ESTIMATING NET GAINS AND LOSSES OF COASTAL WETLANDS IN GALVESTON COUNTY AND CAMERON COUNTY, TX

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

Coastal wetlands serve many important ecological services. One of these important ecological services is there use as storm buffers. Coastal wetlands provide habitat for migratory birds and aquatic species and can improve water quality. In the late 1990s, the US Fish and Wildlife Services published a study outlining the trends of coastal wetlands from the 1950s to early 1990s. In this thesis, wetland gains and losses are calculated for Galveston County and Cameron County between 2001 and 2011. Maps from the National Land Cover Database were used to determine wetland areas for the years 2001, 2006, and 2011. ArcGIS was used to compare land cover between the study periods to determine overall wetland losses and gains. A statistical analysis was performed between wetland loss and population data to determine if increased population density lead to a higher loss of wetlands. Our analysis indicates that wetlands loss is still occurring; however, at a lower rate of loss (0.14% -0.18% annually) than the USFWS study predicted earlier (2.7%). In addition, the majority of wetland losses were because of conversion to upland areas. We found a positive correlation between increased population density and decreased wetland area; however, the trend was not significant. This present study shows how the majority of wetland loss in Galveston and Cameron County is occurring as a result of increased upland areas. In addition, the study shows that the use of online mapping systems can be used as a low-cost alternative to assess land changes when field tests are not feasible.

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I would like to begin by thanking my committee chair, Dr. Miguel Mora, for guiding and advising me through this research process, as well as igniting my interest in wetlands. In addition, I would to thank my committee members Dr. John R Giardino and Dr. Robert Knight for providing insights, advice, and edits on my thesis.

I am also appreciative of all my professors who taught me through my graduate career. Through them I learned to ask questions, think critically, and take interdisciplinary approaches to answer difficult questions. I am also grateful for the help from Cecilia Smith in the GIS library at Texas A&M University who advised me through my GIS analysis.

Finally, thanks to my mother and father and sisters for their encouragement and love during my graduate career. I would also especially like to thank my boyfriend Peter for his continuous patience and support through this journey.

CONTRIBUTORS AND FUNDING SOURCES

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1. INTRODUCTION

Coastal wetlands consist of marshes, swamps, mangroves, and other coastal communities (Blankespoor et al. 2014). Coastal wetlands provide essential habitat for freshwater, estuarine, and marine species, buffer shorelines, export organic carbon to estuaries, and influence biogeochemical cycles (Carle 2011). Both tidal and non-tidal wetlands help lessen the impacts of urban and agricultural developments within coastal watersheds and reduce loadings of nitrogen, phosphorus, sediment, and pathogens to estuarine waters (Carle 2011). Coastal wetlands also serve as a barrier against extreme weather, carbon storage, and provide many benefits to fisheries (Bao 2015).

It has been estimated that 41% of the world's population live within 100 km of the coast (Martinez et al. 2014). Nineteen of the top twenty most densely populated counties worldwide are located along the coast (All and Nelson, 2008). Coastal areas are some of the most rapidly developing areas of the US (Carle 2011). It is estimated that between 1980 and 2003 population growth in coastal areas of the USA was ~33 million people or approximately 23% of the U.S. population (Carle 2011).

The National Oceanic Administration Association (NOAA) estimates that more than 1,500 square miles of coastal wetlands in the United States were lost between 1996 and 2011 (Dahl and Stedman, 2013). A study performed by Bao (2015) estimates that 25%-50% of the world's coastal wetlands have been converted for anthropogenic uses. In 2008, the US Fish and Wildlife Service (USFWS) performed a similar analysis to quantify wetland loss and concluded that between 1998 and 2004 the coastal watersheds of the eastern United States experienced a net loss of 361,000 acres of wetlands

(Diffenderfer, 2014). The USFWS study also concluded that more than 70% of wetland losses between 2004 and 2009 were in watersheds surrounding the Gulf of Mexico. Increased loss-rate during this time was specifically attributed to effects of severe coastal storms such as Hurricane Katrina, Rita, and Ike (Diffenderfer, 2014).

A variety of factors that affect the degree and rate of wetland loss in coastal watersheds are present (All and Nelson, 2008). A few of these factors include sea level rise, erosion, conversion to agricultural lands, human development, and non-point source pollution (All and Nelson, 2008). The loss of coastal wetlands can have many negative effects on the surrounding communities. Besides the effects to local species and ecosystem functions, areas with a high percentage of wetland losses are more susceptible to significant flood damages (Dahl and Stedman, 2013). As a result of coastal wetlands important ecological services, other areas that can be affected are seafood and fishing services, eco-tourism, and water quality.

It is predicted, as the climate continues to change, sea level will also continue to rise. Sea level rise has the potential to alter coastal ecosystems greatly (Geselbracht et al. 2015). Globally, the rate of sea level rise is ~3 mm a year; however, this rate can vary widely in different areas (Anderson et al. 2013). For example, the rate of sea level rise within the northwestern part of the Gulf of Mexico approaches up to 10 mm per year, and rates are considered to increase in the future (Anderson et al. 2013). Some possible effects of sea-level rise include territorial-land loss, wetland loss or change, flood damage, and saltwater intrusion into surface and groundwater (Geselbracht et al. 2015). These possible sea-level effects will result in coastal communities being more vulnerable to flooding and to the other damaging effects of storm surges. A study focused on Long Island, New York, suggests that a small rise of 0.5 m by 2080 will increase the number of people and properties at risk as a result of storm surges by 47% and 73%, respectively (Geselbracht et al. 2015).

Industries and residents of Texas have made the Texas coast their base. A study conducted over the whole 12.8 million- acre Texas coast, comprised of 18 different counties and 754 four-square mile plots (Moulton et al. 1997), estimated that more than a third of the state's population, as well as 70% of its industry, commerce, and jobs, were located within 100 miles of the Texas coastline (Moulton et al. 1997).

According to Moulton et al. (1997) the Texas coast experienced a net loss of 210,590 acres (852.2 sq km) between 1955 and 1992, which can be expressed as an annual net loss of around 5,700 acres (23 sq km). The majority of losses were the result of wetland conversion to urban and rural developments and erosion associated with sea level rise (Moulton et al. 1997).

The population in Texas has continued to increase and the Texas coast has experienced the effects of sea level rise and major hurricanes that can further exacerbate erosion. Wetlands along the coast continue to experience degradation and loss, particularly from conversion to agriculture, rural and urban development, and human recreation (Fitzsimmons et al. 2012). Also, fresh and intermediate marshes have declined nearly 30% in the past forty years (Fitzsimmons et al. 2012). The study performed by Moulton et al. (1997) described the main causes for wetland loss along the

Texas coast has been due to anthropogenic causes such as urban development and conversion to agricultural lands.

While many agencies keep semi-regular maps outlining wetland areas along the Texas Coast, there are few studies that analyze the overall trend of Texas coastal wetlands throughout a span of time. By mapping wetland trends it becomes easier to see where major losses and/or gains are occurring. This will help planners and policy makers determine areas where conservation efforts need to be strengthened, as well as, allow them to better understand the main causes of wetland loss in the area. To properly regulate and maintain the status and health of wetlands, an accurate idea of the current status of our wetlands, especially along the coast is needed. In this study we focus on two coastal counties, Galveston and Cameron, in Texas that have experienced major population and industrial growth.

Galveston County and Cameron County are located on the northern and southern coasts of Texas, respectively (Fig. 1). Galveston is both a top tourist destination, as well as, a large supplier of seafood to Texas and the rest of the US (Moulton et al. 1997). Today it is estimated that annually 4.2 billion dollars are generated to the Texas economy from travel related activities in the Galveston Bay watershed area (Galveston Bay Information Center 2010). Galveston Bay also contributes to a third of the commercial fishing income in Texas and over half of the state’s expenditures for recreational fishing are related or take place in Galveston Bay (Galveston Bay Information Center 2010).

Cameron County is one of the fastest growing counties in the nation. It is the southernmost county in Texas and borders the Gulf of Mexico. Cameron County, which contains the popular tourist destination of South Padre Island has seen a lot of population growth in the 21st century. Population data was accessed from the American Community Survey (ACS) developed by the US Census Bureau (https://www.census.gov/programs-surveys/acs/).The population has grown 20.3% from 2000 to 2014 (335,227 to 420,392) (Table S1). The city of South Padre Island is one of Texas' major tourist destination and receives more than one million visitors annually (AEC, 2012). In 2011, estimates stated that South Padre Island contributed more than $600 million to the surrounding counties economies (AEC, 2012). In addition, one of Cameron County's largest businesses is the shrimp industry. Between 2009 and 2014 33% of Texas shrimp industry value came from Cameron County (Garza and Long 2016). The Port of Brownsville is another major source of the county's revenue. Eco-tourism, such as bird watching, fishing, and sea sports bring in income for local residents (Garza and Long 2016).

Galveston and Cameron County are both popular coastal areas that contribute to the overall economy of Texas. Both counties are at a high risk for wetland loss because of the increase in urbanization and their low elevation. The Texas Gulf Coast has experienced higher than average sea level rise due to major storms and climate change. Projections for sea level rise in South Texas is estimated at 0.18 m – 0.59 m over the 21st century. Total change in relative sea level rise is estimated 0.34-0.75 m at South Padre Island by the end of the 21st century (Uddameri et al. 2013). The main objective of this study was to quantify the overall net gains and losses of coastal wetlands in Galveston and Cameron County from the early 2000s to present and to determine what percentage of the change is result of conversion to upland and/or open water.

This thesis attempts to quantify wetland gains and losses in Galveston and Cameron County, TX. Specifically, to determine the contributions population growth and upland development as well as erosion along the coast play in wetland loss. By learning where and what is causing wetland loss, city, county, and state officials can better manage and focus attention on wetland restoration and conservation.

Our hypothesis is that wetland loss is still occurring along the coast, but at a rate smaller than previous studies have found. Wetland conversion to upland are is still hypothesized to be the main contributor to wetland loss in coastal watersheds due to increased population growth and tourism.

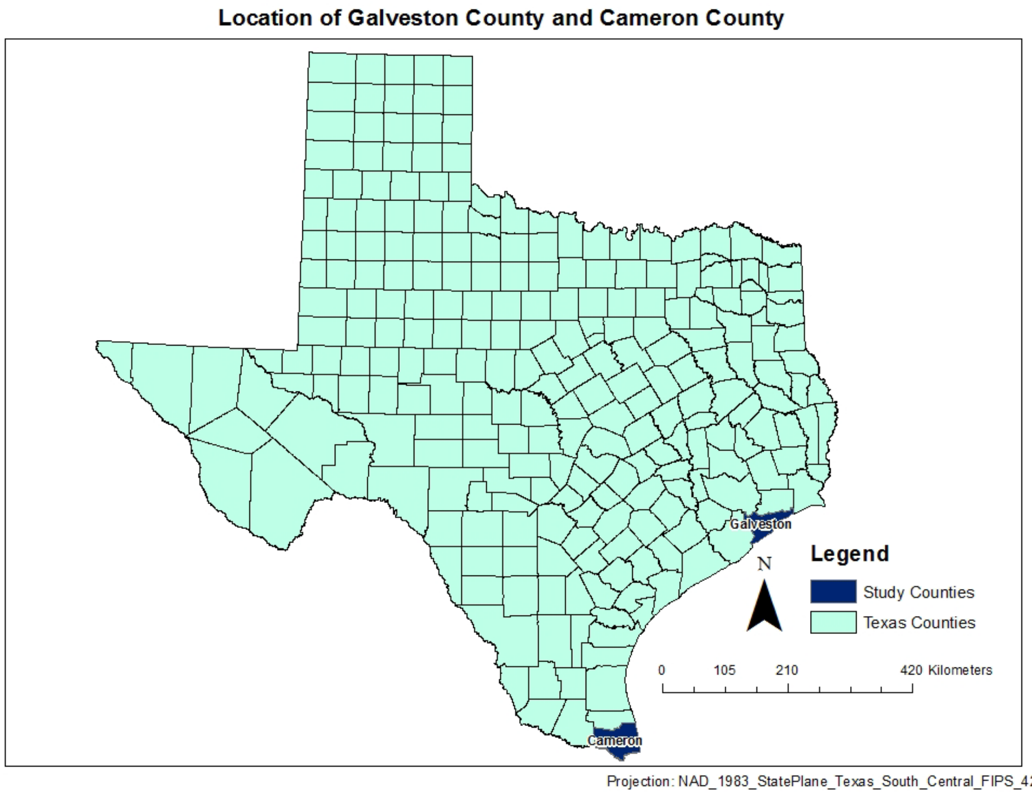

Figure 1. Map of Texas showing the two counties for the study: Galveston and Cameron County

2. METHODS

2.1 National Land Cover Database Maps

The National Land Cover Database (NLCD, http://www.mrlc.gov/finddata.php) is a 30-meter resolution, land- cover database for the Nation produced by the Multi-Resolution Land Characteristics Consortium (MRLC). It provides spatial reference and descriptive data for characteristics of the land surface. Product accuracy can vary by regional geography and specific land type and it is considered to have a high accuracy at a national scale. Formal accuracy assessments have not been performed on the 2006 and 2011 maps, but the NLCD 2001 was found to have and Anderson Level I class accuracy of 85.3%. Land cover data was acquired for the years 2001, 2006, and 2011 from the National Land Cover Database (NLCD). NLCD identifies 16 different land cover classes including: two wetland classes, five natural upland land classes, two agricultural classes, and four urban classes (Carle, 2011). Maps were collected for Texas and then overlaid with county maps to extract the county specific land cover for both Cameron and Galveston County. Map source was chosen based on maps used in similar studies conducted by Carle (2011) and Moulton et al. (1997).

Once imported into ArcGIS 10.3 supplied by the Environmental Systems Research Institute (ESRI), we used the reclassify tool to change the 16 classifications into three main classifications: wetland, upland, and open water (Table S2). Maps showing Galveston County and Cameron County land cover in the new classification system is provided in Appendix A. By simplifying the classification system, it makes it easier to identify land cover through aerial photography and perform accuracy assessments.

2.2 Quantifying Wetland Losses and Gains

ArcGIS 10.3 was used to quantify wetland change throughout the study years. Maps were overlaid on each other and then raster calculator function was first used to identify areas of change. A simplified classification system has been used in order to identify how much of wetland loss is an occurrence of conversion to upland land or due to erosion and sea level rise. A change detection analysis was conducted using raster calculator and classified into three categories: conversion to upland, no change, and conversion to open water. The conversion to upland step identified areas where wetlands were being converted for human use whereas the conversion to open water step classified areas where wetlands were lost or converted into deep water habitats as the result of erosion or manmade lakes/lagoons. The no change in status category signifies that the wetland has not gained or lost acreage during the time period of this study. Quantifying areas that were converted from wetlands to uplands or open water areas were used to evaluate overall wetland gains and losses. The raster calculator function in ArcGIS was utilized to determine land change between our study periods: 2001 to 2006 and 2006 to 2011.

Results were put in a table and percent change was calculated for 2001 to 2006 and 2006 to 2011 for both Galveston County and Cameron County. To determine the percent of land change between intervals, a simple percent change equation was utilized:

$e = \frac{2001\ wetland\ area - 2006\ wetland\ area}{2001\ wetland\ area} \times 100$. This value provided the percent of wetland that had been lost or gained between the intervals. Negative percentages show a percent decrease of wetlands between the years while positive percentages indicate percent increase of wetlands.

2.3 Accuracy Assessment

Accuracy Assessments were performed in both ArcGIS 10.3 and Microsoft Excel. First, aerial photography was acquired from the National Agricultural Imagery Program (NAIP <https://tnris.org/news/2015-01-09/naip-2014-statewide-aerial-available/>). NAIP Imagery is acquired at a one-meter ground sample distance and has general specifications that there should be no more than 10% cloud cover, weather conditions permitting (www.fsa.usda.gov, accessed on 04/28/16). All imagery is also inspected by members of the Farm Service Agency (FSA) for horizontal accuracy and quality by comparing imagery to existing orthorectified imagery. Within the NAIP contract states that "all well-defined points tested shall fall within 6 meters of true ground at a 95% accuracy". Randomized testing was performed in nine states between 2006-2008 and all states flown adhered to this specification (National Agricultural Imagery Program Information Sheet, 2015). NAIP imagery maps over Galveston and Cameron County were taken for the years 2004, 2006, and 2012. These were the years that most closely matched NLCD map years (2001, 2006, 2011). Aerial photography maps were used to locate reference points. Thirty points were located for each land class: upland, wetland, and open water. Afterwards, the classified maps were laid on top of the reference map in ArcGIS and classification actions were performed to determine how accurate our classification map was compared to aerial photography. Aerial photography and reference points used for each NAIP map is provided in Appendix B.

Tables were then exported to Microsoft Excel to calculate the overall accuracy, kappa coefficient, errors of commission, errors of omission, producer accuracy, and user accuracy. The kappa coefficient measures the agreement between classifications and ground truth pixels on a scale from 0 to 1, where 1 represents perfect agreement and 0 represents no agreement. Errors of commission represent pixels that belong to another class that are labeled as belonging to the class of interest, while errors of omission refer to pixels that belong to the ground truth class but the classification technique has failed to classify them in the proper class. Producer accuracy measures the probability that the classifier has labeled an image pixel into the correct ground truth class (Harris 2016). User accuracy indicates the probability that a pixel in a given classification has been labeled into the correct classification (Harris 2016). Field assessments are the preferred way to see the accuracy of classifications, however aerial photography can be used for assessments when a simple classification is used (Carle, 2010). This study utilizes just three classifications, wetland, upland, and open water and does not try to differentiate between vegetated classes, therefore using aerial photography is a suitable way to determine accuracy.

2.4 Statistical Analysis

Total population estimates were taken from the 2014 American Community Survey for the years 2000, 2006, and 2011 in both Galveston County and Cameron County (http://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml, accessed on April 2016). The population data was examined to determine if there was a correlation between wetland loss and population gain. In order to perform this comparison, first the population density between each time frame was calculated (Table S1). Population density was calculated by taking the total population and dividing it by area of the county. A simple linear regression analysis was utilized to test the hypothesis that there was a significant relationship between population growth and wetland loss. Statistical Package for the Social Sciences (SPSS) was used to calculate the regression analysis.

3. RESULTS

3.1 Galveston County Wetland Change

The results from the study showed that between 2001 and 2006 and 2006 to 2011 Galveston County experienced an overall wetland loss of about 5% between each study period (Fig. 2a and 2b). Between 2001 and 2006 there was a 5% gain in upland areas and a 3% increase in uplands for the study period 2006-2011 (Table 1a). When examined in closer detail we observed that there were some wetland gains in Galveston County, however it did not override the losses (Fig. S1). Between 2001 and 2006 the county experienced a wetland loss of 48.58 sq km and a wetland gain of 32.74 sq km (Fig. S1). Fig. 2c and Fig. 2d show where wetlands were gained for our two study periods. Fig. 2e and Fig. 2f show where wetland losses occurred in Galveston. The majority of losses were along the coast/Galveston Island, or close to the city of Galveston (Fig. 2e and 2f). Most of the losses came from wetland conversion to upland instead of wetland conversion to open water (Table 1b). Similarly, most of the newly formed wetlands came from upland conversion to wetlands (Table 1b). The trend is analogous to the results we found between 2006 and 2011. Wetland losses totaled 53.69 sq km, while wetland gains were 37.45 sq km acres. Again, most of the wetland conversion was to upland area and most of the wetland gains were upland conversions to wetlands (Table 1b).

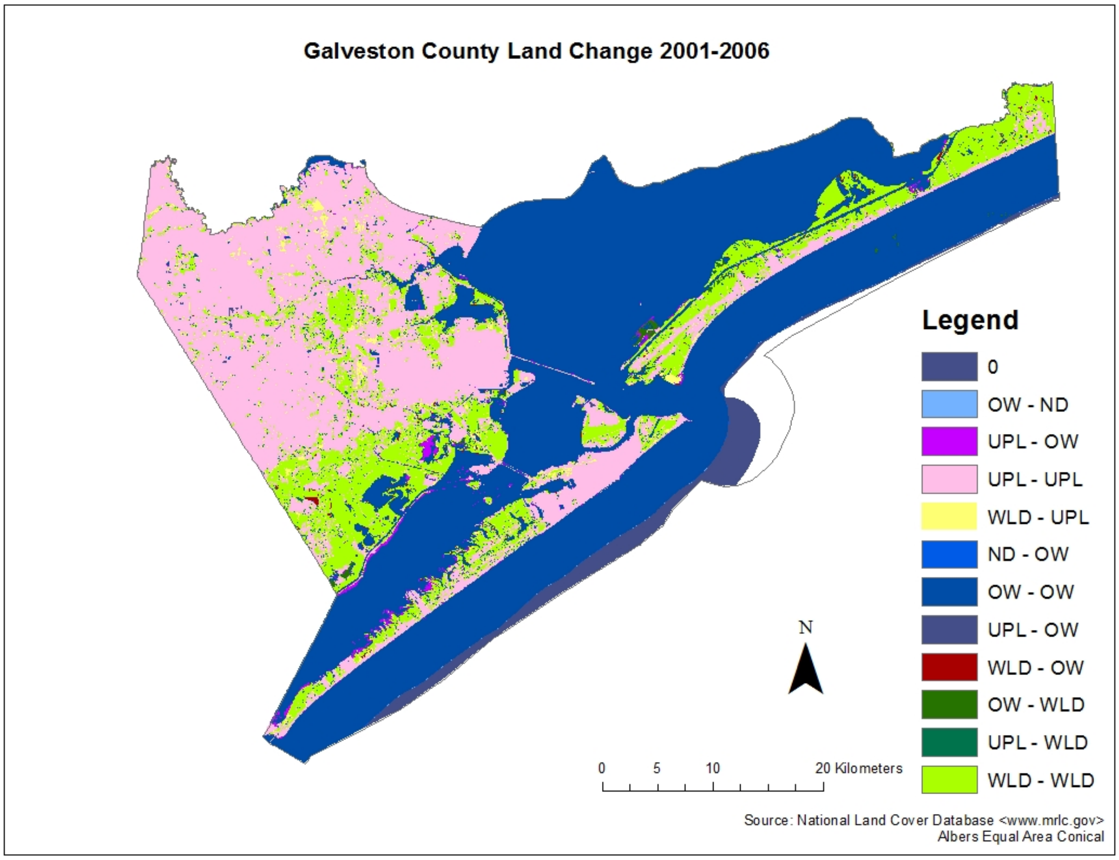

Figure 2a. Land cover change in Galveston County between 2001 and 2006. ND = No Data, OW = Open Water, UPL = Upland, WLD = Wetland. Wetland areas are depicted in shades of green, upland areas in shades of pink, and open water in shades of blue. Wetland area converted to upland area is shown in yellow and wetland area converted to open water is shown in red.

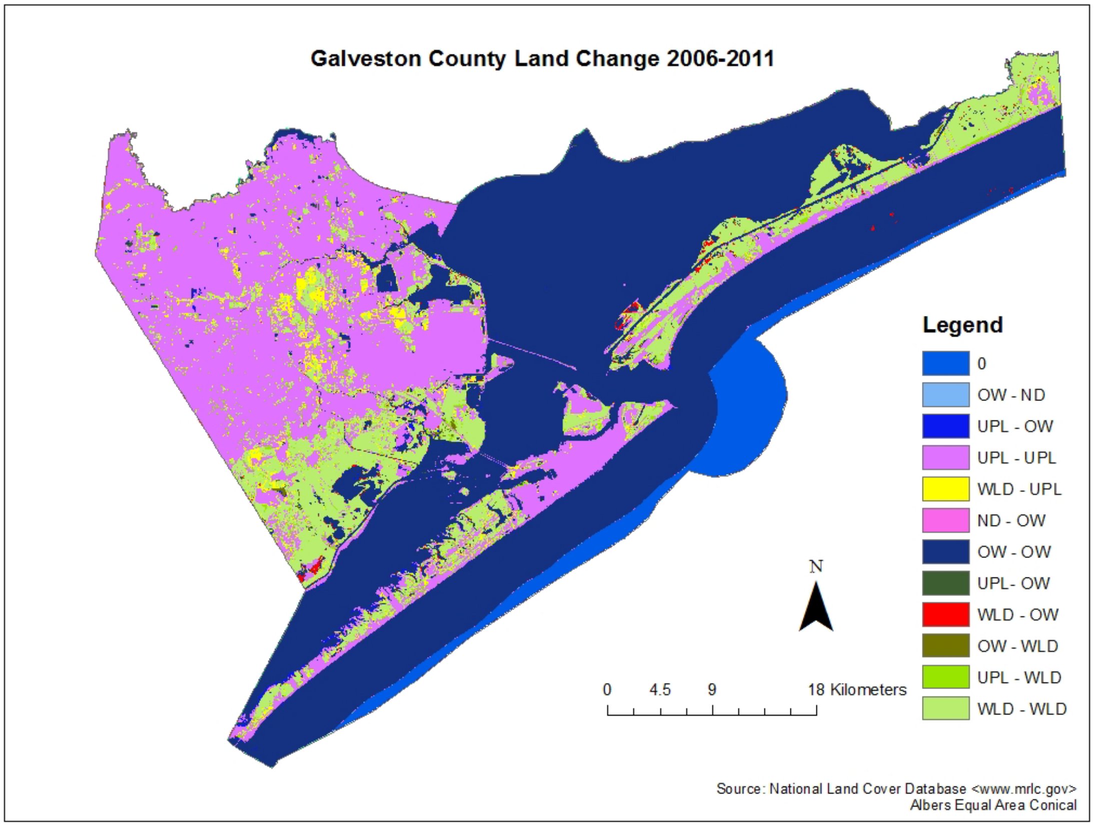

Figure 2b. Land cover change in Galveston County between 2006 and 2011. ND = No Data, OW = Open Water, UPL = Upland, WLD = Wetland. Wetland areas are depicted in shades of green, upland areas in shades of pink, and open water in shades of blue. Wetland area converted to upland area is shown in yellow and wetland area converted to open water is shown in red.

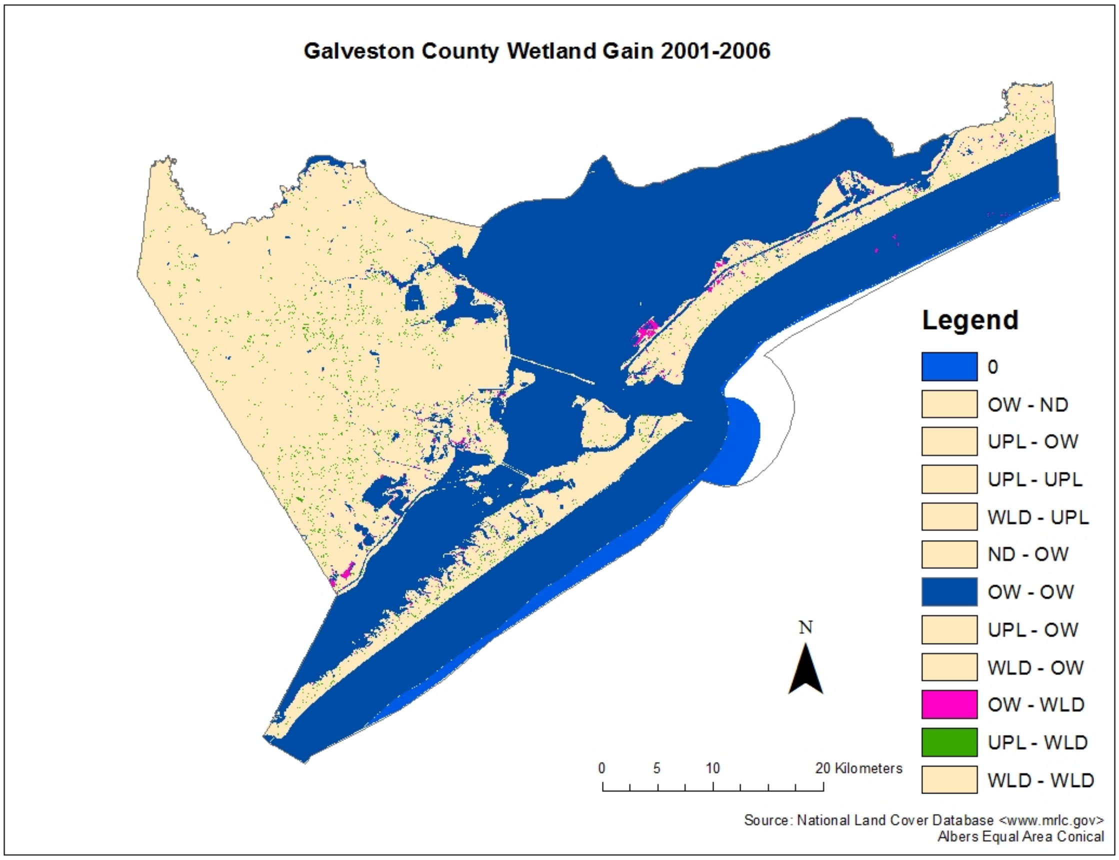

Figure 2c. Wetland gains in Galveston County between 2001 and 2006. Open water areas are shown in blue. Open Water that was converted to wetland area is shown in purple and upland areas converted to wetland areas are shown in green.

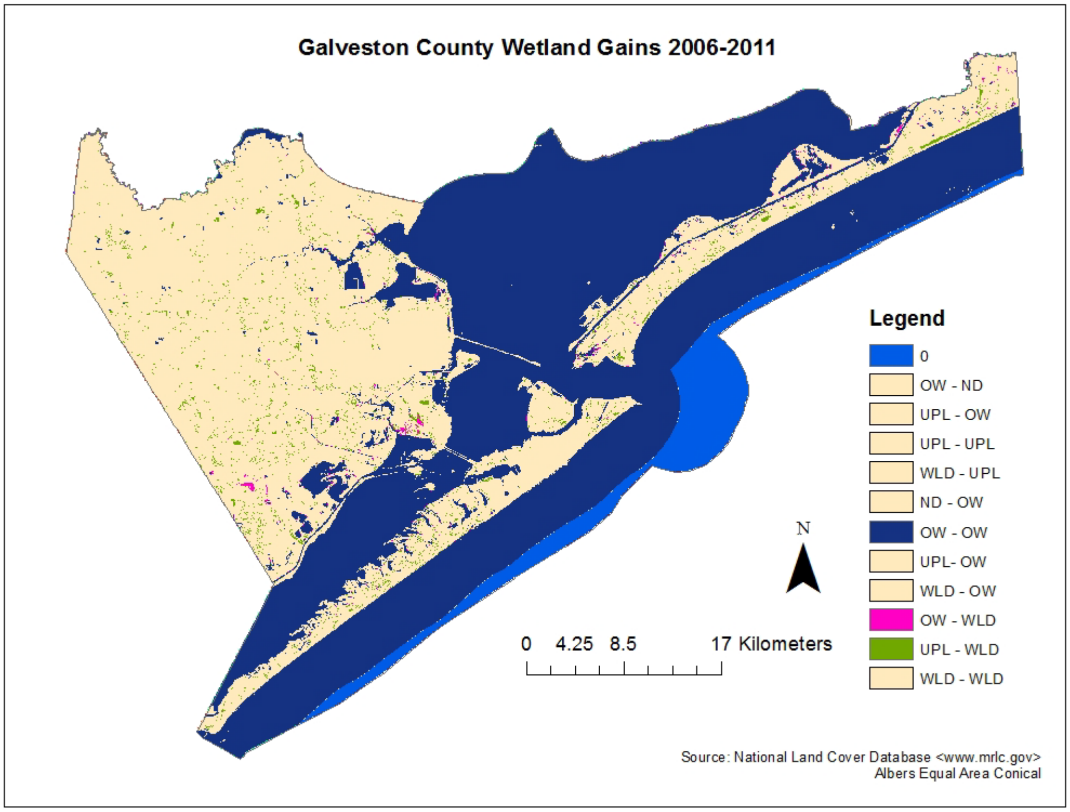

Figure 2d. Wetland gains in Galveston County between 2006 and 2011. Open water areas are shown in blue. Open Water that was converted to wetland area is shown in light blue and upland areas converted to wetland areas are shown in green.

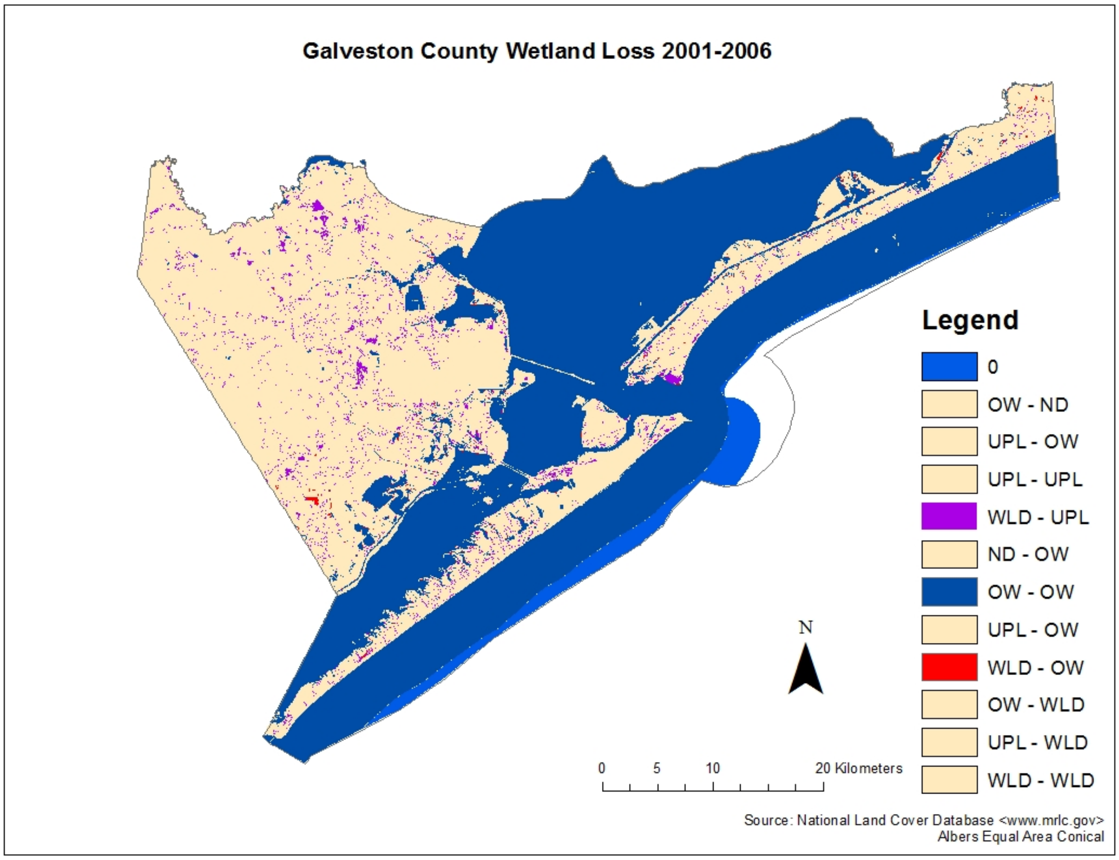

Figure 2e. Wetland loss in Galveston County between 2001 and 2006. Open water areas are shown in blue. Wetland areas converted to upland areas are depicted in purple. Wetland areas converted to open water are shown in red.

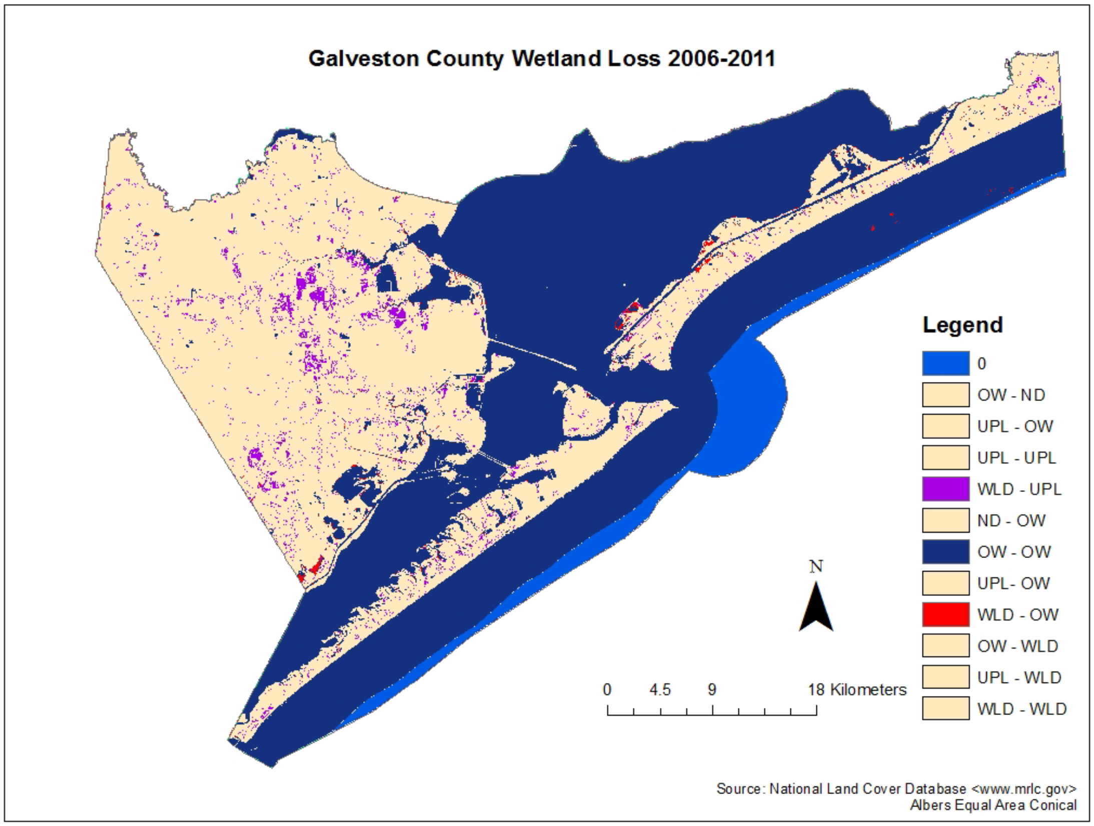

Figure 2f. Wetland loss in Galveston County between 2006 and 2011. Open water areas are shown in blue. Wetland areas converted to upland areas are depicted in purple. Wetland areas converted to open water are shown in red.

Land Cover	% Change 2001-2006	% Change 2006-2011
Upland	4.47%	2.84%
Wetland	-4.59%	-5.10%
Open Water	-1.15%	-0.29%

Table 1a. Galveston County Land Change by each classification. Percent change between 2001-2006 and 2006 and 2011for each land class is listed: upland, wetland, and open water. Negative values indicate percent decreases and positive values indicate percent increases.

Conversion Type	2001-2006 acreage	2006-2011 acreage
Wetland to Upland	10562.82	11213.32
Wetland to Open Water	1441.34	2054.70
Upland to Wetland	5644.58	7711.51
Open Water to Wetland	2445.89	1541.19

Table 1b. Acreage of lost and gained wetlands for Galveston County between the two study periods: 2001-2006 and 2006-2011.

3.2 Cameron County Wetland Change

Cameron County experienced comparable patterns to those of Galveston County; however, on a much smaller scale. Fig. 3a and 3b depicts the breakdown of land changes during our two study periods: 2001 – 2006 and 2006 – 2011. Between 2001 and 2006 about 1.5% of wetlands in Cameron County were lost (Table 2a). For the second study period, 2006 to 2011 only 0.5% of wetlands were lost (Table 2a). The largest land type gained during 2001 – 2006 was open water, which experienced a 4% increase in area (Table 2a). The results showed that during the time period 2001-2006, Cameron County had few wetland gains compared to losses (0.27 sq km gained compared to 6.65 sq km lost), however between 2006-2011 gains were closer to matching losses (7.84 sq km gained compared to 9.95 sq km lost) (Fig. S2). Fig. 3c and 3d show wetland gains in Cameron County, Fig. 3c shows that there were few wetland gains during 2001-2006. South Padre Island and areas near Harlingen experienced most of the wetland loss over the study period (Fig. 3e and 3f). For both study periods, 2001 -2006 and 2006 – 2011, the majority of wetland losses came from conversion to upland (Table 2b). Similarly, most wetland gains came from upland conversion (Table 2b).

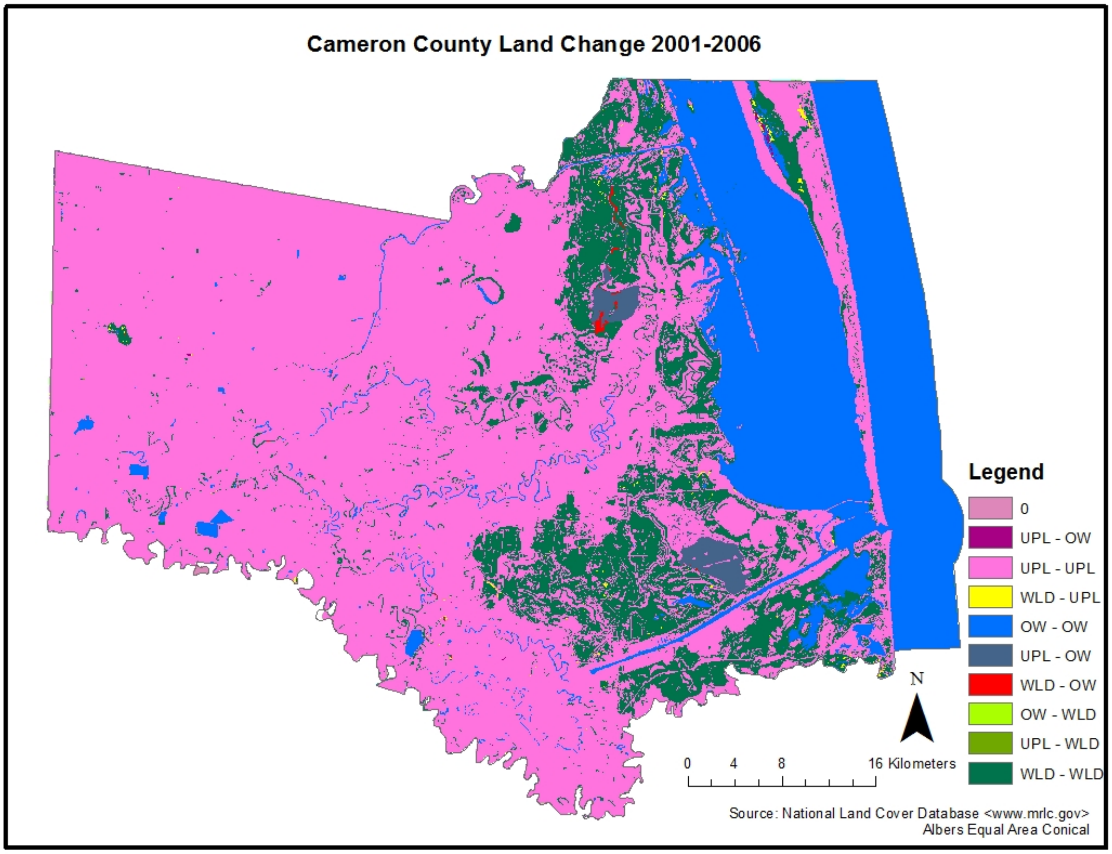

Figure 3a. Land cover change in Cameron County between 2001 and 2006. ND = No Data, OW = Open Water, UPL = Upland, WLD = Wetland. Upland areas are shown in shades of pink, open water is shown in blue, and wetland areas are shown in shades of green. Wetland area converted to upland area is shown in yellow and wetland area converted to open water is shown in red.

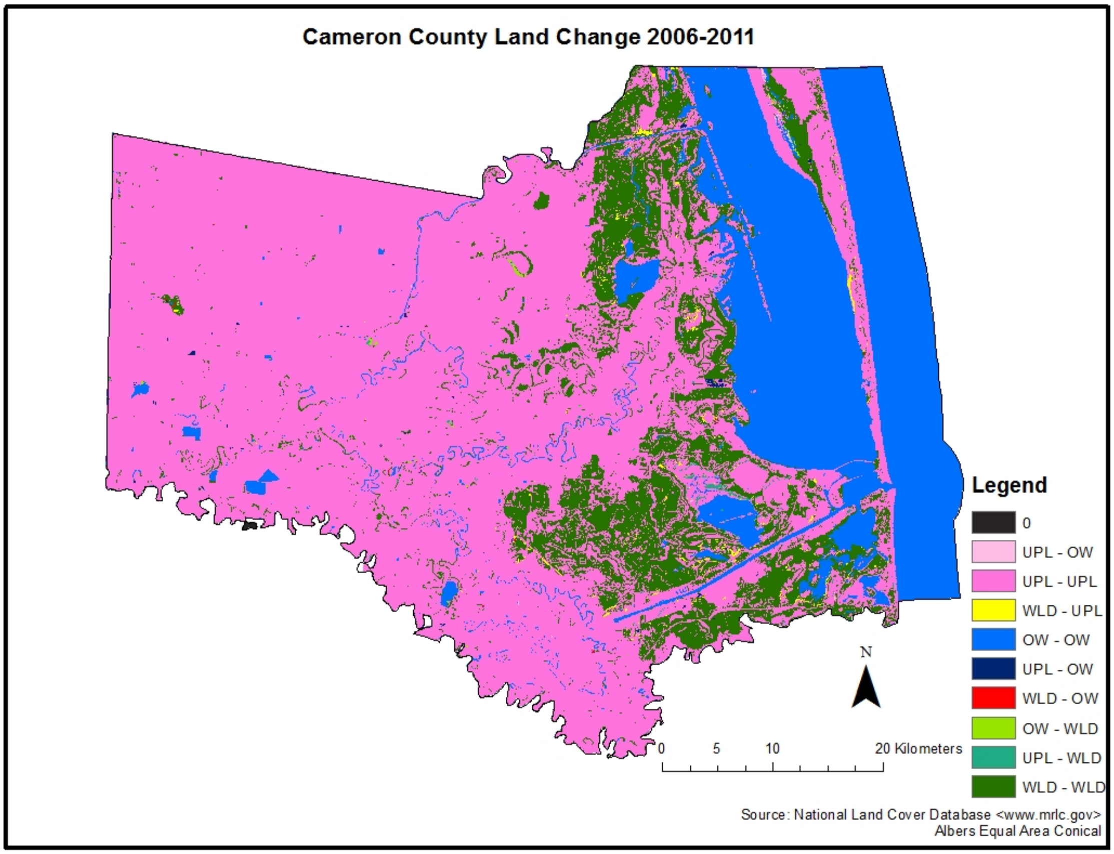

Figure 3b. Land cover change in Cameron County between 2006 and 2011. ND = No Data, OW = Open Water, UPL = Upland, WLD = Wetland. Upland areas are shown in shades of pink, open water is shown in blue, and wetland areas are shown in shades of green. Wetland area converted to upland area is shown in yellow and wetland area converted to open water is shown in red.

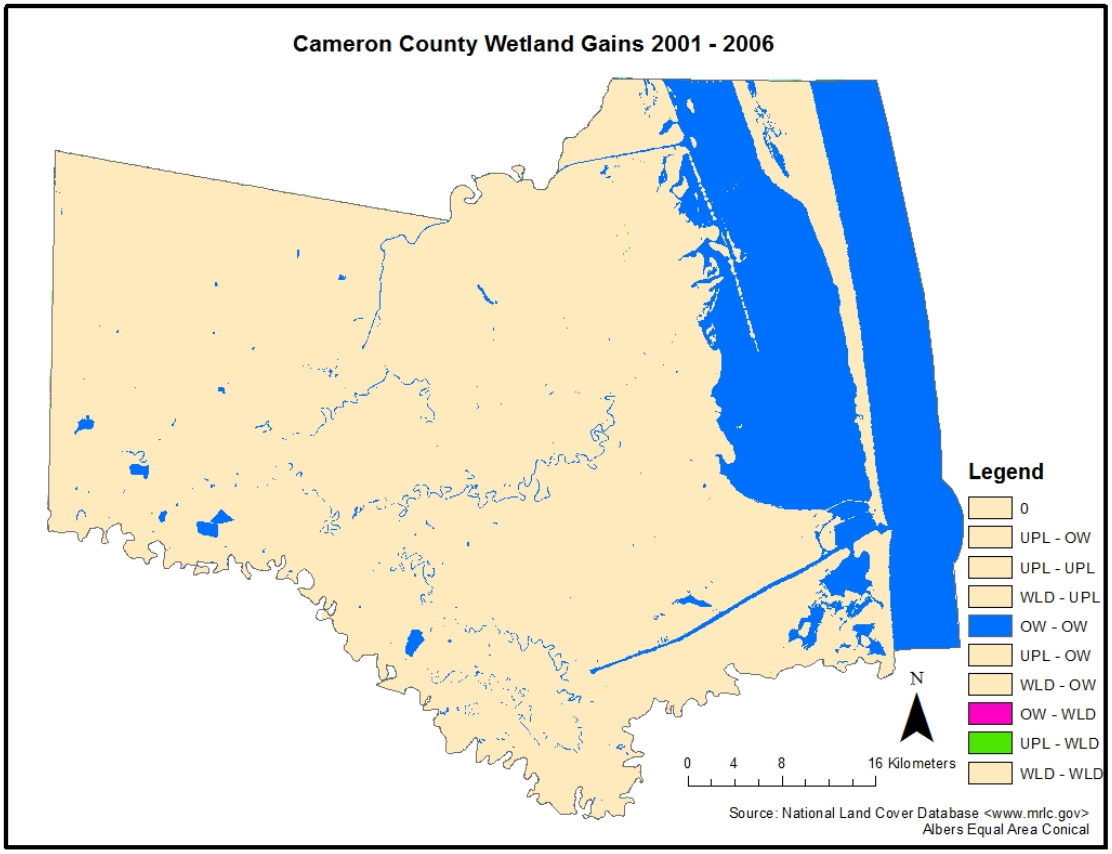

Figure 3c. Wetland gains in Cameron County between 2001 and 2006. Open water areas are shown in blue. Open Water that was converted to wetland area is shown in light blue and upland areas converted to wetland areas are shown in green.

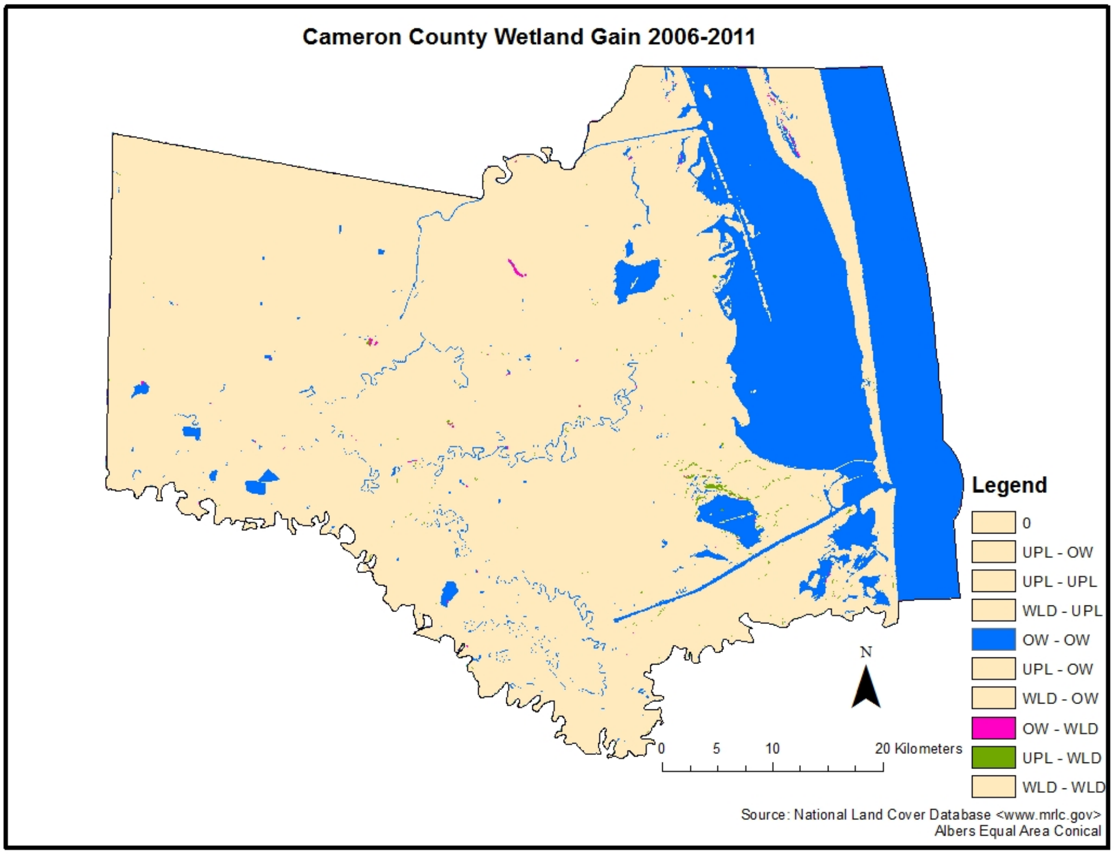

Figure 3d. Wetland gains in Cameron County between 2006 and 2011. Open water areas are shown in blue. Open Water that was converted to wetland area is shown in red and upland areas converted to wetland areas are shown in green.

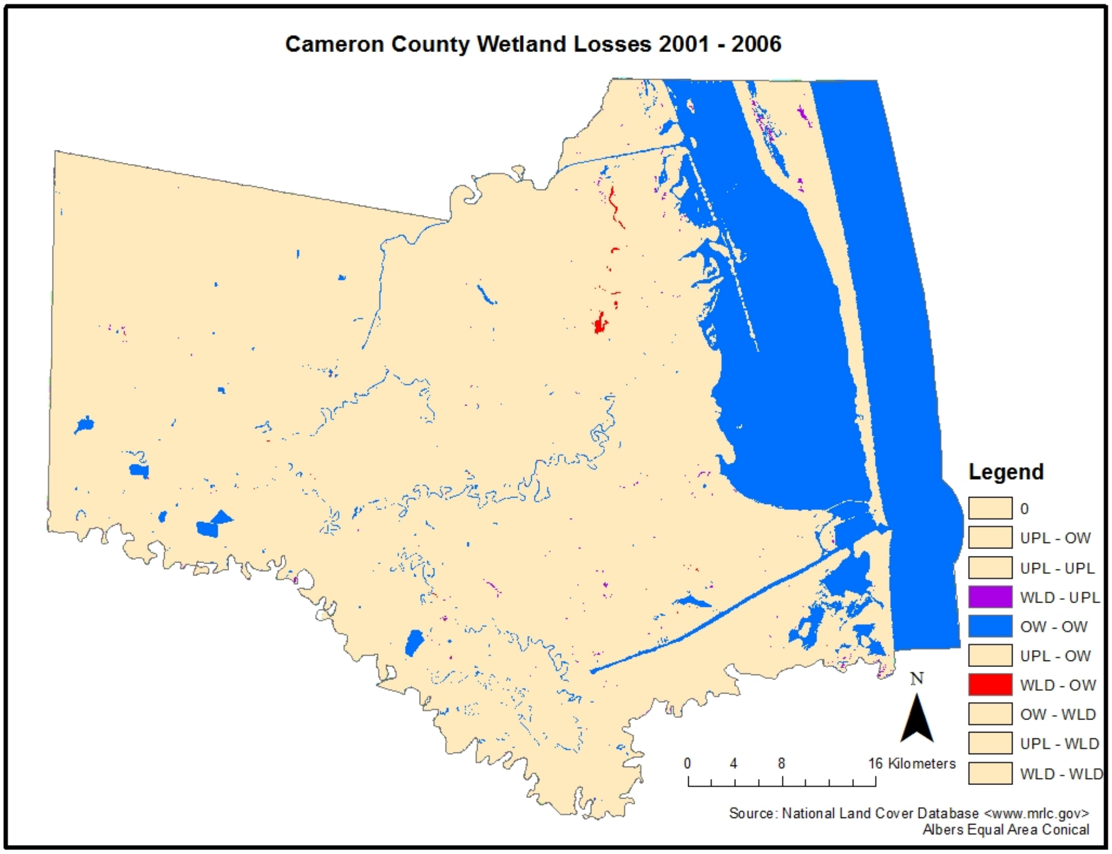

Figure 3e. Wetland loss in Cameron County between 2001 and 2006. Open water areas are shown in blue. Wetland areas converted to upland areas are depicted in purple. Wetland areas converted to open water are shown in red.

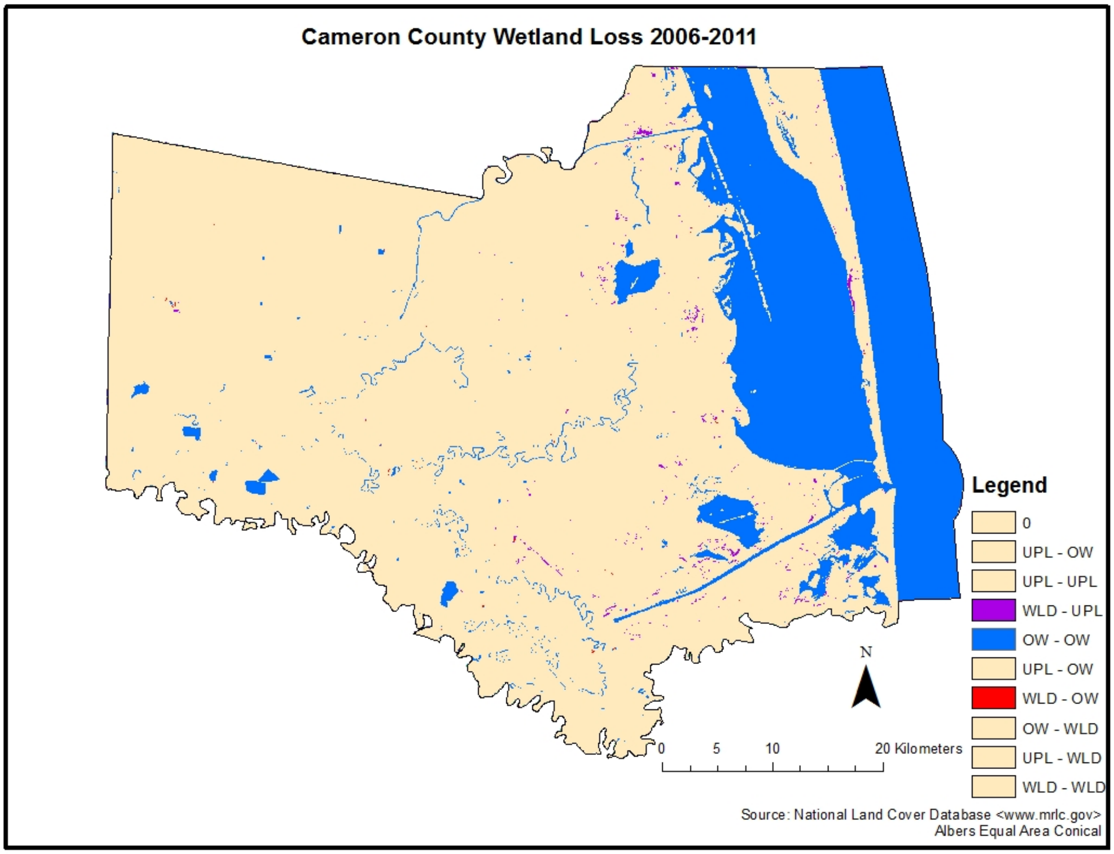

Figure 3f. Wetland loss in Cameron County between 2006 and 2011. Open water areas are shown in blue. Wetland areas converted to upland areas are depicted in purple. Wetland areas converted to open water are shown in red.

Land Cover	% Change 2001-2006	% Change 2006-2011
Upland	-1.1%	0.1%
Wetland	-1.4%	-0.47%
Open Water	4.19%	-.002%

Table 2a. Cameron County Land Change by each classification. Percent change between 2001-2006 and 2006 and 2011for each land class is listed: upland, wetland, and open water. Negative values indicate percent decreases and positive values indicate percent increases.

Conversion Type	2001-2006 acreage	2006-2011 acreage
Wetland to Upland	1,040.58	2,292.00
Wetland to Open Water	603.13	165.91
Upland to Wetland	56.27	1,345.71
Open Water to Wetland	10.45	592.46

Table 2b. Acreage of lost and gained wetlands for Galveston County between the two study periods: 2001-2006 and 2006-2011.

3.3 Accuracy Assessment

Our accuracy assessments showed that our classifications of land cover were 82-98% accurate depending on the year (Table 3). Table 3 shows that the kappa values ranged from 0.82-0.99, which shows a high level of similarity between the classification maps and the aerial photography. The high level of similarity means that we can use the maps and classifications and feel confident that they represent the ground truth changes in land cover. Table S3 also shows that we had high percentage of producer and user accuracy (73% - 100%).

	Year	Galveston County	Cameron County
Overall Accuracy	2001	89.89%	87.78%
	2006	98.89%	82.22%
	2011	95.56%	96.67%
Kappa	2001	0.897	0.875
	2006	0.989	0.818
	2011	0.955	0.960

Table 3. Overall Accuracy and Kappa Values for Accuracy Assessments on the classifications of Galveston and Cameron County for the years 2001, 2006, and 2011.

3.4 Relationship between Population Growth and Wetland Loss

County population data revealed that Galveston County and Cameron County had large increases in population between the years 2000 and 2006, 11.8% and 13.5%, respectively. However, population increase between 2006 and 2011 was much smaller, 4.1% for Galveston County and 6.5% for Cameron County (Table S1). Population density also rose for each county: +0.09 in Cameron County and +0.08 for Galveston County between 2000 and 2011. A strong correlation between wetland change and population density was observed for Cameron County ($R^2 = 0.996$) and Galveston County ($R^2= 0.961$) (Table S4). However, Table S5 in the supplemental data shows that our ANOVA values did not produce values that showed significance. Both values were above the desired $\alpha=0.05$ ($\alpha= 0.06$ for Cameron County and $\alpha=0.177$ for Galveston County).

4. DISCUSSION

The analysis shows that wetland loss is greater than wetland gains for both counties. A greater loss was observed in Galveston County with an overall percent loss of almost 10% of wetlands between 2001 and 2011 while Cameron County experienced an overall loss of 2% over the same time period. In Galveston County upland land area increased 6% over the whole study period 2001 to 2011, while in Cameron County the area that experienced the largest increase was open water, with a 4% total increase.

In Galveston County, wetland loss remained about the same between each study period at about a 5% loss between both five year blocks. However, Cameron County had a 1.5% loss between 2001 and 2006, but only a 0.5% loss between 2006 and 2011. Considering that both counties have experienced a 20% increase in population over the same time period, it would be important to perform a follow-up study that examines why wetland loss has remained constant in Galveston County but has decreased in Cameron County. A look at policy, management practices, and conservation efforts that have been successful in Cameron County could be applied to Galveston County and other coastal counties with hopes to for similar decreases.

In both counties the majority of wetland loss came from a conversion to upland areas. For the total study period 2001 – 2011, over 80% of all wetland loss was due to upland conversion (86% for Galveston County and 81% for Cameron County). Whereas conversion to upland is always a high percentage of wetland loss, it is not usually as high as 80%. For example, a study by the USFWS reported that only 37% of wetland losses were due to upland urban and rural development (Diffenderfer, 2014). One reason for this discrepancy is the broad definition of upland area in our study. The upland classification encompassed 12 of the 15 land classifications from NLCD. Therefore, while over 80% of the loss was due to upland conversion, it does not mean that it was all urban land development. Van Rees and Reed (2014) also showed that on the two most populated islands in Hawaii, Oahu and Hawaii, the majority of their wetland loss was due to urban and rural development. Therefore, it is not uncommon to see high percentages of wetland loss due to upland conversion.

The areas that experienced the most wetland conversion to open water were the islands of both counties; Galveston Island and Bolivar Penisula for Galveston County and South Padre Island for Cameron County. One possible explanation for this is a result of the low elevation of both islands. A study performed in Hawaii looking at where wetland loss was occurring found that 88% of the wetland losses in Hawaii were in areas of low elevations (Van Rees and Reed, 2014).

Contributions to wetland loss due to sea level rise was difficult to quantify on this time scale and therefore is not focused on during the analysis. However, while sea level rise is expected to be a small contributor to overall wetland loss, wetland conversion to open water did occur. Galveston County experienced greater open water gains than Cameron County. Hurricanes and severe tropical storms are a common explanation to quick changes from wetland to open water. Hurricanes can produce massive flooding and strong winds that can erode many areas along the shore line. When looking at historical hurricanes along the Texas coast between 2000-2011 a few main events stand out as possible contributors to open water gains in Galveston County. June

30, 2003 Tropical Storm Bill hits Bolivar Peninsula and causes minor beach erosion (Blood and Traphagan 2003) and on September 13, 2008 Hurricane Ike lands on Galveston as a Category 2 hurricane and inundates many of the islands off the Texas Coast destroying structures on Bolivar Peninsula and Galveston Island (Roth 2012). Hurricane Ike is considered one of the most destructive hurricanes to hit Texas (Roth 2012). In July of 2008 Hurricane Dolly hit South Padre Island with a storm surge of around 1.2 m and can also help to explain open water gains along South Padre Island (Pasch and Kimberlain, 2012).

Although we found a good correlation between population density and wetland loss, the lack of significance did not support the hypothesis that human population growth is the main driver of wetland loss. Other studies have shown a statistical significant relationship between increased population density and a decrease in wetland area (Carle, 2011). These studies note that to show significance they needed large population growth between years (growth >5%) and more data (various years and areas) (Carle, 2011). Therefore, more information and research is needed to assess the relationship between wetland loss and population growth.

Our accuracy assessment showed that when using a simplified classification system, a high accuracy can be achieved. All of our maps had above an 80% overall accuracy rating and kappa values above 0.8 (on a 0 – 1 scale) as well. This shows that mapping wetland losses and gains can be achieved through existing maps and aerial photography when field testing is not accessible. One main issue with some of our assessments were that the NAIP Imagery for the desired year was not complete. The

2006 map for Galveston and Cameron County were both missing part of their islands, Galveston Island and South Padre Island, respectively. This makes our results slightly skewed to just the area that we were able to perform the assessment on. In addition, NAIP imagery did not always match up to the year of the NLCD classification map. For example, the 2004 NAIP imagery map was used to conduct the accuracy assessment on the 2001 classification map. This may be an example of why our 2004 accuracy assessment was one of the lowest in our test locations.

The original US Fish and Wildlife Study about Texas coastal wetlands from the late 1950s to early 1990s concluded that the coast experienced a net loss of 210,590 acres (852.23 sq km), or about 5,700 acres (23.07 sq km)(2.7%) annually (Moulton et al. 1997). In Galveston County, an overall wetland loss of 15.59 sq km occurred between 2001 and 2011, which accounts for a loss of 3.12 sq km annually or 0.95% annual loss in wetlands. Cameron County experienced an overall wetland loss of 8.49 sq km between 2001 and 2011, which accounted for an annual loss of 0.85 sq km or 0.2%. The results of this study show that while wetland loss continues to occur, the percent at which it is decreasing has greatly reduced since the 1950s to 1990s.

One reason for the decrease in the rate of wetland loss is the result of policy change that occurred in 1988 and 1990 (All and Nelson, 2008). In 1988, President George H. W. Bush issued a “no net loss” approach to wetland management and in 1993 changes were made to strengthen restrictions on dredge and fill practices, the establishment of mitigation guidelines for development on wetlands (All and Nelson, 2008). These policies have led to an overall decline in the rate of wetland habitat loss, but it has not stopped the loss of wetlands. This is because the legislation still allows wetland alteration when there is no other practical alternative (All and Nelson, 2008). This goes along with our findings since wetland loss has decreased since the 1990s, but there are still observed losses due to land conversion and erosion.

Several ways to improve the assessment of coastal wetlands can be accomplished using the same methods. Accuracy of wetland mapping can be improved by having a wider array of maps from years in between the three test years (2001, 2006, and 2011). The use of field testing is the most accepted method to confirm map accuracy. In future mapping endeavors it would be important to examine ground truth from sample sites instead of aerial photography. This would allow for the study to go further and look at different types of wetlands and see if there are any trends on their net growth and loss. Most importantly, the next step in a study like ours would be to test the overall health of these wetlands. Since constructed wetlands are being created to replace natural wetlands, it is important to determine if these wetlands are performing to their full potential. This follow up study, would require a lot of more time, but it is important to determine the effectiveness of wetlands ecological services and benefits to the eco-tourism industry.

5. CONCLUSION

The results from our study show two major points. First, our high percent accuracy from our classification maps show that using a simplified classification system can create maps online that closely matches the ground truth. This allows maps to be created for general analysis possible when funds or logistics do not allow field testing.

Second, our analysis helps provide an idea of where the biggest wetland loss is occurring. This can help city planners, developers, and state agencies develop a plan that can cause a greater impact on wetland losses. Our results also allow us to see the current status of Texas coastal wetlands. The study performed by the US Fish and Wildlife Service was published in 1994 and to manage our wetlands effectively, it is important to see where losses and gains are occurring today.

The results from our study show while wetlands loss is still occurring, it is decreasing at a much smaller percent when compared to the 1997 study performed by USFWS. While any wetland loss can cause damages to endangered species, migratory birds, and increase flood risks, it is important to note that improvements have been made. Due to coastal wetlands importance in both human activities and ecological importance, it is necessary to continue to monitor and assess wetlands to ensure that the systems continue to serve at its highest capability.

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SUPPLEMENTAL DATA

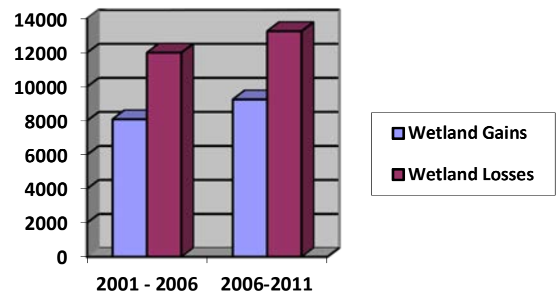


Figure S1. Wetland Gains and Losses in Galveston County between 2001 and 2011. Wetland gains are shown in light purple and wetland losses are shown in deep purple. The y-axis depicts acreage lost or gained between the study periods (x-axis).

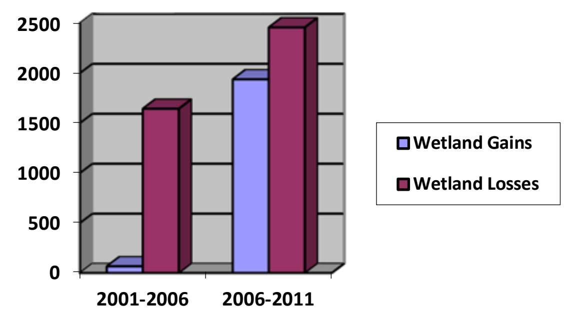


Figure S2. Wetland Gains and Losses in Cameron County between 2001 and 2011. Wetland gains are shown in light purple and wetland losses are shown in deep purple. The y-axis depicts acreage lost or gained between the study periods (x-axis).

County	Year	Total Population	Population Density (per acre)
Cameron County	2000	335,227	0.41
	2006	387,717	0.47
	2011	414,123	0.51
Galveston County	2000	250,158	0.45
	2006	283,551	0.51
	2011	295,747	0.53

Table S1. Population Estimates and Population Density in Cameron and Galveston County for the years 2000, 2006, and 2011.

NLCD Land Cover Classification	Reclassified Category
Open Water	Open Water
Developed, Open Space	Upland
Developed, Low Intensity	Upland
Developed, Medium Intensity	Upland
Barren Land	Upland
Deciduous Forest	Upland
Evergreen Forest	Upland
Mixed Forest	Upland
Shrub/Scrub	Upland
Herbaceous	Upland
Hay/Pasture	Upland
Cultivated Crops	Upland
Woody Wetlands	Wetland
Emergent Herbaceous Wetlands	Wetland

Table S2. Reclassification of National Land Cover Database. The column on the left describes the current classification given by the NLCD and the column on the right shows how it was classified for the purposes of this study.

			Upland	Open Water	Wetland
Galveston County	2004	*Producers Accuracy*	86.67%	96.67%	83.33%
		Users Accuracy	92.86%	85.29%	92.59%
	2006	*Producers Accuracy*	100%	100%	96.67%
		Users Accuracy	96.77%	100%	89.66%
	2012	*Producers Accuracy*	100%	100%	86.67%
		Users Accuracy	88.24%	100%	100%
Cameron County	2004	*Producers Accuracy*	73.33%	100%	90%
		Users Accuracy	100%	76.92%	93.10%
	2006	*Producers Accuracy*	100%	96.67%	50%
		Users Accuracy	66.67%	100%	93.75%
	2012	*Producers Accuracy*	100%	93.33%	96.67%
		Users Accuracy	90.90%	100%	100%

Table S3. Producers and Users Accuracy Percentages for Galveston and Cameron County Accuracy Assessments.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1 (Cameron County)	0.996	0.991	0.982	13.563
2 (Galveston County)	0.961	0.924	0.849	1542.69311

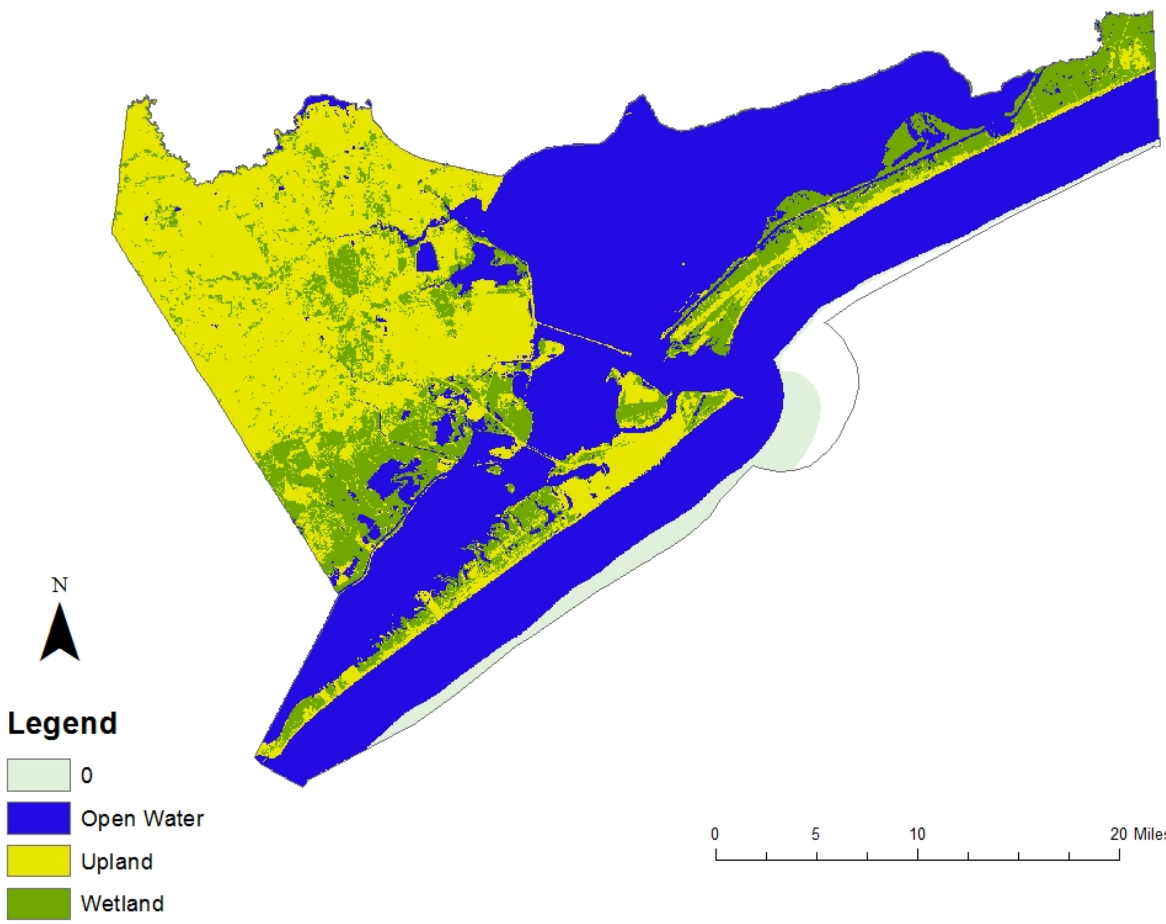
Table S4. R and R Squared values from Linear Regression Model for Cameron and Galveston County.

County		Sum of Squares	df	Mean Square	F	Sig.
Cameron County	**Regression**	20396.244	1	20396.244	110.878	0.060
	Residual	183.953	1	183.953		
	Total	20580.197	2			
Galveston County	**Regression**	29066725.821	1	29066725.821	12.213	0.177
	Residual	2379902.021	1	2379902.021		
	Total	31446627.842	2			

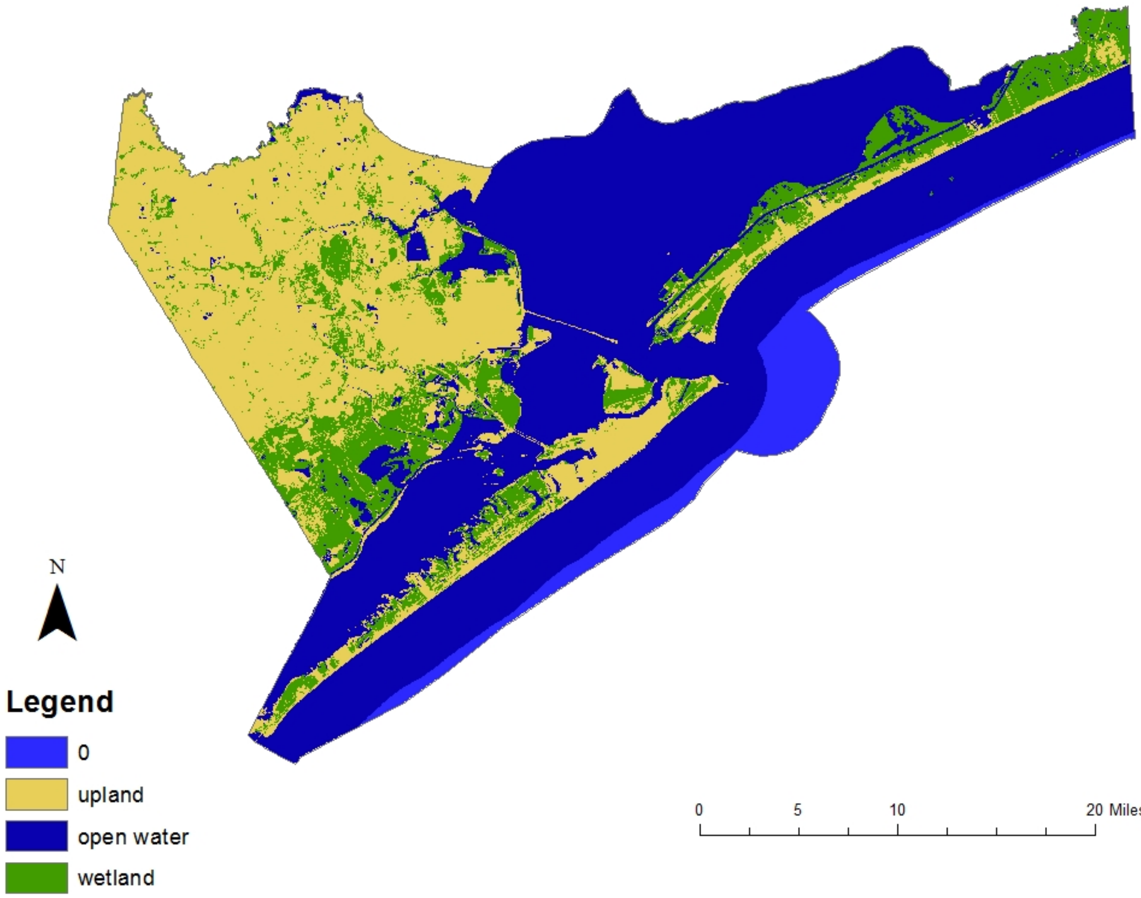
Table S5. ANOVA Results from Linear Regression Model for Cameron and Galveston County (α=0.05). df = degrees of freedom and F = F-statistic.

APPENDIX A

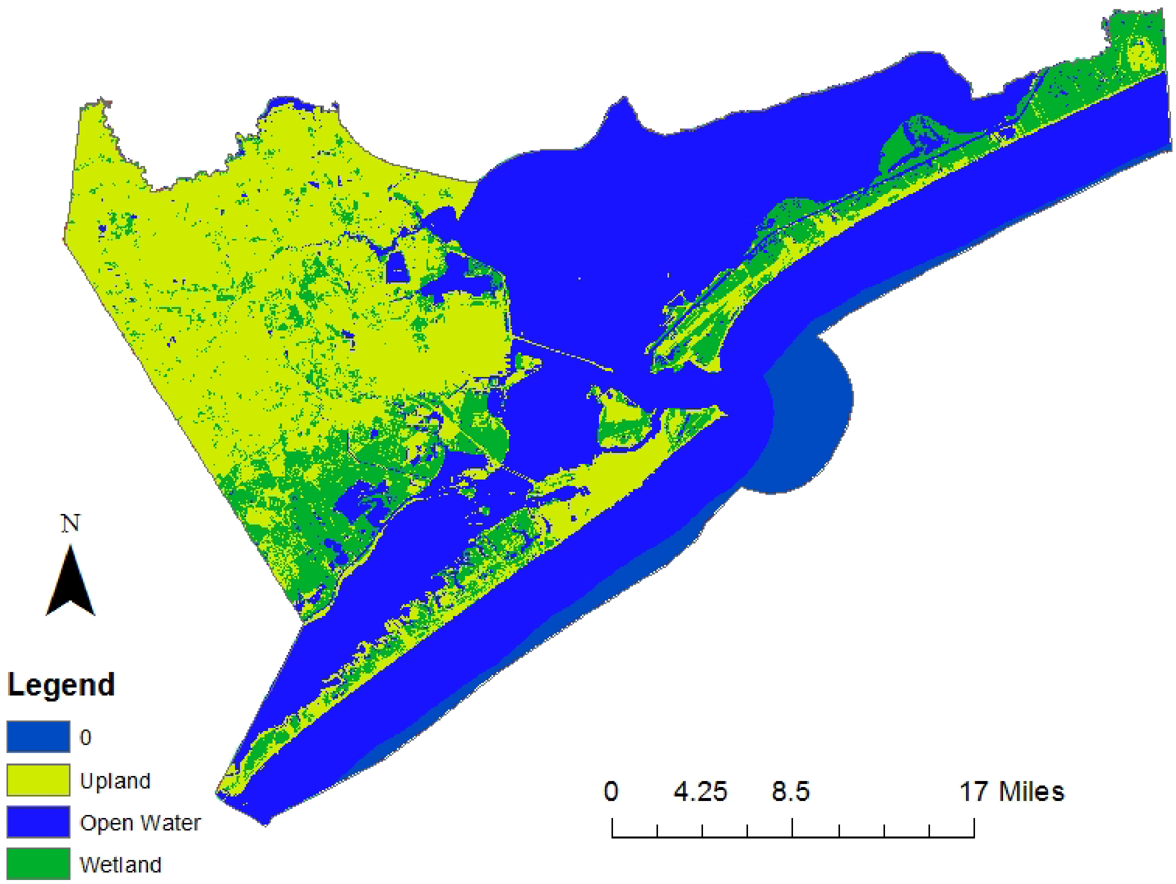
RECLASSIFIED MAPS OF GALVESTON AND CAMERON COUNTY



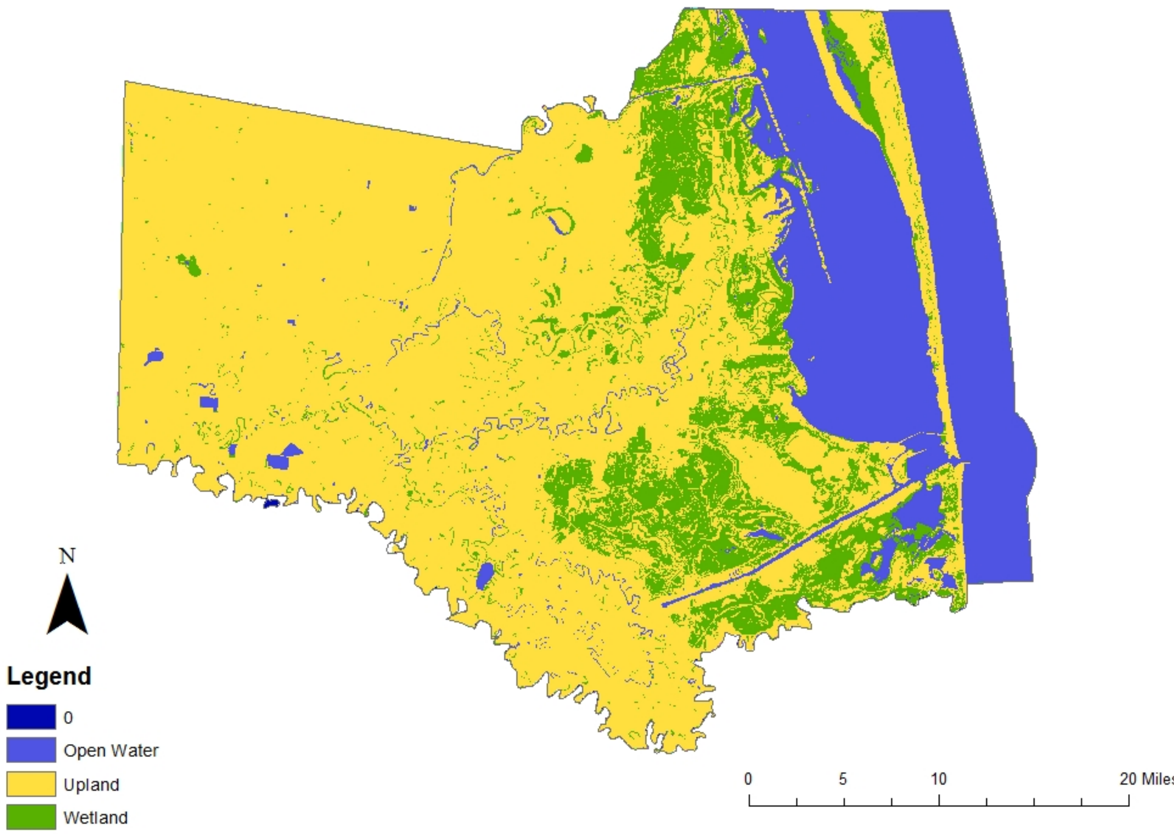
2001 3-category Classification Galveston County



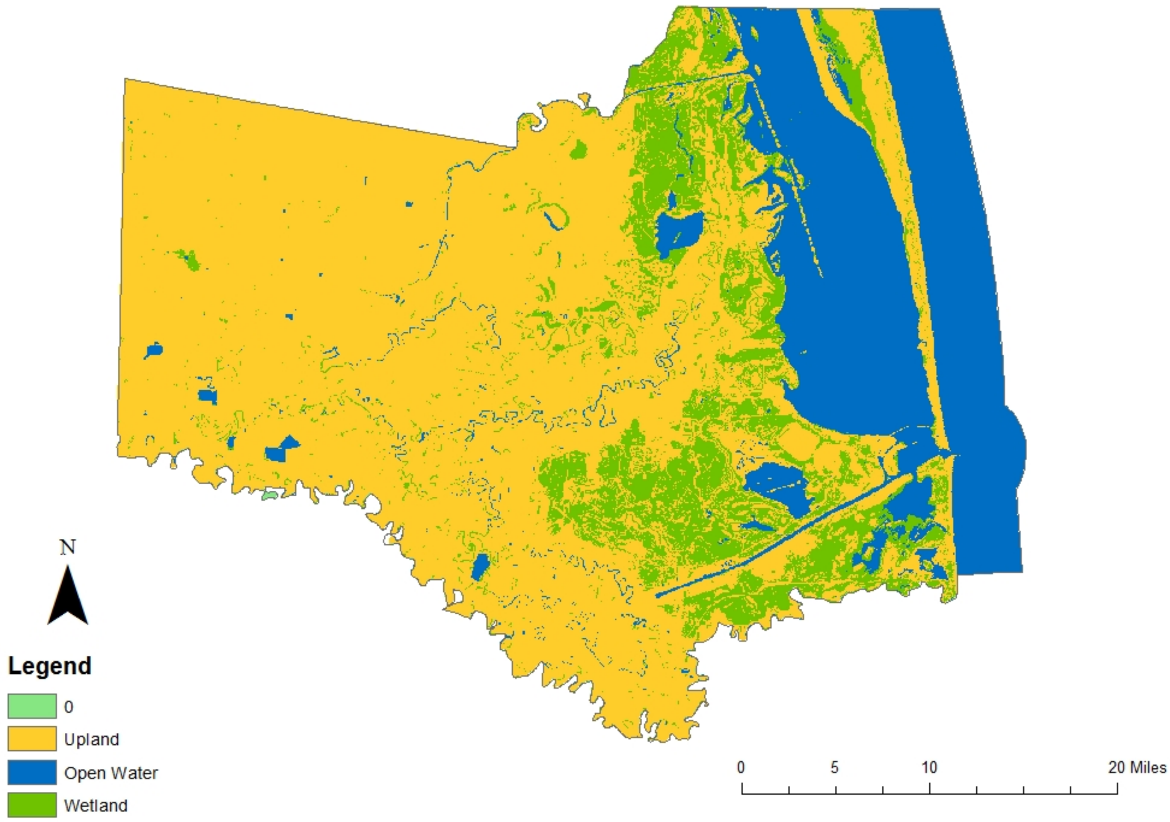
2006 3-category Classification Galveston County



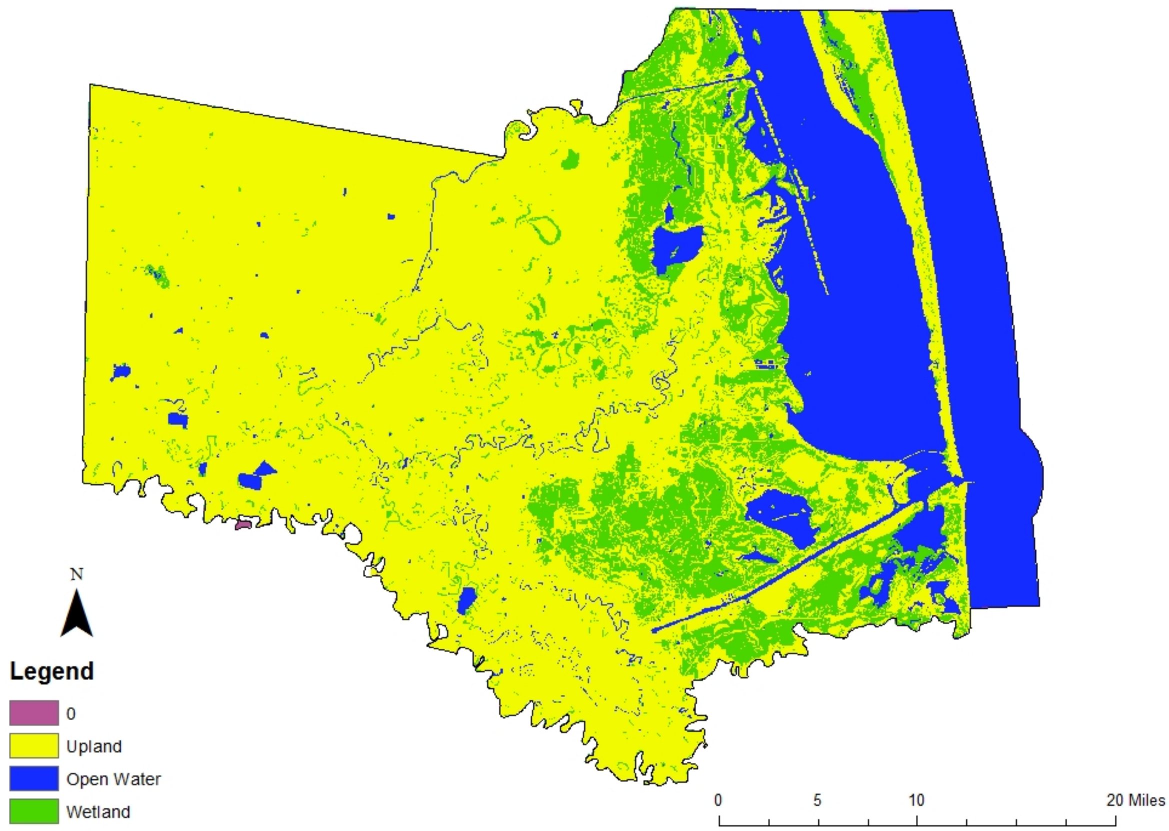
2011 3-category Classification Galveston County



2001 3-category Classification Cameron County



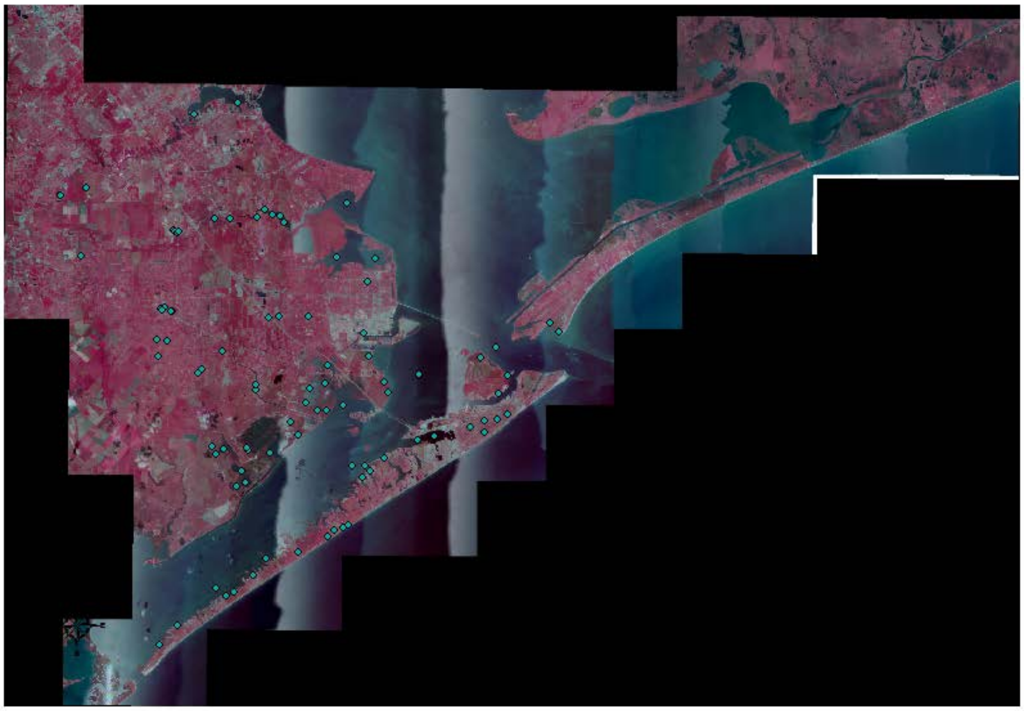
2006 3-category Classification Cameron County



2011 3-category Classification Cameron County

APPENDIX B

NAIP IMAGERY OF GALVESTON AND CAMERON COUNTY

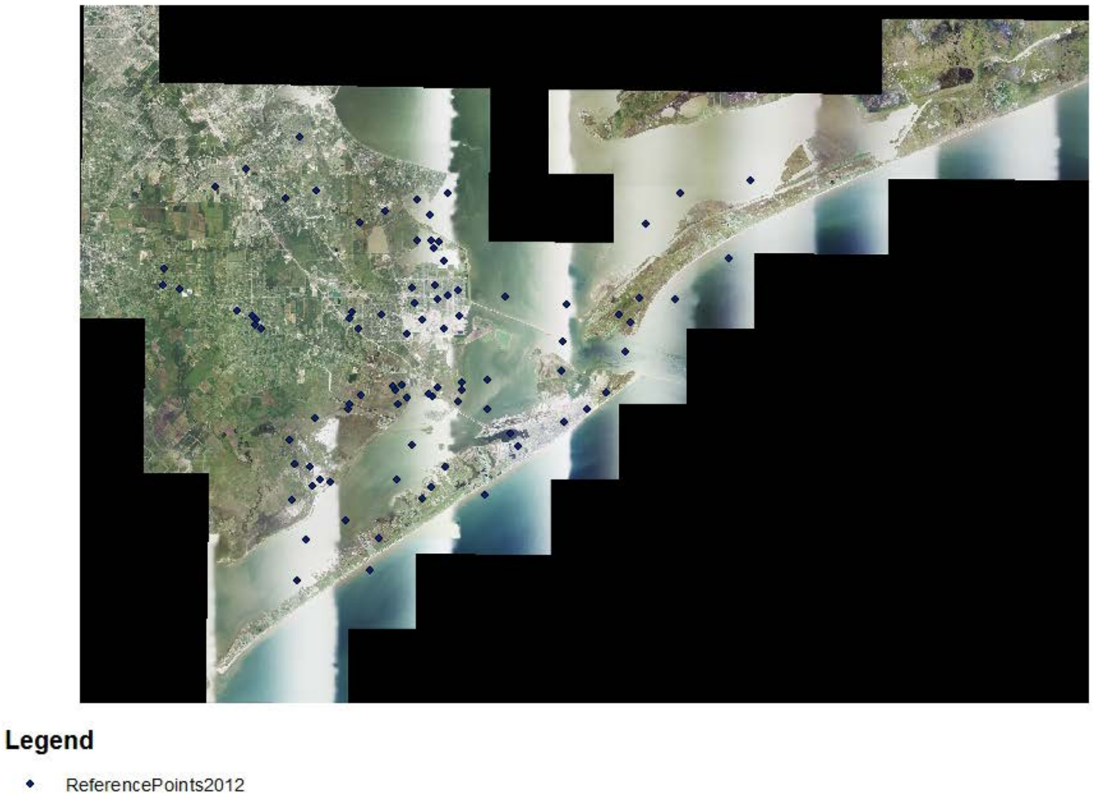


Legend

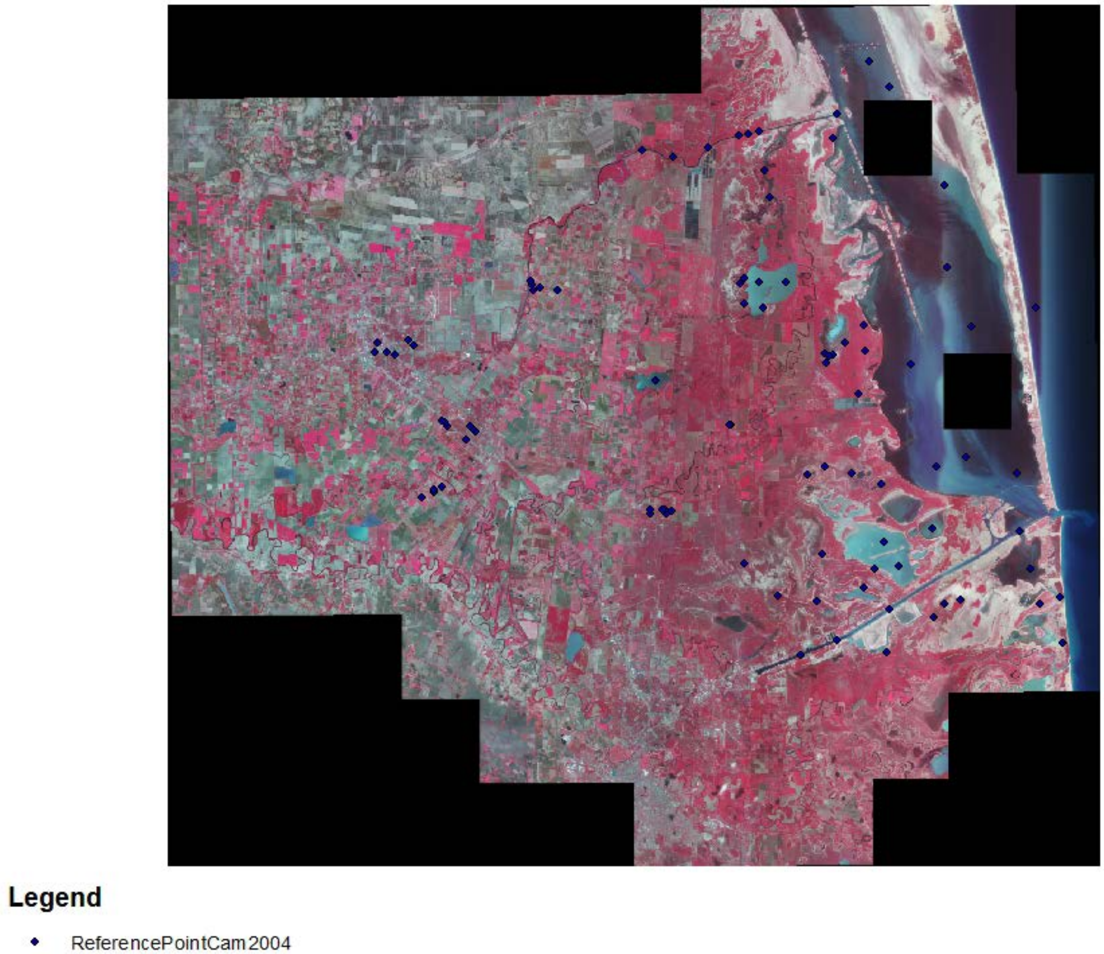
◆ ReferencePoint04Gal

2004 Aerial Imagery of Galveston County

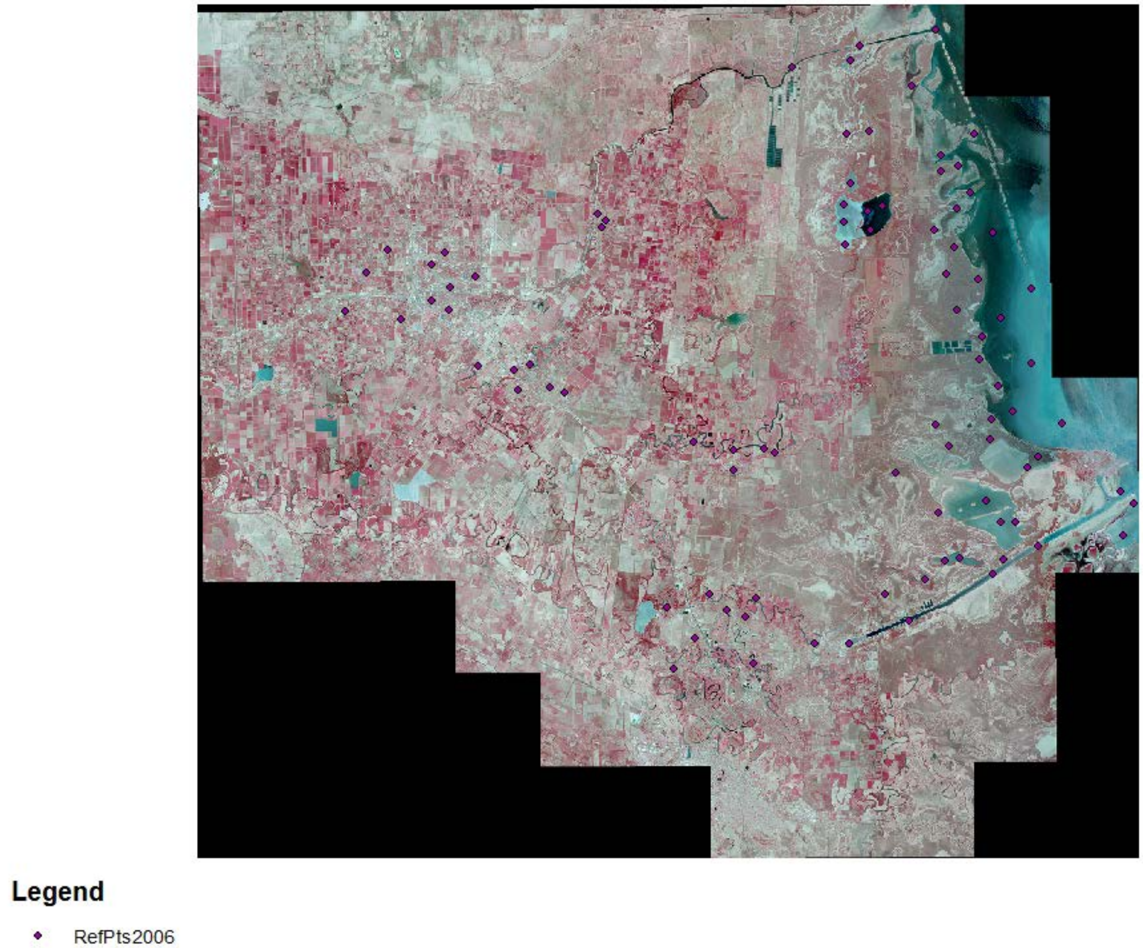
2006 Aerial Image of Galveston County



2012 Aerial Imagery of Galveston County



2004 Aerial Imagery of Cameron County



2006 Aerial Imagery of Cameron County

2012 Aerial Imagery of Cameron County