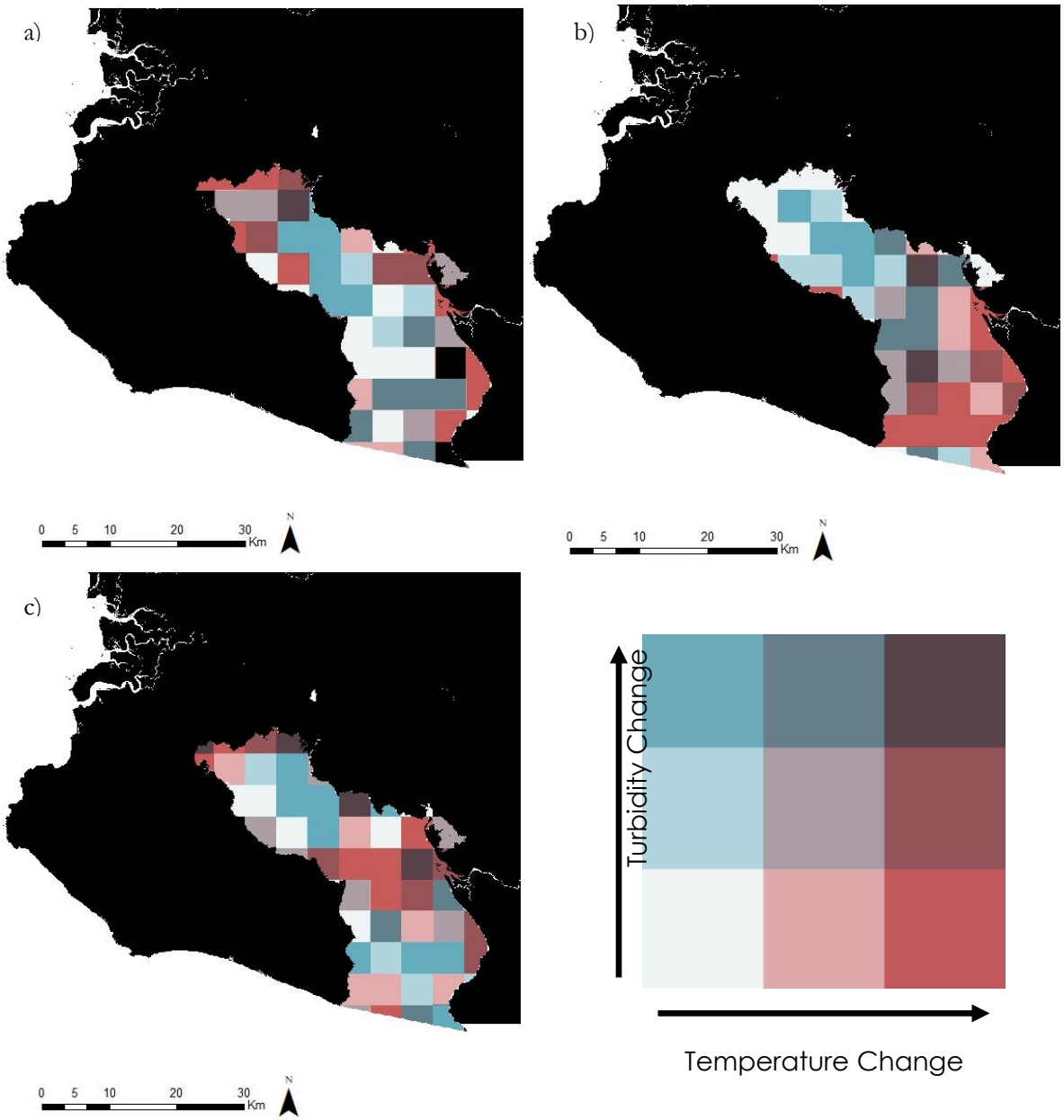

Figure F1. Annual seasonal fluctuations for 2015 (a), 2016 (b), 2017 (c)