# Identifying and Diagnosing Locations of Ongoing and Future Saltwater Wetland Loss: Mangrove Heart Attack

Credit: Whitney Gray, 2011, Little Panther Key, Pine Island Sound

## Charlotte Harbor National Estuary Program
## Technical Report 16-3
## Final 3/9/2017


326 West Marion Avenue
Punta Gorda, Florida 33950
(941) 575-5090
*www.CHNEP.org*

The Charlotte Harbor National Estuary Program is a partnership of citizens, elected officials, resource managers and commercial and recreational resource users working to improve the water quality and ecological integrity of the greater Charlotte Harbor watershed. A cooperative decision-making process is used within the Program to address diverse resource management concerns in the 4,700-square-mile study area. Many of these partners also financially support the Program, which, in turn, affords the Program opportunities to fund projects. The entities that have financially supported the Program include the following:

U.S. Environmental Protection Agency
Southwest Florida Water Management District
South Florida Water Management District
Florida Department of Environmental Protection
Peace River/Manasota Regional Water Supply Authority
Polk, Sarasota, Manatee, Lee, Charlotte, DeSoto, and Hardee Counties
Cities and Towns of Sanibel, Cape Coral, Fort Myers, Punta Gorda, North Port, Venice,
Fort Myers Beach, Winter Haven, Bonita Springs, and Estero.

This publication was authored by:

- Lisa B. Beever, Charlotte Harbor National Estuary Program
- James W. Beever III, Southwest Florida Regional Planning Council
- Roy R. "Robin" Lewis III, Coastal Resources Group, Inc.
- Laura Flynn, Coastal Resources Group, Inc.
- Terry Tattar, University of Massachusetts
- Liz Donley, Charlotte Harbor National Estuary Program
- E.J. Neafsey, Sanibel-Captiva Conservation Foundation

Acknowledgement:

The Charlotte Harbor Aquatic Preserves provided boat access, captains and expertise. Melynda Brown was the captain on July 27, October 8 and November 5, 2015. Mary McMurray was the captain on July 20, August 25, 2015 and February 18, 2016. Arielle Taylor-Manges was the captain on September 9 and September 25, 2015. Estero Bay Aquatic Preserve manager Cheryl Clark captained the boat on November 17, 2015. The Charlotte Harbor Preserve State Park provided off-road access and assistance from Jay Garner on April 18, 2016.

James Beever conceived of the project, was persistent for most of a decade in obtaining the grant funding. Robin Lewis coined the term "Mangrove Heart Attack." Lisa Beever was the GIS Analyst and primary author. Laura Flynn and Liz Donley performed the final edits.

Suggested citation:

Beever, L., J. Beever, R. Lewis, L. Flynn, T. Tattar, E. Donley, E. Neafsey. 2016. Identifying and Diagnosing Locations of Ongoing and Future Saltwater Wetland Loss:
Mangrove Heart Attack. Charlotte Harbor National Estuary Program. Punta Gorda, Florida.

**Charlotte Harbor National Estuary Program**

This "Identifying and Diagnosing Locations of Ongoing and Future Saltwater Wetland Loss: Mangrove Heart Attack" report was developed under Assistant Agreement No. CD-00D23814 awarded by the U.S. Environmental Protection Agency. It has not been formally reviewed by EPA. The views expressed are solely those of the Charlotte Harbor National Estuary Program and EPA does not endorse any products or commercial services mentioned.

# Table of Contents

Executive Summary ........................................ 1

Purpose ........................................ 2

Background ........................................ 3
Mangrove Forest in the CHNEP Study Area ........................................ 6
Mangrove Community Types ........................................ 11
Mangrove Productivity and Ecosystem Functions ........................................ 16
Mangrove Forest Death and Mangrove Forest Heart Attacks ........................................ 17
Salt Marshes of the CHNEP Study Area ........................................ 23
Salt Marsh Types of the CHNEP ........................................ 25

GIS Library of Mapping Resources ........................................ 36
True Color Aerials ........................................ 36
Historic Aerials ........................................ 36
Infrared Aerials ........................................ 38
Lidar ........................................ 39
Water Management District 2008-09 Land Use Maps ........................................ 40
Fish and Wildlife Conservation Commission 2003 Landsat Interpretation ........................................ 41
United State Geological Survey 2015 Landsat Interpretation ........................................ 42

FLUCCS Maps for Charlotte Harbor and Tidal Peace and Myakka Rivers ........................................ 43
Classification of Mangrove Forest Type ........................................ 43
Mapping Techniques ........................................ 46
Mapping Analysis ........................................ 50

Mangrove Forest Field Investigation ........................................ 61
Site Selection ........................................ 61
Field Investigation Methods ........................................ 63
Pre-Visit Analysis ........................................ 72
Mangrove Species Composition by Geomorphology ........................................ 73
Mangrove Forest Structure by Geomorphology ........................................ 80
Mangrove Health by Species and Geomorphology ........................................ 93

Spectral Modeling to Determine Mangrove Condition ........................................ 103
Landsat Data Retrieval and Preparation ........................................ 103
Top of Atmosphere Conversion ........................................ 115
Mangrove v. Not Mangrove calls using Landsat 8 ........................................ 116

Final Mangrove Map Series and Analysis ........................................ 117
Landsat Interpretation Refinement ........................................ 117
Mangrove Geomorphology and Species using Landsat 8 ........................................ 118
Mangrove Geomorphology and Species Recalibration ........................................ 129
Predicted and Observed Species Identification ........................................ 130
Landsat Interpretation of Geomorphology and Species ........................................ 131

Mangrove Condition ........ 136
Comparing Mangrove Condition between Landsat Missions ........ 138
Mangrove Condition Trends ........ 142
Mangrove Condition Status and Trends Summary ........ 145
Comparing Mangrove Condition to Site Investigation Findings ........ 147
Mangroves and Landscape Linkages ........ 148

Catalog of Mangrove Restoration Opportunities ........ 150
Methods ........ 150
Restoration Opportunities ........ 155
Response Examples ........ 160
Implementation ........ 167

Project Accomplishments and Uses ........ 168

Summary ........ 170

Annotated Bibliography ........ 171

Appendix A: Raster Manipulation Methods ........ 206

# Table of Figures

Figure 1: Proportional distributions of emergent wetlands and shoreline conditions of the CHNEP Study Area ........ 3
Figure 2: Mangrove acres by CHNEP watershed ........ 4
Figure 3: Mangrove acres of the CHNEP ........ 5
Figure 4: Proportion of mangrove acres by CHNEP watershed ........ 7
Figure 5: The Six Mangrove Communities ........ 12
Figure 6: Diagrammatic cross-section of the hypothetical mangrove fringing forest zonation in the CHNEP system as predicted by literature ........ 13
Figure 7: Location of mangrove trimming in the CHNEP Study Area ........ 21
Figure 8: The Salt Marshes of the CHNEP (indicated in blue) ........ 25
Figure 9: Acres of Salt Marsh by Type in the CHNEP ........ 28
Figure 10: Distribution of Salt Marshes in the CHNEP Study Area in 2012. ........ 29
Figure 11: Acres of Salt Marsh by Watershed in the CHNEP. ........ 31
Figure 12: Acreage of each Salt Marsh Type in the CHNEP. ........ 32
Figure 13: Relative proportion of salt marsh types in the CHNEP Study Area ........ 33
Figure 14: Upper Peace River Salt Marsh Zonation ........ 34
Figure 15: Middle Peace River Salt Marsh Zonation ........ 34
Figure 16: Lemon Bay Salt Marsh Zonation ........ 35
Figure 17: Estero Bay Salt Marsh Zonation ........ 35
Figure 18: Sample CHNEP Mangrove Site Review Data Sheet, Page One ........ 64
Figure 19: Sample overall trip map for September 25, 2015. ........ 65
Figure 20: Sample overall trip map for Chino Island, PI-08. ........ 65
Figure 21: Horizontal Photos at PI-08 ........ 66
Figure 22: Vertical Photos at PI-08 ........ 67
Figure 23: Team members assessing cover ........ 67
Figure 24: Sample CHNEP Mangrove Site Review Data Sheet, Page Two ........ 69
Figure 25: Sample CHNEP Mangrove Site Review Data Sheet, Page Three ........ 70
Figure 26: Basin Black Mangrove Forest at Part Island ........ 75
Figure 27: Fringe Red Mangrove Forest at Four Mile Cove Ecological Park ........ 76
Figure 28: Fringe White Mangrove Forest at Riverwood ........ 76
Figure 29: Fringe Mixed Mangrove Forest with 50% Buttonwood at Myakka State Forest ........ 77
Figure 30: More Typical Fringe Mixed Mangrove Forest ........ 77
Figure 31: Witch's Brooms in Scrub Red Mangrove Trees ........ 79
Figure 32: Layering of mangrove cover can reduce the light at the forest floor. ........ 81
Figure 33: A typical view of the mangrove fringe, with red mangroves at the front and black mangroves towering over ........ 83
Figure 34: No relationship between Mangrove Species and Elevation ........ 84
Figure 35: Relationship between Geomorphology and Elevation ........ 84
Figure 36: Black mangrove seedling shown in foreground with Batis and Samolus ........ 85
Figure 37: Overwash Island Mangrove Zonation ........ 88
Figure 38: Fringe Mangrove Zonation ........ 89
Figure 39: Riverine Mangrove Zonation ........ 90
Figure 40: Basin Mangrove Zonation ........ 91
Figure 41: Scrub Mangrove Zonation ........ 92
Figure 42: Crown Forms ........ 96
Figure 43: Most commonly used Munsell plant tissue chart pages ........ 101
Figure 44: Most commonly used Munsell plant tissue chart codes ........ 102

Figure 45: Landsat Mission timelines (USGS website) ... 105
Figure 46: Boxplot of short wave infrared 1 (B6-SWIR1) band values by species and mixes .. 120
Figure 47: Boxplot of short wave infrared 1 (B6-SWIR1) band values by geomorphology ... 122
Figure 48: Data distribution of near infrared reflectance by species type (B5) ... 125
Figure 49: Data distribution of shortwave infrared reflectance by species type (B6) ... 125
Figure 50: Data distribution of near infrared reflectance by geomorphology type ... 127
Figure 51: Data distribution of shortwave infrared reflectance by geomorphology type ... 128
Figure 52: Line of mangroves of declining condition mapped as Fringe but interpreted as Basin ... 131
Figure 53: Frequency Distribution of NDVI green based on mangroves on January 28, 2015 . 138
Figure 54: Frequency Distribution of NDVI green based on mangroves on December 26, 1999 ... 139
Figure 55: Frequency Distribution of NDVI green based on mangroves on January 9, 1985 ... 139
Figure 56: Changes of Mangrove Condition between 1985 and 2015. ... 141
Figure 57: Changes of Mangrove Condition between 1985 and 2015 ... 141
Figure 58: Limited relationship between mangrove health at the site and Landsat NDVIg values ... 147
Figure 59: Photograph of Cattle Dock Point Road ... 161
Figure 60: Black Key Basin Mangrove Die-off and Recovery ... 163
Figure 61: Peat Oxidation and Recolonization of Red Mangrove at Die-off Site ... 165

## Table of Tables

Table 1: Types of Salt Marsh of the CHNEP ... 27
Table 2: Salt Marsh Distribution by Type by Watershed Basin ... 28
Table 3: Mangrove Type FLUCCS Codes ... 44
Table 4: Mangrove Die-Off Type FLUCCS Codes ... 45
Table 5: Salt Marsh Type FLUCCS Codes ... 46
Table 6: Live Mangrove Acreages ... 50
Table 7: Dead Mangrove Acreages ... 51
Table 8: 2015 Mangrove FLUCCS Level 4 ... 52
Table 9: 2011 Salt Marsh Acreages by Estuary Segment ... 53
Table 10: 2015 Salt Marsh Acreages by Estuary Segment ... 53
Table 11: Differences between Salt Marsh Acreages documented in 2011 and 2015 ... 54
Table 12: Additional Segments not mapped in 2015 ... 54
Table 13 : 2009 Water Management District Acreages by Estuary Segment ... 55
Table 14: 2015 Acreages by Estuary Segment ... 55
Table 15: Differences between 2009 WMD Land Use and 2015 Map ... 55
Table 16: Additional WMD Segments not mapped in 2015 ... 55
Table 17: 2009 FWC Acreages by Estuary Segment ... 56
Table 18: 2015 Acreages by Estuary Segment ... 56
Table 19: Differences between 2003 FWC Land Use and 2015 Map ... 56
Table 20: Additional FWC Segments not mapped in 2015 ... 56
Table 21: Acreage identified as mangrove by USGS for whole pixels ... 57
Table 22: Acreage mapped as mangrove but not identified as mangrove by USGS for whole pixels ... 57
Table 23: Comparison of Agency Habitat Type Determinations ... 72
Table 24: Pre- versus Post Field Visit Geomorphology ... 74

Table 25: Pre- versus Post Field Visit Mangrove Species ... 74
Table 26: Species Composition by Geomorphology ... 75
Table 27: Species Presence by Geomorphic Type ... 78
Table 28: Species Presence by Geomorphic Type as a percentage ... 78
Table 29: Cover where trees exist ... 80
Table 30: Cover including non-presence ... 80
Table 31: Tallest Tree Height (in feet) ... 82
Table 32: Tallest Tree Height by geomorphology ... 82
Table 33: Average Tallest Tree by Species and Geomorphology ... 82
Table 34: Seedlings ... 85
Table 35: Propagules on Trees ... 86
Table 36: Understory Coverage ... 86
Table 37: Folivory ... 93
Table 38: Dead Branches ... 93
Table 39: Tree Health ... 94
Table 40: Tree Health by Mangrove Species ... 94
Table 41: Tree Health by Geomorphology ... 95
Table 42: Elevation by Tree Health ... 95
Table 43: Crown form by mangrove species ... 96
Table 44: Leaf Color sorted by hue, yellow to green ... 98
Table 45: Leaf Color sorted by Value, dark to light ... 99
Table 46: Leaf Color sorted by chroma, neutral gray to saturated ... 100
Table 47: Mangrove Species Reflectance means and standard deviations ... 118
Table 48: Mangrove Species Reflectance as a percentage of total mean ... 119
Table 49: Lower and Upper extent to define each species and species mix, based on FLUCCS120
Table 50: Mangrove Geomorphology Reflectance means and standard deviations ... 121
Table 51: Mangrove Geomorphology as a percentage of total mean ... 121
Table 52: Mangrove Geomorphology Upper and Lower Reflectance Limits ... 123
Table 53: Mangrove Species Reflectance means and standard deviations ... 124
Table 54: Mangrove Species Reflectance as a percentage of total mean ... 124
Table 55: Lower and Upper extent to define each species and species mix ... 126
Table 56: Mangrove Geomorphology Reflectance means and standard deviations ... 126
Table 57: Mangrove Species Geomorphology as a percentage of total mean ... 127
Table 58: Lower and Upper extent to define each geomorphic type ... 128
Table 59: Lower and Upper extent to define each geomorphic type ... 129
Table 60: Lower and Upper extent to define each geomorphic type ... 130
Table 60: 2015 and 1985 NDVIgreen groups ... 140
Table 62: Condition Trend Acreage by Mangrove Estuary Segment ... 142
Table 63: Condition Trend Scores by Mangrove Estuary Segment ... 143
Table 64: Condition Trend Scores by Mangrove Geomorphology ... 144
Table 65: Condition Trend Scores by Mangrove Geomorphology ... 144
Table 66: Distribution of Restoration Opportunities by Mangrove Estuary Segment ... 154
Table 67: Mangrove Restoration Opportunities ... 159

# Table of Maps


Map 1: Gallagher Keys in 2014 and 1951 .......... 37
Map 2: Gallagher Keys 1999 Infrared .......... 38
Map 3: Gallagher Keys 2010 Lidar Digital Elevation Model Image .......... 39
Map 4: 2008-2009 Water Management District Land Use Map .......... 40
612: Mangrove Swamps in green and 500: Water in blue .......... 40
Map 5: 2003 Florida Fish and Wildlife Commission Landsat 7 Interpretation of Mangrove Extent 41
Map 6: 2015 USGS Landsat Interpretation of Mangrove Extent .......... 42
Map 7: Mangrove Estuary Segments .......... 48
Map 8: Water Management District Map of Mangrove (green) and Salt Marsh (pink) .......... 49
Map 9: Geomorphic and Species Structure of Mangrove and Salt Marsh .......... 49
Map 10: 2015 FLUCCS Level 3, By Habitat Type .......... 51
Map 11: 2015 FLUCCS Level 4, by geomorphic type .......... 52
Map 12: Tidal Peace River Mangrove and Salt Marshes .......... 58
Map 13: Tidal Myakka River Mangrove and Salt Marshes .......... 58
Map 14: West Wall Charlotte Harbor Mangrove and Salt Marshes .......... 59
Map 15: Cape Haze Mangrove and Salt Marshes .......... 59
Map 16: East Wall Charlotte Harbor Mangrove and Salt Marshes .......... 60
Map 17: Lower Charlotte Harbor Mangrove and Salt Marshes .......... 60
Map 18: Initial Site Selection Locations .......... 62
Map 19: Completed Site Visit Locations .......... 71
Map 20: Bands 1 (coastal aerosol) and 2 (blue) .......... 106
Map 21: Bands 3 (green) and 4 (red) .......... 107
Map 22: Bands 5 (near infrared, NIR) and 6 (short wave infrared1, SWIR1) .......... 108
Map 23: Bands 7 (short wave infrared 2, SWIR2) and 8 (Pan-Chromatic) .......... 109
Map 24: Bands 9 (cirrus) and 10 (Thermal Infrared 1, TIRS1) .......... 110
Map 25: Band 11 (Thermal Infrared 2, Tirs2) And False Infrared (Bands 5, 4, 3) .......... 111
Map 26: Natural Color (Bands 4, 3, 2 )and False Color 1 (Bands 6, 5, 4) .......... 112
Map 27: False Color 2 (Bands 7, 6, 4) and False Color 3 (Bands 7, 5, 3) .......... 113
Map 28: Mangroves as dark orange (Bands 5, 6, 7 .......... 114
Map 29: World View-2 Coverage of CHNEP and Mangrove Estuary Segments in Late 2015 .......... 115
Map 30: 2015 CHNEP/SWRPC Geomorphic Maps compared with Landsat Interpretation .......... 132
Map 31: Landsat Interpretation of Mangrove Species .......... 133
Map 32: 2015 CHNEP/SWRPC FLUCCS Level 5 Maps compared with Landsat Interpretation 134
Map 33: Close-up of Cape Haze Landsat Interpretation .......... 135
Map 34: 2015 Mangrove Condition .......... 137
Map 35: Mangrove and Landscape Linkages .......... 148
Map 36: NDVIg indicated poor condition that could not be seen on the aerial .......... 151
Map 37: NDVIg indicated poor condition that could be seen at 500 scale .......... 152
Map 38: Distribution of Recommended Actions .......... 153
Map 39: Restoration Opportunity at Cattle Dock Point Road .......... 160
Map 40: Black Key Basin (island on the right) .......... 162
Map 41: The Great West Wall Die-off .......... 164
Map 42: Clam Bayou Restoration in Progress .......... 166

# Executive Summary

The Charlotte Harbor National Estuary Program (CHNEP) partnered with the Southwest Florida Regional Planning Council (SWFRPC), Coastal Resource Group Inc., University of Massachusetts and Sanibel-Captiva Conservation Foundation Marine Laboratory to characterize Charlotte Harbor mangroves, evaluate mangrove condition trends and recommend restoration opportunities. EPA funded this work through a Wetland Program Development Grant, (CD-00D23814) during fiscal years 2015 and 2016. Florida Department of Environmental Protection also supported the work by providing boat access to mangrove sites and funding a portion of the mapping analysis (SO908).

Since the 1970s, mangrove forests have been characterized by six geomorphic types: Overwash Island, Fringe, Riverine, Basin, Hammock and Scrub. Southwest Florida includes four mangrove species: red mangrove, black mangrove, white mangrove and buttonwood. Classic mangrove zonation suggests that mangrove species are found with red mangrove most waterward, followed by black mangrove, then white mangrove with buttonwood most landward. Mangrove forest data were collected at 56 sites. Mangrove species mixes were far more common than classic mangrove zonation would suggest. Buttonwoods were found on the mangrove shoreline and red mangroves were found in the high scrub. Conceptual diagrams were prepared representing actual Charlotte Harbor mangrove forests by geomorphic type.

CHNEP staff mapped mangroves by geomorphology and species/species mixes for Charlotte Harbor proper (including the tidal Peace and Myakka Rivers). Mapped information and site data were used in combination with Landsat multispectral data to develop mangrove geomorphic and species interpretations for the entire CHNEP area. The results offer an astonishingly sensitive and detailed interpretation suggesting underlying hydrology, difficult to map from aerial photography and Lidar digital elevation models alone.

The highlight of the project is the use of the “Green Normalized Difference Vegetation Index.” Pastor-Guzman *et al* (2015) found this index describes mangrove canopy chlorophyll at the landscape scale received by Landsat sensors. Known areas of poor mangrove condition and excellent mangrove condition corresponded to the results of the index using 2015 Landsat data. The 2015 index was coupled with 1985 Landsat data to develop a mangrove condition trend.

The project team assembled to identify restoration opportunities included four mangrove biologists and a regional planner, all with on-site experience in the Charlotte Harbor area. The 2015 mangrove condition and 1985 to 2015 mangrove condition change maps were used to identify 90 potential restoration opportunities throughout the study area. In addition, sites with poor or declining condition due to natural causes, where there was no remedy or where restoration was in progress were identified.

The mangrove condition and change tool has many potential uses. Mangrove quality can now be measured and targets set, pursuant to CHNEP policy. Changes of mangrove vigor as a result of restoration can be measured, even after the restoration has taken place. This tool needs no pre-restoration monitoring because of the ongoing collection and archiving of Landsat data. Restoration opportunities can be identified easily in other areas now that the tool has been vetted.

# Purpose

This project defines the distribution, abundance, and composition of saltwater wetlands, including mangrove ecosystems in southwest Florida;  assesses the fate of these ecosystems as they respond to human-caused hydrologic and climate change stressors; identifies locations of mangrove forest die-offs and location of potential future loss; documents changes in the position, composition and health of the landward and waterward edges of fringing mangrove ecosystems and changes in the relative proportions of mangrove ecosystem types. The project focuses on large mortality areas with adjacent areas showing stress and long term trends indicating little or no natural recovery, and expansion of the die-off to potentially thousands of acres. Project outputs include a method to identify saltwater wetlands to species utilizing aerial GIS and Lidar elevation data coupled with landscape position; documentation of the landward and waterward edges of mangrove extents; identification of important habitat linkages; identification of restoration opportunities associated with manmade and sea level rise hydrologic changes; development of landscape scale management recommendations for the recovery of damaged mangrove areas; and identification of historical trends in and cumulative impacts to mangrove distribution relative to human impacts, storm impacts, hydrology and sea level in the mangrove ecosystems of Southwest Florida.

This project directly implements the Charlotte Harbor National Estuary Program's (CHNEP) Comprehensive Conservation and Management Plan (CCMP) Quantitative Objectives and Priority Actions. Specifically, FW-1: Protect, enhance and restore native habitats ….including mangrove, salt marsh; FW-C: Restore …estuarine wetlands areas; and SG-S: Post raw data, GIS and technical analysis on the Internet under data management strategy.

# Background

Subtropical saltwater wetlands include mangrove forest and salt marsh which provide significant biochemical and ecological processes supporting primary production, nursery and physical habitat for a wide variety of marine/estuarine vertebrates and invertebrates. Approximately 224,579 ha. (554,515 acres) of mangroves and 35,327.1 ha. (87,258 acres) of salt marshes remain in Central and South Florida (USFWS Multispecies Recovery Plan 1999).

The value and central role of saltwater wetlands in the ecology of South Florida has been well established by numerous scientific investigations directed at primary productivity, food web interactions and habitat function. Saltwater wetlands have a significant ecological role as nursery ground and habitat for a variety of significant sport and commercial fishery species, as well as endangered and threatened species and species of special concern. Saltwater wetlands improve water quality and clarity by filtering upland runoff and trapping waterborne sediments and debris and serve as important coastal barriers attenuating the effects of storm damage. Unaltered saltwater wetlands contribute to the overall natural setting and visual aesthetics of Florida's estuarine waterbodies, thus contributing significantly to the economy of the coastal counties of region and the state. The Multi-Species Recovery Plan for South Florida, published by the USFWS in 1999, identified the maintenance of the structure, function, and ecological processes of mangroves and recommended as a Restoration Objective the prevention of any further loss, fragmentation, or degradation of this habitat type in South Florida.

CHNEP identifies these areas in need of special protection due to the multiple ecological functions that support Florida's native habitat, tourism, and fisheries economies.

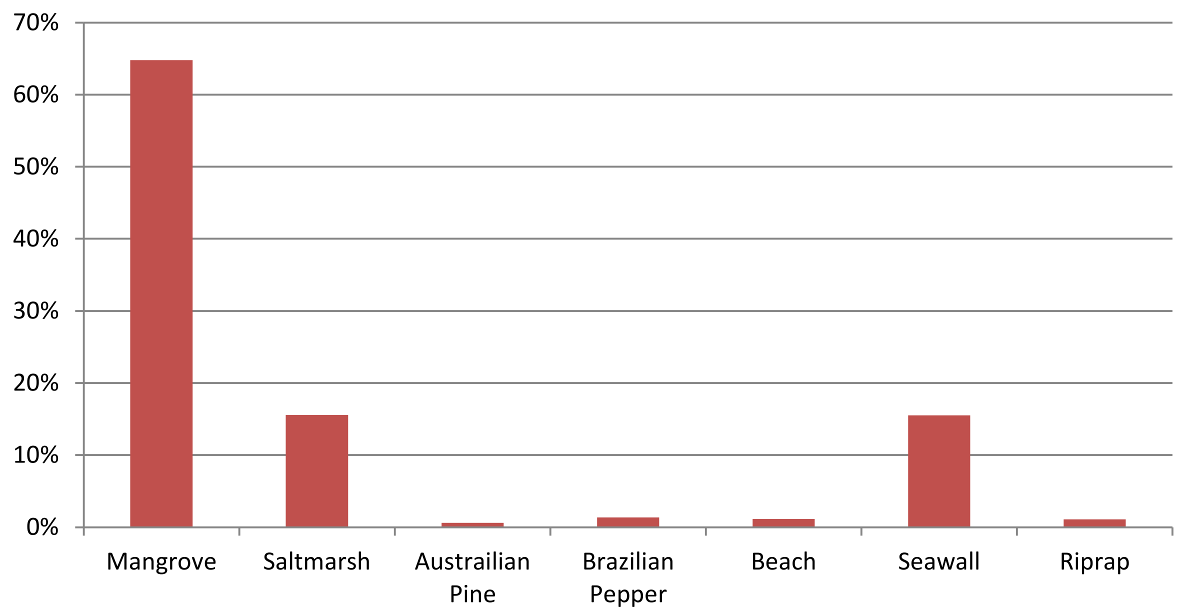



**Figure 1: Proportional distributions of emergent wetlands and shoreline conditions of the CHNEP Study Area**

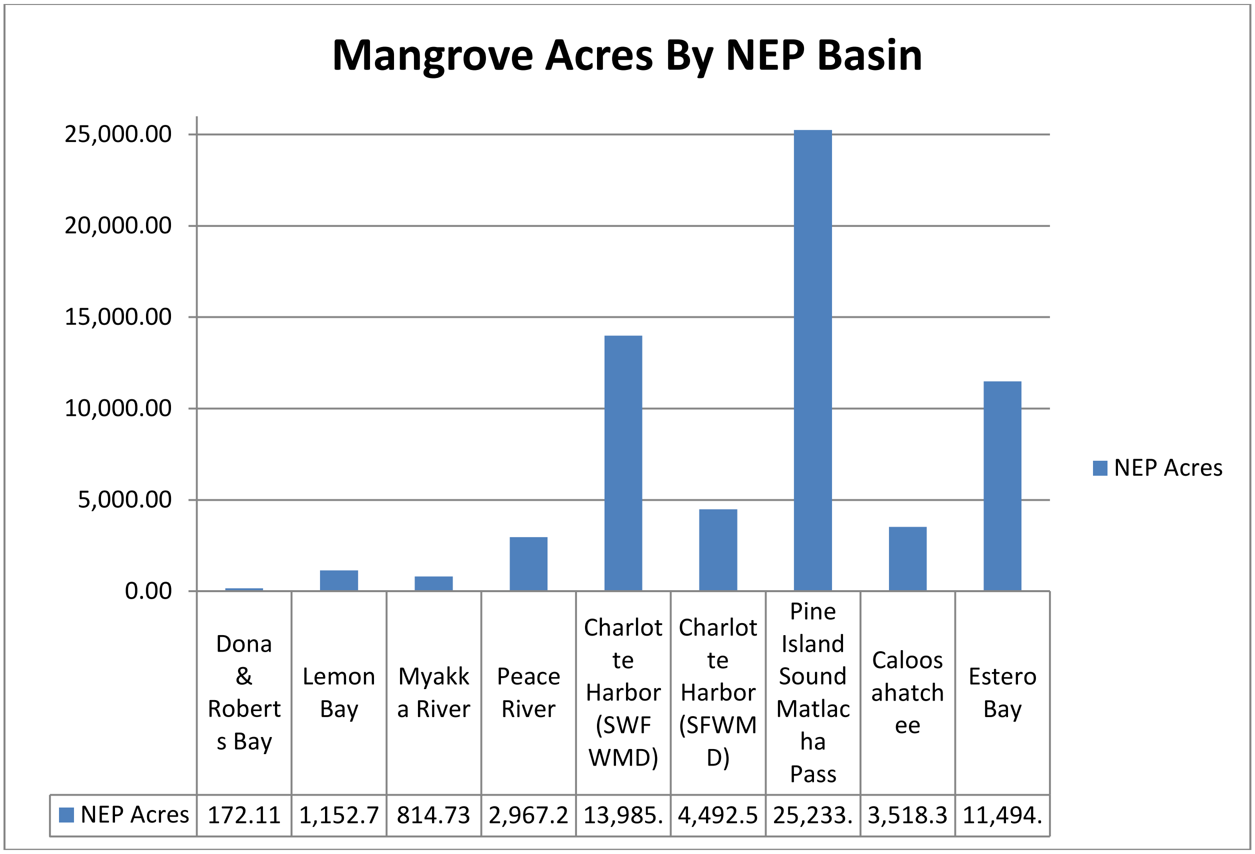



**Figure 2: Mangrove acres by CHNEP watershed. (Beever *et al.* 2011)**


**Figure 3: Mangrove acres of the CHNEP (Beever *et al.* 2011)**

## Mangrove Forest in the CHNEP Study Area

Mangrove Distribution

Mangrove trees are the most dominant emergent vegetation in the CHNEP study area and form a distinctive broad margin around the estuaries of the CHNEP. It was estimated in 2011 that they cover 25,831.8 hectares (63,831.96 acres) and may extend inland several kilometers (miles) from open water (Beever *et.al*. 2011) The four mangrove species found in southwest Florida include red mangroves *(Rhizophora mangle*), which typically inhabit the areas closest to the water's edge; black mangroves (*Avicennia germinans*) that are generally inland of red mangroves, often within a shallow basin; white mangroves (*Laguncularia racemosa*), which are usually landward of black mangroves; and buttonwoods (*Conocarpus erectus*) which occur in areas landward of white mangroves. Mangrove forests occupy the inner, low energy shorelines of the estuary. These trees generally range at maturity from 3.7 to 10.7 meters (12 to 35 feet) in height in the CHNEP study area, but may occur as stunted reproductive morphotypes on tidal flats, such as high marshes, that have elevated salinities.

Mangroves are tropical species restricted by frost and vegetative competition to intertidal regions in tropical and subtropical sheltered waterbodies. Mangroves in the subtropical regions of south Florida represent the northern limits of these tropical species that have been able to colonize because of the warm ocean waters and warm currents along the Florida coastline combined with dependably warm winters (Tomlinson 1986). However, the distribution of mangroves in North America has changed through geologic time. When the red mangrove evolved in the Cretaceous, southwest Florida was a great coral reef in shallow seas. There may have been a few mangroves surrounding small islands and on the coastline in what is currently Georgia. By the Eocene, when black and white mangroves evolved, mangroves extended as far north as South Carolina. During the Pleistocene Ice Ages, mangroves were absent from the Florida coastline and *Spartina* marshes dominated the estuarine intertidal. During the past few centuries mangrove distribution has changed in response to short-term climatic fluctuations. Currently, mangrove distribution is expanding northward in response to a warmer climate. Today black mangroves are now found, albeit in shrub form around the entire Gulf of Mexico shoreline and other mangroves are spreading northward of former limits on both Gulf and Atlantic coasts. Currently over 90 percent of the mangroves in Florida occur in the four southern counties of Lee, Collier, Dade, and Monroe.

The local distribution of mangroves is affected by a variety of interacting factors primarily including microclimate, substrate type, tidal fluctuation, terrestrial nutrients, wave energy, and, salt water, but also by sea level rise and shore erosion, interspecific competition, and seed dispersal. The interrelations of these factors can alter the intertidal distribution of mangrove species.

The availability of fresh water and nutrients influences the location, size, structure, and productivity of mangrove communities in south Florida. Mangroves reach their greatest size and health in southwest Florida where a positive interaction occurs between fresh water, nutrients, and shorelines with low slope and low wave energy. Along parts of the west coast (Charlotte Harbor, Sarasota Bay, and Boca Ciega Bay), mangrove communities support the continued existence of barrier islands against tidal and wave forces. Mangrove communities typically maintain their population to the carrying capacity of the environment (Tomlinson 1986). Associated vegetation usually occurs adjacent to a mangrove community along transition zones, but such associates are not restricted to mangrove communities. Several salt marsh grasses (e.g., *Juncus* spp.) occur with mangroves along transition zones of saline marshes. Smooth cordgrass (*Spartina alterniflora*) communities colonize in bare substrate and disturbed mangrove areas and serve as nurse species for mangrove establishment (Lewis and Dunstan 1975) along with saltwort (*Batis maritima*), but are typically eventually replaced by mangroves (Gilmore and Snedaker 1993, Crewz and Lewis 1991).

Fluctuations in sea-level rise along the Florida peninsula can limit the distribution of mangroves, particularly if the rate of sea level rise exceeds the rate of mangrove forest growth and substrate accretion and if the landward slopes provide no suitable habitat for forest retreat as sea level rises (Wanless 1998). The construction of seawalls behind mangrove forests prevents such shoreline adjustment. This is can be referred to as “coastal squeeze.”

The distribution of mangroves in the Charlotte Harbor NEP study area was compiled from delineation completed in 1988 by the SFWMD and in 1990 by the SWFWMD. The wetlands were delineated from color infrared aerial photographs. A series of maps from these data is presented and described in the following text. These data are currently being updated by both Water Management Districts using photographs made in 1995. This project developed methods to identify and map mangrove distributions by species (including red mangrove, *Rhizophora mangle*, black mangrove, *Avicennia germinans*, white mangrove, *Laguncularia racemosa*, and buttonwood, *Conocarpus erectus*).

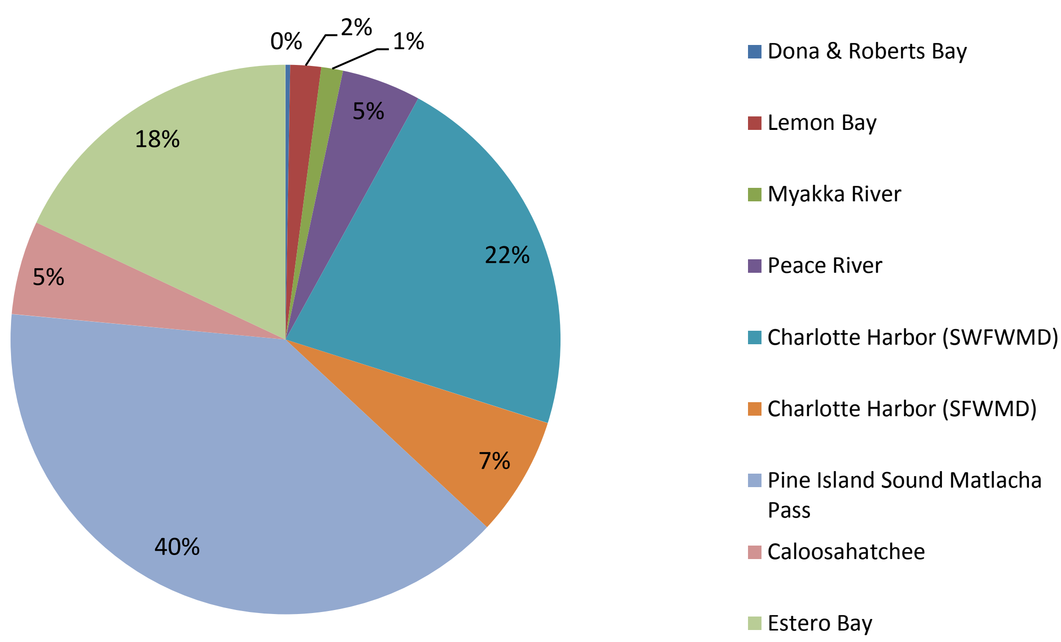



**Figure 4: Proportion of mangrove acres by CHNEP watershed (Beever *et al.* 2011)**

The sense of synonymy for mangroves is unusual in that the same term is used to describe both the individual tree species and the total plant community including the individual tree species. Synonyms for the term mangrove include mangrove forest, tidal forest, tidal swamp forest, mangrove community, mangrove ecosystem, mangal (Macnae 1968), and mangrove swamp. The Florida Land Use Classification and Cover System (FLUCCS) (FDOT 1985) identifies mangroves generally as 612: Mangrove Swamps, and specifically as 6121: Red Mangrove, 6122: Black Mangrove, 6123: White Mangrove, and 6124: Buttonwood.

Mangrove Forest Types

Mangrove ecosystems are a mosaic of different types of forest, with each type providing different physical habitats, topology, niches, microclimates, and food sources for a diverse assemblage of animals. Mangroves have important structural properties including the trapping and, under certain conditions, stabilization of intertidal sediments and the formation of organic soils and mucks, providing protection from wave and wind erosion, provision of a dendritic vegetative reef surface in the subtidal and intertidal zones, and the complex of a multi-branched forest with a wide variety of surface and subsurface habitats.

*Red mangroves* are distinguished by the presence of a dendritic network of aerial prop roots extending from the trunk and drop roots from the lower branches to the soil. The prop roots are important adaptations to living in anaerobic substrates, providing gas exchange, and an anchoring system, as well as absorbing ability. Within the soil, micro-roots stabilize fine silts and sands, maintaining water clarity and quality. Red mangroves may attain heights of 25-38 m (82-125 ft.) in the rich deltas of riverine forests, but average 8-10 m (26-33 ft.) on most fringing shorelines, and occur as smaller trees at their northern extents or in marginal habitats such as the coral rock salt ponds of the Florida Keys. Red mangrove bark is grey and the interior wood red. Red mangroves can form a variety of crown shapes from short continuous scrubby crown to uneven discontinuous crowns. As trees gain size and age and put down large prop root supports, significant lateral as well as vertical growth occurs. This habit of spreading laterally has contributed to the nickname of ”walking trees”. The leaves are shiny, deep green on the top surface with a paler underside. Flowers are small and white with four petals and four bracts, and are wind pollinated. The germinated seed remains attached to the branch while it produces long (25 to 30 cm (10 to 12 inch)) pencil or torpedo-shaped propagules.

*Black mangroves* have distinctive horizontal cable roots that radiate from the tree with short, vertical erect aerating branches (pneumatophores) extending 2-20 cm (1-8 inches) above the substrate. Under hydrologic stress black mangroves produce adventitious roots directly from the trunk of the tree. The trees grow straight and erect attaining heights of 40 m (131 ft.), and averaging 20 m (66 ft.). Black mangrove bark is dark and scaly. Black mangrove leaves are narrow, elliptic or oblong, shiny dark green above and pale, almost cream green with short dense hairs below. The upper surface of leaves can be encrusted with salt excreted by the tree. The bilaterally symmetric white flowers are showy and pollinated by members of the Hymenoptera order of insects, which includes honeybees (Tomlinson 1986). The black mangrove is the source of mangrove honey. The germinated seed produces propagules the size and shape of lima beans (Odum and McIvor 1990). Black mangroves are shade tolerant and sun intolerant when immature, but become shade intolerant with maturation (Snedaker 1982). This produces different growth forms in immature and mature trees, and can result in mature black mangroves being overtopped or shaded by adjacent mangroves, landward trees, exotic vegetation or structures (Brown *et al.* 1988).

*White mangroves* grow either in tree form or shrub form up to heights of 15 m (50 ft.) or more. The growth form tends to be erect. Some white mangroves form erect, blunt-tipped pneumathodes (Tomlinson 1986) if growing in anaerobic or chemically stressed soils. White mangroves may also produce lateral adventitious roots directly from the main stem if hydrologically stressed. White mangrove bark is light colored and relatively smooth. Leaves are fleshy, flattened ovals with rounded ends. The same pale green color is on both upper and lower surfaces. Two glands that excrete nectar and are called extrafloral nectaries are found at the apex of the petiole. Small yellowish flowers are found in alternate rows on the terminal ends of branches. These germinate small (1-1.5 cm (0.4-0.6 inch)), football-shaped propagules. In the northern part of their range, white mangroves may not propagate on the tree and true propagules are not formed.

*Buttonwoods* grow to 12-14 m (40-46 ft.) in height in a shrub or tree form, but do not produce true propagules in Florida (Tomlinson 1986). Buttonwood bark is grey and very furrowed, providing attachment sites for epiphytes. Leaves are thin, broad to narrow, and pointed. There are two morphotypes: the green buttonwood, with medium green leaves, found on peninsular Florida; and the silver buttonwood, with pale pastel green leaves, historically limited to the Florida Keys but now widespread by nursery practices. It is thought the silver buttonwood is an adaptation to the rocky, dry habitats associated with the islands. Two alternate glands that excrete extra floral nectar are found at the apex of the petiole. Tiny brownish flowers are found in a sphere on the terminal ends of branches. These produce a seed cluster known as the “button.” Buttonwoods are able to grow in areas seldom inundated by tidal waters. The mangrove adaptations to the osmotic desert of salt water also allowed buttonwoods to utilize arid areas of barrier islands and coastal strands. Because of its landward range and intolerance of anaerobic soils, the buttonwood is legally considered a wetland plant, but not a mangrove in Florida Statutes.

All four mangrove species flower in the spring and early summer. Propagules fall from late summer through early autumn.

Mangrove forest canopy heights depend upon climate; particularly freeze limits, topography, substrate type and the extent of human disturbance, with undisturbed mature mangrove communities having a continuous canopy that is high, dense and complex, whereas in naturally disturbed mangrove areas, the canopy is lower with more irregular growth (Tomlinson 1986). Dense mangrove forests do not typically have understory plant associations, except for mangrove seedlings.

Areas of tree fall or other openings in the canopy provide opportunity for other halophytic plants and young mangroves to flourish in the newly available sunlight. Mangrove associates, including up to 30 species of vascular plants, occur in transitional areas with mangroves, but are not restricted to mangrove communities. Several salt marsh grasses (e.g., *Juncus*, *Sporobolus, Distichlis littoralis, Distichlis spicata*) and succulent herbs (*Salicornia, Sesuvium, and Batis* spp.) occur with mangroves along transition zones of saline marshes. Smooth cordgrass (*Spartina alterniflora*) communities often colonize bare emergent areas with or without nearby mangrove roots, but are eventually displaced by mangrove shadowing (Gilmore and Snedaker 1993, Lewis and Dunstan 1975). This species has been characterize as a “nurse” species that appears to facilitate mangrove establishment on bare mud or sand surfaces such as dredged material deposits (Lewis and Dunstan 1975).

## Mangrove Community Types

Six mangrove community types have been characterized based on their different geomorphic and hydrological processes (Lugo and Snedaker 1974).

*Overwash mangrove forests* are islands frequently inundated, or over-washed, by tides resulting in high rates of organic matter deposition and usually containing red mangroves of a maximum height of 7 m (23 ft.). *Fringe mangroves* form thin forests bordering water bodies with standard mangrove zonation, attaining maximum height of 10 m (33 ft.).

*Riverine mangroves* are in the flood plains and along embankments of tidal creeks and rivers but are still flooded by daily tides. Red, black, and white mangroves are usually present, and the canopy layer can reach heights of 18-20 m (60-66 ft.).

*Basin mangrove forests* occur in depressions along the coast and further inland that collect precipitation and sheetflow and that are tidally influenced. These forests can attain heights of 15 m (50 ft.). Red mangroves are more common along the coastal areas, while blacks and whites dominate further inland. Influences from daily tides decrease further inland. In areas where salinity is concentrated by evaporation and major tidal flushing occurs seasonally, black mangroves dominate.

*Hammock forests* grow on higher elevated, typically highly organic ground, and rarely exceed 5 m (16 ft.) in height. These are often surrounded by other wetland types, both freshwater and salt water marsh, and may be historical islands.

*Scrub or dwarf forests* are found in peninsular south Florida and the Florida Keys and rarely grow taller than 1.5 m (5 ft.), which may be a result of fewer available nutrients on rocky substrates. Two contrasting conditions produce these forests: low-nutrient, oceanic-salinity waters, as in the Keys, and, the most landward, frost-cropped edges of forests, as at the landward limits of the mangrove forest adjacent to high marsh.

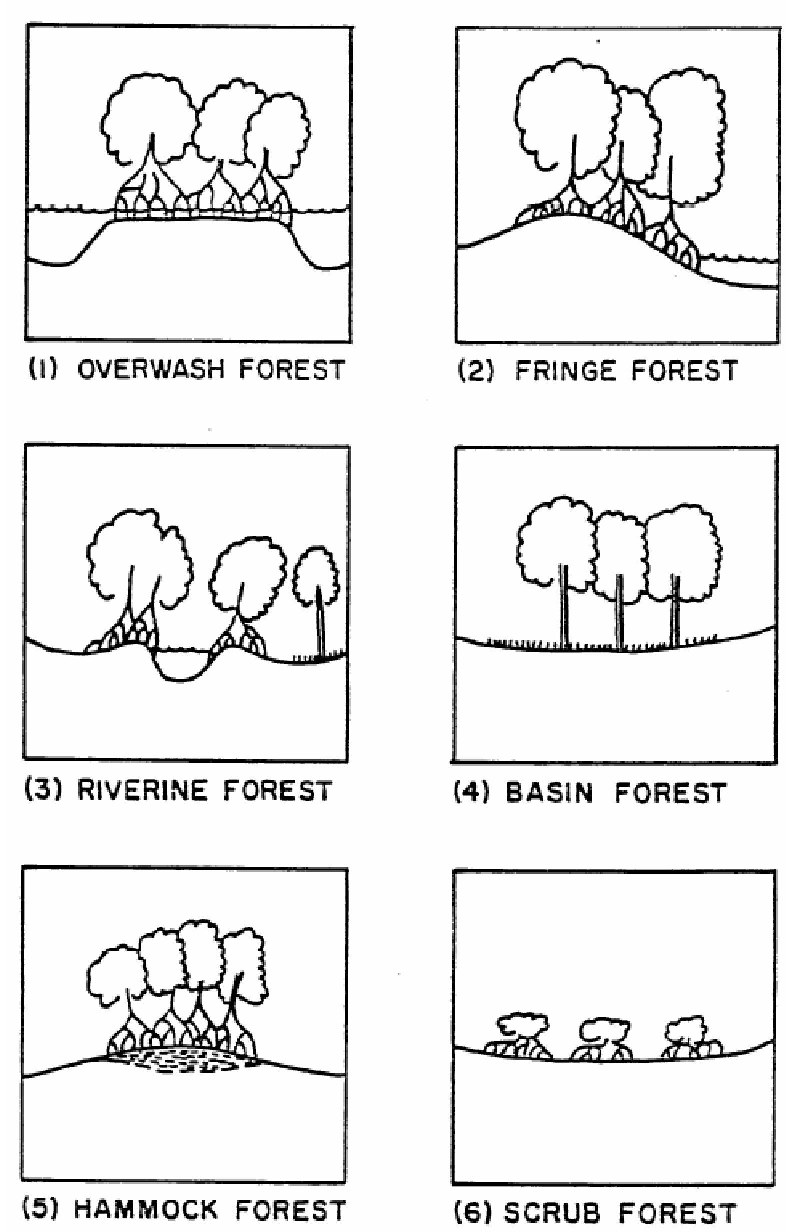



**Figure 5: The Six Mangrove Communities (redrawn by Harris *et al.* 1983 from Odum *et al.* 1982, after Lugo and Snedaker 1974.)**

The process of propagule dispersal, sorting, and colonization is highly variable and is influenced by a variety of physical and biological factors which may contribute to the zonation of mangroves (Rabinowitz 1978b). Vegetative dispersal and establishment is accomplished mainly through propagules. Dispersal of mangrove propagules is primarily accomplished by water currents and tides. Although propagules can be carried to a variety of areas, often mangroves are established only for the short term in sub-optimal, inhospitable areas which have high fetch, shallow soils, high wave action or other environmental stresses, and thus eventually disappear.

Mangroves are considered pioneer species because of their ability to establish on otherwise unvegetated substrates. Once individuals begin to colonize a disturbed area, same-age communities are established with little variance in the structure because new development of successive colonizers is arrested by the closed canopy. This process may be facilitated by other pioneer "nurse species" such as smooth cordgrass or saltwort.

The standard zonation of mangroves consists of red mangroves in the lower and middle intertidal zone, black mangroves in the upper intertidal areas that are occasionally flooded and white mangroves in patches on higher elevated grounds that are less frequently flooded. Buttonwoods are located further inland in areas that are within the limits of the highest tides (Tomlinson 1986). This pattern can be found on low-slope shorelines with low wave-action, organic soil, even salinity gradient, warm water, and sheet flow delivery. However, mangrove zonation is often more complex and mixed forests of red, black, white , and buttonwoods are the most frequently observed type of mangrove fringing zonation in the CHNEP study area.

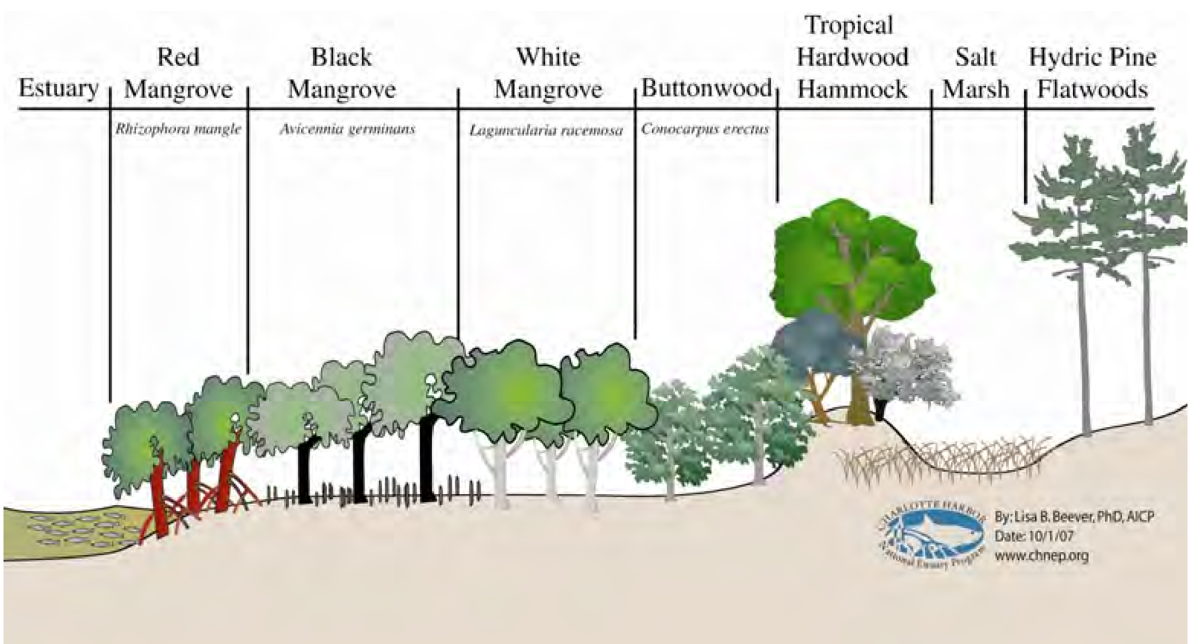



**Figure 6: Diagrammatic cross-section of the hypothetical mangrove fringing forest zonation in the CHNEP system as predicted by literature. (Beever *et al.* 2011)**

Historically, succession theory viewed red mangroves as the younger colonizing or pioneer stage which was located more seaward, with black and white mangroves as more mature stages located more landward, and adjacent tropical hardwood forests as the climatic stage (Davis 1940). Mangrove forests were considered different than other vegetative communities in not experiencing traditional plant succession, but replacement succession primarily as a function of sea level rise, where mangroves must either keep up with the rise in sea level or retreat from rising water levels. On shorter time scales, the community was thought to experience fluctuations in habitat type and species composition as a result of changes in such factors as hydrologic pattern. Current thinking, however, now considers mangrove distribution and zonation within and between forests to be the result of a variety of edaphic and site-specific historical factors. The determinate factors can be very different in different locations (Rabinowitz 1978).

Mangroves can grow on many different types of substrates and can affect their substrate through peat formation and altering sedimentation. Mangroves are found on fine inorganic muds, muds with high organic content, peat, sand, rock, coral, oysters and some man-made surfaces if there are sufficient crevices for root attachment. Mangroves grow better in areas of low wave energy along shorelines, river deltas, and flood plains where fine sediments, muds, and clays accumulate and peats will form (Odum *et al.* 1982). Fluctuating tidal waters are important for transporting nutrients, controlling soil salinities, and dispersing propagules. Mangroves are richer along coasts with high levels of rainfall, heavy runoff, seepage, and a resultant increase in sedimentation which provides a diversity of substrate types and nutrient levels higher than that of sea water (Tomlinson 1986). Red, black, and white mangroves can grow in completely anaerobic soils (Lee 1969) but are limited to tidal inundation periods of approximately 30% with intermittent exposed periods of approximately 70% of the time (Lewis 2005). Black mangroves grow best in soils of high salinity. Red mangroves grow best in areas of estuarine salinity with regular flushing. White mangroves grow best in areas with freshwater input on sandy soils. Mangroves have a harder time surviving in soils with salinities of 70-80 ppt. (Day *et al.* 1987). Red mangrove is limited by soil salinity above 60 to 65 ppt. (Teas 1979). White mangroves grow stunted at 80 ppt. and black mangroves can grow at soil salinities of up to 90 ppt.

Mangroves can modify soils by organic contributions and peat formation particularly in southwest Florida and the north shoreline of Florida Bay. This peat appears to be primarily from red mangrove root material and can reach thicknesses of several meters. Mangrove peat has a low pH (4.9 to 6.8). When mangrove soils are drained by human activity they may experience dramatic increases in acidity due to oxidation of reduced sulfur compounds in the formerly anaerobic soils. This creates “cat clays” (pH 3.5 to 5.0) that can kill all vegetation, including the mangroves.

Mangroves are facultative halophytic species. Salt water is not required for growth. Mangroves are limited to areas that have partial inundation of brackish or saline water as noted above and cannot persist solely in fresh water principally as the result of interspecific competition from much faster growing freshwater wetland plants but including intolerance of long periods of inundation. Salinity is addressed by salt exclusion and storing salt in the red mangrove or salt-secretion in black and white mangroves, and the buttonwood.

Mangroves are able to grow in a wide variety of surface waters in a range of salinities from 0 to 40 ppt. Coastal salinities generally range from 18 to 30 ppt. throughout southwest Florida, except in parts of the Caloosahatchee River that experience hypersaline conditions of over 40 ppt. when the flow of freshwater is denied by lock closures and in isolated back bays.

Inland from the fringe, the mangrove forest intermixes with salt marsh species and provides habitat to organisms that can withstand changing water levels. Common salt marsh species found in this ecotone are saltwort (*Batis maritima*), perennial glasswort (*Salicornia virginica* or *Sarcocornia ambigua*), and saltgrass (*Distichlis spicata*). As water levels change with daily tides and seasonal influences, the organisms here migrate to adjacent permanent water habitats. This area is an important foraging area during periods of low water because organisms become concentrated in small pools of water, making it easy for predators to capture prey. Juvenile endangered wood storks are especially dependent on these conditions.

Further inland, the mangrove forests mix with tropical hardwood hammock species. Organisms rely on the arboreal and terrestrial components of this transition community. Commonly associated hardwood species include cabbage palms (*Sabal palmetto*), Jamaica dogwood (*Piscidia piscipula*), West Indian mahogany (*Swietenia mahagoni*), stopper (*Myrtus verrucosa*), poison wood, black bead (*Pithecellobium keyense*), and gumbo limbo (*Bursera simaruba*) (Shromer and Drew 1982). The transition between these two adjacent communities provides an important ecotone, where species can take advantage of resources from both communities. Mammals and reptiles move from the hardwood forests to feed in the mangrove community.

The lower reaches of tidal river mouths display a mixture of mangrove and salt marsh vegetation. Further upstream the less saline admixture of upland watershed drainage combined with estuarine waters provides a euryhaline zone which can support up to 29 species of vascular halophytic plants. In this ecotone between mangroves/salt marsh and the freshwater wetlands, the dominant plant species change in response to seasonal variations in salinity, water volume, air and water temperature, nutrient loading and grazing pressures. Diversion of fresh water by unnatural water control and water withdrawal projects and activities shifts plant species composition in favor of more salt tolerant plants. The gross productivity of riverine wetlands increases when surface freshwater input increases; however net production decreases because of osmoregulatory stress. The new productivity is optimal at medial salinity. In these moderate to low salinity waters, a wide variety of plant communities can develop, depending on sediment, elevation and season. Widgeon grass, a submerged grass tolerant of wide salinity changes, vegetates sandy shallow channels, providing habitat for fishes and invertebrates in similar fashion to sea grasses. River banks support a variety of emergents, including mangroves, three squares and bulrushes, fringe rushes, *Juncus* rushes, spikerushes, cattails, giant reed, leather fern, saltgrass, knotgrass, cordgrasses, asters, pinks, coastal water hyssop, and many of the salt marsh herbs. The health of the mangrove estuary depends upon the health of its tributaries and headwaters. If the riverine wetlands are destroyed, the creeks channelized, and the water quality degraded in the watershed external of the boundaries of the mangroves, it is not possible for the mangroves to retain their total fishery and wildlife habitat values.

## Mangrove Productivity and Ecosystem Functions

Productivity:

Biomass is the amount of living matter in a given habitat, expressed either as the weight of organisms per unit area or as the volume of organisms per unit volume of habitat. Measures of mangrove biomass vary with age, dominant species, and locality. Healthy mangroves often accumulate large amounts of biomass in their roots, and the above-ground biomass to below-ground biomass ratio of mangrove forests is significantly low compared to that of upland forests (ANCOVA, $P < 0.01$) (Komiyama *et al*. 2008).

Studies of south Florida estuarine food webs have found that 85% of the detrital food base and the dissolved organic matter food base is from mangroves (Honde and Schekter 1978 and Lewis *et al.* 1985). Detritus is dominantly leaves but also includes leaf and propagule stalks, small twigs, roots, flowers and propagules. These are fragmented by processors into detritus, decaying organic material coated with and created by algae, fungi, bacteria and protozoa. This detritus is further fragmented, consumed and excreted by a number of primary consumers dominated by small crustaceans. The leaf base material itself is not directly consumed, but the algae, fungi, bacteria and protozoal biomass on it is. This results in the excretion of a smaller detrital particle which again becomes the base for a detrital garden of microorganisms. This process is repeated many times utilizing the detrital particle to its full nutritive value to the estuarine ecosystem. Eventually the particle attains a small enough size for use by filter feeders and deposit feeders. Entire stems and large branches are not available to this system directly but have to be processed by a much slower system of marine and terrestrial borers and slow decay.

Ecosystem Functions:

The relationship between mangroves and their associated marine life in South Florida cannot be overemphasized. Tree stems and branches provide nesting sites, hunting perches, and protection for a very diverse group of arboreal arthropods, such as mangrove tree crabs and mangrove skipper butterflies, and estuarine birds including roseate spoonbills, white ibis, wood storks, heron species, egret species, pelican species, ospreys, and bald eagles. The complex structure of prop roots, pneumatophores and stems provides living spaces for numerous periphytic and epifaunal organisms, topological structures for a rich invertebrate fauna, shade for thermoregulation, and cover from predation for large populations of small fishes, nektonic and benthic crustaceans, annelids, mollusks, and echinoderms. This combination of shelter and food source makes the mangrove forest a rich nursery and feeding ground for the juvenile and adult forms of many commercially and ecologically significant species of fish and other vertebrates. Many animals associated with mangroves, oyster bars and open unvegetated waters by day, such as pomadasyid fishes, forage in seagrass beds at night. Many estuarine fishes spend their early life in mangroves and then move as adults to complete life cycles in sea grass habitats. Species associated with prop roots include 74 species of epiphytic algae (Rehm 1974), eight species of crabs, nine species of polychaetes, plus 22 other species of invertebrates (Courtney 1975).

Mangrove forest tidal creeks provide both aquatic organisms from nearby oceanic or estuarine habitats and resident small forage fish species with access to the mangrove wetland forest floor on high tides, and refuge on low tides within the creek beds themselves. A multitude of predatory birds, fish, crustaceans, mollusks, reptiles, and mammals use this avenue to hunt and capture the abundance of available prey. Several endangered, threatened, and rare species use tidal creeks such as the common snook (*Centropomus undecimalis*), green sea turtle (*Chelonia mydas*), American crocodile (*Crocodylus acutus*), American alligator (*Alligator mississippiensis*), and the herbivorous West Indian manatee (*Trichechus manatus latirostrus*).

The economic importance of mangroves to the state is significant. According to Bell *et al.* (1982), during 1980-1981, 5.25 million recreational and saltwater anglers spent 58.5 million angler days fishing and generated over $5 billion in direct and indirect income to the state economy. The monetary value of 4.7 tons of mangrove litter has been estimated by Leaird (1972) at $4,000 per acre per year, using the conversion rate of $1 = 10,000 kilocalories. Evaluation of mangroves in Lee County, utilizing conservative estimators, found that a mature 6 meter (20 ft.) tall canopy of red mangrove forest contributed $2,040.54 per year in commercial fisheries landings in 1970 dollars, not adjusted for inflation. These values do not reflect recreational fisheries values which are from 5.6 to 6.5 times the primary sales of commercial fisheries (Lewis *et al.* 1982). Nor do they include the erosion protection value, the tourist income generated from tours, bird watching, canoeing and recreational non-fishing boating in mangrove estuaries, the water quality enhancement of point and non-point sources of water pollution, the privacy screen value and habitat value of these mangroves to endangered and threatened species. In kind replacement value of a dead mature red mangrove is in the thousands of dollars. One nurseryman gave a cost estimate of raising a red mangrove from seedling to age 15 then transplant of over $11,000, with survival as low as 30% (David Crewz, DNR pers. comm.). Total replacement cost for 1 acre of dead mangroves to age 15 would be approximately $4.4 million.

## Mangrove Forest Death and Mangrove Forest Heart Attacks

Mangrove ecosystems are susceptible to both natural and human induced impacts leading to death. Large hurricanes are the primary natural factor that can cause excessive damage. The structure of mangrove forests is influenced by the presence or absence of hurricanes. Forests that experience high frequency of hurricanes have more simple structures than those with few or no hurricanes.

The two natural forces that may negatively impact mangrove forests, and which, due to exacerbating activities of human, may need human management intervention, are hurricanes and sea-level rise.

Extensive, periodic damage to mangrove ecosystems from large hurricanes is part of the environment that this system evolved with. Hurricane Donna in 1960 created extensive damage over an area exceeding 40,500 ha (100,000 acres) with 25% to 100% loss of mature trees (Craighead and Gilbert 1962). Mangroves were killed by direct shearing at 2 to 3 m (6 to 10 ft.) above the ground, complete wash-outs of overwash islands, and obstruction of air exchange through prop roots and pneumatophores by coatings of marl, mud and organics over the lenticels. The burial of these aerial roots was the largest cause of death. The entire aquatic system was subsequently negatively affected by the oxygen depletion caused by the decomposition of large amounts of dead organic material (Tabb and Jones 1962). Lugo *et al.* (1976) have hypothesized that severe hurricanes occur in South Florida on intervals of 25 to 30 years and that the ecosystem has adapted to this cycle by reaching maturity in the same cycles.

The two main human-caused changes affecting mangrove communities today are the effects of urbanization, and the alteration of fresh and saltwater hydroperiods by water management practices. Man can alter the distribution and structure of mangrove communities through direct destruction by cutting and by dredge and fill activities.

In Florida it is likely that more mangroves have been killed by diking, impounding, and permanent flooding of the aerial root system than by any other activity except, perhaps, outright destruction through dredge and fill Any activity that covers the root systems with water or mud for a long period will kill the trees by preventing oxygen transport to the deeper roots (Odum and Johannes, 1975; Patterson-Zucca, 1978; Lugo, 1981, Lewis *et al*. 1985, Brockmeyer *et al*. 1997). Restriction of tidal circulation with causeways and undersized culverts can also damage stands of mangroves, particularly if salinities are lowered sufficiently to allow freshwater vegetation to flourish and the flooding regime is increased. Alterations in the natural fresh water flow regime through diking, impounding, and flooding activities in order to control mosquitoes and build waterfront structures affects the salinity balance and encourages exotic vegetation growth. As a result of changing natural sheet flow, mangroves have experienced a change in water and soil salinities.

Australian pine tree and Brazilian pepper are two exotic plant species that invade the fringes of mangrove communities as a result of changes in water flow.

Two factors render mangroves susceptible to certain types of pollutants. First, because they are growing under metabolically stressful conditions, any factor that further stresses the tree may be potentially fatal. Second, their modified root systems with lenticels and pneumatophores are especially vulnerable to clogging (Odum and Johannes, 1975).

All mangrove tree species are particularly susceptible to herbicide damage (Walsh *et al*. 1973; Tschirley, 1969; Orians and Pfeiffer, 1970; Westing, 1971; and Odum *et al*. 1974.) As was discovered in South Vietnam, many species of mangroves are highly susceptible to herbicides. At least 100,000 ha of mangroves were defoliated and killed by the U.S. military actions (Walsh *et al*, 1973). In Florida, Teas and Kelly (1975) reported that black mangroves are somewhat resistant to most herbicides but that red mangroves are extremely sensitive. The red mangrove is particularly sensitive due to the small reserves of viable leaf buds. The stress of a single defoliation can be sufficient to kill the entire red mangrove tree.

Although mangroves are not negatively affected by highly eutrophic waters, they can be killed by heavy suspended loads of fine, flocculent material. These can come from untreated sugarcane wastes, pulp mill effluent, and ground bauxite and other ore wastes (Odum and Johannes, 1975).

Petroleum and its by-products pose a particularly serious threat to mangroves. Crude oil kills mangroves by coating and clogging pneumatophores; severe metabolic alterations occur when petroleum is absorbed by lipophylic substances on mangrove surfaces (Baker, 1971). Lewis (1980), de laCruz (1982) and Duke (2016) present reviews of the effects of oil spills in mangrove ecosystems. Damage from oil spills has been documented and reviewed by Odum and Johannes (1975), and Carlberg (1980). Petroleum oils and by-products kill mangroves by coating aerial and submerged roots and by direct absorption by lipophyllic receptors on the mangrove. This leads to metabolic dysfunction from destruction of cellular permeability and dissolution of hydrocarbons in lipid portions of chloroplasts (Baker 1971). Attached fauna and flora are killed directly. Effects are also long-term and require years to complete. Some severe effects, including tree death can take place months or years after a spill (Lewis 1979a, 1980b). Little can be done to prevent damage once it has occurred. Common dispersants used to combat oil spills are toxic to vascular plants (Baker 1971). Damage from the actions of mechanical abrasion, trampling, compaction during cleanup can add rather than remove negative environmental impacts. Where oil drilling has occurred in association with mangrove shorelines significant adverse impacts have occurred (Longley *et al.* 1978).

Over the years, dredge-and-fill operations have reduced mangrove habitat in the CHNEP study area by about 25% (Beever *et al*. 2011). In addition to direct loss, urban and agricultural runoff changes water flows to interfere with the beneficial functions performed by mangrove systems. The high cost of developing mangrove habitat is ultimately paid by taxpayers in terms of flood damage, shoreline erosion and water quality corrections. Despite increased regulation, cutting and trimming, impounding, and hydrologic alteration continues to threaten mangroves.

The loss of mangrove productivity to Florida estuarine food chains is well documented for certain locations. Since the early 1900's, mangrove communities in south Florida have steadily disappeared (Snedaker *et al.* 1990). As of 1974, there were approximately 190,000 ha (469,500 acres) of mangroves remaining in Florida (Coastal Coordinating Council 1974). Northern Biscayne Bay has lost 82% of its mangrove acreage (Harlem 1979). Along the Indian River Lagoon, 92% or 13,083 ha (32,000 acres) of red and black mangroves was impounded for mosquito control between 1955 and 1974 (Gilmore and Snedaker 1993). In the Tampa Bay area, 44% of the tidal vegetation, including mangroves, was destroyed through dredge and fill activities over a 100 year period (Lewis *et al.* 1979). Lee County has lost 19% of its original mangroves (Estevez 1981). In the upper Florida Keys, over 15% or 8,306 ha (20,500 acres) of the original mangrove forests were cleared for residential and commercial construction purposes by 1991 (Strong and Bancroft 1994).

Statewide estimates vary on total mangrove loss. Conservative values of 3 to 5% were derived by Lindall and Saloman (1977). More recent work which includes destruction up to the time of Lindall and Saloman indicates a 23% statewide loss (Lewis *et al.* 1985). This value includes areas of mangrove area expansion such as Charlotte Harbor where there has been a 19% increase due to conversion of high marsh and salt flats through mosquito ditching.

While the effects of mangrove trimming, if performed properly in limited view windows, on productivity would be difficult to measure, the effects of mangrove hedging and improper trimming can be substantial, with losses of 8.6 tons of carbon/hectare/year when a 6 meter (20 foot) tall canopy is reduced to 1.5 meters (5 feet) in height. In an urbanized aquatic preserve where the majority of the shoreline could be subjected to hedging, this could result in a local loss of approximately 87% of the annual productivity of the mangrove ecosystem. At Key Biscayne Golf Course in 1979, one acre of mature Coastal Band red mangroves were pruned to a height of

1.8 to 2.4 meters (six to eight feet) to provide a better view from the Golf Course restaurant. Within six months almost all of these trees were dead (Dade County Environmental Resource Management 1982).

A comparison of cut and adjacent natural mangrove fringes in seven of the eight Southwest Florida aquatic preserves was performed, utilizing standardized methods of measurement of mangrove productivity including standing crop (Heald 1971, Teas 1979, Pool *et al* 1975); and leaf parameters (Beever *et al* 1979, Twilley and Steyer 1988). Statistically significant reduction in net primary productivity export (83%), reduction of standing leaf crop (71%), reduction of flower production (95%), reduction of propagule production (84%), and reduction of leaf clusters (70%) resulted from the cutting of the 4.9 meter (16.1 feet) tall fringing red mangrove to 1.7 m (5.4 feet). Similarly, reduction of net primary productivity export (72%), reduction of standing leaf crop (49%), reduction of propagule production (73%), and reduction of terminal branches (45%) resulted from cutting a 3.4 meter tall fringing white mangrove area to 1.3 m. Habitat utilization by associated large visible fauna was significantly reduced (79%) by mangrove trimming. For the parameters measured, no net positive benefit of mangrove trimming/cutting could be confirmed. The documented evidence of this study and existing literature (1989, Twilley and Steyer 1988) indicate that mangrove cutting is deleterious to the estuarine environment; the mangrove trees themselves, and the fauna which depend upon mangroves for habitat and primary production (Beever 1996).

Sudden and chronic die-offs of mangroves and other saltwater wetlands can be common in Florida. Most are small and can be attributed to natural events such as lightning strikes and freezes from cold fronts. Of greater concern, are larger mortality areas, often covering hundreds of acres with adjacent areas showing stress and long term trends indicating little or no natural recovery, and expansion of the die-off to potentially thousands of acres (Lewis 2013, USFWS 20. Robin Lewis (2014) and Lewis *et al*. (2016) refer to these events as “mangrove forest heart attacks.” Sea level rise impacts combined with anthropogenic changes in mangrove forests in Florida appear to be contributing to these events. Lewis (2014) reported to the CHNEP TAC three documented die-offs ranging in size from less than an acre to over 200 acres at three locations in Florida: Tampa Bay, Clam Bay near Naples, and within the Rookery Bay National Estuarine Research Reserve (RBNERR) in Collier County. All have been monitored for hydrologic changes, and the Clam Bay site and RBNERR site have undergone some restoration. The Tampa Bay site is currently being restored.

Proper diagnoses of hydrologic modifications that lead to mangrove death due to extensive long term flooding is essential. Treatment through hydrologic restoration, not just planting of saltwater wetlands, is also essential once mangrove deaths are noted. However, preemptive restoration of tidal flows prior to large scale mangrove deaths is the preferred and more cost-effective alternative. Ecological functions could theoretically be returned quickly to baseline conditions with preemptive restoration instead of waiting for visible deaths of trees, and then an expensive multi-decadal restoration effort (Lewis *et al*. 2016).

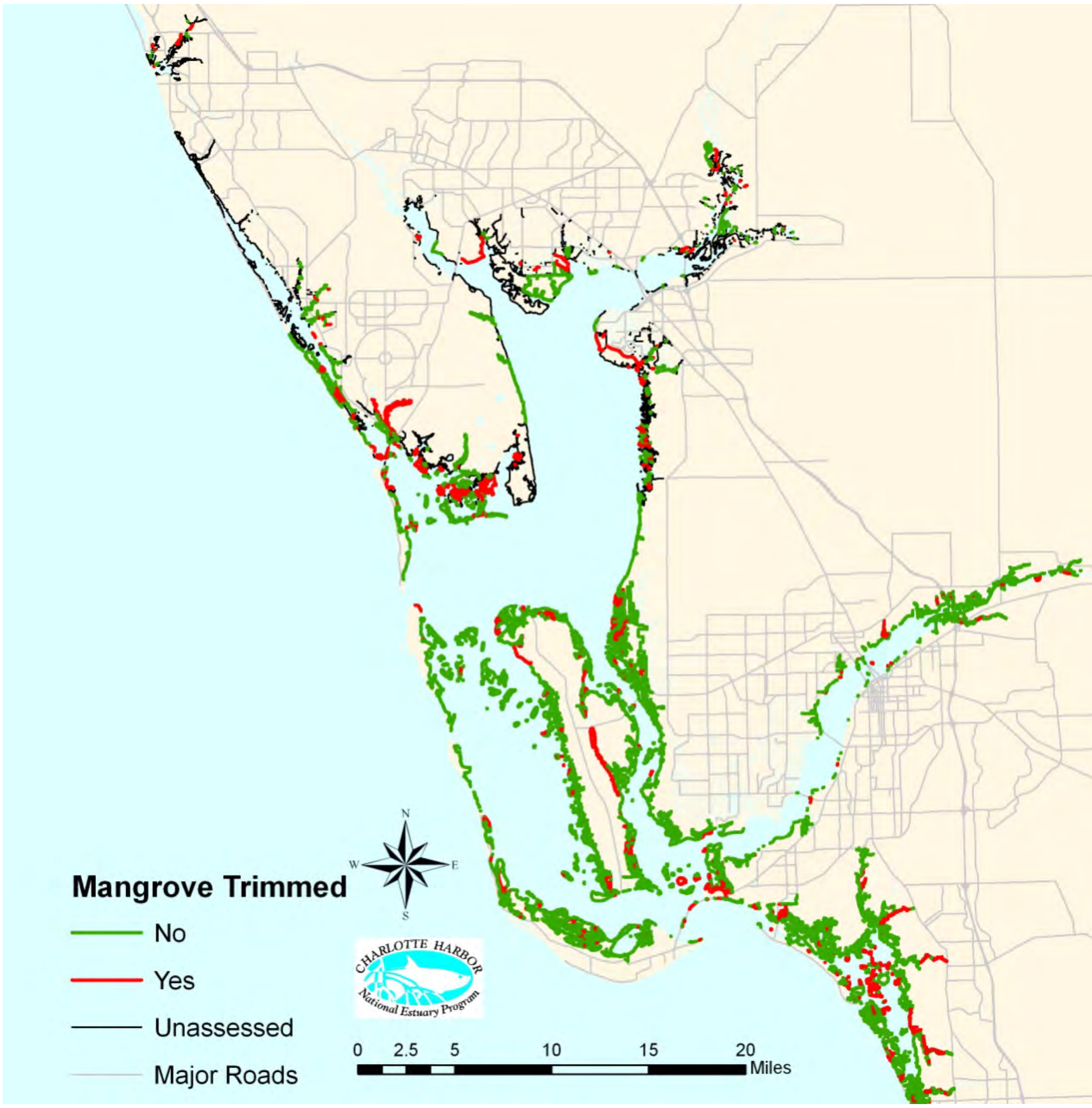



**Figure 7: Location of mangrove trimming in the CHNEP Study Area**

Mangrove trimming has been regulated by Florida statue since 1995, with implementation by administrative code rule. The statute gives the FDEP authority to regulate Professional Mangrove Trimmers. In addition homeowners are authorized to conduct trimming under certain circumstances. The level of compliance with mangrove trimming permitting rules in Florida is low (20% since Chapter 17-27 F.A.C. was implemented) and violations significantly outnumber permitted projects (Beever and Cairns 2002; USFWS 1999). Enforcement staffing levels of FDEP field personnel for south Florida averages one compliance staff person per seven counties and one enforcement staff person (independent of permitting) per 3.5 counties. This staff is responsible for all FDEP compliance and violations for all permits in all wetlands in FDEP jurisdiction. As a result, the ability of FDEP staff to concentrate on and the time allotted to mangrove trimming violations is small compared to the extent of the resource and the number of permits and enforcement cases.

Karst and Acidification

The underlying geology of coastal southwest Florida including the CHNEP is karstic. Karst topography is a landscape formed from the dissolution of soluble rocks which in Florida is the limestone laid down by millions of years of deposition and coral reef formation that makes-up the basement rock for the region. As limestone is dissolved by acidic waters the topography is characterized by underground drainage systems with sinkholes and caves. The development of karst occurs whenever acidic water starts to break down the surface of bedrock near its cracks, or bedding planes. As the bedrock limestone continues to break down, its cracks tend to get bigger. As time goes on, these fractures will become wider, and eventually, a drainage system of some sort may start to form underneath. If this underground drainage system does form, it will speed up the development of karst arrangements there because more water will be able to flow through the region.

The carbonic acid that causes these features is formed as rain passes through the atmosphere picking up carbon dioxide ($CO_2$), which dissolves in the water. Once the rain reaches the ground, it passes through soil that can provide much more $CO_2$ to form a weak carbonic acid solution, which dissolves calcium carbonate. The peat formed by mangrove detrital accumulation is characteristically acidic and can add significant acidity to pore water in the soils. When mangrove peats become anoxic there is a formation of sulfides which accumulate from the estuarine waters since it is excluded from the mangrove roots by selective permeability. The oxidation of sulfides leading to the formation of sulfuric acid is also be one of the corrosion factors in karst formation. As oxygen ($O_2$)-rich surface waters seep into deep anoxic peats above karst systems, they bring oxygen, which reacts with sulfide present in the system ($H_2S$) to form sulfuric acid ($H_2SO_4$). Sulfuric acid then reacts with calcium carbonate, causing increased erosion within the limestone formation.

These natural processes create, through time, depressions ion in anoxic mangrove areas that cause karst collapse that can become depressions and ultimately open water ponds and pools typically with a circular configuration. These resemble sinkholes or cenotes (closed basins) but with the water surface at the top of the depression because the feature is formed at sea-level not at a higher upland elevation.

Increased acidity in precipitation from the burning of vegetation and fossil fuels can increased the acidity available to dissolve limestone. One of the consequences of global warming from fuel combustions, trash and debris incineration, and agricultural burning is increasingly acid rain with acidification of fresh, estuarine and marine waters. For more than 200 years, or since the industrial revolution, the concentration of carbon dioxide ($CO_2$) in the atmosphere has increased due to the burning of fossil fuels, trash, land clearing, and agricultural practices. The oceans and other waters absorb about 30 percent of the $CO_2$ that is released in the atmosphere, and as levels of atmospheric $CO_2$ increase, so do the levels in the waters. When $CO_2$ is absorbed by water, a series of chemical reactions occur resulting in the increased concentration of hydrogen ions. This increase causes the water to become more acidic and causes carbonate ions to be relatively less abundant. This can accelerate the natural limestone dissolution process in mangrove systems.

Additionally it is expected that the changing climate along the Gulf Coast combined with such activities as dredging, constructing reservoirs, diverting surface water, and pumping groundwater could accelerate local subsidence and sinkhole formation in areas underlain by limestone (Twilley *et al.* 2001). Carbonate sediment dissolution will accelerate as rain and surface waters pH decreases (Orr *et al*. 2005).

The net results of these processes are areas of open water without mangrove forest where in the past mangrove forest had existed. These locations are not restorable since subsidence creates water depths too deep for mangrove reestablishment.

## Salt Marshes of the CHNEP Study Area

Salt marshes are communities of emergent halophytic (salt tolerant) vegetation, periphytic and floating algae, and/or included bare soils in areas alternately inundated and drained by tidal action, often daily but at the extreme seasonally.

Salt marsh community types are characterized by differences in their dominant vegetation, location, and tidal interaction and have been described as low marsh, high marsh, cordgrass marsh, *Spartina* marsh, *Salicornia* marsh, *Juncus* marsh, salt pan, tidal marshes, and transitional zone. The general term "salt marsh" is used in scientific and general literature to include all coastal salt marsh-related habitats (tidal marsh, salt marsh, brackish marsh, coastal marsh, coastal wetlands, tidal wetlands, low marsh, high marsh) with such common species as, *Spartina alterniflora, Spartina patens, Salicornia virginica, Juncus roemerianus, Distichlis spicata*, and *Batis maritima;* as well as unvegetated areas associated with these communities including salterns (United Kingdom), salinas (Spanish), salt pans (actually more appropriate for desert habitats), salt pannes (California USA), salt barrens (USGS), and white zone (Davis 1999, Egler 1952); although white zone is also used to identify areas of dried-down periphytic algal freshwater wetlands.

Some authors distinguish the salt marsh from brackish marshes as being frequently or continuously flooded by relatively shallow, high salinity water. The National Wetlands Research Center of the United States Geological Survey defines a saltwater marsh as having a salinity of

15-18 parts per thousand or greater (NWRC 2007), but many other definitions are utilized and accepted by the scientific community.

Brackish salt marshes develop where significant freshwater influxes dilute the seawater to brackish levels of salinity. This commonly happens in estuaries of coastal rivers or near the mouths of coastal rivers with heavy freshwater discharges in the conditions of low tidal ranges. A brackish marsh and intermediate marsh are characterized by lesser salinities than full salt marshes. The National Wetlands Research Center defines brackish marshes as those with a salinity range from three (3) to 15 parts per thousand, and an intermediate salt marsh as a marsh occurring where the salinity is about three (3) parts per thousand to 0.5 parts per thousand (NWRC 2007).

Coastal salt marsh is synonymous with the "coastal salt marsh" described by Davis (1967), Hartman (1996), and Cox *et al*. (1994); and "marine and estuarine tidal marsh" of FNAI (1990). The Florida Natural Areas Inventory (1990) defines salt marshes as "expansive inter- or supra-tidal areas occupied by rooted emergent vascular macrophytes smooth cordgrass (*Spartina alterniflora*), needle rush (*Juncus roemerianus*), swamp sawgrass (*Cladium mariscoides*), saltwort (*Batis maritima*), saltgrass (*Distichlis spicata*), glasswort (*Salsola kali*), and a variety of epiphytes and epifauna."

High marsh is a tidal marsh zone located above the mean high-water line (MHW) which in contrast to the low marsh zone is inundated infrequently during periods of extreme high tide and storm surge associated with coastal storms. The high marsh is the intermittent zone between the low marsh and the uplands, an entirely terrestrial area rarely flooded during events of extreme tidal action precipitated by severe coastal storms.

Salt marshes have been studied extensively for many years with Ragotzkie *et al*. (1959), Chapman (1960) and Teal and Teal (1969) conducting some of the pioneering work. Thorough descriptions of general salt marsh ecology are given by Ranwell (1972), Adam (1990), Pomeroy and Wiegert (1981), and Mitsch and Gosselink (1986, 1993). Wiegert and Freeman (1990) and Montague and Wiegert (1990) provide overviews on southeast Atlantic and Florida marshes, respectively. The FLUCCS code for all the coastal salt marsh plant communities includes: 642 (saltwater marshes). The Florida Natural Areas Inventory (FNAI) State Rank for salt marsh is S4

For the purposes of this study the term salt marsh will be utilized in the fullest sense that it is applied in the mapping by the CHNEP, FDOT, SFWMD, SWFWMD, and FFWCC and their literature and reports including the saline conditions (0.5 to 100 ppt.) of the habitat and the emergent halophytic vegetation that dominate it (Zedler 1984). For the purposes of this study a salt marsh can possess low-growing halophytic shrubs up to 1.5 meters in height provided the shrubs cover less than 25% of the area.

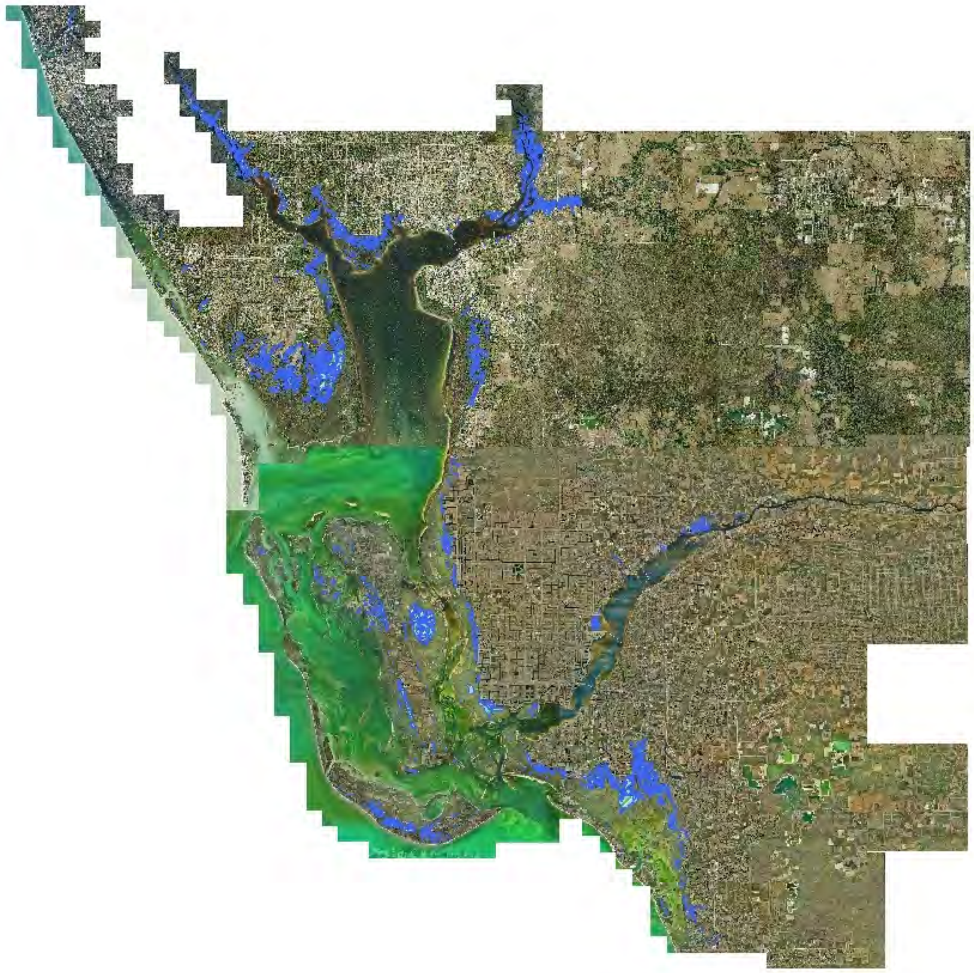


**Figure 8: The Salt Marshes of the CHNEP (indicated in blue)**
**Source: SWFRPC/CHNEP 2012**

Salt Marsh Types of the CHNEP

The subtropical climate of South Florida supports a diverse community of both tropical and temperate flora. These conditions create different salt marsh communities than those typical of the southeast Atlantic and northern Gulf of Mexico. The community types and spatial extent vary due to latitudinal and geographic differences (Montague and Wiegert 1990). A transition between the more typical salt marshes and mangrove forests occurs on the east coast at about 30 N (Odum *et al.*1982). Unlike the common *Spartina* or *Juncus* monotypic stands of north Florida, South Florida salt marsh vegetation is often intermixed with mangroves.

Hydrogeomorphically, based upon tidal and landscape position, there are two types of saltmarsh in the CHNEP: fringing and high, Based on this study, we are able to state that the high marshes cover more than twice as much area, 10,457.56 acres (70.4%) as fringing marshes 4,398.54 acres (29.6%).

At the commencement of this project existing literature (USFWS 1999) recognized five (5) types of salt marsh for Florida. In the course of our study and field work we have been able to identify twelve (12) types of salt marsh in the CHNEP boundary in southwest Florida.

The classic zonation of low and high marsh are confused by the wide range of occurrence of salt marsh species such as black needle rush that range over 3 1/2 feet of relative elevation of sea level, essentially spanning the full range of low to highest marsh. The variety of salt marsh communities in Southwest Florida includes (1) smooth cordgrass, (2) marshes dominated by black needle rush, (3) marsh dominated by leather fern, (4) marsh dominated by saltmarsh bulrush, (5) high salt marsh-mangrove transition with a black mangrove shrub layer (6) high marsh algal marsh lacking vascular plants, (7) high marsh saltern (salt pan, salinas, white zone), (8) high marsh dominated by succulents including glasswort and saltwort, (9) high marsh mixed vegetation herbaceous (10) high marsh dominated by salt grasses, key grass, knotgrass, (11) high marsh with a shrub layer of buttonwood, salt bush, and marsh elder, and (12) a special type of high marsh found on barrier islands dominated by Baker's cordgrass and leather fern.

Salt marshes are the most common emergent habitats in the middle and upper large riverine portions of the study area, and exist to some extent throughout the estuary. Fringing emergent native salt marsh wetland shorelines can constitute a significant part of Myakka River and Peace River watershed shorelines. The Peace River marshes clearly dominate the distribution of directly tidal salt marshes in the CHNEP. High salt marsh communities occur in the transitional areas between mangroves, and fresh water marshes or coastal uplands.

| SALT MARSH TYPES OF THE CHNEP | | | |
|---|---|---|---|
| **Type** | **Combined numeric code for this study** | **FLUCCS Code** | **FLUCCS Manual Description** |
| **smooth cordgrass** | 10 | 6421 | Cordgrass |
| **black needle rush** | 21 | 6442 | Needlerush |
| **leather fern** | 22 | none | none |
| **saltmarsh bulrush** | 23 | none | none |
| **shrub mangrove** | 30 | 6122 | Black mangrove |
| **algal** | 31 | 650 | Non-Vegetated, including tidal flats, shorelines, intermittent Ponds, Oyster Bars |
| **saltern** | 32 | 720 | Sand Other Than Beaches, including dunes as the major feature |
| **marsh meadow Succulents** | 33 | 643 | Wet Prairie |
| **marsh meadow mixed** | 34 | 643 | Wet Prairie |
| **marsh meadow grasses** | 35 | 643 | Wet Prairie |
| **shrub buttonwood** | 36 | 6124 | Buttonwood |

**Table 1: Types of Salt Marsh of the CHNEP**

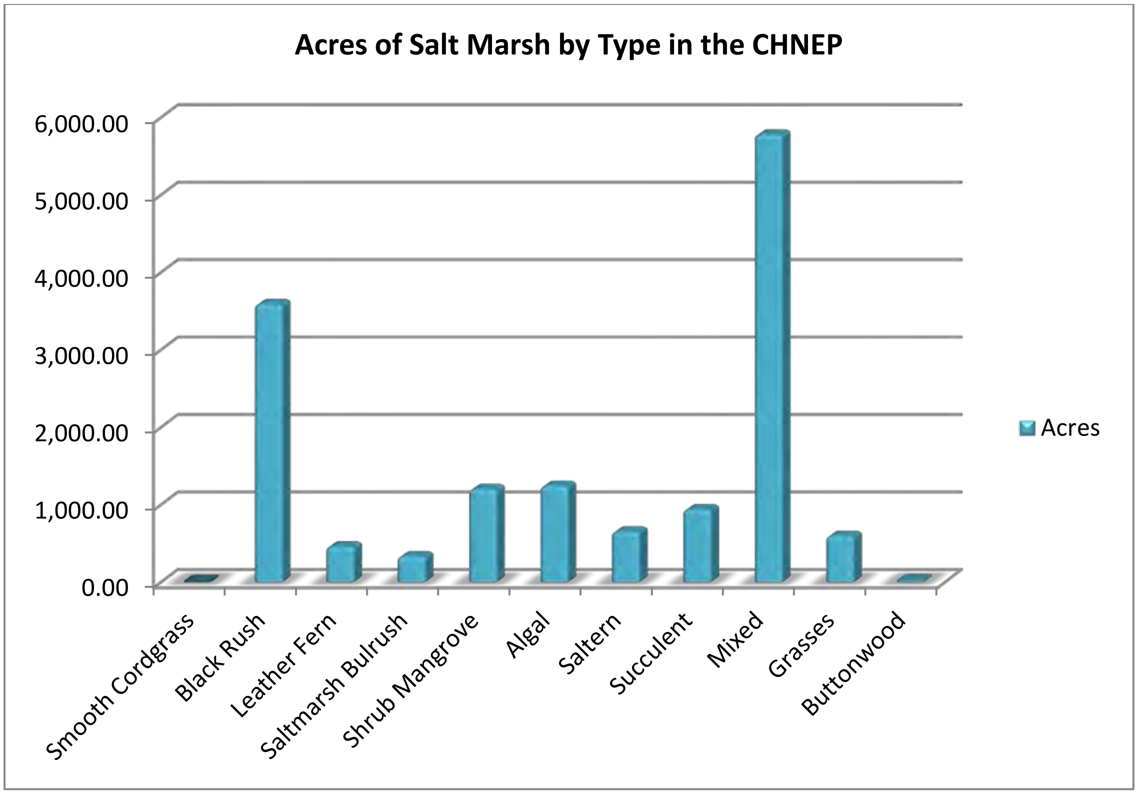



**Figure 9: Acres of Salt Marsh by Type in the CHNEP**
**Source: SWFRPC/CHNEP 2012**

| Code | 10 | 21 | 22 | 23 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Basin | Smooth Cordgrass | Black Needle Rush | Leather Fern | Bulrush | Shrub Mangrove | Algal | Saltern | Succulent | Mixed | Grasses | Shrub Button-wood | Total |
| Peace River | 0 | 1,446 | 238 | 337 | 51 | 8 | 1 | 33 | 181 | 5 | | 2,302 |
| Myakka River | | 1,029 | 52 | | 5 | 17 | 8 | 7 | 129 | 44 | | 1,292 |
| Dona & Roberts Bay | | 30 | 5 | | | | 0 | | | | | 36 |
| Lemon Bay | 0 | 11 | 38 | | 1 | 12 | 11 | 22 | 25 | 42 | | 162 |
| Charlotte Harbor | | 190 | 8 | | 315 | 248 | 328 | 307 | 2,623 | 203 | | 4,223 |
| Pine Island Sound | 3 | 22 | 8 | | 540 | 421 | 100 | 404 | 1,980 | 201 | 1 | 3,679 |
| Caloosahatchee | | 139 | 77 | | 46 | 7 | 11 | 4 | 66 | 40 | | 389 |
| Estero Bay | | 726 | 39 | | 247 | 533 | 198 | 167 | 780 | 66 | 19 | 2,774 |
| Total | 3 | 3,594 | 465 | 337 | 1,206 | 1,245 | 658 | 944 | 5,784 | 601 | 20 | 14,857 |

**Table 2: Salt Marsh Distribution by Type by Watershed Basin**


**Figure 10: Distribution of Salt Marshes in the CHNEP Study Area in 2012.**
**In both aerial and map format. Source: D. Cobb and J. Beever, SWFRPC 2012**

Tidal fringing salt marshes constitute 23% of the Peace River shoreline, 11% of the Myakka River shoreline, 6% of the Caloosahatchee River, 5% of the Dona and Roberts Bays shorelines, 5% of the Estero Bay shoreline, 4% of the Pine Island Sound, Matlacha Pass and Lemon Bay shorelines and 1% of the shoreline of Charlotte Harbor proper.

The types of fringing marsh are skewed in their extent with black needle rush dominating at 82% of all fringing marshes, followed by leather fern (11%), saltmarsh bulrush (8 %) and smooth cordgrass at 1%.

Multiple factors interact to determine the formation, structure, and ecological processes of salt marshes including (1) climate, (2) hydrology, and (3) physical factors. Climatic factors include temperature and rainfall; hydrologic factors include tidal inundation, wave energy, climate, rainfall, freshwater flow, and evapotranspiration; and physical factors include elevation and slope, sediment and soil composition, and surface water and soil salinity.

Mangroves primarily dominate the CHNEP tidal shoreline, although there are patches of transitional salt marsh habitat. Within these zones, dominant species include cordgrasses (*Spartina spp.*), saltgrass (*Distichlis spp.*), glasswort (*Salicornia spp.*), and sea purslane (*Sesuvium* spp.) (Drew and Schomer 1984). Salt marshes of the CHNEP occur in several different hydrogeomorphic settings. Small patches of low marshes are found in protected coves in Dona Bay, Roberts Bays, Lemon Bay, and tributary rivers and streams. Needlerush dominates salt marsh communities of the major rivers (e.g., Myakka and Peace Rivers). Expansive black needle rush low and middle marshes are found in the Myakka and Peace Rivers and in smaller representation in the creeks tributary to Lemon Bay, Charlotte Harbor, Caloosahatchee River, and Estero Bay, often replaced by leather fern and saltmarsh bulrush marsh in fresher water estuarine streams and river oligohaline zones. Monotypic stands of black needlerush (*Juncus roemerianus*) can be common in slightly elevated areas with less tidal inundation. High salt marshes form parallel to the main estuaries' shorelines at the landward side of mangrove fringes starting in shrub black mangroves, extending into open algal marsh, open salt barrens and blending into salt meadows or algal marshes. The high marshes form narrow linear bands on islands like Sanibel Island and Pine Island and as larger expanses on the mainland shores of Cape Haze, Charlotte Harbor, Matlacha Pass, and Estero Bay, often several kilometers from the open shoreline. The interior wetland habitat of Sanibel Island has linear bands of lower salinity brackish marsh dominated by Baker's cordgrass and leather fern.

This study mapped 14,852.95 acres of salt marsh of all types within the CHNEP study area boundaries. This includes 35.7 acres in the Dona and Roberts Bay watersheds, 162.2 acres in the Lemon Bay watershed, 1,291.7 acres in the Myakka River watershed, 2,301.6 acres in the Peace River watershed, 4,222.7 acres in the greater Charlotte Harbor watershed, 1,346.2 acres in the Pine Island Sound watershed, 2,329.4 acres in the Matlacha Pass watershed, 389.3 acres in the Caloosahatchee River watershed, and 2,773.9 acres in the Estero bay watershed.

We believe the apparent differences in salt marsh acreage from earlier mapping by FWC and the WMDs is not the result of an actual increase in salt marsh extents as much as it is a result of the improved mapping methods of this study. Significant areas of salt marsh were mapped as mangrove forest in the earlier mapping efforts and areas of mangrove were designated as salt marsh. In some watersheds areas of freshwater marsh and bare sand upland areas were mapped as salt marsh.

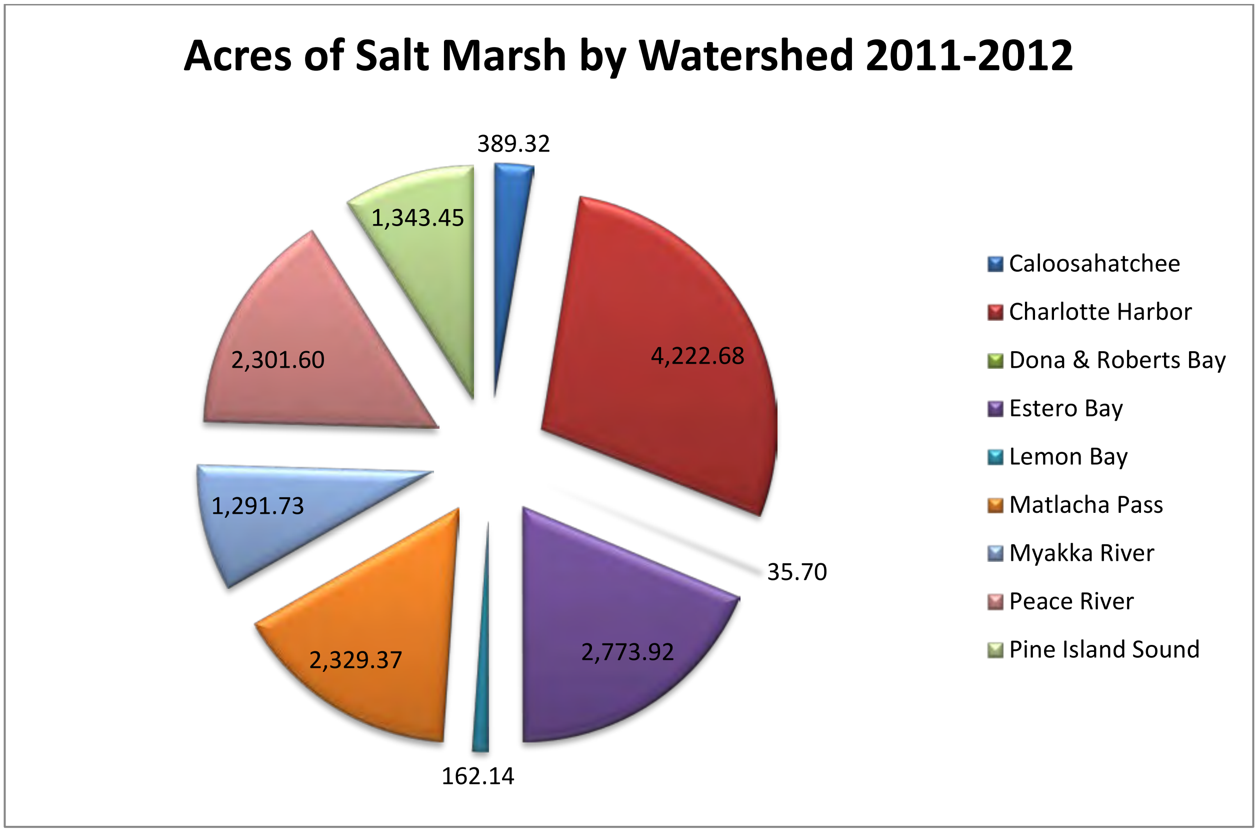



**Figure 11: Acres of Salt Marsh by Watershed in the CHNEP.**
**Source D. Cobb and J. Beever SWFRPC**

The salt marshes of the CHNEP are unequally distributed with the most in the Charlotte Harbor Proper watershed (28%), 19% in Estero Bay watershed, 16% in the Matlacha Pass watershed, 15% in the Peace River watershed, 9% each in the Pine Island Sound and Myakka River watersheds, 3% in the Caloosahatchee River watershed, 1% in the Lemon Bay watershed, and 0.2 % in the Dona and Roberts Bays watershed.

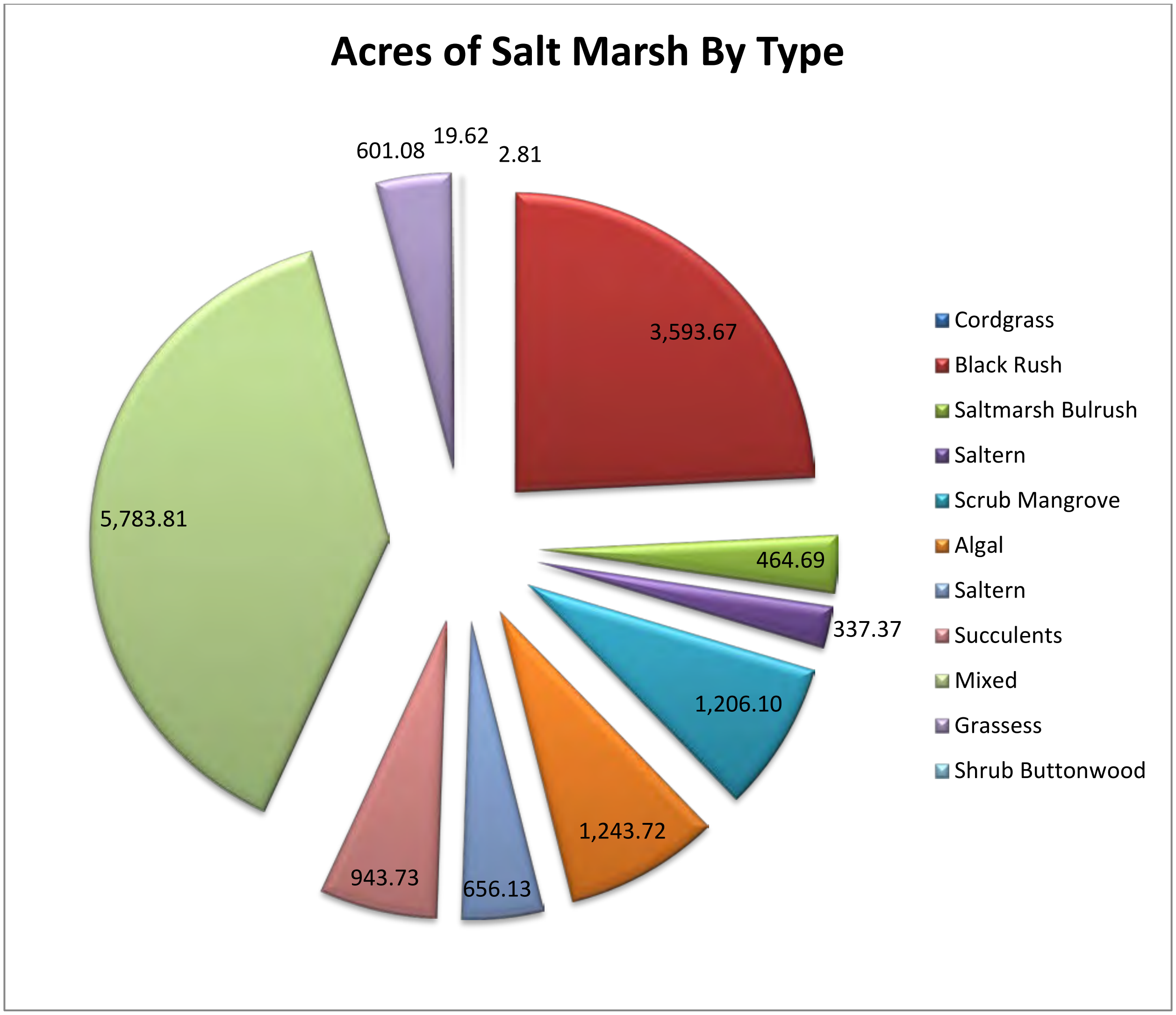



**Figure 12: Acreage of each Salt Marsh Type in the CHNEP.**
**Source: D. Cobb and J. Beever SWFRPC April 30, 2012**

Mixed high marsh is the most common form of salt marsh in the CHNEP (5,783.81 acres) comprizing 38.93 % of total salt marsh extents among all watersheds. Black needle rush marsh is second at 3,593.67 acres (24.19%) including both fringing and high marsh ecotypes of black needle rush. Algal marsh is 1,243.72 acres (8.38%). Shrub mangrove high marsh is 1,206.10 acres (8.12%).

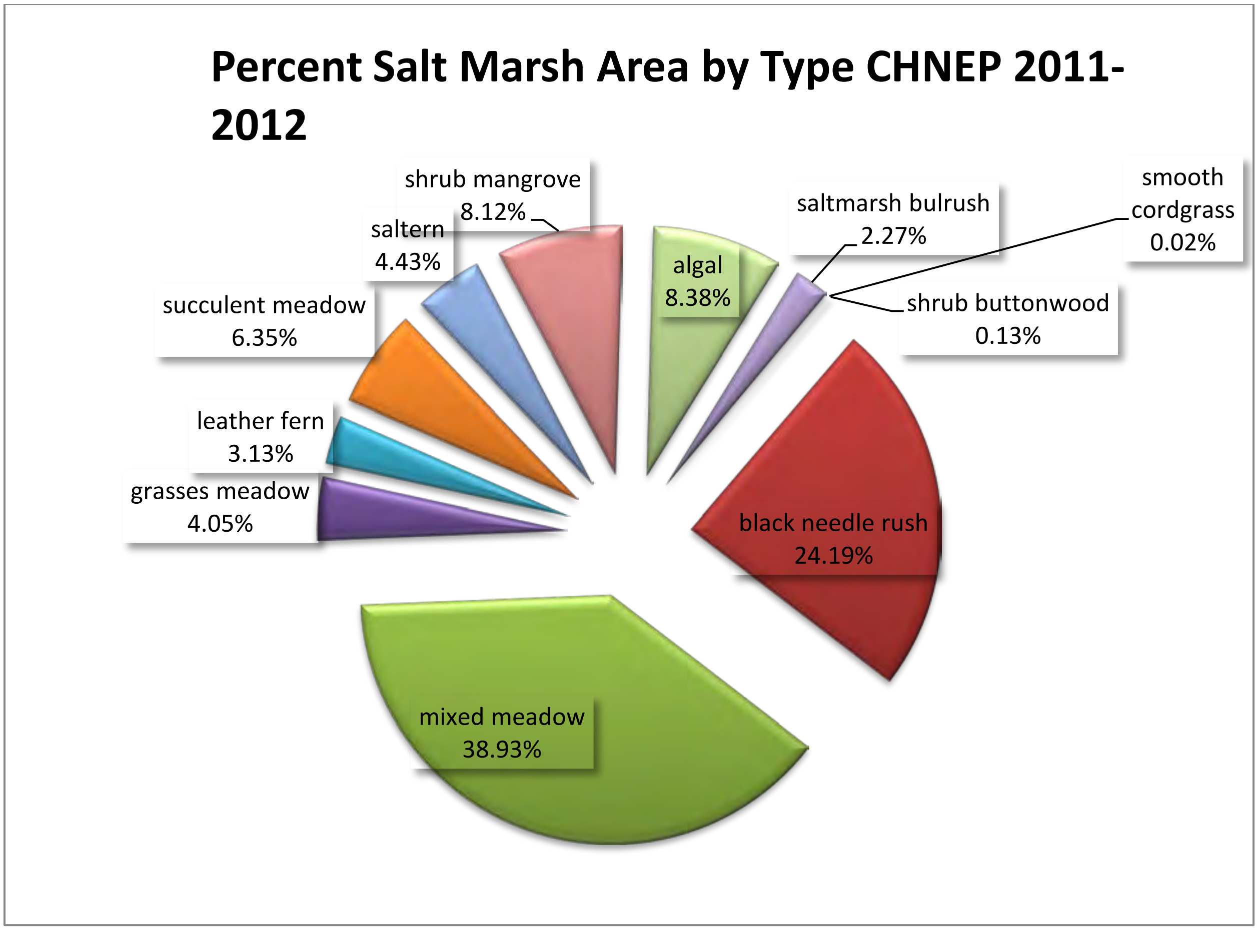



**Figure 13: Relative proportion of salt marsh types in the CHNEP Study Area**
**Source: D. Cobb and J. Beever SWFRPC April 30, 2012**

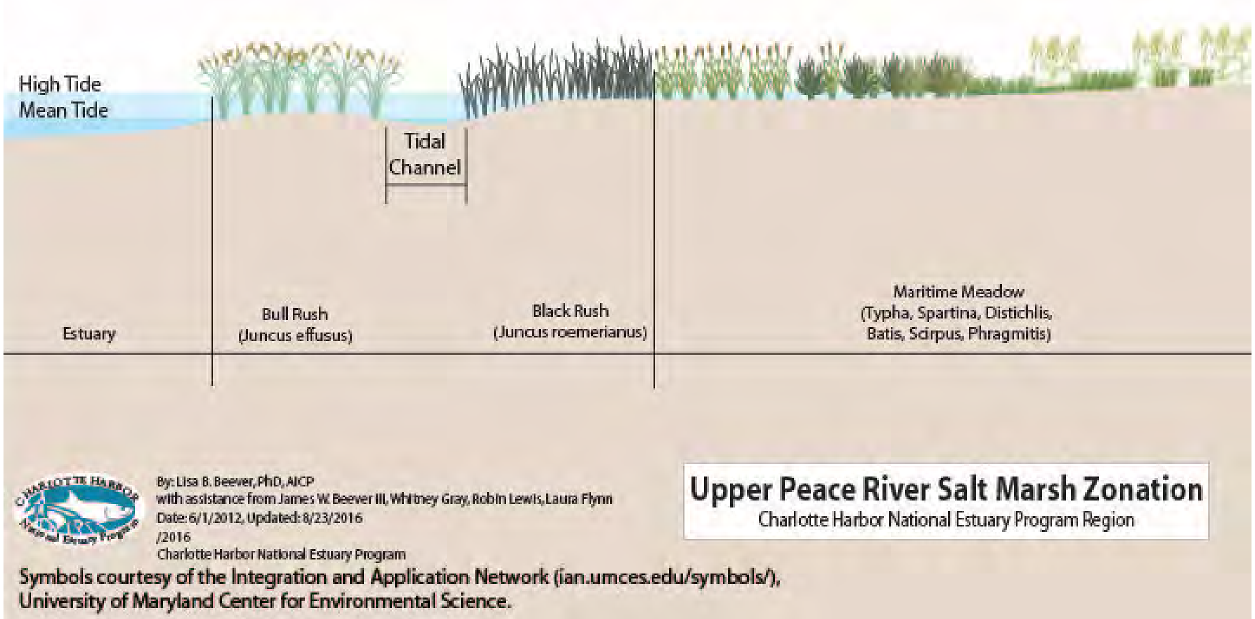



**Figure 14: Upper Peace River Salt Marsh Zonation**

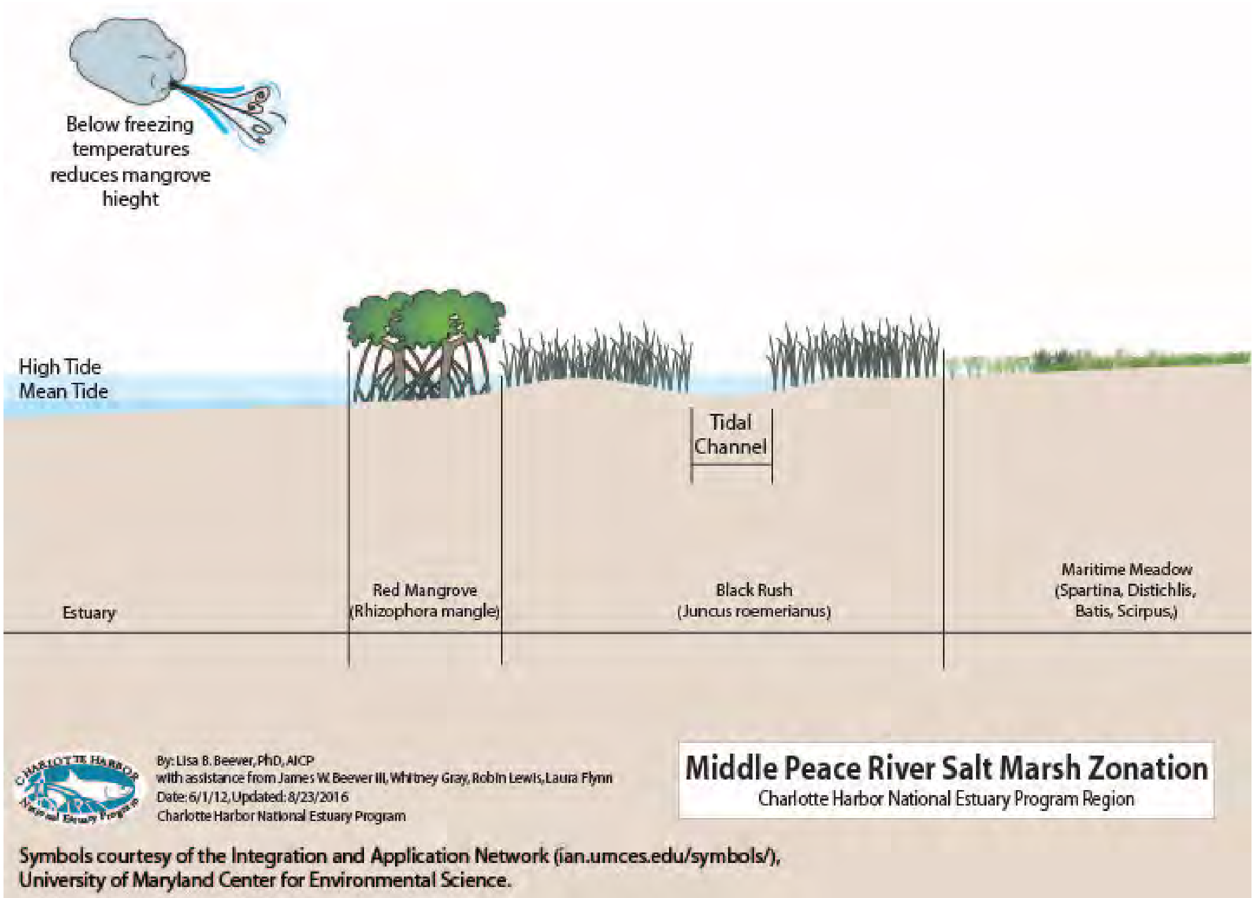



**Figure 15: Middle Peace River Salt Marsh Zonation**

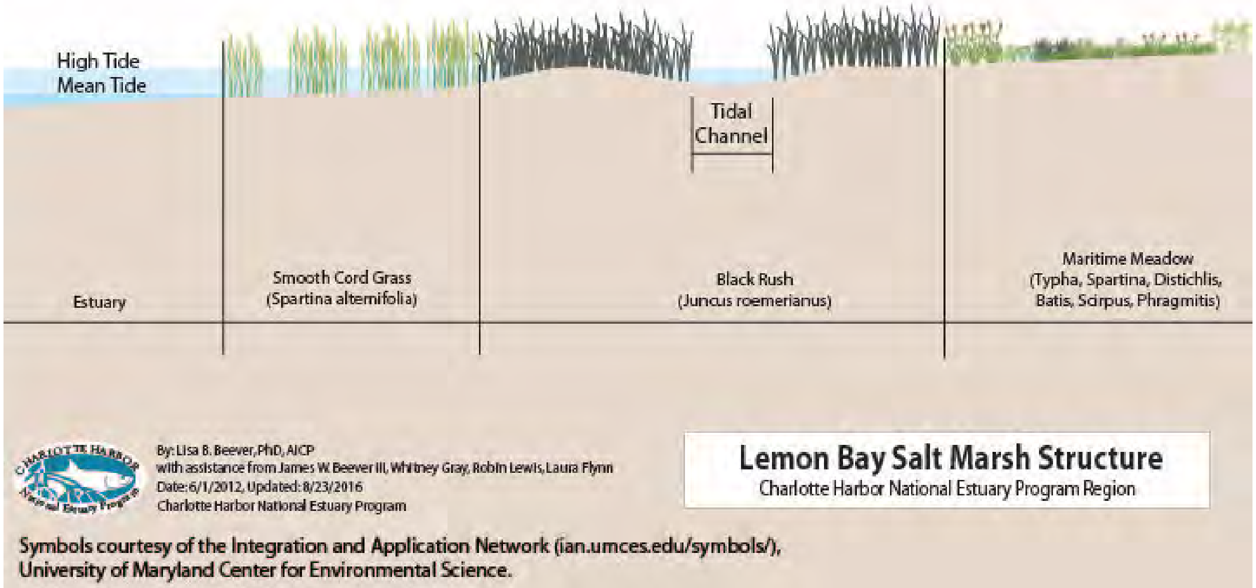



**Figure 16: Lemon Bay Salt Marsh Zonation**

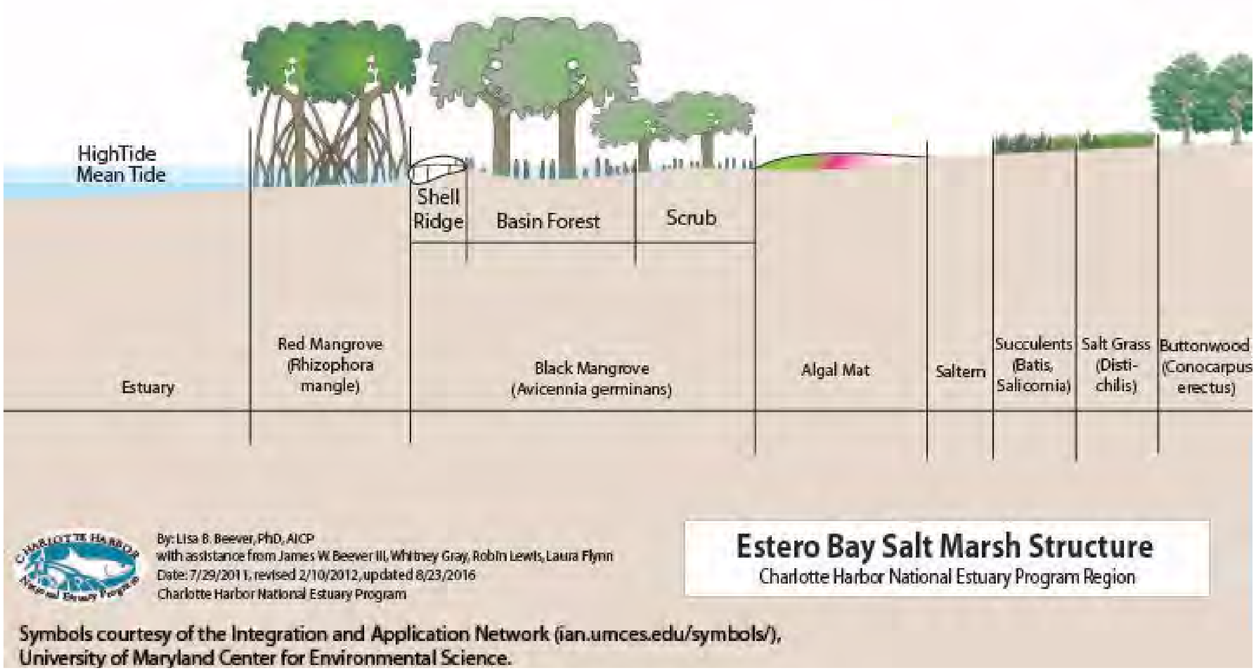



**Figure 17: Estero Bay Salt Marsh Zonation**

# GIS Library of Mapping Resources

The project team assembled a GIS library of true color aerial photography combined with infrared reflectance data and LiDAR elevation data to form the first run of reflectance data to test at site visits. Though Landsat data was not listed, such imagery is the best free source of reflectance data. USGS provided the project team the first run of reflectance data to test. The majority of the mapping resources were collected in January 2015. ArcGIS 10.2.1 was used throughout the project.

## True Color Aerials

The true color aerials were used to assist with mapping mangroves by geomorphic and species type, identify site investigation locations, evaluate mangrove health and identify potential restoration opportunities. Counties in southwest Florida conduct aerial photography flights annually. The data are primarily collected for use by the County property Appraiser. However, counties and other agencies have numerous uses.

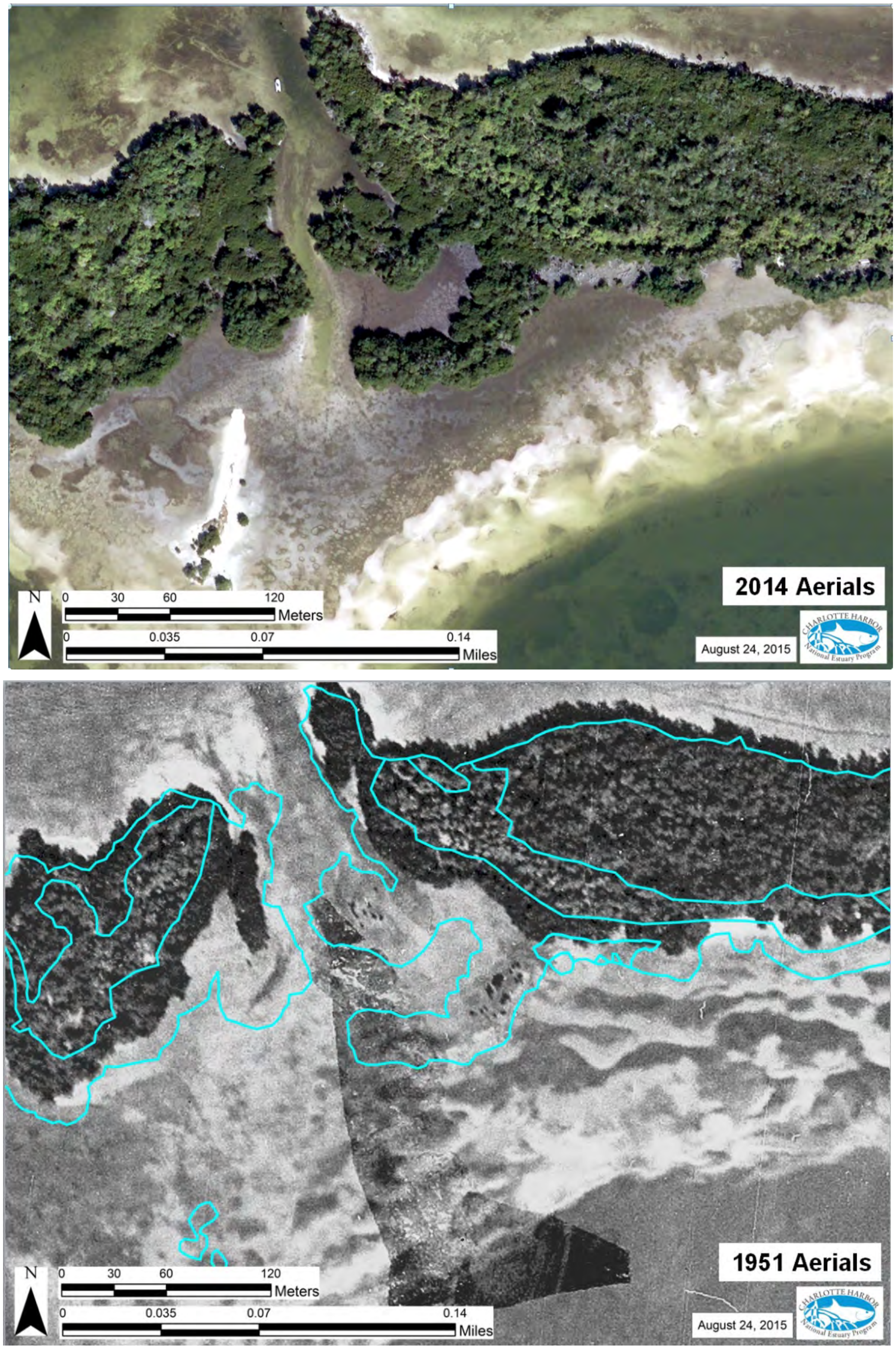
Each photograph is called a tile. The tiles are georectified for use in a GIS environment. Although the proposal called for conducting reflectance runs on the true-color aerials, this is not practical. For example, dark shadows read as black whether the shadow is cast by a mangrove, cypress tree or building. In addition, light variation often changes the general color and texture of a habitat from one tile to the next. Finally, true color aerials are built upon red, green, blue spectra. Infrared aerials provide the best tool to assess changes of mangrove species.

True color aerials were collected from Sarasota, Lee and Charlotte Counties for 2014. This year was the most recent year available when the project commenced in December 2014. The few images necessary for DeSoto County was collected from http://labins.org/mapping_data/aerials/hi-resolution_images.cfm. Land Boundary Information System (LABINS) is sponsored by the Florida Department of Environmental Protection, Division of State Lands, Bureau of Surveying and Mapping. The complete set for the four counties was 834 GB in size.

Lee County prepared a multiresolution seamless image database (Mr SID) for its 2014 aerials which aided in management of the true color aerials.

## Historic Aerials

Historic aerials were used to help evaluate changes in salt marsh and mangrove habitats since the 1950s. They were especially useful when considering restoration opportunities. As part of its historic benthic habitat mapping project, CHNEP generated a geo-rectified set of aerials from the late 1940’s to early 1950’s. Though the imagery was not collected for the full extent of the CHNEP study area, the coverage was sufficient to include mangroves of the period. This dataset was very useful to test assumptions regarding mangrove changes. For example, although sea level has increased by nearly 6 inches, mangroves in some areas have expanded. In addition, tropical hardwood hammocks (lighter in value than surrounding mangroves) appear stable.



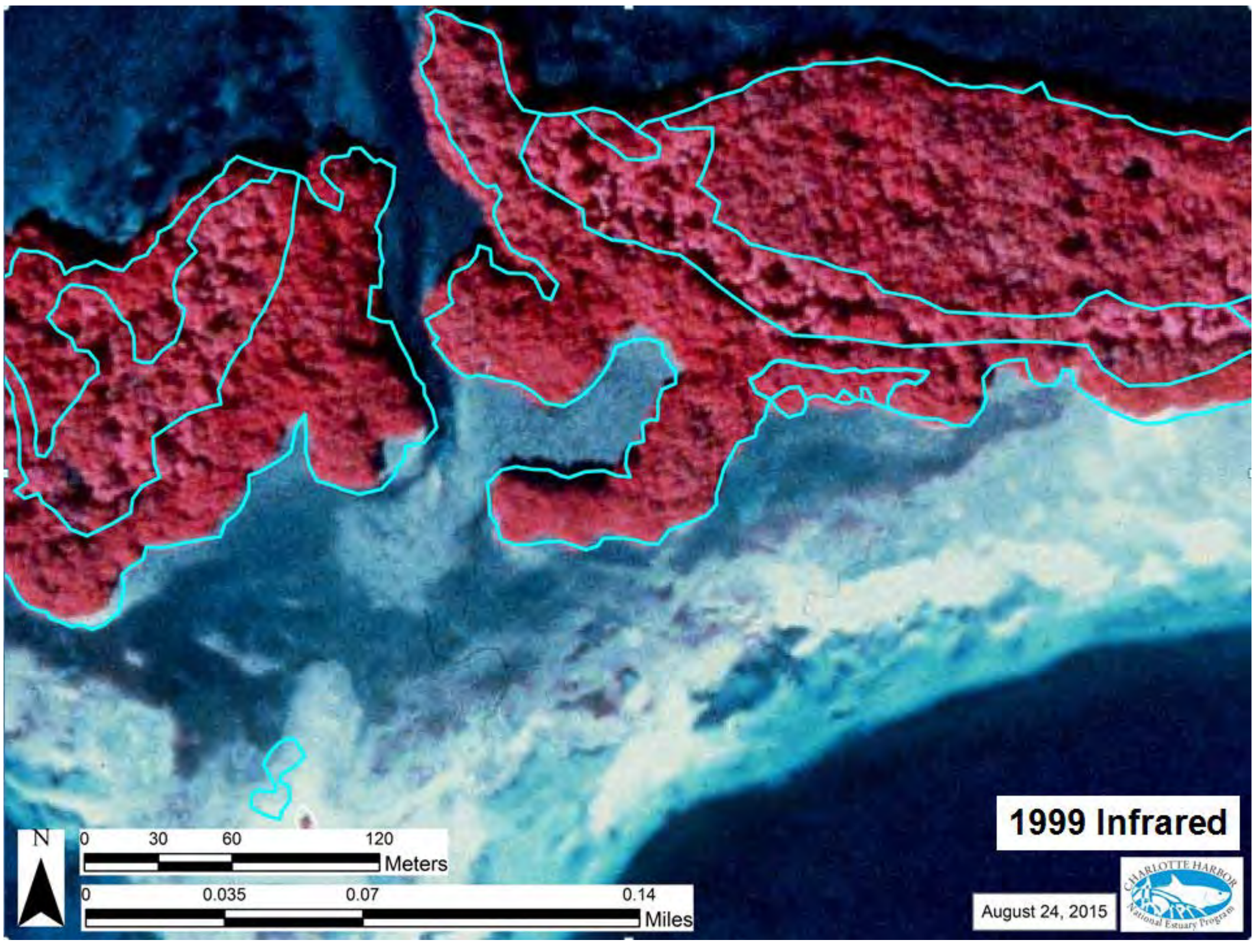

**Map 1: Gallagher Keys in 2014 and 1951**

## Infrared Aerials

Infrared aerials were used to help distinguish mangrove species and highlighted the benefits of the three infrared Landsat bands. Aerial photographs in the infrared were last collected statewide in 1999. The imagery is available as area-wide MrSiDs, from a LABINS FTP site: ftp://146.201.97.137/doqq2/1999/StatePlane_W/MrSid/.

Because variation between mangroves within the same species occurs based on tidal position and other factors, distinguishing mangroves can be difficult. In the 1999 infrared imagery, black mangroves appear purple, red mangroves appear ruby red, and white mangroves appear pink. Infrared photography has been an important aid in hand mapping mangroves by species.

It also highlights the benefit of Landsat imagery which include three of its seven 30 meter bands in the infrared.



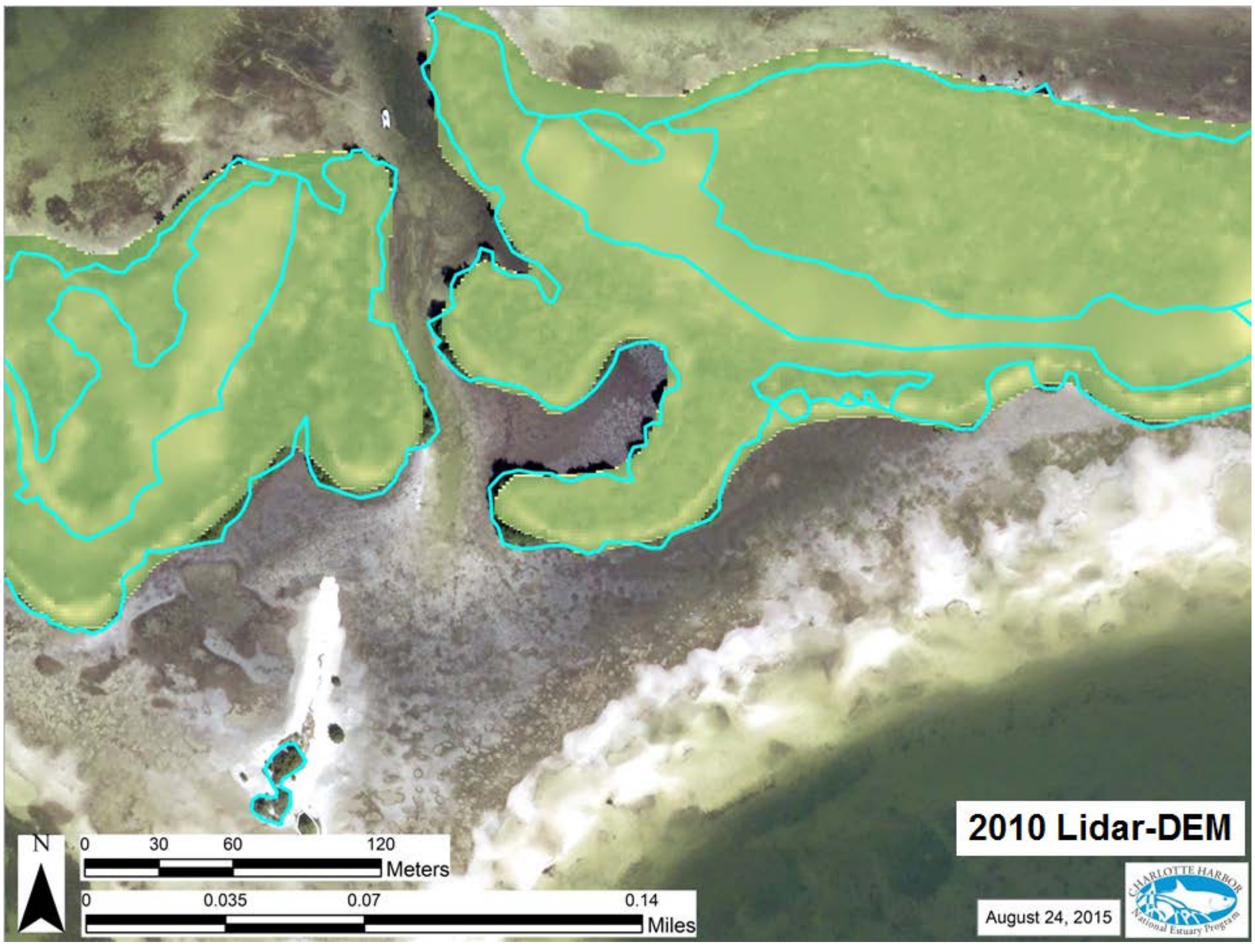

**Map 2: Gallagher Keys 1999 Infrared**

## Lidar

Lidar imagery was used to help identify mangroves by geomorphic type and identify elevation of investigation sites. Digital Elevation Models (DEMs) are developed using Lidar data. The Lidar images were collected from the County GIS departments. They provide an important view to the ground and elevation.

Lidar evaluation, coupled with aerial photographs assisted in the identification of mangrove forest geomorphology, especially with basins, hammock and scrubs. Geomorphic type was identified in relationship to the surrounding topography. This is especially true for identifying basins and hammocks from fringe forests.

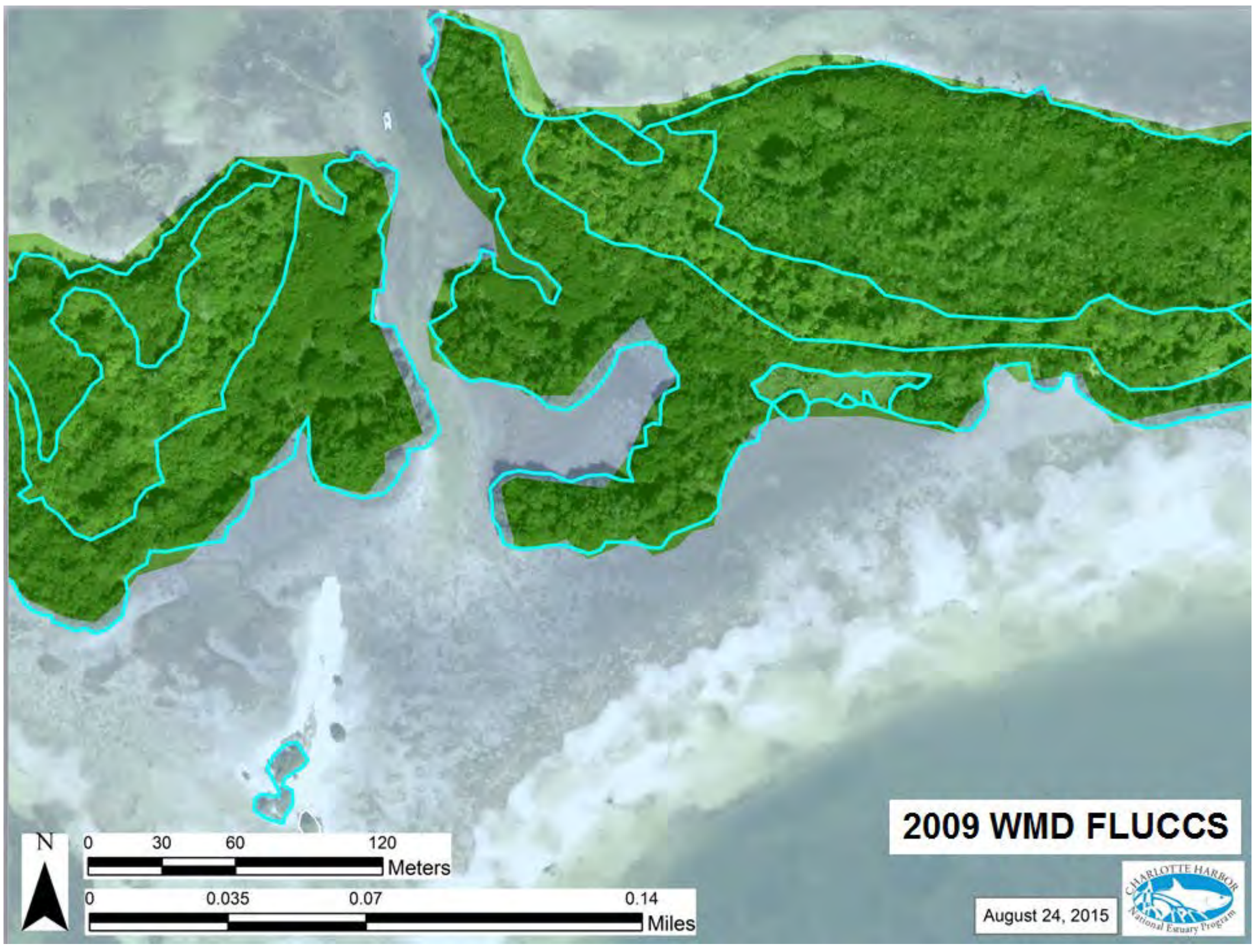
In addition, features such as mosquito control ditches, spoil piles and tidal creeks are more apparent using Lidar imagery.




**Map 3: Gallagher Keys 2010 Lidar Digital Elevation Model Image**

## Water Management District 2008-09 Land Use Maps

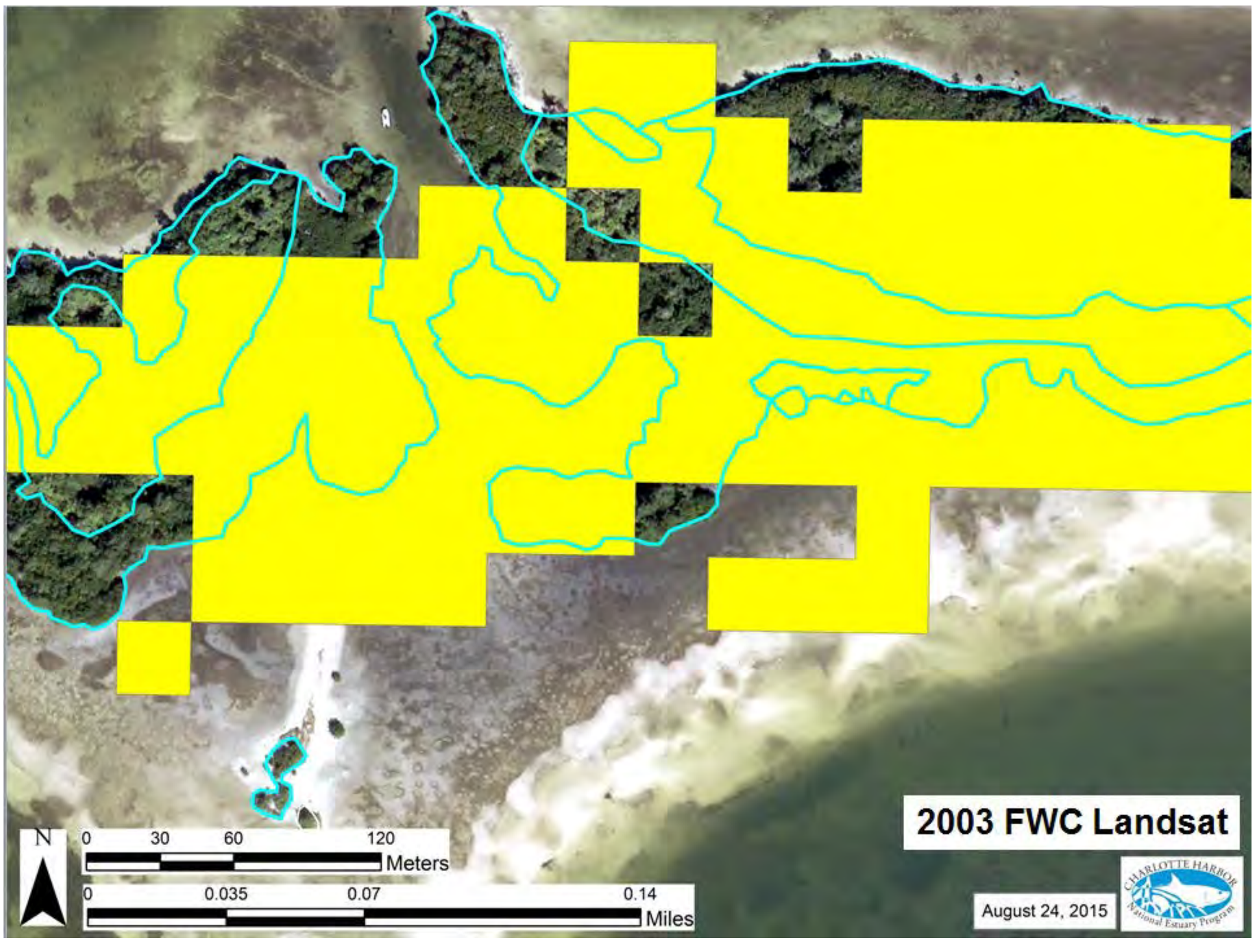
South Florida Water Management District (SFWMD) and the Southwest Florida Water Management District (SWFWMD) FLUCCS (Florida Land Use and Cover Classification System) codes (FDOT 1999) were used to fill in areas where detailed Level 5 mapping was not conducted. South Florida Water Management District (SFWMD) and the Southwest Florida Water Management District (SWFWMD) conduct land use and vegetative cover mapping using FLUCCS (Florida Land Use and Cover Classification System) codes (FDOT 1999). Both districts conducted early mapping in 1995 and performed a detailed update in 1999, apparently relying on the 1999 infrared imagery. Both districts have conducted multiple updates of major land use changes. Because of the time and expense of map updates, natural changes of vegetative cover were not captured.  Later efforts to update land use maps reflect the earlier 1999 maps where vegetative cover was undisturbed.




**Map 4: 2008-2009 Water Management District Land Use Map**
**612: Mangrove Swamps in green and 500: Water in blue**

## Fish and Wildlife Conservation Commission 2003 Landsat Interpretation

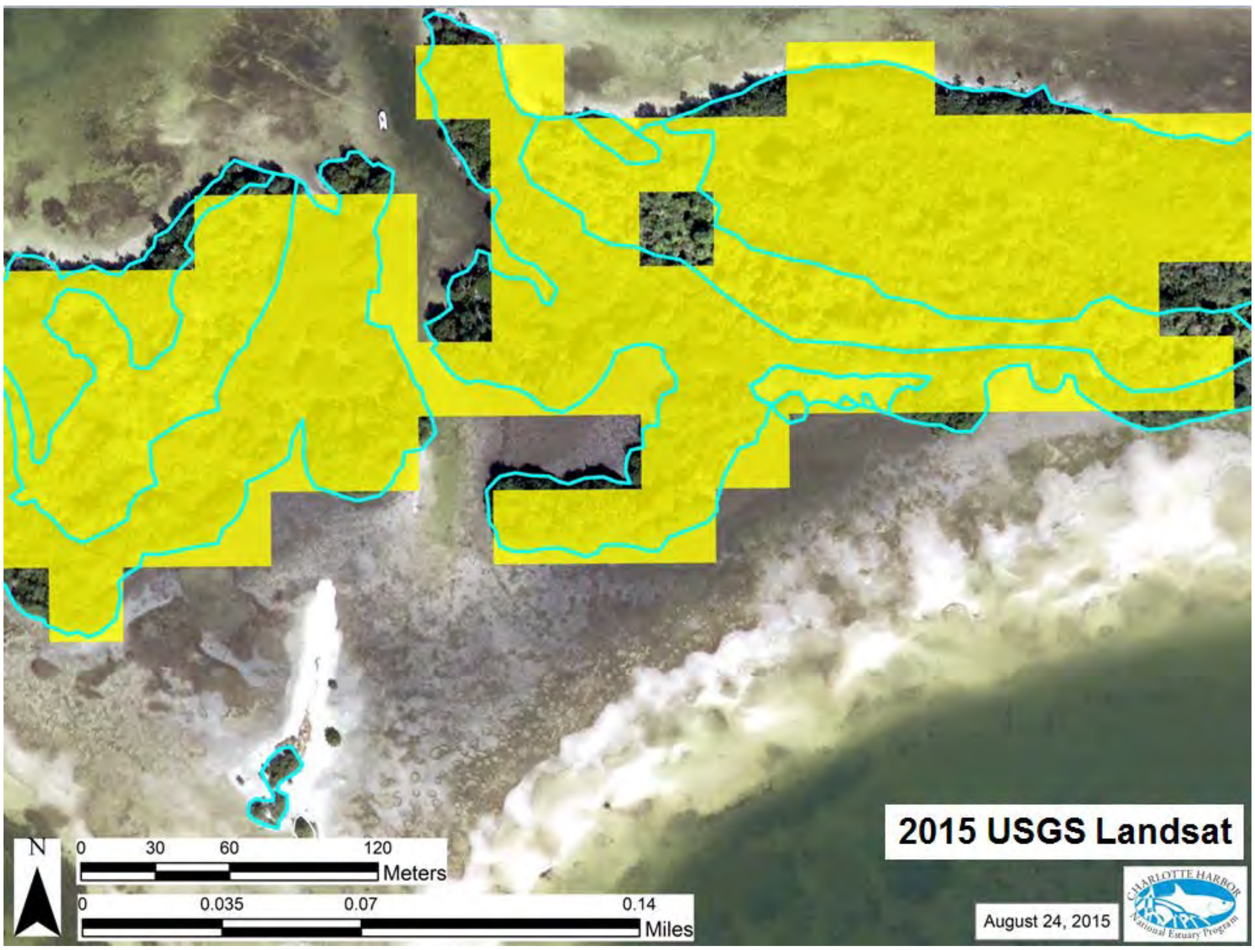
The Fish and Wildlife Conservation Commission (FWC) habitat maps were compared with investigation sites and detailed level 5 FLUCCS mapping. FWC prepared a statewide habitat map using Landsat Imagery in 2003. Landsat 7 data appears to require more precise geo-referencing to be compatible with aerial photography and data from other Landsat missions. Data appear approximately 60 meters East-South-East of its actual location. For presentation of the imagery the error is unimportant. For analysis between aerial photography, other Landsat missions and other data, Landsat 7 data require a step to geo-reference the data.




**Map 5: 2003 Florida Fish and Wildlife Commission Landsat 7 Interpretation of Mangrove Extent**

## United State Geological Survey 2015 Landsat Interpretation

United State Geological Survey (USGS) maps were used as the first run reflectance analysis for the project and served as a benchmark for the project. On March 2015, Chandra Giri and Jordon Long, USGS, provided the project with draft January 28, 2015 mangrove coverage based on their procedures to estimate mangrove acreages worldwide. The results were generally similar to aerial photograph interpretation conducted by water management districts in 2008-09 for FLUCCS code 612: Mangrove Swamps and excellent for regional mangrove comparisons.




**Map 6: 2015 USGS Landsat Interpretation of Mangrove Extent**

# FLUCCS Maps for Charlotte Harbor and Tidal Peace and Myakka Rivers

In order to recalibrate the spectral data assessment, the project team decided to hand-map mangroves by geomorphic type and species for a significant portion of the study area. In this way, a geoprocess could be used to identify typical spectral range combinations which typically are found associated with mangroves by species or geomorphic type.

## Classification of Mangrove Forest Type

To develop a map by mangrove type, a system of Florida Land Use, Cover and Forms Classification System (FLUCCS 1999) for mangrove types was developed. The system cascades from the most general as FLUCCS level 1. For mangroves and salt marsh, Level 1 is 600: Wetlands. Level 2 for mangroves is 610: Wetland Hardwood Forests and salt marsh is 640: Vegetated Non-Forested Wetlands. At level 3, mangrove is 612: Mangrove Swamps and salt marsh is 642: Saltwater Marshes. A new level 3 category was developed for dead mangroves. Since 435: Dead Trees is available for upland trees, 635: Dead Mangroves was established for the project.

FLUCCS allows for additional levels. The project named level 4 for its geomorphic classification and level 5 for its species. In general this follows the classification convention used by SWFRPC/CHNEP in its 2011 salt marsh study.

As presented in the background section, mangrove geomorphic type includes: 1) Overwash Forest; 2) Fringe Forest; 3) Riverine Forest; 4) Basin Forest; 5) Hammock Forest; and 6) Scrub Forest. Therefore, the fourth position in the FLUCCS protocols will relate to these numbers. In addition, the CHNEP study area includes linear, modified mangrove features that are not mangrove forest. For the development of this system, we have named it 7) Altered Hedge. The term “hedge” is used here to describe a row of trees, as opposed to a forest. A hedge need not be “hedged,” or cut to uniform height. Altered mangrove hedges are found in front of urban lots and along manmade ditches and no longer resemble a forest in structure.

The level 5 position is reserved for species type. We used 1) red (*Rhizophora mangle*), 2) black (*Avicennia germinans*), 3) white (*Laguncularia racemosa*), and 4) buttonwood (*Conocarpus erectus*). Additional numbers are mangroves of different mixes including 5) red-black-white; 6) black-white-buttonwood and 7) red-white. For example, 61225: red-black-white mixed fringe forest is the most common mangrove type found in the CHNEP study area. In addition, 61266: black-white-buttonwood mixed scrub forest is the most commonly missed mangrove type in current mapping. Prior to a site investigation, we were perplexed by what appeared to be a red mangrove forest on a high area shown in Lidar. Upon site investigation, it was confirmed to be a 61267: red-white mixed scrub forest.

The combination of level 4 geomorphic type and level 5 species type describes all live mangrove forests found in the CHNEP study area.

| FLUCSDESC | LEV4 | LEV5 | LEV4DESC | LEV5DESC |
|---|---|---|---|---|
| MANGROVE SWAMPS | 6121 | 61211 | OVERWASH MANGROVE FOREST | OVERWASH RED MANGROVE FOREST |
| MANGROVE SWAMPS | 6121 | 61219 | OVERWASH MANGROVE FOREST | OVERWASH DEAD MANGROVE FOREST |
| MANGROVE SWAMPS | 6122 | 61221 | FRINGE MANGROVE FOREST | FRINGE RED MANGROVE FOREST |
| MANGROVE SWAMPS | 6122 | 61225 | FRINGE MANGROVE FOREST | FRINGE MIXED MANGROVE FOREST |
| MANGROVE SWAMPS | 6123 | 61231 | RIVERINE MANGROVE FOREST | RIVERINE RED MANGROVE FOREST |
| MANGROVE SWAMPS | 6123 | 61233 | RIVERINE MANGROVE FOREST | RIVERINE WHITE MANGROVE FOREST |
| MANGROVE SWAMPS | 6123 | 61235 | RIVERINE MANGROVE FOREST | RIVERINE MIXED MANGROVE FOREST |
| MANGROVE SWAMPS | 6124 | 61245 | BASIN MANGROVE FOREST | BASIN MIXED MANGROVE FOREST |
| MANGROVE SWAMPS | 6124 | 61242 | BASIN MANGROVE FOREST | BASIN BLACK MANGROVE FOREST |
| MANGROVE SWAMPS | 6125 | 61251 | HAMMOCK MANGROVE FOREST | HAMMOCK RED MANGROVE FOREST |
| MANGROVE SWAMPS | 6125 | 61253 | HAMMOCK MANGROVE FOREST | HAMMOCK WHITE MANGROVE FOREST |
| MANGROVE SWAMPS | 6125 | 61254 | HAMMOCK MANGROVE FOREST | HAMMOCK BUTTONWOOD FOREST |
| MANGROVE SWAMPS | 6125 | 61255 | HAMMOCK MANGROVE FOREST | HAMMOCK MIXED MANGROVE FOREST |
| MANGROVE SWAMPS | 6126 | 61262 | SCRUB MANGROVE FOREST | SCRUB BLACK MANGROVE FOREST |
| MANGROVE SWAMPS | 6126 | 61264 | SCRUB MANGROVE FOREST | SCRUB BUTTONWOOD FOREST |
| MANGROVE SWAMPS | 6126 | 61265 | SCRUB MANGROVE FOREST | SCRUB MIXED MANGROVE FOREST |
| MANGROVE SWAMPS | 6126 | 61266 | SCRUB MANGROVE FOREST | SCRUB WHITE MANGROVE BUTTONWOOD FOREST |
| MANGROVE SWAMPS | 6127 | 61271 | ALTERED MANGROVE HEDGE | ALTERED RED MANGROVE HEDGE |

**Table 3: Mangrove Type FLUCCS Codes**

Dead mangroves combine 635: Dead Mangroves with level 4 geomorphic type and level 5 species type to describe these forests. For example: 63542: dead basin black forest is the most common site for mangrove heart attack. Furthermore: 63521: dead red fringe forest is most common in the areas that Hurricane Charley destroyed mangrove. We note that many of these areas have rebounded in the last decade.

| FLUCSDESC | LEV4 | LEV5 | LEV4DESC | LEV5DESC |
|---|---|---|---|---|
| MANGROVE SWAMPS-DIEOFF | 6351 | 63511 | OVERWASH MANGROVE FOREST | OVERWASH RED MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6351 | 63519 | OVERWASH MANGROVE FOREST | OVERWASH DEAD MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6352 | 63521 | FRINGE MANGROVE FOREST | FRINGE RED MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6352 | 63525 | FRINGE MANGROVE FOREST | FRINGE MIXED MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6353 | 63531 | RIVERINE MANGROVE FOREST | RIVERINE RED MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6353 | 63535 | RIVERINE MANGROVE FOREST | RIVERINE MIXED MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6354 | 63545 | BASIN MANGROVE FOREST | BASIN MIXED MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6354 | 63542 | BASIN MANGROVE FOREST | BASIN BLACK MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6355 | 63551 | HAMMOCK MANGROVE FOREST | HAMMOCK RED MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6356 | 63562 | SCRUB MANGROVE FOREST | SCRUB BLACK MANGROVE FOREST |
| MANGROVE SWAMPS-DIEOFF | 6356 | 63564 | SCRUB MANGROVE FOREST | SCRUB BUTTONWOOD FOREST |
| MANGROVE SWAMPS-DIEOFF | 6357 | 63571 | ALTERED MANGROVE HEDGE | ALTERED RED MANGROVE HEDGE |

**Table 4: Mangrove Die-Off Type FLUCCS Codes**

| FLUCSDESC | LEV4 | LEV5 | LEV4DESC | LEV5DESC |
|---|---|---|---|---|
| SALTWATER MARSHES | 6421 | 64211 | SUBTIDAL SALTWATER MARSH | SMOOTH CORDGRASS (10) |
| SALTWATER MARSHES | 6422 | 64221 | TIDAL SALTWATER MARSH | BLACK NEEDLE RUSH (21) |
| SALTWATER MARSHES | 6422 | 64222 | TIDAL SALTWATER MARSH | LEATHER FERN (22) |
| SALTWATER MARSHES | 6422 | 64223 | TIDAL SALTWATER MARSH | BULRUSH (23) |
| SALTWATER MARSHES | 6423 | 64231 | SUPERTIDAL SALTWATER MARSH | ALGAL SALTWATER MARSH (31) |
| SALTWATER MARSHES | 6423 | 64232 | SUPERTIDAL SALTWATER MARSH | SALTERN (32) |
| SALTWATER MARSHES | 6423 | 64233 | SUPERTIDAL SALTWATER MARSH | SUCCULENT MEADOW SALTWATER MARSH (33) |
| SALTWATER MARSHES | 6423 | 64234 | SUPERTIDAL SALTWATER MARSH | MIXED MEADOW SALTWATER MARSH (34) |
| SALTWATER MARSHES | 6423 | 64235 | SUPERTIDAL SALTWATER MARSH | GRASS MEADOW SALTWATER MARSH (35) |
| SALTWATER MARSHES | 6423 | 64236 | SUPERTIDAL SALTWATER MARSH | SHRUB BUTTONWOOD MARSH (36) |
| SALTWATER MARSHES | 6423 | 64237 | SUPERTIDAL SALTWATER MARSH | SHRUB BLACK MANGROVE MARSH (30) |

**Table 5: Salt Marsh Type FLUCCS Codes**

## Mapping Techniques

Mapping techniques evolved with the project. The first mapping tests were conducted in the Imperial River area. The working base map was developed by:

- Combining 612: Mangrove Swamp and 642: Saltwater Marsh from the water management district maps. Designating both areas as mangrove;
- Super-imposing the SWFRPC/CHNEP 2011 salt marsh map on top and designating it as the area of salt marsh

During this first test, 6127: Altered Hedge was identified as an additional geomorphic mangrove type.

Since site investigations were to start in the northern part of the study area, hand-mapping moved to Peace River, then across to the Myakka River and down both walls of Charlotte Harbor.

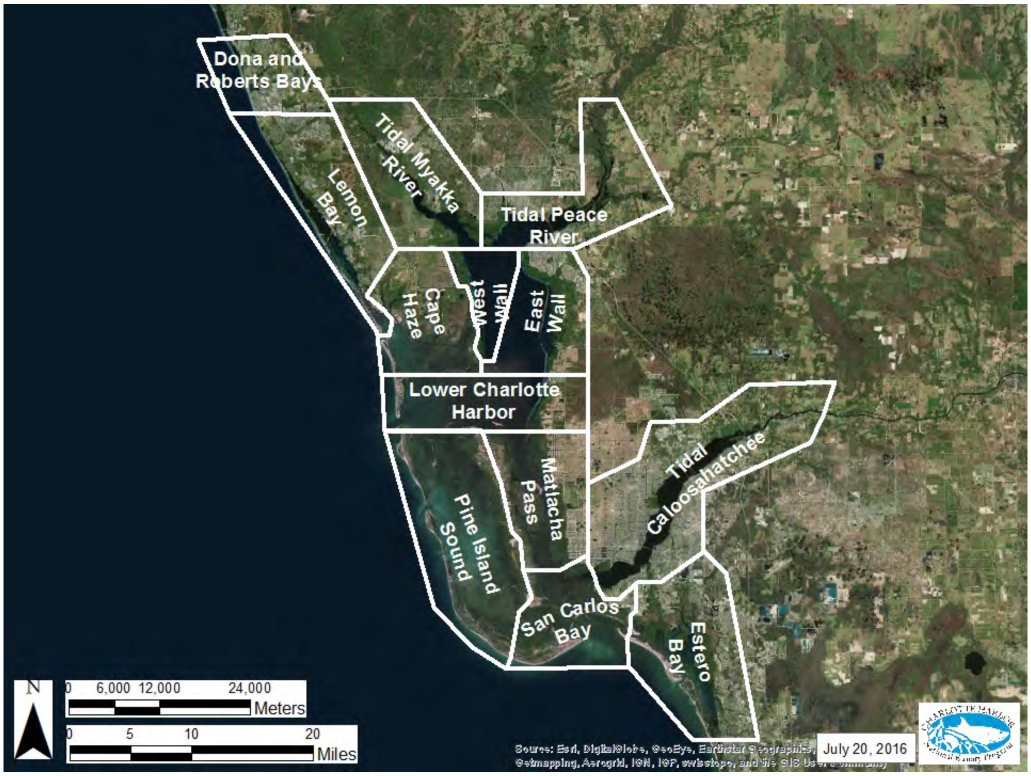
Soon after beginning work on the Peace River map, it was found that creating the polygons from scratch was more efficient. The 2011 salt marsh map floats over the mangrove mapping and is geoprocessed into the mangrove map after it is finished. At first, drawing the mosquito control ditches and spoil piles by hand was acceptable. However, as the density of these features increased, a quicker geoprocessed method was developed. These features were engineered and had a similarity in width. Therefore polylines were drawn down the center of each ditch. A point was placed in the center of each spoil pile. Typical widths were measured and a buffer applied to these features. After the polygon file was created, these features were geoprocessed into the mangrove polygon file, before the salt marsh file was processed in. Areas and buffers are as follows:

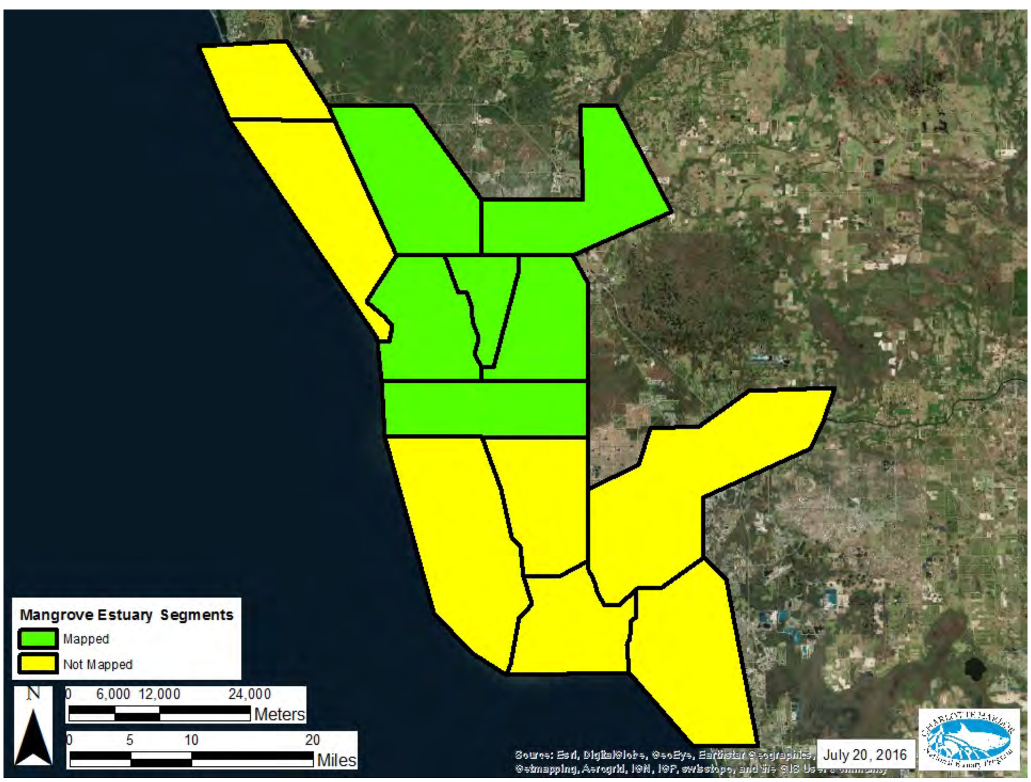
- Manchester- Altered mangrove hedge associated with the ditches had a cross-section of 42 feet, so a buffer of 21 feet was used. Spoil piles had a cross-section of 30 feet so a radius of 15 feet was used.
- Cape Haze, East Wall and Lower Charlotte Harbor- Altered mangrove hedge associated with the ditches had a cross-section of 40 feet, so a buffer of 20 feet was used. Spoil piles had a cross-section of 25 feet so a radius of 12.5 feet was used.

The Peace River and Myakka River segments were completed to share with other mangrove specialists, especially those working on mapping mangroves. This occurred in concert with the Coastal Habitat Integrated Mapping and Monitoring Program (CHIMMP) workshop held on September 14-15, 2015. Presentations were made on progress on the Mangrove Heart Attack mapping and on Mangrove Heart Attack restoration approaches by project team members.

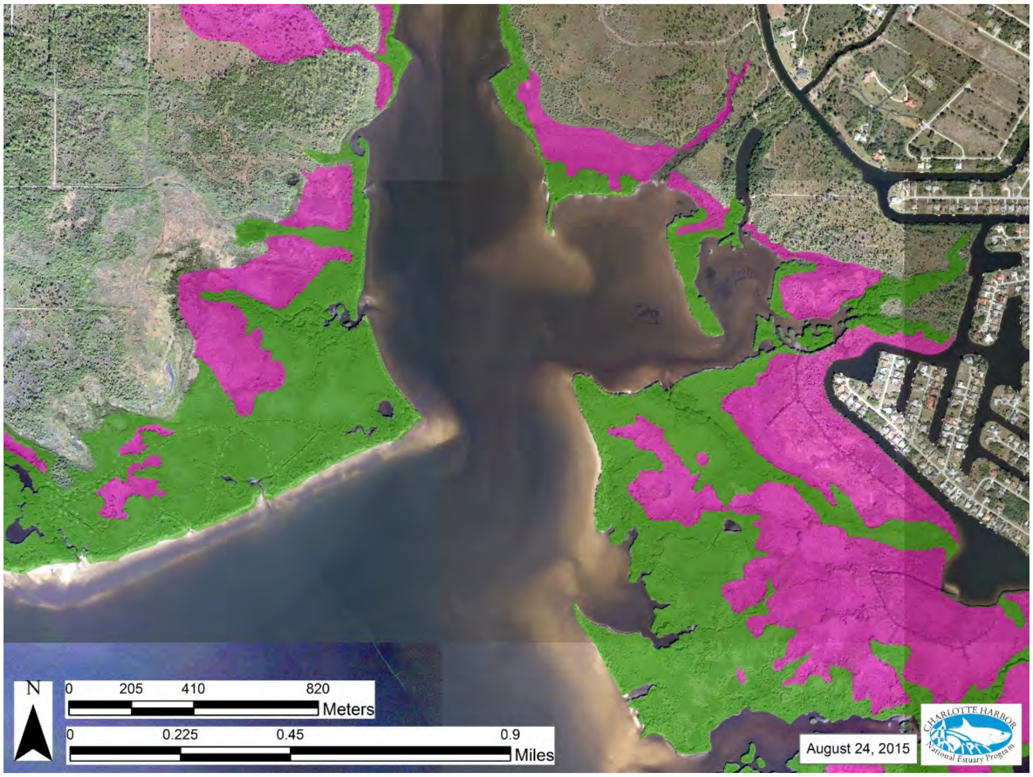
The West Wall and Cape Haze segments were completed January 6, 2016. These segments benefited by lessons learned in the earlier mapping efforts and include large areas of most of the geomorphic types and species. This was selected as an area for early calibrate with Landsat data. The East Wall and Lower Charlotte Harbor Segments were completed as a finished product on July 20, 2016 and united with the earlier work.

The mapping segments are shown below. In addition, an example comparing mangrove and salt marsh mapping by the water management district to the project geomorphic and species mapping completed in the project follows.

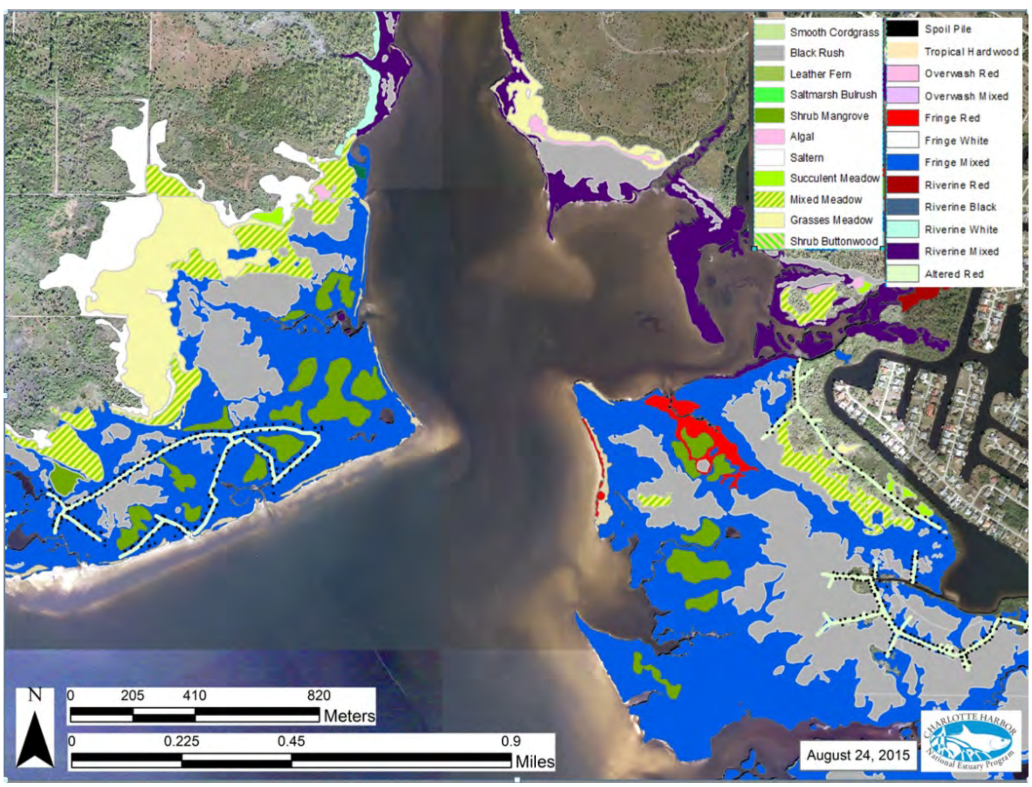



**Map 7: Mangrove Estuary Segments**




**Map 8: Water Management District Map of Mangrove (green) and Salt Marsh (pink)**




**Map 9: Geomorphic and Species Structure of Mangrove and Salt Marsh**

## Mapping Analysis

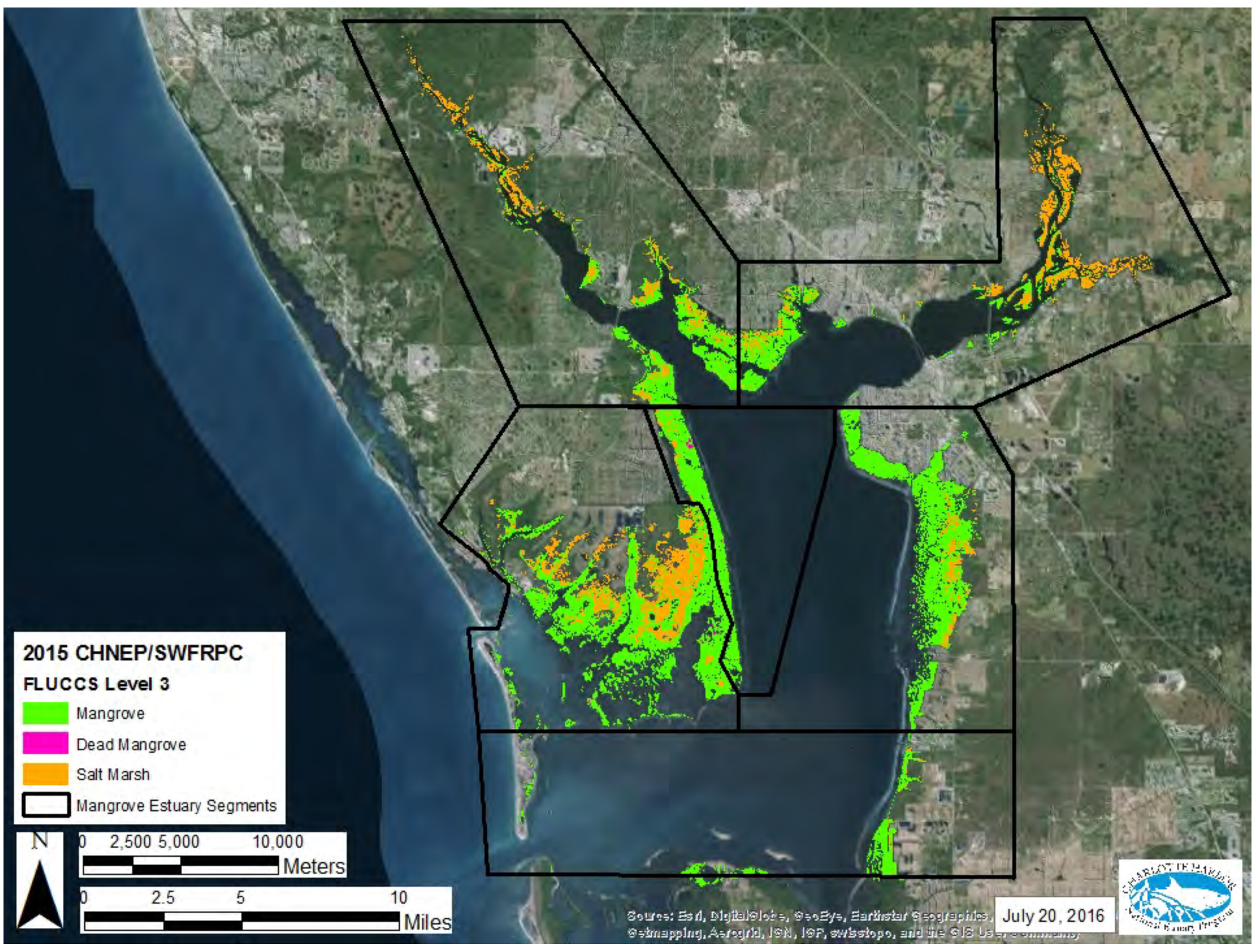
Below is a table that presents the estuary segments and the respective mangrove and salt marsh acreages.

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Overwash Island- Red | 61211 | 0.30 | 0.08 | 0.11 | 6.37 | 2.55 | 4.65 | 14.16 |
| Overwash Island- Mixed | 61215 | 0.27 | 0.24 | 1.16 | 9.69 | 41.01 | 1.54 | 54.27 |
| Fringe-Red | 61221 | 10.75 | 40.76 | 236.36 | 263.44 | 220.70 | 55.12 | 835.16 |
| Fringe-Black | 61222 | 0.31 | | 8.78 | 42.86 | 332.16 | 1.95 | 386.06 |
| Fringe-White | 61223 | 1.18 | 64.43 | | 75.78 | 39.91 | | 181.29 |
| Fringe-Buttonwood | 61224 | | | | | 8.28 | 0.69 | 8.97 |
| Fringe-Mixed | 61225 | 1,193.93 | 2,138.51 | 2,186.17 | 5,405.97 | 4,124.39 | 869.51 | 16,055.48 |
| Riverine-Red | 61231 | 16.76 | 5.04 | | 14.52 | 1.61 | 0.20 | 38.12 |
| Riverine-Black | 61232 | 7.78 | 2.02 | | 30.59 | | | 40.40 |
| Riverine-White | 61233 | 1.12 | 27.14 | | 7.20 | 0.41 | | 35.86 |
| Riverine-Mixed | 61235 | 777.30 | 385.62 | | 202.69 | 26.07 | 33.56 | 1,425.24 |
| Basin-Red | 61241 | | | | | 1.61 | | 1.61 |
| Basin-Black | 61242 | 22.28 | 87.89 | 84.91 | 177.92 | 135.93 | 45.31 | 554.40 |
| Basin-Mixed | 61245 | | 6.48 | | 667.16 | 3.37 | 18.84 | 695.84 |
| Hammock-Red | 61251 | | | | 5.46 | | | 5.46 |
| Hammock-White | 61253 | | | | 27.91 | | | 27.91 |
| Hammock-Buttonwood | 61254 | | | | 0.86 | | | 0.86 |
| Hammock-Mixed | 61255 | | | | 6.94 | | 1.51 | 8.45 |
| Scrub-Black | 61262 | 1.02 | 12.76 | 10.09 | 122.04 | 0.04 | 1.51 | 152.52 |
| Scrub-White | 61263 | | | | 2.75 | | | 2.75 |
| Scrub-Mixed | 61266 | 0.33 | 0.94 | | 552.76 | 352.05 | 35.87 | 954.04 |
| Altered-Red | 61271 | 81.55 | 57.93 | | 112.76 | 108.33 | 2.03 | 362.81 |
| Altered-White | 61273 | | | | 2.56 | | | 2.56 |
| Altered-Buttonwood | 61274 | | | | | 1.45 | | 1.45 |
| Altered-Mixed | 61275 | 22.55 | 19.84 | | 60.44 | 10.73 | 43.24 | 156.79 |
| | | 2,137.43 | 2,849.65 | 2,527.57 | 7,798.65 | 5,410.59 | 1,115.52 | 22,002.43 |

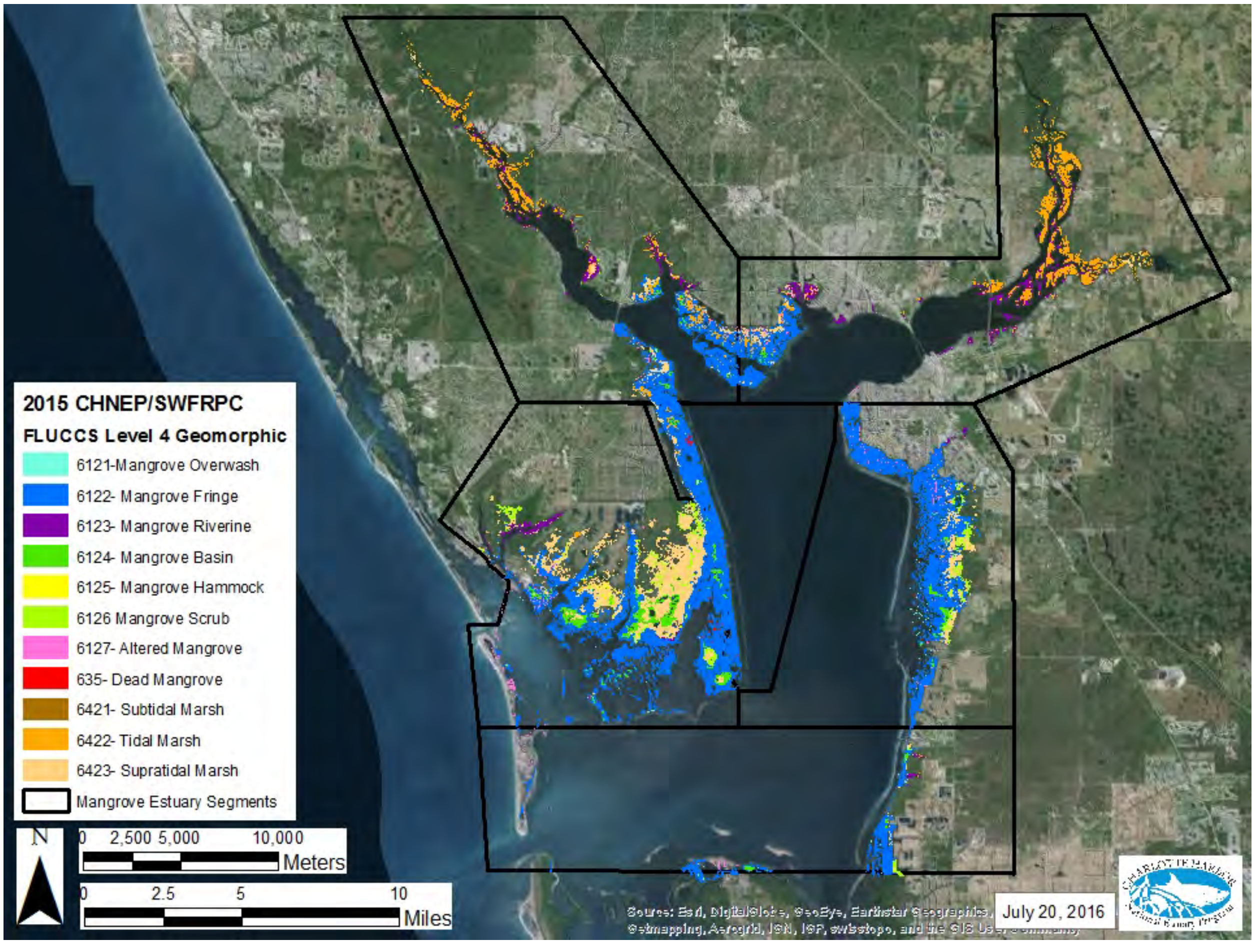
**Table 6: Live Mangrove Acreages**

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Overwash Island- Red | 63511 | | | | | 0.33 | 0.31 | 0.64 |
| Overwash Island- Mixed | 63515 | | | | 0.15 | 3.40 | | 3.55 |
| Fringe-Red | 63521 | | | 2.06 | 5.43 | 0.78 | 0.54 | 8.82 |
| Fringe-Mixed | 63525 | 0.92 | 2.40 | 24.77 | 20.46 | 7.67 | 0.11 | 56.33 |
| Riverine-Mixed | 63535 | 0.19 | | | | 0.08 | | 0.28 |
| Basin-Black | 63542 | | | | 1.44 | | | 1.44 |
| Altered-Mixed | 63575 | 0.43 | | | | | | 0.43 |
| | | 1.54 | ` | 26.83 | 27.48 | 12.26 | 0.96 | 71.49 |

**Table 7: Dead Mangrove Acreages**




**Map 10: 2015 FLUCCS Level 3, By Habitat Type**




**Map 11: 2015 FLUCCS Level 4, by geomorphic type**

By mapping mangroves and salt marsh by geomorphic type, it becomes apparent that tidal marsh (in orange) have an affinity to riverine mangrove forests (in purple) and supratidal marshes (in light orange) have an affinity for fringe mangrove forests (in blue) and scrub mangrove forests (in light green).

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Overwash | 6121 | 0.57 | 0.32 | 1.27 | 16.06 | 43.56 | 6.19 | 68.43 |
| Fringe | 6122 | 1,206.17 | 2,243.69 | 2,431.30 | 5,788.04 | 4,725.44 | 927.27 | 17,466.95 |
| Riverine | 6123 | 802.96 | 419.81 | 0.00 | 254.99 | 28.09 | 33.76 | 1,539.62 |
| Basin | 6124 | 22.28 | 94.37 | 84.91 | 845.08 | 140.90 | 64.15 | 1,251.85 |
| Hammock | 6125 | 0.00 | 0.00 | 0.00 | 41.16 | 0.00 | 1.51 | 42.67 |
| Scrub | 6126 | 1.35 | 13.70 | 10.09 | 677.55 | 352.10 | 37.38 | 1,109.31 |
| Altered | 6127 | 104.10 | 77.76 | 0.00 | 175.76 | 120.50 | 45.27 | 523.60 |
| | | 2,137.43 | 2,849.65 | 2,527.57 | 7,798.65 | 5,410.59 | 1,115.52 | 22,002.43 |

**Table 8: 2015 Mangrove FLUCCS Level 4**

Comparison with 2011 Salt Marsh Mapping Effort

During mapping, additional salt marshes were identified and added to the mapping. Actual mixed meadow salt marsh increases were identified around the Alligator Creek Salt Marsh Restoration area, on the East Wall.

| Description | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Smooth Cordgrass | 64211 | 0.04 | | | | | | 0.04 |
| Black Rush | 64221 | 1,384.22 | 1,151.91 | 43.87 | 35.40 | 38.97 | 14.77 | 2,669.14 |
| Leather Fern | 64222 | 238.23 | 55.42 | | 10.32 | 1.44 | | 305.41 |
| Saltmarsh Bulrush | 64223 | 337.43 | | | | | | 337.43 |
| Algal | 64231 | 16.53 | 23.42 | | 190.43 | 51.29 | 3.32 | 284.99 |
| Saltern | 64232 | 1.29 | 16.15 | | 259.52 | 64.94 | 5.21 | 347.11 |
| Succulent Meadow | 64233 | 22.60 | 26.95 | 6.14 | 243.58 | 68.07 | 1.28 | 368.62 |
| Mixed Meadow | 64234 | 155.81 | 230.67 | 49.18 | 2,295.05 | 217.52 | 20.82 | 2,969.05 |
| Grasses Meadow | 64235 | 4.76 | 46.76 | 11.88 | 115.81 | 114.35 | 3.85 | 297.40 |
| Buttonwood Shrub | 64236 | | | | | | | 0.00 |
| Black Mang. Shrub | 64237 | 50.25 | 6.05 | | 315.36 | | | 371.65 |
| Total | | 2,211.15 | 1,557.33 | 111.07 | 3,465.47 | 556.58 | 49.25 | 7,950.85 |

**Table 9: 2011 Salt Marsh Acreages by Estuary Segment**

| Description | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Smooth Cordgrass | 64211 | 0.04 | | | | | | 0.04 |
| Black Rush | 64221 | 1,405.81 | 1,176.23 | 44.33 | 39.32 | 40.79 | 14.89 | 2,721.37 |
| Leather Fern | 64222 | 238.85 | 55.40 | | 10.32 | 1.44 | | 306.01 |
| Saltmarsh Bulrush | 64223 | 348.01 | 0.05 | | | | | 348.06 |
| Algal | 64231 | 16.52 | 23.45 | | 190.92 | 51.59 | 3.32 | 285.80 |
| Saltern | 64232 | 1.28 | 21.39 | | 291.05 | 66.75 | 5.80 | 386.27 |
| Succulent Meadow | 64233 | 23.06 | 26.95 | 6.14 | 246.60 | 71.98 | 1.28 | 376.01 |
| Mixed Meadow | 64234 | 155.75 | 230.87 | 49.16 | 2,313.24 | 239.46 | 24.84 | 3,013.32 |
| Grasses Meadow | 64235 | 4.76 | 46.74 | 11.88 | 145.83 | 120.13 | 9.56 | 338.89 |
| Black Mang. Shrub | 64237 | 49.62 | 6.05 | | 318.64 | | | 374.31 |
| Total | | 2,243.71 | 1,587.12 | 111.51 | 3,555.91 | 592.14 | 59.69 | 8,150.08 |

**Table 10: 2015 Salt Marsh Acreages by Estuary Segment**

| Description | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Smooth Cordgrass | 64211 | | | | | | | 0.00 |
| Black Rush | 64221 | 21.59 | 24.32 | 0.46 | 3.92 | 1.82 | 0.12 | 52.24 |
| Leather Fern | 64222 | 0.62 | -0.02 | | | | | 0.60 |
| Saltmarsh Bulrush | 64223 | 10.59 | 0.05 | | | | | 10.63 |
| Algal | 64231 | | 0.03 | | 0.49 | 0.30 | | 0.80 |
| Saltern | 64232 | | 5.24 | | 31.53 | 1.81 | 0.59 | 39.16 |
| Succulent Meadow | 64233 | 0.46 | -0.01 | | 3.02 | 3.91 | | 7.38 |
| Mixed Meadow | 64234 | -0.06 | 0.20 | -0.02 | 18.18 | 21.94 | 4.02 | 44.27 |
| Grasses Meadow | 64235 | | -0.02 | | 30.02 | 5.78 | 5.71 | 41.49 |
| Black Mang. Shrub | 64237 | -0.62 | | | 3.28 | | | 2.66 |
| Total | | 32.57 | 29.79 | 0.44 | 90.44 | 35.56 | 10.44 | 199.23 |
| Increase | | 1.47% | 1.91% | 0.39% | 2.61% | 6.39% | 21.19% | 2.51% |

**Table 11: Differences between Salt Marsh Acreages documented in 2011 and 2015**

| Description | FLUCCS | Dona and Roberts Bays | Estero Bay | Lemon Bay | Matlacha Pass | Pine Island Sound | San Carlos Bay | Tidal Caloosa-hatchee | Total |
|---|---|---|---|---|---|---|---|---|---|
| Smooth Cordgrass | 64211 | | | 0.04 | | 2.72 | | | 2.76 |
| Black Rush | 64221 | 27.94 | 726.37 | 9.97 | 6.26 | 7.89 | 7.88 | 138.51 | 924.82 |
| Leather Fern | 64222 | 5.29 | 38.57 | 31.30 | 0.28 | 4.68 | 2.54 | 76.55 | 159.21 |
| Saltmarsh Bulrush | 64223 | | | | | | | | 0.00 |
| Algal | 64231 | | 528.04 | 0.60 | 72.62 | 334.68 | 19.98 | 4.37 | 960.29 |
| Saltern | 64232 | 0.04 | 132.81 | 2.11 | 47.16 | 45.35 | 80.87 | 2.54 | 310.87 |
| Succulent Meadow | 64233 | | 164.84 | | 122.98 | 275.10 | 8.57 | 3.56 | 575.06 |
| Mixed Meadow | 64234 | | 732.06 | 5.54 | 1,412.58 | 349.57 | 251.27 | 64.37 | 2,815.40 |
| Grasses Meadow | 64235 | | 52.76 | | 122.22 | 11.60 | 77.23 | 39.91 | 303.72 |
| Buttonwood Shrub | 64236 | | 4.05 | | 0.90 | | 14.66 | | 19.61 |
| Black Mang. Shrub | 64237 | | 186.10 | 1.38 | 298.26 | 90.39 | 243.31 | 15.07 | 834.51 |
| | Total | 33.27 | 2,565.59 | 50.95 | 2,083.26 | 1,121.98 | 706.33 | 344.88 | 6,906.26 |

**Table 12: Additional Segments not mapped in 2015**

Comparison with 2009 Water Management District Land Use Map

During mapping, additional salt marshes were identified and added to the mapping. Actual mixed meadow

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Mangrove | 612 | 2,435.23 | 2,271.08 | 2,478.46 | 7,280.45 | 5,404.26 | 1,227.04 | 21,096.52 |
| Salt Marsh | 642 | 2,378.85 | 1,744.04 | 219.65 | 3,245.58 | 89.87 | 55.70 | 7,733.70 |
| Total | | 4,814.08 | 4,015.12 | 2,698.12 | 10,526.03 | 5,494.13 | 1,282.74 | 28,830.22 |

**Table 13 : 2009 Water Management District Acreages by Estuary Segment**

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Mangrove | 612 | 2,137.43 | 2,849.65 | 2,527.57 | 7,798.65 | 5,410.59 | 1,115.52 | 22,002.43 |
| Salt Marsh | 642 | 2,243.71 | 1,587.12 | 111.51 | 3,555.91 | 592.14 | 59.69 | 8,150.08 |
| Total | | 4,382.69 | 4,439.18 | 2,665.92 | 11,382.04 | 6,014.99 | 1,176.17 | 30,224.01 |

**Table 14: 2015 Acreages by Estuary Segment**

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Mangrove | 612 | -297.80 | 578.57 | 49.11 | 518.20 | 6.33 | -111.52 | 905.91 |
| Salt Marsh | 642 | -135.14 | -156.92 | -108.14 | 310.33 | 502.27 | 3.99 | 416.39 |
| Total Wetlands | | -432.94 | 421.65 | -59.03 | 828.53 | 508.60 | -107.53 | 1,322.30 |
| % mangrove difference | | -12.23% | 25.48% | 1.98% | 7.12% | 0.12% | -9.09% | 4.29% |
| % salt marsh difference | | -5.68% | -9.00% | -49.23% | 9.56% | 558.88% | 7.15% | 5.38% |
| % Wetland Difference | | -8.96% | 10.56% | -1.19% | 8.13% | 9.48% | -8.31% | 4.83% |

**Table 15: Differences between 2009 WMD Land Use and 2015 Map**

| Type | FLUCCS | Dona and Roberts Bays | Estero Bay | Lemon Bay | Matlacha Pass | Pine Island Sound | San Carlos Bay | Tidal Caloosa-hatchee | Total |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 612 | 58.46 | 10,453.41 | 865.67 | 12,026.62 | 8,842.04 | 6,146.29 | 2,434.07 | 40,826.55 |
| Salt Marsh | 642 | 41.21 | 1,897.30 | 44.99 | 1,686.21 | 360.23 | 231.24 | 372.34 | 4,633.52 |
| Total | | 99.67 | 12,350.71 | 910.65 | 13,712.83 | 9,202.27 | 6,377.53 | 2,806.40 | 45,460.06 |

**Table 16: Additional WMD Segments not mapped in 2015**

Comparison with 2003 Fish and Wildlife Conservation Commission Landsat Map

FWC prepared a statewide map of habitats using Landsat 7 data in 2003.

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Mangrove | 612 | 1,758.44 | 1,868.05 | 2,396.83 | 7,611.09 | 4,737.48 | 1,172.18 | 19,544.07 |
| Salt Marsh | 642 | 2,866.50 | 3,086.64 | 485.97 | 2,515.87 | 840.50 | 142.68 | 9,938.16 |
| Total | | 4,624.95 | 4,954.69 | 2,882.79 | 10,126.95 | 5,577.98 | 1,314.86 | 29,482.22 |

**Table 17: 2009 FWC Acreages by Estuary Segment**

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Mangrove | 612 | 2,137.43 | 2,849.65 | 2,527.57 | 7,798.65 | 5,410.59 | 1,115.52 | 22,002.43 |
| Salt Marsh | 642 | 2,243.71 | 1,587.12 | 111.51 | 3,555.91 | 592.14 | 59.69 | 8,150.08 |
| Total | | 4,382.69 | 4,439.18 | 2,665.92 | 11,382.04 | 6,014.99 | 1,176.17 | 30,224.01 |

**Table 18: 2015 Acreages by Estuary Segment**

| Type | FLUCCS | Tidal Peace River | Tidal Myakka River | West Wall | Cape Haze | East Wall | Lower Charlotte Harbor | Total |
|---|---|---|---|---|---|---|---|---|
| Mangrove | 612 | 378.99 | 981.60 | 130.75 | 187.56 | 673.11 | -56.66 | 2,458.36 |
| Salt Marsh | 642 | -622.79 | -1,499.52 | -374.46 | 1,040.04 | -248.36 | -82.99 | -1,788.07 |
| Total Wetlands | | -243.80 | -517.92 | -243.71 | 1,227.60 | 424.75 | -139.65 | 670.29 |
| % mangrove difference | | 21.55% | 52.55% | 5.46% | 2.46% | 14.21% | -4.83% | 12.58% |
| % salt marsh difference | | -21.73% | -48.58% | -77.05% | 41.34% | -29.55% | -58.17% | -17.99% |
| % Wetland Difference | | -5.24% | -10.40% | -7.52% | 12.39% | 7.83% | -10.55% | 2.52% |

**Table 19: Differences between 2003 FWC Land Use and 2015 Map**

| Type | FLUCCS | Dona and Roberts Bays | Estero Bay | Lemon Bay | Matlacha Pass | Pine Island Sound | San Carlos Bay | Tidal Caloosa-hatchee | Total |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 612 | 59.38 | 10,673.40 | 955.46 | 11,558.14 | 9,814.77 | 6,249.38 | 2,238.73 | 41,549.27 |
| Salt Marsh | 642 | 143.05 | 1,726.14 | 421.39 | 1,691.07 | 337.72 | 483.17 | 553.99 | 5,356.53 |
| Total | | 202.43 | 12,399.54 | 1,376.84 | 13,249.21 | 10,152.50 | 6,732.55 | 2,792.72 | 46,905.80 |

**Table 20: Additional FWC Segments not mapped in 2015**

Comparison with 2015 USGS Landsat Map

Rather than look at total mangroves extent, we reviewed the USGS Landsat map, counted as a first reflectance run. Since the polygon may clip a pixel that is predominately another cover type, we looked at nearly whole pixels. Since 900 square meters is 0.22239484332 acres, we counted pixels that were equal to or over 0.222394 acres. We did not apply this to the FWC Landsat mapping because of the geo-referencing problem already discussed. A pixel that FWC mapped as mangrove may be off of the mangrove area it identified.

Because overwash island mangrove forests, hammock mangrove forests and altered mangrove hedges all tend to be small, a total of less than 2 acres were mapped which incorporated whole pixels.

USGS identified 97% of all the fringe mangrove forests mapped, 98% of the basin mangrove forests mapped, 85% of riverine mangrove forests that were mapped and 33% of scrub mangroves that were mapped.

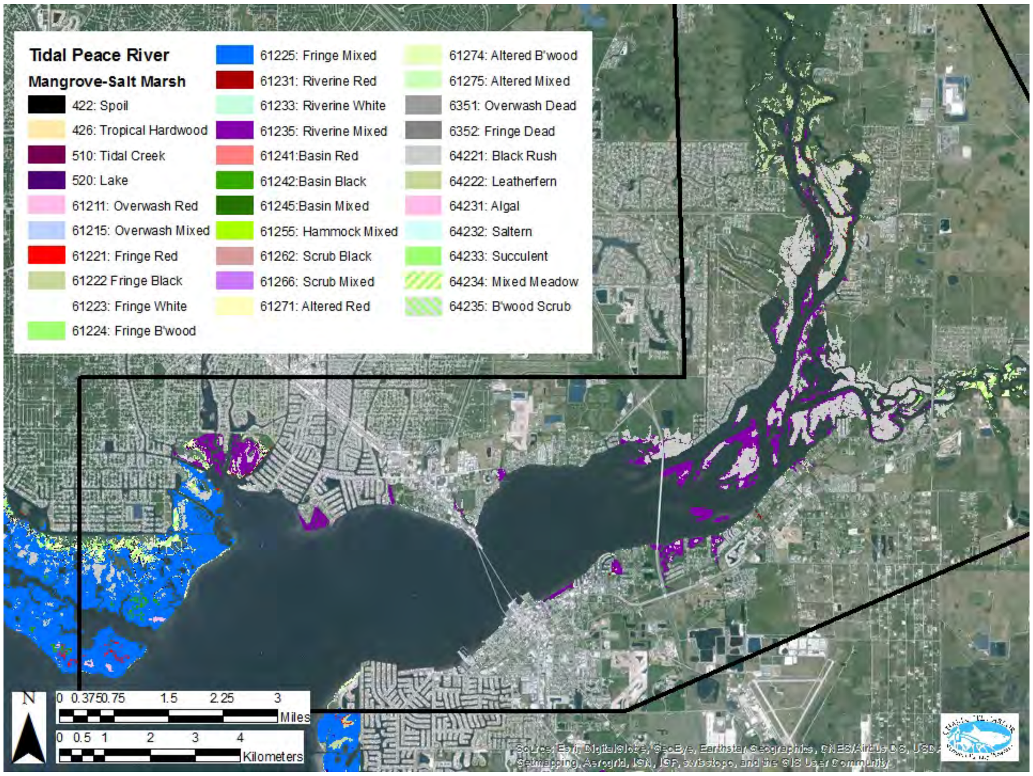
| Type | Tidal Peace River | Tidal Myakka River | Cape Haze | West Wall | East Wall | Lower Charlotte Harbor | Total Of Acres | Percent Correct |
|---|---|---|---|---|---|---|---|---|
| Overwash | | | 0.44 | | 0.89 | | 1.33 | 85.71% |
| Fringe | 659.62 | 1,127.10 | 2,844.65 | 1,530.97 | 2,074.72 | 433.23 | 8,670.29 | 96.55% |
| Riverine | 205.94 | 24.24 | 69.83 | | 2.89 | 6.23 | 309.13 | 84.50% |
| Basin | 1.11 | 21.79 | 450.79 | 31.80 | 80.73 | 39.14 | 625.37 | 97.60% |
| Hammock | | | 0.67 | | | | 0.67 | 11.11% |
| Scrub | | 2.22 | 75.17 | 2.67 | 26.69 | 0.22 | 106.97 | 33.13% |
| Altered | 0.44 | 0.22 | 0.89 | | 0.22 | | 1.78 | 33.33% |
| Total | 867.12 | 1,175.58 | 3,442.45 | 1,565.44 | 2,186.14 | 478.82 | 9,715.54 | 94.12% |
| Percent Correct | 98.36% | 90.87% | 94.55% | 99.45% | 91.37% | 88.71% | 94.12% | |

**Table 21: Acreage identified as mangrove by USGS for whole pixels**

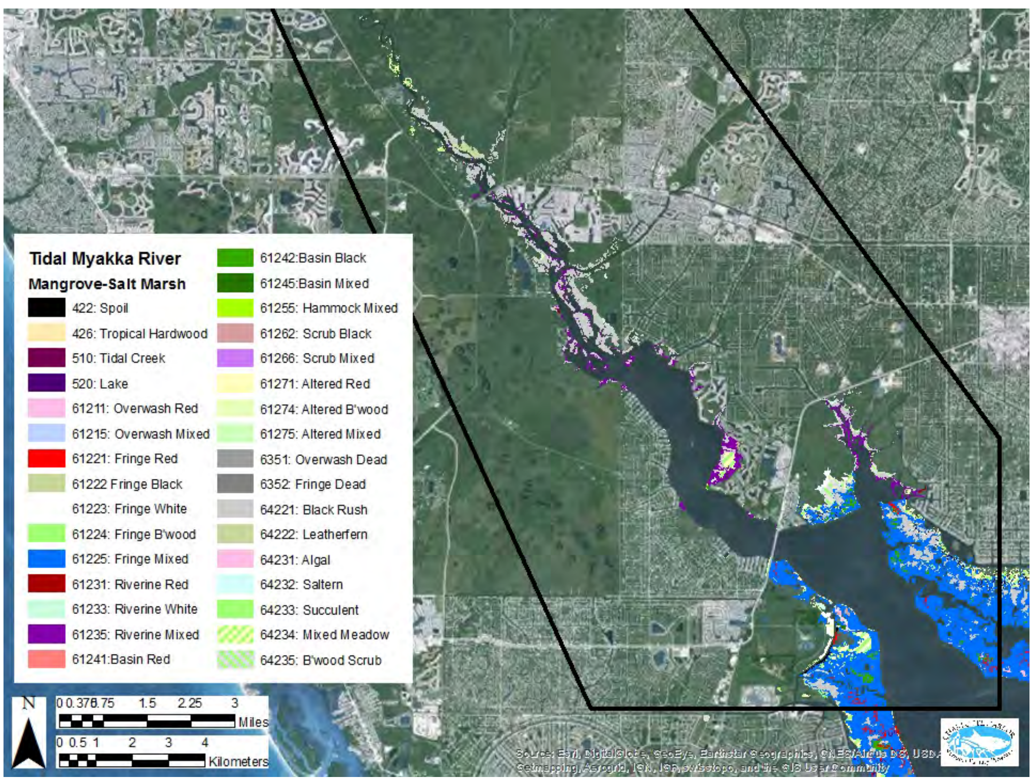
| Geomorph | Tidal Peace River | Tidal Myakka River | Cape Haze | West Wall | East Wall | Lower Charlotte Harbor | Total Of Acres |
|---|---|---|---|---|---|---|---|
| Overwash | | | | | 0.22 | | 0.22 |
| Fringe | 6.89 | 70.50 | 82.51 | 8.67 | 102.08 | 39.36 | 310.02 |
| Riverine | 7.56 | 43.81 | 2.89 | | 2.45 | | 56.71 |
| Basin | | 0.67 | 12.68 | | 2.00 | | 15.35 |
| Hammock | | | 5.34 | | | | 5.34 |
| Scrub | | 0.44 | 94.74 | | 99.86 | 20.91 | 215.95 |
| Altered | | 2.67 | 0.22 | | | 0.67 | 3.56 |
| | 14.46 | 118.09 | 198.38 | 8.67 | 206.60 | 60.94 | 607.14 |

**Table 22: Acreage mapped as mangrove but not identified as mangrove by USGS for whole pixels**

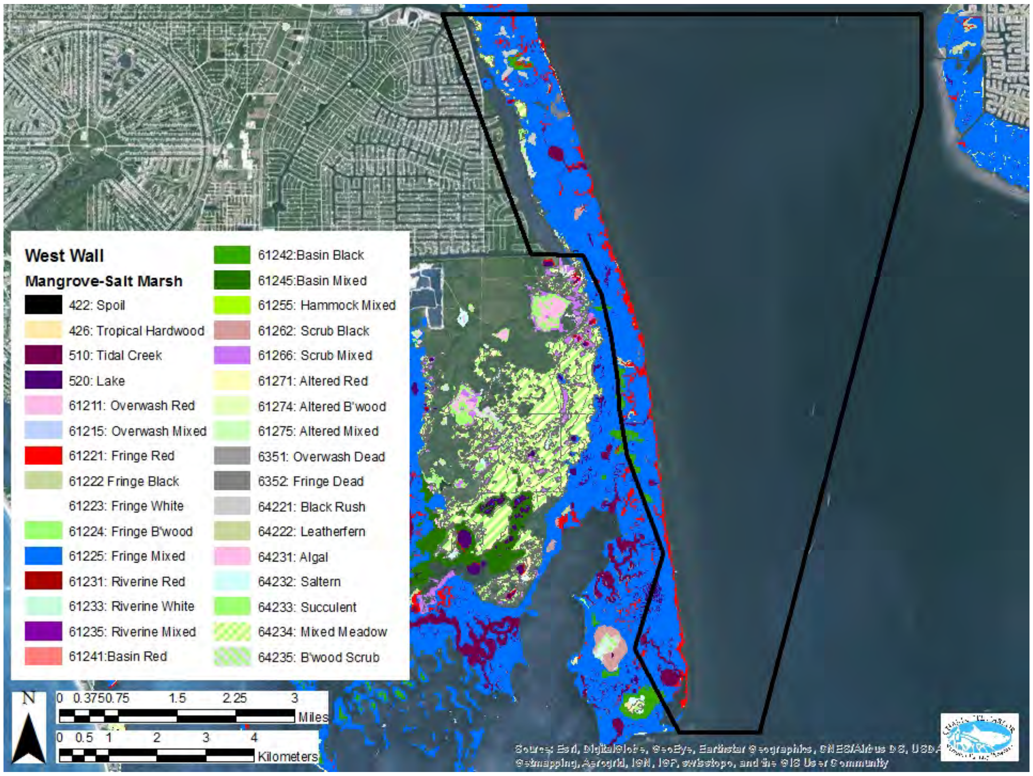
<u>Detailed Level 5 FLUCCS Maps</u>: The following maps present mangroves and salt marshes by geomorphic and species type.



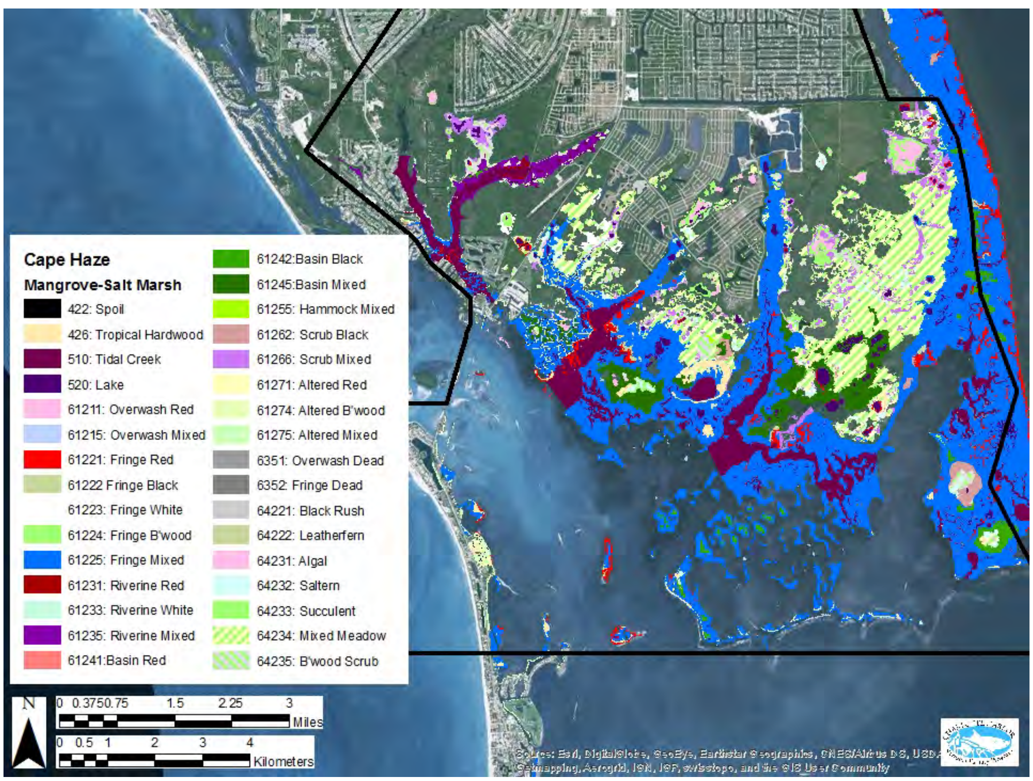
Map 12: Tidal Peace River Mangrove and Salt Marshes



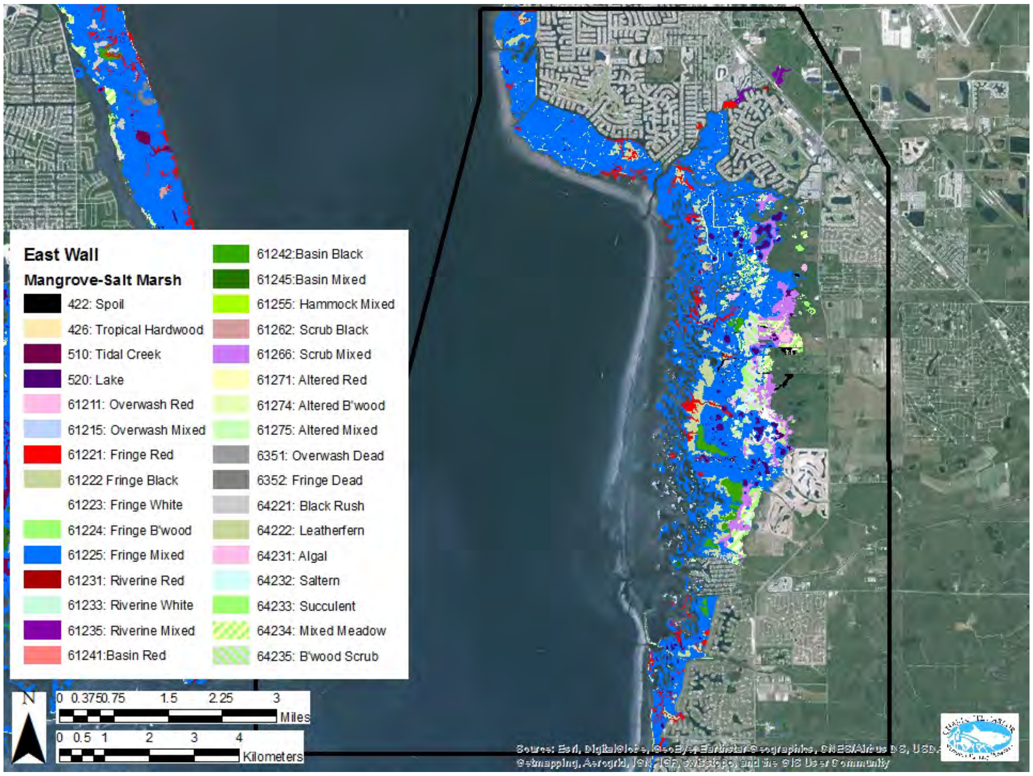
Map 13: Tidal Myakka River Mangrove and Salt Marshes



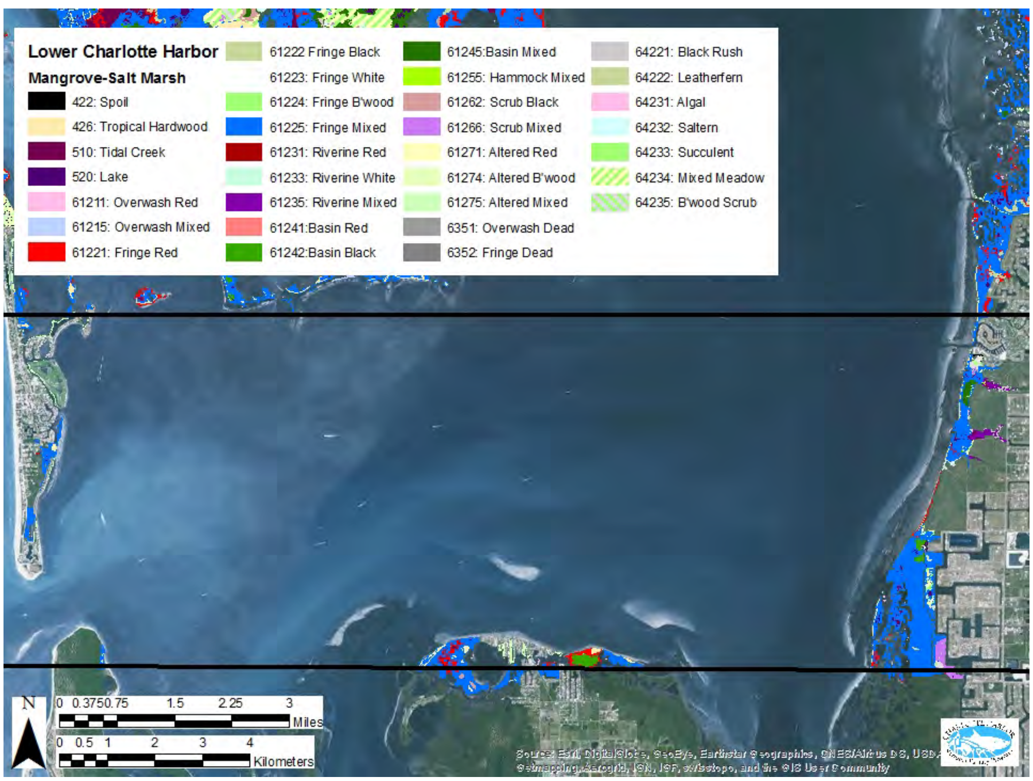
Map 14: West Wall Charlotte Harbor Mangrove and Salt Marshes



Map 15: Cape Haze Mangrove and Salt Marshes




Map 16: East Wall Charlotte Harbor Mangrove and Salt Marshes




Map 17: Lower Charlotte Harbor Mangrove and Salt Marshes

# Mangrove Forest Field Investigation

The project included site investigation of 54 mangrove sites. This section discusses site selection, field methods and data analysis.

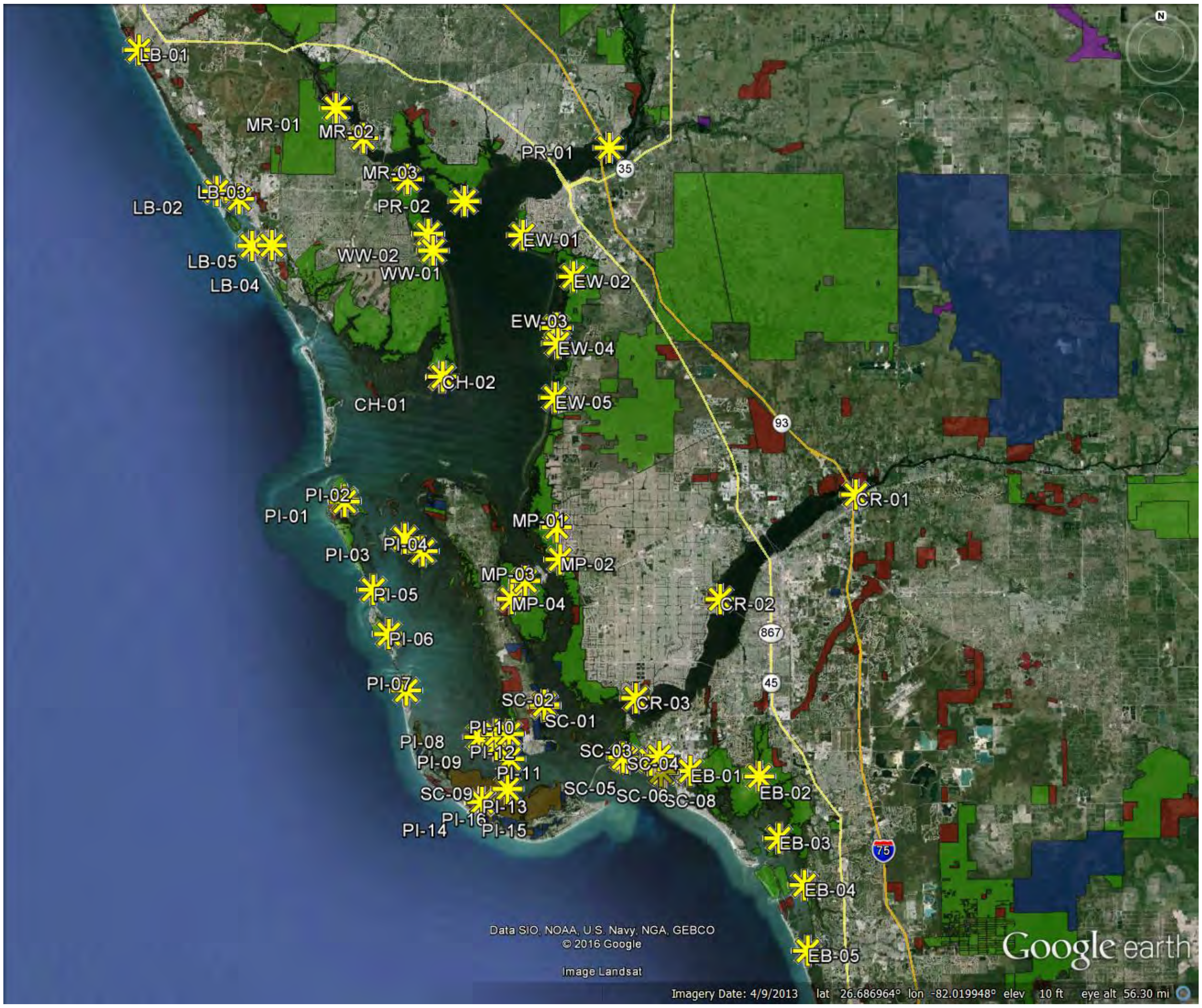
## Site Selection

On January 13, 2015, Southwest Florida Mangrove Biologist Jim Beever identified 56 sites to investigate. The variety of sites provided likely locations for reference sites and die-off sites.

Field visit sites were selected on the basis of four, often complementary criteria:

1. The first selection criterion was sites that were exemplars of specific geomorphologic and mangrove species forest types. For example sites of overwash red mangrove, basin black mangrove, mixed riverine mangrove forest, red mangrove fringe, mixed mangrove fringe, black mangrove scrub, white mangrove fringe and buttonwood forest were selected.
2. The second selection criterion was sites at the expected boundary areas between mangrove forest types.  or example, an ecotone between fringing mangroves and basin mangroves or places where the dominance of one species changed to another would be field examined.
3. The third selection criterion was sites that appear to have mangrove forest death or which were showing signs of stress indicative of future mangrove forest death. Some of these were sites that had been seen during prior field experiences by team members. Others were sites that looked dead on the aerials, looked chlorotic in foliage or were otherwise discolored with areas of bright green Batis in a forest landscape, red colored water, or open areas of grayish muck.
4. The fourth criterion was very unusual sites where it was not clear what the mangrove forest type was. For example an area of high elevation with what appeared to be red mangrove vegetation cover.

The locations were documented as a point file in ArcGIS and distributed to the team as a GoogleEarth KMZ file for review. The KMZ was loaded into a Garmin Oregon 450 GPS unit for use in the field to locate the point.



**Map 18: Initial Site Selection Locations**

## Field Investigation Methods

The 3-page site review datasheet was created to assist in field collection. The first page was devoted to collection of pre-visit data. Such information included:

- Site Identification Code built on mangrove segment abbreviation and a number sequentially applied north to south.
- Location including Township, Range, Section, Latitude and Longitude.
- Ownership including Owner and Property Appraiser account or STRAP number.
- CHNEP Estuary Segment
- Waterbody
- Mangrove Forest Type which related back to the site selection criteria.
- Elevation from Lidar/Digital Elevation Model supplied from CHNEP's coastal county governments.
- Tidal Position, high, medium or low.
- Adjacent upland habitat (if any) derived from 2014 aerial photographs interpretation and on 2008/09 Southwest Florida Water Management District and South Florida Water Management District Florida Land Use and Cover Classification System (FLUCCS) polygon mapping.
- FWC mapping, based on the Florida Fish and Wildlife Conservation Commission 2003 habitat map derived from Landsat 7 analysis.
- WMD mapping, based on 2008/09 Southwest Florida Water Management District and South Florida Water Management District Florida Land Use and Cover Classification System (FLUCCS) polygon mapping.
- USGS mapping, based on 2015 Landsat 8 mangrove analysis.
- Percent tree cover, from 2014 aerial photographs.
- Human impacts in site, including ditching, fill, vehicles, bait digging, etc. from 2014 aerial photographs.
- Adjacent human impacts, including dikes, roads, canals, bulkheads, etc. from 2014 aerial photographs.

The pre-site review was accomplished using GIS and the internet to access Property Appraiser's information at: http://gissvr.leepa.org/GeoView2/ and https://www.ccappraiser.com/rp_real_search.asp coupled with a 2007 account shapefile.

The first page of the CHNEP Mangrove Site Review Data Sheet is shown below, completed for PI-08, Chino Island. The note at the bottom was added as a result of the field visit. In this example, the site investigation was completed on September 25, 2015. Access to the site was obtained via United States Department of Interior U.S. Fish and Wildlife Service Special Use Permit dated September 22, 2015. The permit allowed for Research/Monitoring. Specifically the permit allows "Surveying vegetation community structure to assess mangrove die off and validate remote sensing mapping outputs. Sites to be surveyed include: Chino Island and Ding Darling NWR-Tarpon Bay."

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **CHNEP Mangrove Site Review Data Sheet** | | | | | | | **Page 1 of 3** |
| **PI-08** | **9/25/2015** | | | | | **US Fish & Wildlife Service** | |
| **Location** | **Township** | **Range** | **Section** | **Lat.** | **Long.** | ACCOUNT | 32-45-22-00-00003.0000 |
| Chino Island | 46 | 22 | 32 | 26.5042659 | -82.12757687 | | |

| **From Pre-Visit Aerials:** | |
|---|---|
| CHNEP Estuary Segment | Pine Island Sound-Matlacha Pass |
| Water body | Pine Island Sound |
| Mangrove Forest Type (from photographic aerial) | Basin Black Mangrove die-off? |
| Elevation (from LIDAR) | 1.009092 |
| Elevation (from other sources) | |
| Tidal Position | Medium |
| Adjacent upland habitat type (if any) | None |
| FWC mapped as | Mangrove Swamp |
| WMD mapped as | Mangrove Swamps |
| USGS mapped as | Mangrove |
| % tree cover | 10% |
| Human impacts in site (ditching, fill, vehicles, bait digging, etc.) | Canal 400 feet from site. |
| Adjacent human impacts (dikes, roads, canals, bulkheads, etc.) | None |

It apears there was a major flooding event 20 to 30 years ago. Batis and seedlings indicate healthy. 10 to 15 years of recovery



**Figure 18: Sample CHNEP Mangrove Site Review Data Sheet, Page One**

Prior to site investigation, maps were prepared to assist with navigation. There was an overall map which showed the sites to be visited on that day along with a more detailed map. The more detailed map was used to discuss site access with the Captain and site visit team members in the field. Sample of these maps follow.

The Charlotte Harbor Aquatic Preserves provided boat access, captains and expertise. Melynda Brown was the captain on July 27, October 8 and November 5, 2015. Mary McMurray was the captain on July 20, August 25, 2015 and February 18, 2016. Arielle Taylor-Manges was the captain on September 9 and September 25, 2015. Estero Bay Aquatic Preserve Manager Cheryl Clark captained the boat on November 17, 2015. The Friends of the Charlotte Harbor Aquatic Preserves and Estero Bay Buddies assisted in procuring the equipment to provide boat access for the project.

The Charlotte Harbor Preserve State Park provided off-road access and assistance from Jay Garner on April 18, 2016. Ralph Allen, Kingfisher Fleet, was contracted for provide boat access to sites on May 19, June 12 and June 17, 2015. Additional site investigation days were conducted by normal vehicular access as a carpool on October 27, 2015 and January 13, 2016.

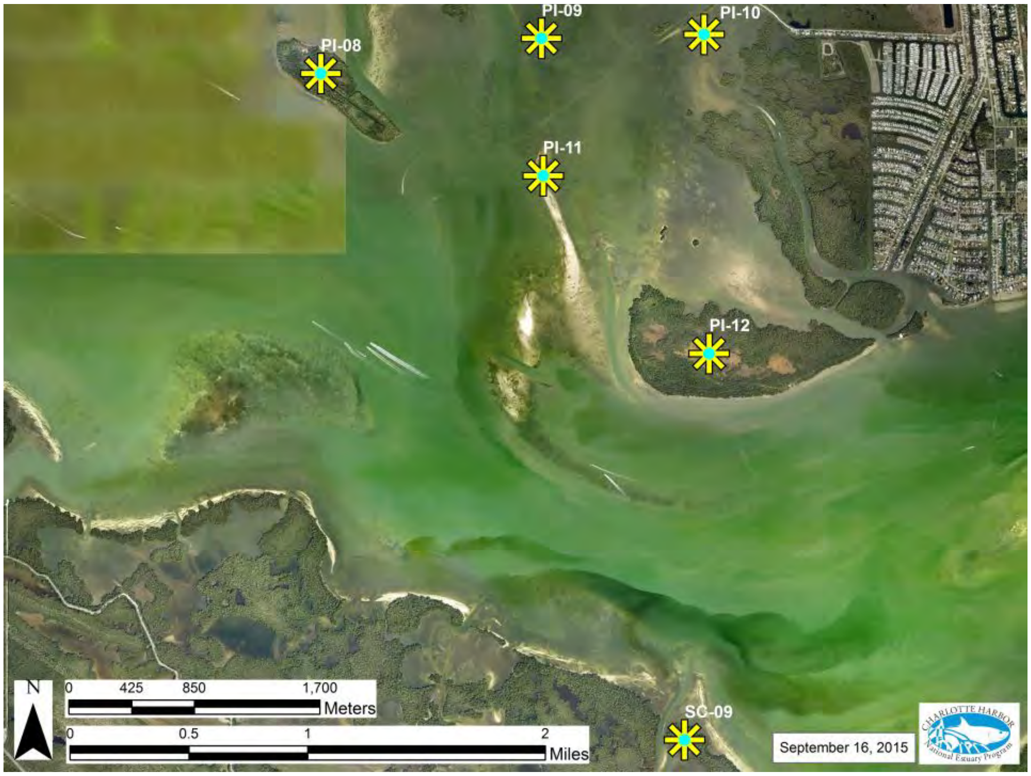



**Figure 19: Sample overall trip map for September 25, 2015.**

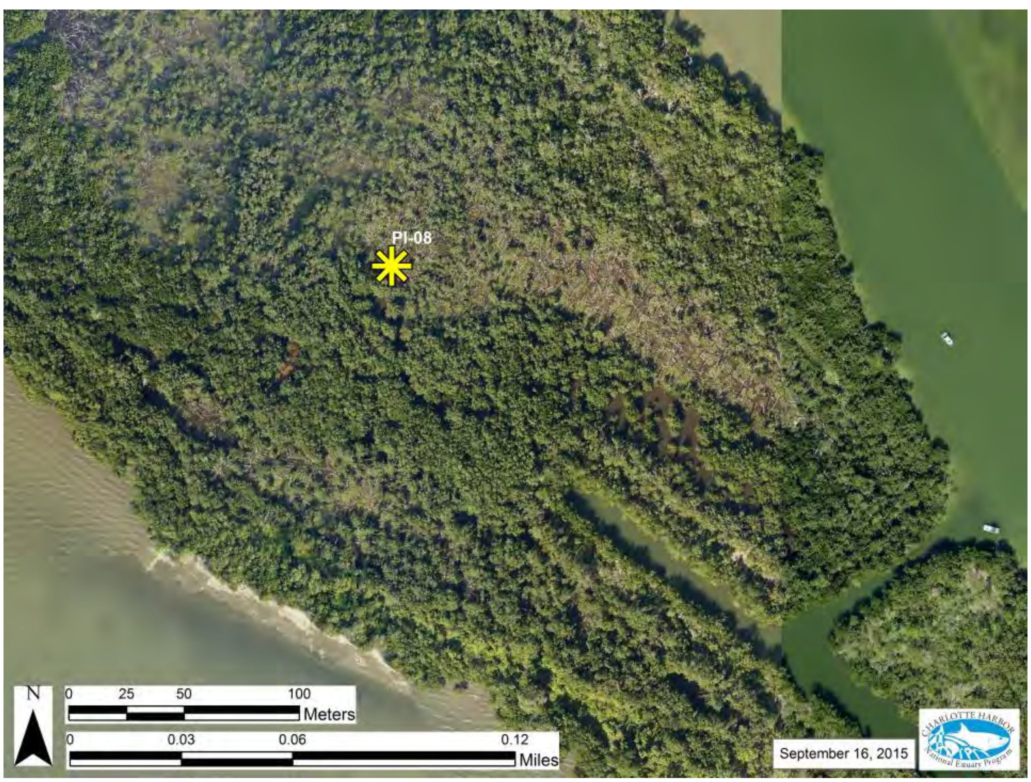



**Figure 20: Sample overall trip map for Chino Island, PI-08.**

Trip to and from PI-08

The Garmin Oregon 450 GPS unit assisted in navigation through the mangrove forest. The team picked through the forest, molded by relative ease through different parts of the forest. Side trips were relatively common. One is shown at the lower right side of the photograph, visiting a choked tidal creek.

Because of heavy canopy cover, GPS links to the satellites were often distorted as shown here.

Upon arrival at the site, photographs were taken, horizontally and vertically at the four cardinal points.


**Figure 21: Horizontal Photos at PI-08**


**Figure 22: Vertical Photos at PI-08**

**Figure 23: Team members assessing cover**

Site investigation team members completed the data sheets together, using consensus and various tools.

Munsell Plant Tissue Color Charts were ordered from Pantone to characterize leaf color for each mangrove species found at each site. The pages were protected by clear plastic bags and shown on the left.

In addition, a densitometer was acquired from Ben Meadows Company to estimate canopy density. The white unit is shown in Terry's hand in the right side of the photograph.

The site for review was defined as 1000 square meters, roughly a 100 x 100 foot area. After photographs were acquired, the team members searched for the presence of the four mangrove types. After individuals were found, the team characterized each mangrove species according to the following:

- Presence, yes or no.
- Percent cover.
- Tallest Tree Height. Though the form shows meters, feet and inches were used for efficiency in the field. Inches were converted to feet in the office as a common unit.
- Shortest Tree Height. Though the form shows meters, feet and inches were used for efficiency in the field. Inches were converted to feet in the office as a common unit.
- Seedlings Present, yes or no.
- Propagules Present, yes or no.
- General Crown Form.
- Leaf Color, using the Munsell Plant Tissue Color Charts.
- Estimated Percent Folivory, by reviewing the damage on a set of typical leaves.
- Estimated Percent Dead Branches, by reviewing the damage on a set of typical trees within the species.
- Estimated Percent Crown Density, by using the densitometer underneath a typical tree of the species.
- Tree Health, including healthy, early decline, moderate decline, severe decline and dead.

The form also allowed for data to be taken concerning submerged aquatic vegetation (SAV) and certain species of exotic vegetation. SAV did not tend to grow to the mangroves edge, SAV could be at varying distances to the mangrove shoreline, sites were usually distant from SAV locations and the sites could have been accessed from multiple locations. Therefore, the team could not arrive at a consistent method to collect this information.

No Australian pine or mahoe was found at any site. Brazilian pepper was found at one site that was not mangrove, so was not included in the analysis.

A list of potential understory comprised page three. If the method were replicated we would recommend that an open area to note understory cover replace the SAV and exotics portion of the form, providing for a single double-sided form for each site.

We documented observations on the form which were found to be useful for later potions of the project, including the Catalog of Restoration Opportunities.

A sample of page 2 and 3 are shown below for Chino Island, PI-08.

| From Onsite Visit: | | | | PI-08 | 9/25/2015 | Page 2 of 3 |
|---|---|---|---|---|---|---|
| **Mangrove Species & Conditions (in a 1,000 $m^2$ area)** | **Red Mangrove (*Rhizophora mangle*)** | **Black Mangrove (*Avicennia germinans*)** | **White Mangrove (*Laguncularia racemosa*)** | **Buttonwood (*Conocarpus erectus*)** | | |
| Present (Y/N) | Y | Y | N | N | | |
| % Cover | 5% | 30% | N | N | | |
| Tallest Tree Height (m) | 15' | 20' | N | N | | |
| Shortest Tree Height (m) | 1' | 6" | N | N | | |
| Seedlings Present (Y/N) | Y | Y | N | N | | |
| Propagules on Trees (Y/N) | Y | Y | N | N | | |
| General Crown Form | Columnar | Spreading | N | N | | |
| Leaf Color (Munsell or Leaf Color Chart) | 7.5 GY 3/2 | 5 GY 4/4 | N | N | | |
| Estimated % Folivory | 2% | 2% | N | N | | |
| Estimated % Dead Branches | 2% | 5% | N | N | | |
| Estimated % Crown Density | 50% | 50% | N | N | | |
| Tree Health (1 healthy, 2 early decline, 3 moderate decline, 4 severe decline, 5 dead) | 1 | 1 | recovering site - old dead mangroves | N | | |

There is no canopy; readings are from a single tree for both red and black mangrove.

**Submerged Aquatic Vegetation (Associated with Mangrove Community)**

| SAV Species | Present (Y/N) | % Cover |
|---|---|---|
| Manatee grass (*Syringodium filiforme*) | | |
| Shoal grass (*Halodule wrightii*) | | |
| Tape grass (*Vallisneria american* a) | | |
| Turtle grass (*Thalassia testudinum*) | | |
| Widgeon grass (*Ruppia maritima*) | | |
| Other: epibenthis algae | | |

**Invasive Exotic Vegetation (Assoicated with Mangrove Communit)**

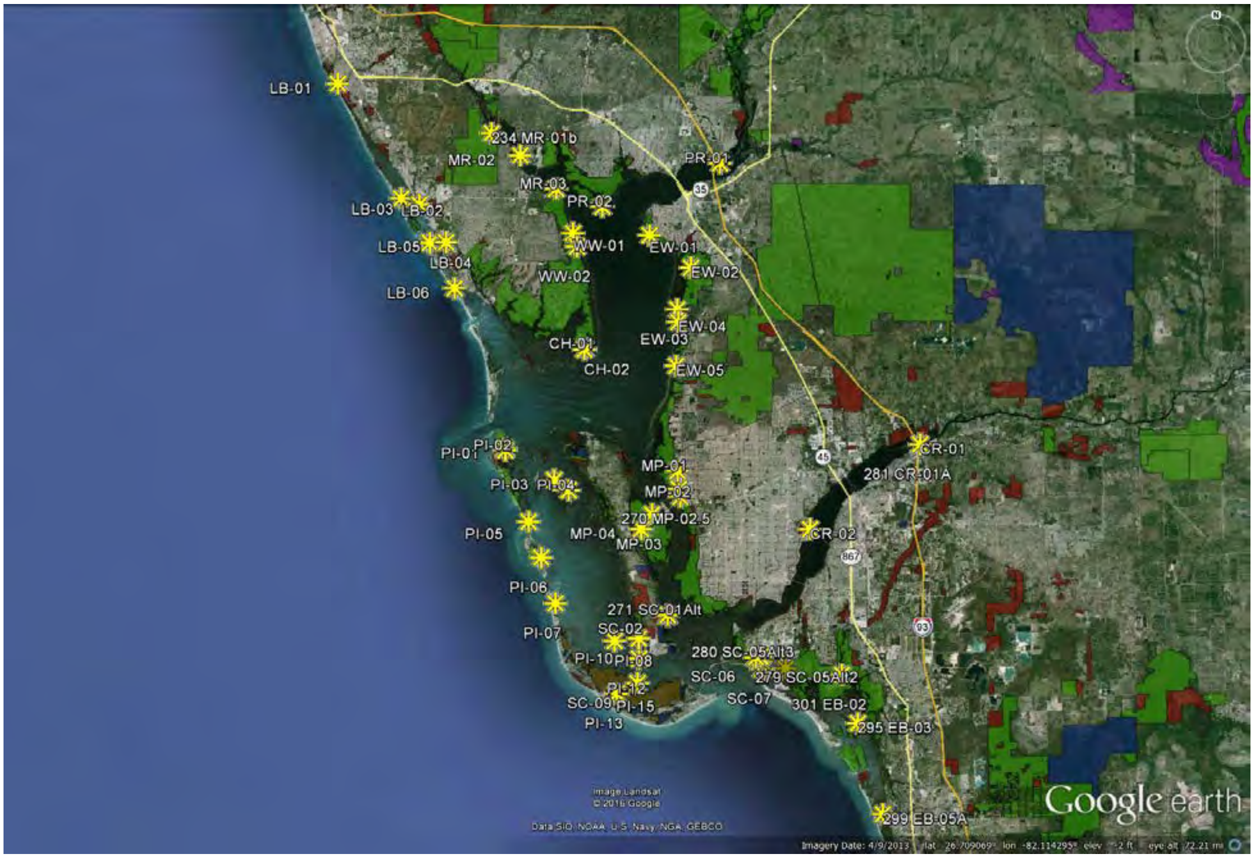
| Exotic Species | % Cover | Tallest Tree Ht (m) | Shortest Tree Ht (m) |
|---|---|---|---|
| Brazilian pepper (*Schinus terebinthifolius*) | | | |
| Australian pine (*Casuarina agustifolia*) | | | |
| mahoe (*Talipariti tiliaceum*) | | | |

Surrounding area (route to site) indicate stress - noticeable channel blockages; pneumatophores blocking tidal creeks, the velocity of flow insufficient to maintain clear channels and possibly associated with the proposed development.

**Figure 24: Sample CHNEP Mangrove Site Review Data Sheet, Page Two**

| From Onsite Visit (Continued): | | | | | PI-08 | 9/25/2015 | Page 3 of 3 |
|---|---|---|---|---|---|---|---|
| **Upland/Wetland Plant Species** | **Present (Y/N)** | **% Cover** | | **Upland/Wetland Species** | **Present (Y/N)** | **% Cover** | |
| Annual glasswort (*Salacornia bigelovii* ) | | | | saltmarsh morning-glory (*Ipomea sagittata* ) | | | |
| Baker's cordgrass (*Spartina bakerii* ) | | | | Saltwater falsewillow (*Baccharis angustifolia* ) | | | |
| Big leaf marshelder (*Iva frutescens* ) | | | | samphire (*Philoxerus vermicularis* ) | | | |
| Black rush (*Juncus roemerianus* ) | | | | scorpionstail (*Heliotrope angiospermum* ) | | | |
| Bushy sea ox-eye daisey (*Borrchia frutescens* ) | | | | sea blite (*Suada linearis* ) | | | |
| Carolina sealavender (*Limonium carolianum* ) | | | | sea purselane (*Sesuvium portulacastrum* ) | | | |
| Chaff flower (*Alternanthera ramossima* ) | | | | seacoast marshelder (Iva imbricata) | | | |
| Coastal searocket (*Cakile lanceolata* ) | | | | seashore dropseed (*Sporobolus virginicus* ) | | | |
| Giant wild pine airplant (*Tillandsia utriculata* ) | | | | seashore paspalum (*Paspalum vaginatum* ) | | | |
| Groundsel (saltbush) tree (*Baccharis halimifolia* ) | | | | seaside goldenrod (*Solidago sempervirens* ) | | | |
| gulf cordgrass (*Spartina spartinae* ) | | | | seaside jackbean (*Canavalia rosea* ) | | | |
| heavenlyblue morning-glory (*Ipomea violacea* ) | | | | seaside primrosewillow (*Ludwigia maritima* ) | | | |
| Juba's bush blood-leaf (*Iresine diffusa* ) | | | | smooth cordgrass (*Spartina alternifolia* ) | | | |
| leather fern (*Acrostichum aureum* ) | | | | southern needleleaf airplant (*Tillandsia setacea* ) | | | |
| leather fern (*Acrostichum danaeifolium* ) | | | | spider lily (*Hymenocallis aloifolia* ) | | | |
| Medicine vine (*Hippocratea volubilis* ) | | | | tree sea ox-eye daisey (*Borrchia arborescens* ) | | | |
| moonflowers (*Ipomea alba* ) | | | | twisted airplant (*Tillandsia* flexuosa) | | | |
| perrenial glasswort (*Sarcocornia ambigua* ) | | | | wand goldenrod (*Solidago stricta* ) | | | |
| rubber vine (*Rhabdadenia biflora* ) | | | | water pimpernel (*Samolus ebracteatus* ) | | | |
| salt grass (*Distichlis spicata* ) | | | | Other | | | |
| salt wort (*Batis maritima* ) | Y | 80% | | Other | | | |

**Figure 25: Sample CHNEP Mangrove Site Review Data Sheet, Page Three**




**Map 19: Completed Site Visit Locations**

A total of 15 separate site investigation trips were conducted and included 56 sites, two of which were not mangrove sites upon investigation.

At each location, the CHNEP Mangrove Site Review Data Sheets were completed. In cases where private access was not granted prior to site investigation, nearby alternate sites were found if possible. Sites where bird rookies were active were bypassed. On occasions where an interesting site was found on the way to a specified site, data were collected at these new sites. In addition, sites were added that seemed to make no sense from the aerial photos coupled with Lidar/digital elevation model. One site was over 4 feet elevation with red mangrove coverage. We used this to confirm the Lidar information and photo interpretation techniques. This site was, in fact, a predominately red mangrove scrub.

## Pre-Visit Analysis

GIS maps from agencies were used to determine habitat types for the sites that where to be visited. The Florida Fish and Wildlife Commission and the U.S. Geological Survey used Landsat imagery for their analysis. These datasets were both 67% correct (37 of 55 calls). The Water Management Districts used aerial photo interpretation and were 73% correct (40 of 55 calls). Although the maps are dated 2008, it appears much of the natural area was mapped in 1999 and not revised.

| FWC-2003 | WMD-2008 | USGS-2015 | Verified Mangrove | Verified Not Mangrove |
|---|---|---|---|---|
| Mangrove Swamp | Mangrove Swamps | Mangrove | 31 | |
| Salt Marsh | Saltwater Marsh | Not Mangrove | 3 | |
| Open Water | Mangrove Swamps | Not Mangrove | 3 | |
| Mangrove Swamp | Mangrove Swamps | Not Mangrove | 3 | |
| Open Water | Mangrove Swamps | Mangrove | 2 | |
| Mangrove Swamp | Saltwater Marsh | Not Mangrove | 2 | |
| Wetland Hardwood Forest | Mangrove Swamps | Mangrove | 1 | |
| Pinelands | Pine Flatwoods | Not Mangrove | 1 | |
| Pinelands | Mangrove | Mangrove | 1 | |
| Open Water | Wet Prairies | Not Mangrove | 1 | |
| Open Water | Tidal Flat | Not Mangrove | 1 | |
| Open Water | Open Water | Not Mangrove | 1 | |
| Open Water | Bays and Estuaries | Not Mangrove | 1 | |
| Mangrove Swamp | Tidal Flats | Mangrove | 1 | |
| High Impact Urban | Shrub and Brushland | Not Mangrove | 1 | |
| Mangrove Swamp | Mangrove Swamps | Not Mangrove | | 1 |
| Mangrove Swamp | Mangrove Swamps | Mangrove | | 1 |
| 37 | 40 | 37 | 53 | 2 |

**Table 23: Comparison of Agency Habitat Type Determinations**

## Mangrove Species Composition by Geomorphology

A total of nine sites could not be accessed. Five sites that were identified for field investigation were not conducted because permission was not granted from the private property owner. Three sites we planned to access had active bird rookeries, so we did not access the sites. A final site could not be accesses because of dangerously deep water cutting us off from site access.

In many cases we found alternative nearby sites. Nine sites had no pre-visit description of site geomorphology or mangrove species description.

Of the 54 mangrove sites where data were taken, there were:

- 3 Overwash Islands
- 29 Fringe
- 6 Riverine
- 12 Basin
- 4 Scrub.

Though we had identified a location that was potentially a hammock mangrove forest, we could not access the site. We can assume that this geomorphic mangrove forest type is less common than the other five geomorphic types.

The analysis applies only to the sites where we were able to visit and cannot characterize the mangrove forest geomorphic types in general. We intentionally sought unexpected mangrove forests. For example, a forest that appeared dominated by red mangroves but Lidar indicated that the location was in excess of 4 feet elevation. The site, in fact, was a red/white mangrove scrub. However, we can paint a better picture of mangrove forest structure and function based on identified patterns.

At the 54 mangrove sites where mangrove species were assessed, we evaluated:

- 42 Red Mangrove locations
- 46 Black Mangrove locations
- 35 White Mangrove locations
- 6 Buttonwood. locations.

Of 47 sites planned and visited, 32 geomorphic types were called correctly in preview, or 68%. All but one of the 15 errors related to Fringe Mangrove Forest, nine which were fringe but identified as another geomorphic type and five which were identified as fringe but was another mangrove forest type. The one other incorrect call as a Riverine Mangrove Forest was not mangrove at all, but an exotic infested area.

On the following tables, colors have been used to highlight interesting aspects of the tables, usually for portions which are discussed separately.

| | Site Visit Data | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pre-Geomorph | Overwash Island | Fringe | Riverine | Basin | Scrub | Not Mangrove | No Access | Total |
| No Pre-Visit Call | 1 | 3 | 2 | 3 | | | | 9 |
| Overwash Island | 2 | 2 | | | | | 3 | 7 |
| Fringe | | 17 | | 3 | 1 | 1 | 1 | 23 |
| Riverine | | 3 | 4 | | | 1 | 2 | 10 |
| Basin | | 4 | | 6 | | | 2 | 12 |
| Hammock | | | | | | | 1 | 1 |
| Scrub | | | | | 3 | | | 3 |
| Total | 3 | 29 | 6 | 12 | 4 | 2 | 9 | 65 |

- Rows are pre-visit, Columns are confirmed with field visits.

**Table 24: Pre- versus Post Field Visit Geomorphology**

Of 47 sites planned and visited, 13 species mix were called correctly, or 28%.The most common errors were calling sites a monoculture of red or black when, in fact, the sites were of mixed species with 2 or 3 mangrove species. The two sites miscalled as mangroves were either tropical hardwood hammock or exotic infested.

| | Site Visit Data | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pre-Species | Black | Buttonwood | Mixed | None | Red | White | No Access | Total |
| No Pre-Visit Call | 3 | | 2 | | 3 | 1 | | 9 |
| Black | 6 | | 7 | | | | 2 | 15 |
| Buttonwood | | 1 | 1 | | | | | 2 |
| Mixed | | | 1 | | | | 1 | 2 |
| Red | 2 | | 19 | 1 | 5 | 2 | 6 | 35 |
| Red/Buttonwood | | | | 1 | | | | 1 |
| White | | | | | 1 | | | 1 |
| Total | 11 | 1 | 30 | 2 | 9 | 3 | 9 | 65 |

- Rows are pre-visit, Columns are confirmed with field visits.

**Table 25: Pre- versus Post Field Visit Mangrove Species**

Half of sites had a red/black/white mangrove mix, while only 24% had any kind of mangrove monoculture. Eight sites (15%) were basin black mangroves. Two sites (4%) were fringe red mangroves and two sites (4%) were riverine red mangroves. One site (2%) was fringe white mangroves. No monocultures were found in overwash islands or mangrove scrub.

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Total | Percent |
|---|---|---|---|---|---|---|---|
| Red, black, white | 1 | 20 | 2 | 2 | 2 | 27 | 50% |
| Black mangrove | | | | 8 | | 8 | 15% |
| Red, black mangrove | 1 | 2 | 1 | 2 | | 6 | 11% |
| Red mangrove | | 2 | 2 | | | 4 | 7% |
| Red, black, white , buttonwood | | 2 | 1 | | | 3 | 6% |
| Red, White mangrove | 1 | 1 | | | | 2 | 4% |
| White mangrove | | 1 | | | | 1 | 2% |
| Black, white, buttonwood | | 1 | | | | 1 | 2% |
| Black, buttonwood | | | | | 1 | 1 | 2% |
| White, buttonwood | | | | | 1 | 1 | 2% |
| Total | 3 | 29 | 6 | 12 | 4 | 54 | |

**Table 26: Species Composition by Geomorphology**

**Figure 26: Basin Black Mangrove Forest at Part Island**

**Figure 27: Fringe Red Mangrove Forest at Four Mile Cove Ecological Park**

**Figure 28: Fringe White Mangrove Forest at Riverwood**


**Figure 29: Fringe Mixed Mangrove Forest with 50% Buttonwood at Myakka State Forest**

**Figure 30: More Typical Fringe Mixed Mangrove Forest**

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Total |
|---|---|---|---|---|---|---|
| Red Mangrove | 3 | 27 | 6 | 4 | 2 | 42 |
| Black Mangrove | 2 | 26 | 4 | 12 | 2 | 46 |
| White Mangrove | 2 | 25 | 4 | 2 | 2 | 35 |
| Buttonwood | | 3 | 1 | | 2 | 6 |
| Total | 7 | 81 | 15 | 18 | 8 | 129 |

**Table 27: Species Presence by Geomorphic Type**

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Total |
|---|---|---|---|---|---|---|
| Red Mangrove | 100% | 93% | 100% | 33% | 50% | 78% |
| Black Mangrove | 67% | 90% | 67% | 100% | 50% | 85% |
| White Mangrove | 67% | 86% | 67% | 17% | 50% | 65% |
| Buttonwood | 0% | 10% | 17% | 0% | 50% | 11% |
| Total | 58% | 70% | 63% | 38% | 50% | 60% |

**Table 28: Species Presence by Geomorphic Type as a percentage**

Red, black and white mangroves are well distributed all geomorphic types except for basins, were black mangroves dominate. Buttonwoods were the least commonly found at study sites. There was an average of 2.3 mangrove species found at the sites, give or take 1. Overwash islands, fringe and riverine are the most dynamic locations, subject to storm effects and greater mangrove species diversity and are less protected that basin and scrub mangrove forests.

Using Kendall's Tau B correlation coefficient we found:

- Red mangroves are often co-located with white mangroves (pos, .001 level). No other species are correlated. This finding violates concept of mangrove zonation.
- Tallest red mangroves are not with other mangrove species. They are at the water's edge and tidal creeks. (neg, .05 level) .

Please note that .001 has a higher level of significance than .01 which has a higher level of significance than .05. Kendall's Tau B was used because the data need not be normally distributed, that is, follow a bell curve.

We found 2 scrub mangrove forests where red mangroves were found. One was found using aerial imagery and Lidar elevation. The other was a scrub that unexpectedly had red mangroves.

Uncontrolled shoot formation, referred to as "witch's brooms" in plant pathology terminology, was found only on red mangroves that were height suppressed. Witches brooms have not been found in black or white mangroves. Red mangroves with witch's brooms were usually no taller than 1 to 2 meters and located in scrub mangrove forest. The cause of witches brooms in red mangrove has been linked with shoot infection of a secondary fungus pathogen. The only other known cause of the witches broom symptoms on red mangrove was herbicide injury, which occurred as a result of melaleuca control spraying near mangrove forests. In the absence of nearby herbicide use, the presence of witches brooms on red mangrove can be considered a symptom of stress.


**Figure 31: Witch's Brooms in Scrub Red Mangrove Trees**

## Mangrove Forest Structure by Geomorphology

Key elements that describe forest structure are cover by tree species, tree height, landscape position (elevation), reproduction and understory components.

Cover

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Cover |
|---|---|---|---|---|---|---|
| Red Mangrove | 81% | 63% | 77% | 36% | 60% | 63% |
| Black Mangrove | 1% | 25% | 17% | 65% | 12% | 34% |
| White Mangrove | 10% | 10% | 10% | 50% | 10% | 12% |
| Buttonwood | | 3% | 50% | | 35% | 25% |

**Table 29: Cover where trees exist**

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Cover |
|---|---|---|---|---|---|---|
| Red Mangrove | 81% | 58% | 77% | 12% | 16% | 49% |
| Black Mangrove | 1% | 21% | 9% | 65% | 8% | 28% |
| White Mangrove | 7% | 9% | 5% | 8% | 7% | 8% |
| Buttonwood | 0% | 1% | 8% | 0% | 23% | 2% |

**Table 30: Cover including non-presence**

Red mangroves dominate the cover on overwash islands, fringe and riverine mangrove forests. Although more sites with black mangroves were identified, red mangroves had a higher total coverage.

When non-presence of mangrove species are counted as 0%, the importance of buttonwood in the scrub mangrove environment is better expressed.

When all species cover is added together, mangrove tree cover averages 82%. The cover within a forest was measured as high as 285% with layering. On a bright and sunny day, these forests can be quite dark at the floor.

**Figure 32: Layering of mangrove cover can reduce the light at the forest floor.**

Using Kendall's Tau B correlation coefficient we found:

- Black mangrove cover is greater where there are fewer mangrove species. There appears to be more space for black mangrove cover (neg, .05 level).
- Red and black mangrove cover are inversely related (neg, .05 level).
- There is greater black mangrove cover in basins and less in overwash and fringe (pos, .01 level).
- Where there is little black mangrove cover, there is probably shading by red mangroves, which also reduces black mangrove crown density. Where there is more black mangrove cover, sun is making it to the black mangroves (pos, .05 level).

Tallest Tree

The tallest tree within the 100 square meter site was estimated for each species.

| Species | Mean | Number of Sites | Std. Deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Red Mangrove | 14.2 | 42 | 7.2513 | 1.2 | 35 |
| Black Mangrove | 18.0 | 46 | 7.9683 | 1.0 | 35 |
| White Mangrove | 13.4 | 35 | 6.9756 | 3.0 | 35 |
| Buttonwood | 9.1 | 7 | 3.5170 | 3.5 | 14 |
| All species | 15.1 | 130 | 7.6340 | 1.0 | 35 |

**Table 31: Tallest Tree Height (in feet)**

Black mangrove trees appear, on average, taller than other tree species

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Maximum Height |
|---|---|---|---|---|---|---|
| Red Mangrove | 20 | 35 | 30 | 20 | 8 | 35 |
| Black Mangrove | 25 | 35 | 25 | 30 | 12 | 35 |
| White Mangrove | 20 | 35 | 20 | 15 | 6 | 35 |
| Buttonwood | | 14 | 10 | | 12 | 14 |
| All species | 25 | 35 | 30 | 30 | 12 | 35 |

**Table 32: Tallest Tree Height by geomorphology**

In the fringe mangrove forest, we found individual red, black and white mangroves at 35 feet in height. All mangrove species attained their maximum height in the fringe. However, we looked at more fringe sites.

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Tallest |
|---|---|---|---|---|---|---|
| Red Mangrove | 20 | 13 | 17 | 16 | 8 | 14 |
| Black Mangrove | 20 | 19 | 14 | 18 | 12 | 18 |
| White Mangrove | 18 | 13 | 17 | 14 | 6 | 13 |
| Buttonwood | | 9 | 10 | | 10 | 9 |
| All Species | 19 | 15 | 16 | 17 | 9 | 15 |

**Table 33: Average Tallest Tree by Species and Geomorphology**

The average tallest tree better describes mangrove forest structure. The tallest trees tended to be on overwash islands, followed by basin forests. Though red, black and white mangrove trees could get tallest in the fringe, this may have more to do with the number from fringe mangrove sites that were investigated. There were higher odds of finding taller trees,

On average black mangroves tended to be tallest tree species.

**Figure 33: A typical view of the mangrove fringe, with red mangroves at the front and black mangroves towering over.**

Landscape Position (Elevation)

Elevation for each site was determined using Lidar Digital Elevation Models. The following figures confirm a lack of relationship between mangrove species and elevation.

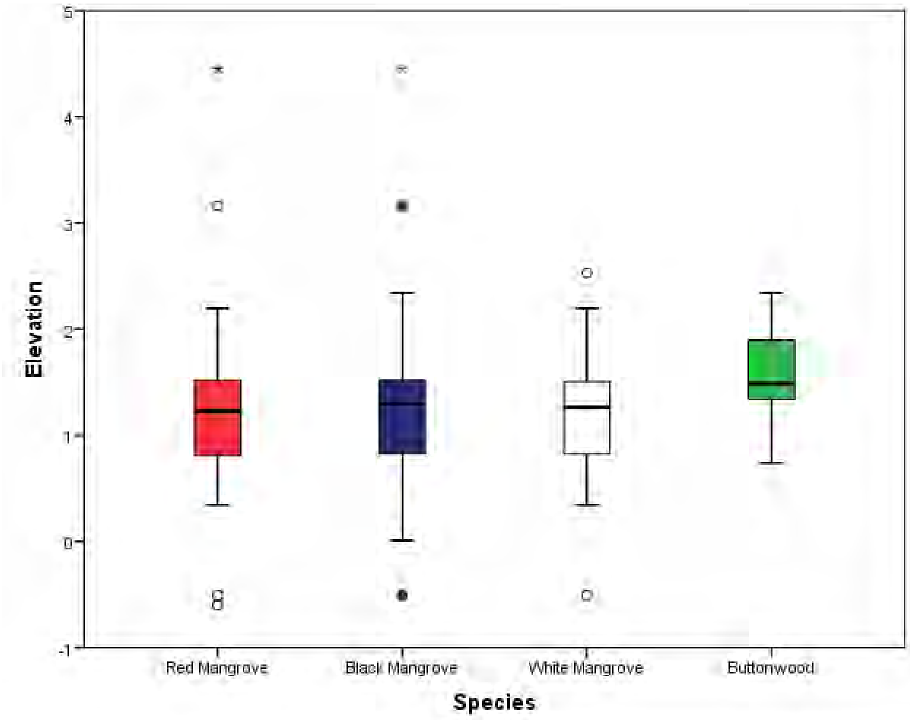



**Figure 34: No relationship between Mangrove Species and Elevation**

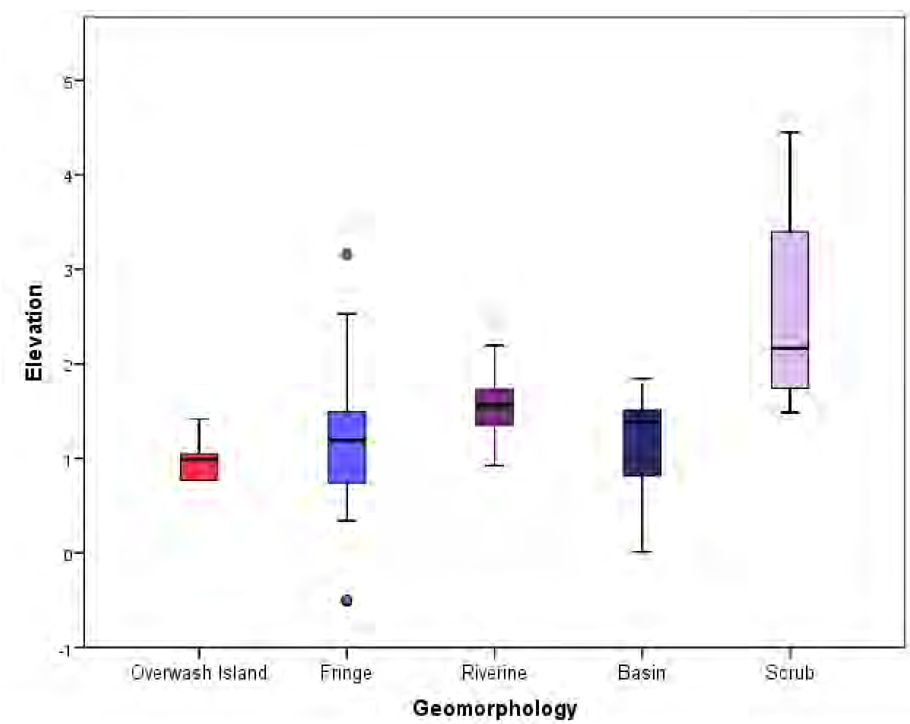



**Figure 35: Relationship between Geomorphology and Elevation**

Reproduction

Reproduction in mangrove forests can be identified by the presence of seedlings and propagules.

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Seedlings |
|---|---|---|---|---|---|---|
| Red Mangrove | 67% | 85% | 100% | 75% | 100% | 86% |
| Black Mangrove | 0% | 54% | 50% | 75% | 100% | 59% |
| White Mangrove | 50% | 76% | 25% | 0% | 01% | 60% |
| Buttonwood | | 0% | 0% | | 50% | 17% |
| All Species | 43% | 69% | 60% | 67% | 63% | 66% |

**Table 34: Seedlings**

Seedlings were all between 2 and 6 inches tall. All mangrove species were found as seedlings. Red mangroves were found as seedlings at 86% of sites where they were present. White mangroves were at 60%, followed by black mangroves at 59% and buttonwoods at 17% of sites. Using Kendall's Tau B correlation coefficient we found:

- Red and white mangrove cover reduces red mangrove seedlings, probably by shading (neg, .05; .001 level).
- There is less likelihood of red seedlings when buttonwoods are present (neg, .05 level).
- There is less likelihood of black seedlings when red mangroves are present and red cover is greater (neg, .05 level).
- More likelihood of black seedlings when black mangrove cover is greater (pos, .05 level).
- Tallest black mangroves correlate with white seedlings (pos, .05 level). Pneumatophores are trapping white propagules. More normal tidal cycle, organics in pneumatophores too.

**Figure 36: Black mangrove seedling shown in foreground with Batis and Samolus**

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Propagules |
|---|---|---|---|---|---|---|
| Red Mangrove | 67% | 22% | 17% | 25% | 50% | 26% |
| Black Mangrove | 0% | 8% | 0% | 33% | 0% | 13% |
| White Mangrove | 0% | 0% | 0% | 0% | 0% | 0% |
| Buttonwood | | 0% | 100% | | 100% | 50% |
| All Species | 29% | 10% | 13% | 28% | 38% | 16% |

**Table 35: Propagules on Trees**

Propagules sprout before dropping off the tree, known as vivipary. Buttonwoods possess seed cases rather than propagules. Buttonwoods had seed cases at 50% of sites, reds had propagules at 26%, black mangroves had propagules at 13% and white propagules were found at no sites. Using Kendall's Tau B correlation coefficient we found:

- As red mangrove cover and red crown density decreases and black and white mangrove cover increases, there are more black propagules (.05 level).
- Red and black propagules were positively correlated, demonstrating a normal, healthy forest (pos, .01 level).

Understory

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Coverage |
|---|---|---|---|---|---|---|
| Blackrush | | 50% | | 50% | | 38% |
| Glasswort | | | | 30% | | 30% |
| Golden leatherfern | 30% | | | 5% | | 18% |
| Jamaican caper | | 1% | 10% | | | 6% |
| Leatherfern | | 10% | | | | 15% |
| Nickerbean | | | 5% | | | 5% |
| Pancium sp | | 5% | | | | 5% |
| Rubbervine | 85% | | | 20% | | 53% |
| Saltbush | | 40% | | | | 40% |
| Saltgrass | | 27% | | 50% | | 35% |
| Saltwort (Batis) | | 46% | 50% | 15% | 10% | 26% |
| Sea oxeye daisy | | 2% | | | | 2% |
| Seablite | | 2% | | 1% | | 2% |
| Seagrape, wild lime, cactus | | 5% | | | | 5% |
| Sea purselane | | 5% | | 1% | | 3% |
| Christmas berry | | 3% | | | | 3% |
| Average | 17% | 12% | 16% | 18% | 3% | 14% |

**Table 36: Understory Coverage**

On average, understory covered 17.5% of sites. The greatest number of understory species found was 4. Batis was the most common at 30% of sites. On average, exotic rubbervine covered the most area, between 20 and 82% at 2 sites. Using Kendall's Tau B correlation coefficient we found:

- Batis cover appears to make a good medium for black and red propagule entrapment, especially in die-off locations (pos, .01 level).
- There is less understory where red and white mangroves are present (neg, .01 level). Understory presence require open canopy which red mangroves do not offer and an extra layer of white mangroves shades out.
- There is an inverse relationship with the number of mangrove species and understory presence (neg, .01 level) Layering, not open to promote understory.

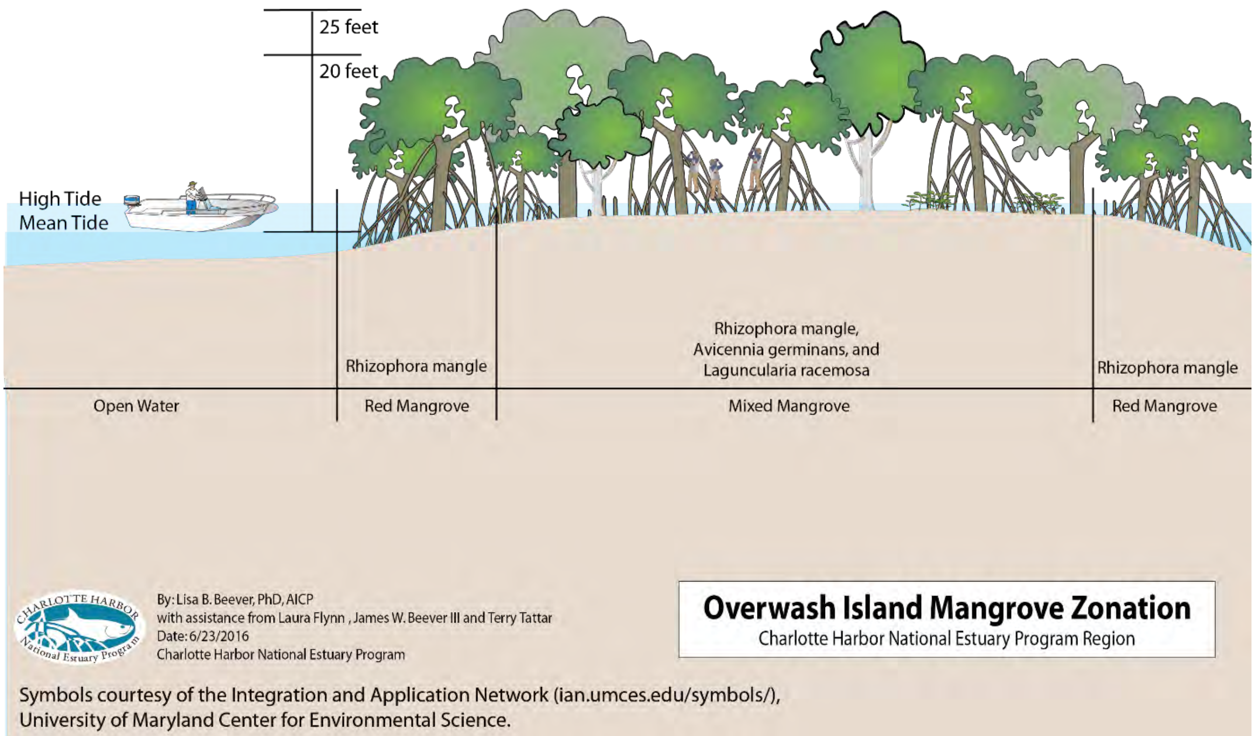
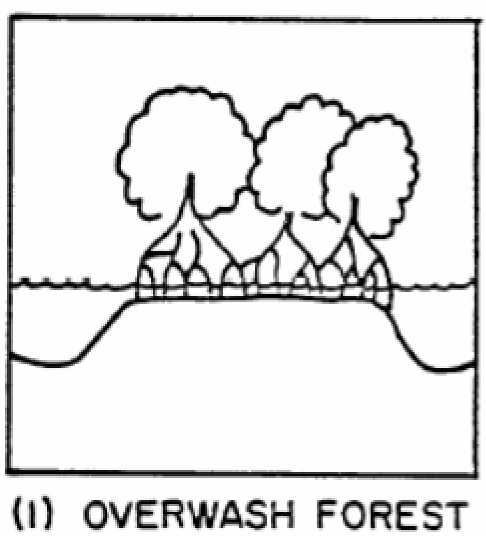



**Figure 37: Overwash Island Mangrove Zonation**




Overwash Islands are dominated with a red mangrove tree cover (81%). In addition, these mangrove forests can include both black and white mangroves. The three species were generally around 20 to 25 feet in height. We found no example of buttonwoods during our site investigation.

Because of the generally low elevation and tidal flow across the sites, access to these sites often involved climbing across the mangrove prop roots.

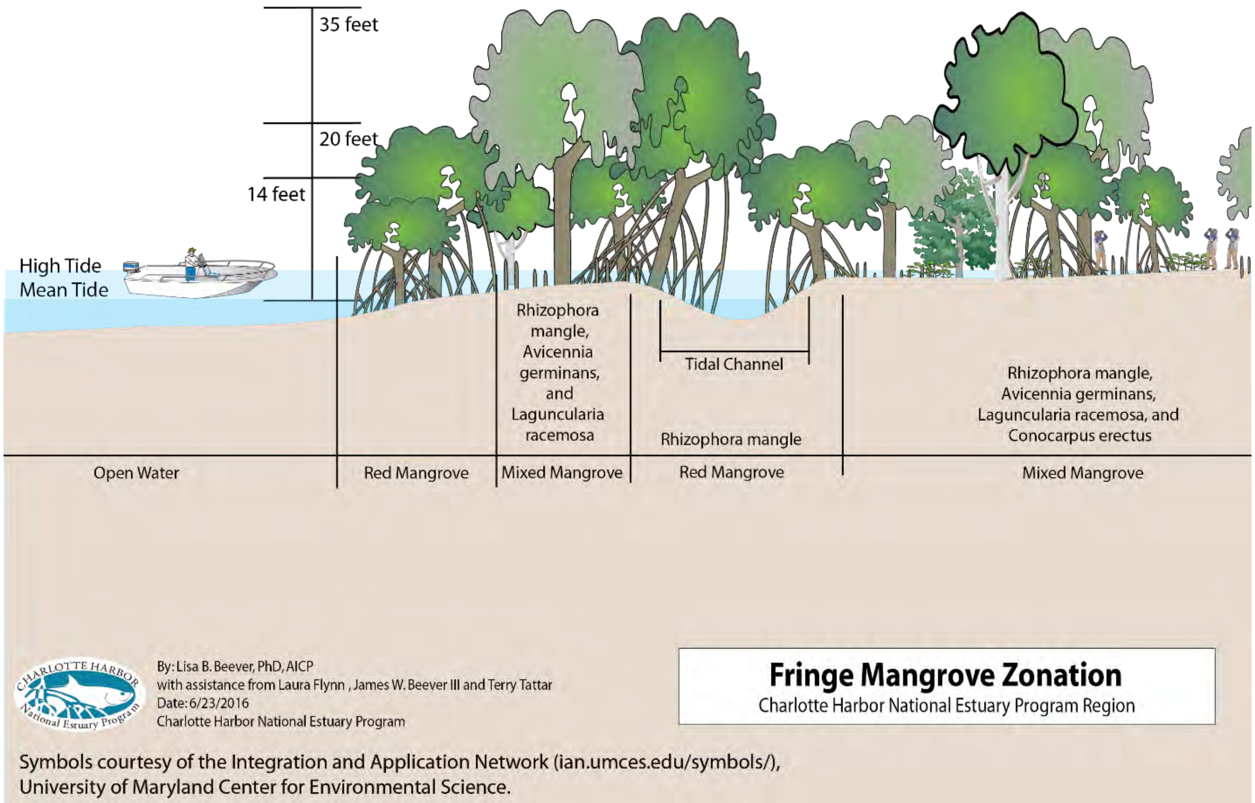
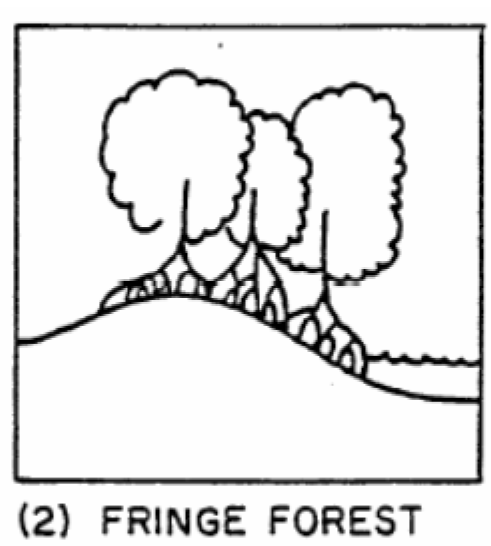



**Figure 38: Fringe Mangrove Zonation**




Fringe mangroves forests are the most extensive of all mangrove geomorphic types in the CHNEP study area. Though red mangrove trees dominated the cover type (58%), black mangroves (21%) and white mangroves (9%) provide significant additional cover. Occasional buttonwoods add to forest diversity.

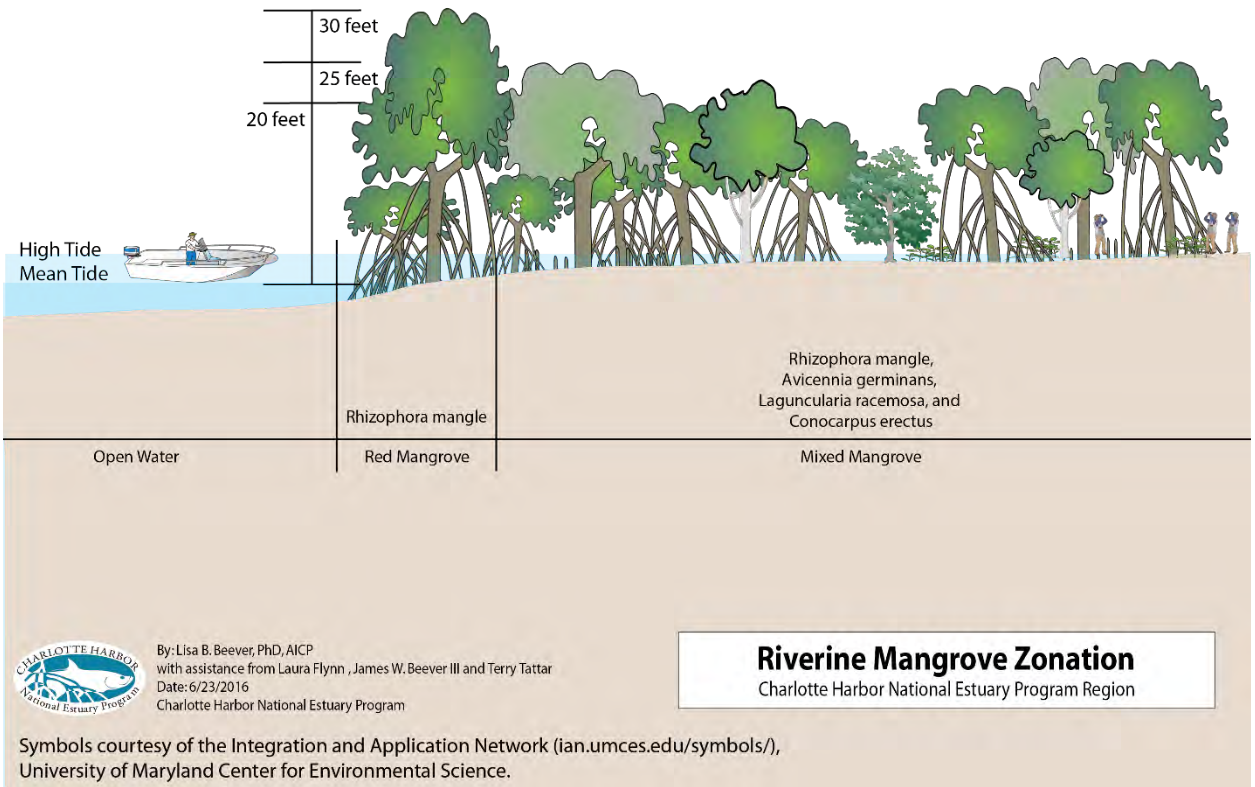
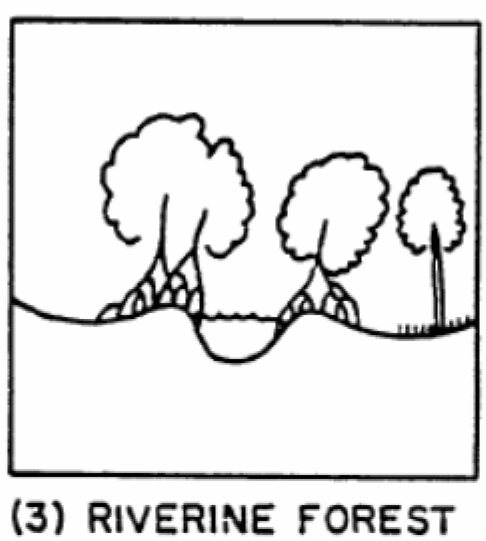



**Figure 39: Riverine Mangrove Zonation**




Riverine mangrove forests, like overwash islands, are highly dominated by red mangroves, with an average cover of 77%. Like fringe mangrove forests, riverine forests are diverse with shorter black mangroves, white mangroves and buttonwoods.

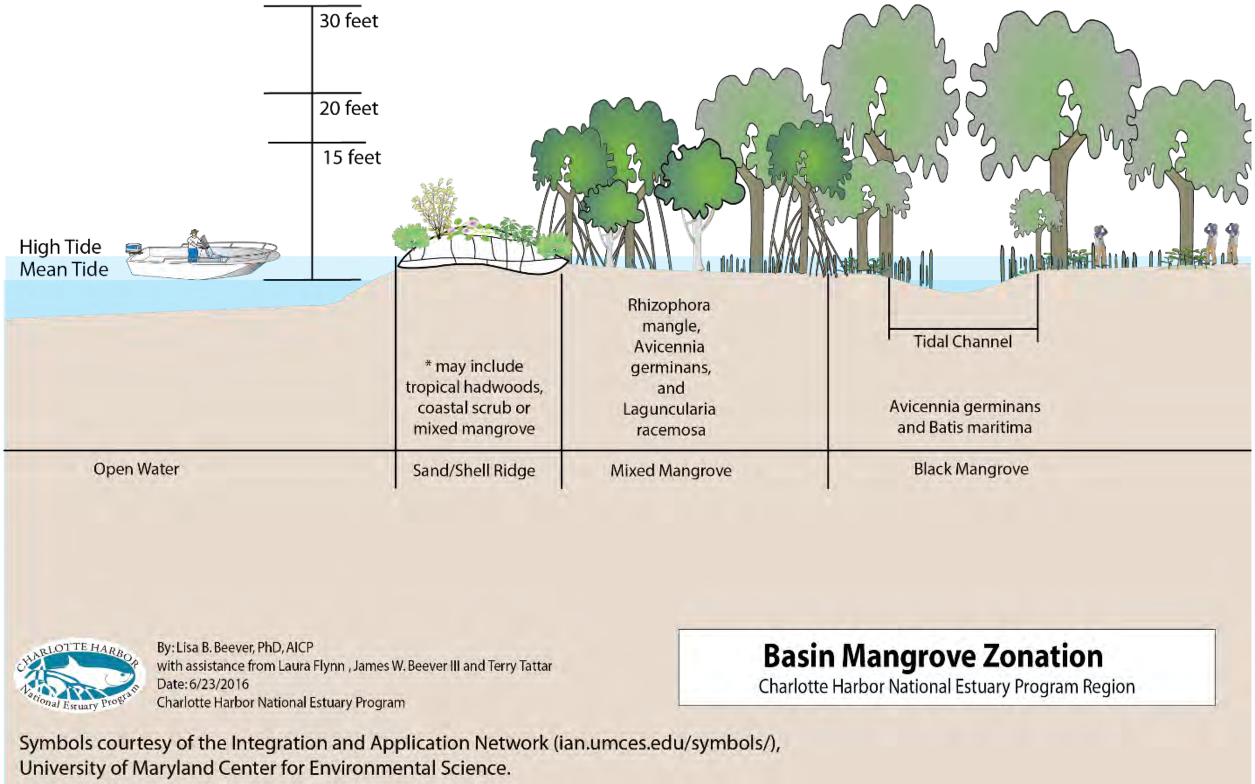
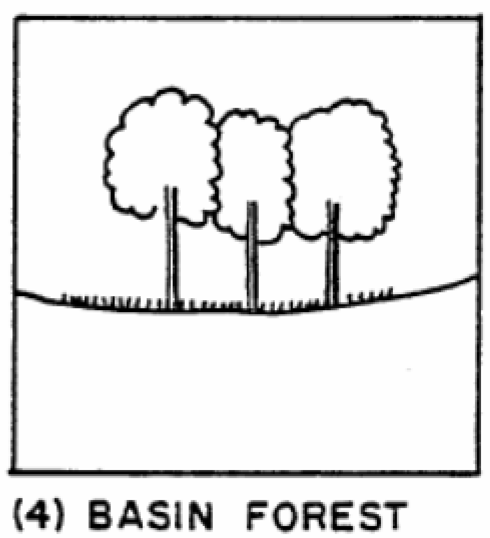



**Figure 40: Basin Mangrove Zonation**




In the CHNEP study area, basins are often defined with a sand/shell ridge which make the difference between a fringe or a basin mangrove forest. Black mangroves dominate the cover of basin mangrove forests (65%), However, red and white mangroves can also be present.

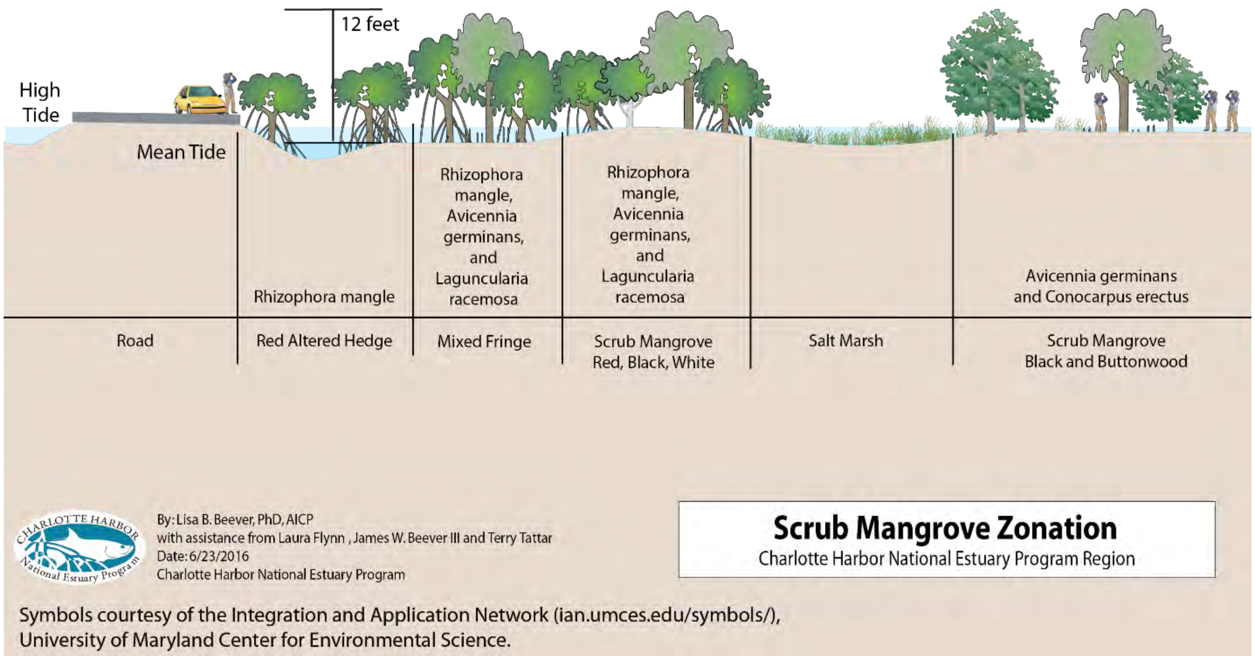
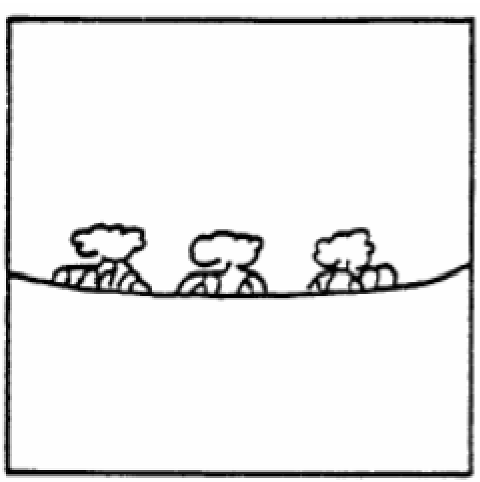



**Figure 41: Scrub Mangrove Zonation**



(6) SCRUB FOREST

Scrub mangroves forests possess the shortest mangroves coupled with the least cover. Buttonwood cover was measured at 23% for all scrub systems evaluated.

## Mangrove Health by Species and Geomorphology

Key elements that describe mangrove health include folivory, dead branches and general assessment of health. In addition, leaf color and crown form were considered.

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Folivory |
|---|---|---|---|---|---|---|
| Red Mangrove | 18% | 16% | 14% | 7% | 8% | 15% |
| Black Mangrove | 14% | 11% | 16% | 8% | 10% | 11% |
| White Mangrove | 18% | 14% | 10% | 8% | 6% | 13% |
| Buttonwood | | 20% | 10% | | 11% | 15% |
| All Species | 17% | 14% | 13% | 8% | 8% | 13% |

**Table 37: Folivory**

Folivory ranged between 0% and 37.45% at sites with mangroves (normalized for cover). Buttonwood had the greatest average folivory at 15%, reds at 14.5%, whites at 13% and Blacks at 11%. Black leaves are salty and not preferred.

- More folivory in overwash islands, less in basins and scrubs. Red folivory is highest on overwash islands (Beever 1979).
- White folivory is increased in presence of black mangroves and in the presence more mangrove species (pos, .01 level). Perhaps white mangroves are a more available food source.
- Red, black and white mangrove folivory were inter-correlated (pos, .001 level). They share folivores like *Automeris io* and *Ectdylopha*.

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Folivory |
|---|---|---|---|---|---|---|
| Red Mangrove | 18% | 9% | 9% | 2% | 12% | 10% |
| Black Mangrove | 13% | 17% | 20% | 14% | 15% | 16% |
| White Mangrove | 50% | 24% | 31% | 35% | 4% | 28% |
| Buttonwood | | 33% | 50% | | 10% | 32% |
| All Species | 27% | 18% | 21% | 14% | 11% | 18% |

**Table 38: Dead Branches**

- The presence of any species of seedlings and propagules is more likely when the percentage of dead black mangrove branches are high (pos, .05 level). The open canopy promotes seedling development.
- Black mangrove folivory and black mangrove dead branches (pos, .001 level) and buttonwood dead branches (pos, .05 level) correlate. Perhaps blacks and buttonwoods share folivores and dead branches attract folivores.

| Species | Overwash Island | Fringe | Riverine | Basin | Scrub | Average Tree Health |
|---|---|---|---|---|---|---|
| Red Mangrove | 1.6 | 1.0 | 1.3 | 1.0 | 1.0 | 1.1 |
| Black Mangrove | 1.4 | 1.7 | 1.8 | 2.1 | 1.5 | 1.8 |
| White Mangrove | 2.4 | 1.6 | 2.0 | 2.5 | 1.0 | 1.8 |
| Buttonwood | | 1.2 | 2.0 | | 1.0 | 1.3 |
| All Species | 1.8 | 1.4 | 1.7 | 1.9 | 1.2 | 1.6 |

**Table 39: Tree Health**

The scale to assess mangrove tree health was:

1. Healthy
2. Early Decline
3. Moderate Decline
4. Severe Decline
5. Dead.

| Species | Mean | Number of Sites | Std. Deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Red Mangrove | 1.146 | 41 | .4775 | 1.0 | 3.0 |
| Black Mangrove | 1.783 | 46 | 1.0309 | 1.0 | 5.0 |
| White Mangrove | 1.800 | 35 | 1.0233 | 1.0 | 4.0 |
| Buttonwood | 1.250 | 6 | .4183 | 1.0 | 2.0 |
| All species | 1.559 | 128 | .9106 | 1.0 | 5.0 |

**Table 40: Tree Health by Mangrove Species**

Red, black, white and buttonwood mangrove forests all had healthy examples. Sixty-six percent (66%) of the 128 mangroves evaluated were healthy. On average, red mangroves were the healthiest (1.15), followed by buttonwood (1.25), black mangroves (1.78) and white mangroves (1.8). Total forests had an average health of 1.6 (s.d. 0.8).

- In presence of black mangroves, red tree health is better (neg, .05 level). Where there are no blacks, conditions can be more stressful such as water's edge and in tidal creeks which often had hydrologic alterations in this study.
- Red seedlings are present where black mangroves are dying back. The canopy is opening up and the reds are taking advantage. Black die-off may be occurring because of extended periods of flooding which reds can tolerate better. (pos, .05 level) .

| Geomorphology | Mean | Number of Sites | Std. Deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Overwash Island | 1.857 | 7 | 1.0690 | 1.0 | 3.0 |
| Fringe | 1.500 | 82 | .8924 | 1.0 | 4.0 |
| Riverine | 1.500 | 14 | .6504 | 1.0 | 3.0 |
| Basin | 1.889 | 18 | 1.1827 | 1.0 | 5.0 |
| Scrub | 1.214 | 7 | .3934 | 1.0 | 2.0 |
| All types | 1.559 | 128 | .9106 | 1.0 | 5.0 |

**Table 41: Tree Health by Geomorphology**

| Geomorphology | Mean | Number of Sites | Std. Deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Healthy | 1.207 | 84 | 0.80 | -0.5 | 4.4 |
| Not quite early decline | 1.486 | 1 | | 1.5 | 1.5 |
| Early Decline | 1.466 | 23 | 0.85 | -0.5 | 4.4 |
| Moderate Decline | 1.488 | 13 | 0.63 | 0.3 | 3.2 |
| Severe Decline | 1.396 | 6 | 0.34 | 1.0 | 2.0 |
| Dead | 1.354 | 1 | | 1.4 | 1.4 |
| Total | 1.294 | 128 | 0.78 | -0.5 | 4.4 |

**Table 42: Elevation by Tree Health**

One location included entirely dead mangroves: a basin black mangrove forest on York Island.

Five locations included mangroves in severe decline:

- Basin black mangroves south of Summerlin and west of John Morris Roads in San Carlos Bay/Bunche Beach Preserve (SC-05 Alt2).
- Fringe black mangroves (with healthy white mangroves and red mangroves in early decline) off of a manmade canal south of Bayside Estates (EB-01 $2^{nd}$ site).
- Fringe black and white mangroves (with healthy red mangroves) on Fish Trap Bay in Bonita Springs (EB-05A).
- Fringe white mangroves (with moderate decline black and early decline red mangroves) located north of Beach Road in Englewood (LB-02).
- Fringe white mangroves (with early decline black and healthy red mangroves) north of Pine Island Road (MP-03).

The *Cytospora* canker disease on red mangroves was not found at any of our site visits in Charlotte Harbor. This disease was frequently encountered on stressed red mangroves in southwest Puerto Rico and on wind-injured red mangroves in Charlotte Harbor soon after Hurricane Charley. It may be concluded that the current health of the red mangrove trees we examined in this study was good. The only exception would be the dwarf red mangroves with witch's brooms.

Crown forms for mangroves included:

- Spreading (33%)
- Columnar (29%)
- Spreading/Columnar (16%)
- Oval (15%)
- Round (5%).

There was variation by mangrove species. Over half of white mangroves were columnar. Red mangroves were typically either spreading or columnar. Most black mangroves were somewhere between spreading or columnar. A few examples were oval or round. No mangroves were upright, pyramidal, vase-shaped or weeping.

Crown shape by geomorphic type was largely driven by the species assemblage within each type.

In addition, tree health did not affect crown form.

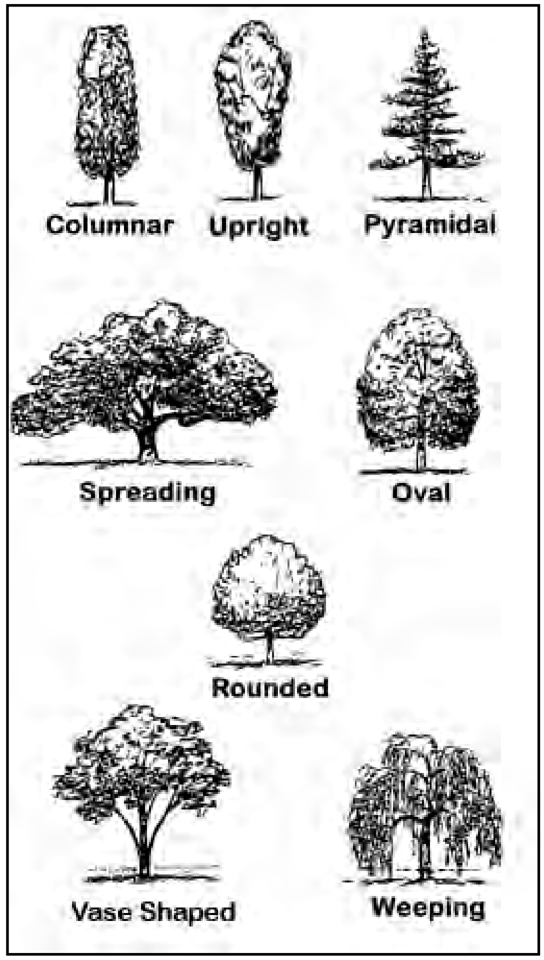



**Figure 42: Crown Forms**

| Crown Form | Red Mangrove | Black Mangrove | White Mangrove | Buttonwood | Total |
|---|---|---|---|---|---|
| Columnar | 38% | | 57% | 17% | 28% |
| Oval | 14% | 17% | 17% | | 15% |
| Round | | 17% | 3% | 17% | 8% |
| Spreading | 43% | 26% | 23% | 67% | 32% |
| Spreading/Columnar | 5% | 41% | | | 16% |
| Total | 32% | 36% | 27% | 5% | 100% |

**Table 43: Crown form by mangrove species**

Leaf color was determined using the Munsell Plant Tissue Color Book, 2012. A sample leaf was selected for each species at each site. The sample leaf was most closely matched to the color chip. The chips each had a code that described hue, value and chroma.

There are five principal classes of hue:

- Red (R),
- Yellow (Y),
- Blue (B),
- Green (G) and
- Purple (P).

There are an additional 5 intermediate hues (e.g. GY) halfway between the principal hues. Each of these 10 steps is broken into 10 substeps, so that 100 hues are given an integer value. In practice, color charts conventionally specify 40 hues in increments of 2.5, with the named hue given number 5. Five hues were found among the mangrove leaves: 5Y, 2.5GY, 5GY, 7.5GY and 2.5G, from yellow to a slightly yellow green.

The value notation indicates the degree of lightness or darkness of a color in relation to a neutral gray scale which extends from theoretically pure black (0) to a theoretical pure white (10). Lighter colors are indicated by numbers ranging above 5. The values of mangrove leaves ranged from 3 (dark) to 7 (light).

The chroma notation of color indicates the strength (saturation) or degree of departure of a particular hue from neutral gray to more intense color. The chroma scale extends from 1 for neutral gray out to 10, 12, 14 or farther depending on the saturation of the color. The chroma of mangroves ranged from almost grey (2) to very saturated (10).

The complete Munsell notation for any chromatic color is written Hue Value/Chroma, or H V/C.

The Munsell chip sheets and corresponding notation sheets were placed in clear zip-close plastic bags. Sample leaves from each of the mangrove species present on site were placed behind the chips and matched up to the chip that was closest in appearance.

Red mangrove leaves were found in 10 colors. Black mangrove leaves were found in 19 colors. White mangrove leaves were found in 15 colors. Buttonwoods were found in 5 colors. There were six colors which exceeded 15% of leaf samples by species (except for buttonwood where single samples were 17%).

The average hue for the leaves of all mangrove species was 5GY, fully green yellow. Red mangrove leaves tended toward the green range (neg, .05). Red mangrove leaves were the darkest with an average value of 3.6 and buttonwood were the lightest with an average value of 4.7 (pos., .001). Red mangrove leaves were the least saturated (most grey) with an average chroma of 3.9 and black mangroves were the most saturated (least grey) with an average chroma of 5.0 ( pos., .01). There was no relationship between geomorphology and leaf color.

| Leaf Color | Red | Black | White | Buttonwood | Total |
|---|---|---|---|---|---|
| 5 Y 5/2 | | | 3% | | 1% |
| 2.5 GY 3/4 | | | 3% | | 1% |
| 2.5 GY 5/2 | | 2% | | | 1% |
| 2.5 GY 5/4 | | 7% | 6% | 33% | 6% |
| 2.5 GY 5/6 | | 2% | 3% | | 2% |
| 2.5 GY 6/2 | | 2% | | | 1% |
| 2.5 GY 6/6 | | 2% | | | 1% |
| 2.5 GY 6/8 | | 2% | | | 1% |
| 5 GY 3/4 | 32% | 14% | 9% | | 17% |
| 5 GY 4/3 | | 2% | | | 1% |
| 5 GY 4/4 | 15% | 16% | 23% | | 17% |
| 5 GY 4/6 | 12% | 14% | 23% | 17% | 16% |
| 5 GY 4/8 | | 5% | 3% | | 2% |
| 5 GY 5/4 | | 7% | 6% | | 4% |
| 5 GY 5/6 | 2% | | | | 1% |
| 5 GY 6/10 | | | 3% | | 1% |
| 7.5 GY 3/2 | 22% | | | | 7% |
| 7.5 GY 3/4 | 5% | 7% | 3% | 17% | 6% |
| 7.5 GY 4/2 | 2% | 7% | | | 3% |
| 7.5 GY 4/3 | 2% | | | | 1% |
| 7.5 GY 4/4 | | | 9% | 17% | 3% |
| 7.5 GY 5/6 | | 2% | | | 1% |
| 7.5 GY 7/6 | | 2% | | | 1% |
| 7.5 GY 7/8 | | 2% | 3% | | 2% |
| 2.5 G 6/4 | 5% | 2% | 3% | | 3% |
| 2.5 G 6/8 | 2% | | | | 1% |
| 2.5 G 7/6 | | | | 17% | 1% |
| 2.5 G 7/8 | | 2% | 3% | | 2% |
| | 33% | 35% | 28% | 5% | 100% |

**Table 44: Leaf Color sorted by hue, yellow to green**

Buttonwood leaves tended to be the most yellow, but had examples toward the green. Most red, black and white mangrove leaves were green-yellow, with red mangrove leave the most green on average.

| Leaf Color | Red | Black | White | Buttonwood | Total |
|---|---|---|---|---|---|
| 2.5 GY 3/4 | | | 3% | | 1% |
| 5 GY 3/4 | 32% | 14% | 9% | | 17% |
| 7.5 GY 3/2 | 22% | | | | 7% |
| 7.5 GY 3/4 | 5% | 7% | 3% | 17% | 6% |
| 5 GY 4/3 | | 2% | | | 1% |
| 5 GY 4/4 | 15% | 16% | 23% | | 17% |
| 5 GY 4/6 | 12% | 14% | 23% | 17% | 16% |
| 5 GY 4/8 | | 5% | 3% | | 2% |
| 7.5 GY 4/2 | 2% | 7% | | | 3% |
| 7.5 GY 4/3 | 2% | | | | 1% |
| 7.5 GY 4/4 | | | 9% | 17% | 3% |
| 5 Y 5/2 | | | 3% | | 1% |
| 2.5 GY 5/2 | | 2% | | | 1% |
| 2.5 GY 5/4 | | 7% | 6% | 33% | 6% |
| 2.5 GY 5/6 | | 2% | 3% | | 2% |
| 5 GY 5/4 | | 7% | 6% | | 4% |
| 5 GY 5/6 | 2% | | | | 1% |
| 7.5 GY 5/6 | | 2% | | | 1% |
| 2.5 GY 6/2 | | 2% | | | 1% |
| 2.5 GY 6/6 | | 2% | | | 1% |
| 2.5 GY 6/8 | | 2% | | | 1% |
| 5 GY 6/10 | | | 3% | | 1% |
| 2.5 G 6/4 | 5% | 2% | 3% | | 3% |
| 2.5 G 6/8 | 2% | | | | 1% |
| 7.5 GY 7/6 | | 2% | | | 1% |
| 7.5 GY 7/8 | | 2% | 3% | | 2% |
| 2.5 G 7/6 | | | | 17% | 1% |
| 2.5 G 7/8 | | 2% | 3% | | 2% |
| | 33% | 35% | 28% | 5% | 100% |

**Table 45: Leaf Color sorted by Value, dark to light**

Red mangrove leaves were the darkest and buttonwoods the lightest.

| Leaf Color | Red | Black | White | Buttonwood | Total |
|---|---|---|---|---|---|
| 7.5 GY 3/2 | 22% | | | | 7% |
| 7.5 GY 4/2 | 2% | 7% | | | 3% |
| 5 Y 5/2 | | | 3% | | 1% |
| 2.5 GY 5/2 | | 2% | | | 1% |
| 2.5 GY 6/2 | | 2% | | | 1% |
| 5 GY 4/3 | | 2% | | | 1% |
| 7.5 GY 4/3 | 2% | | | | 1% |
| 2.5 GY 3/4 | | | 3% | | 1% |
| 5 GY 3/4 | 32% | 14% | 9% | | 17% |
| 7.5 GY 3/4 | 5% | 7% | 3% | 17% | 6% |
| 5 GY 4/4 | 15% | 16% | 23% | | 17% |
| 7.5 GY 4/4 | | | 9% | 17% | 3% |
| 2.5 GY 5/4 | | 7% | 6% | 33% | 6% |
| 5 GY 5/4 | | 7% | 6% | | 4% |
| 2.5 G 6/4 | 5% | 2% | 3% | | 3% |
| 5 GY 4/6 | 12% | 14% | 23% | 17% | 16% |
| 2.5 GY 5/6 | | 2% | 3% | | 2% |
| 5 GY 5/6 | 2% | | | | 1% |
| 7.5 GY 5/6 | | 2% | | | 1% |
| 2.5 GY 6/6 | | 2% | | | 1% |
| 7.5 GY 7/6 | | 2% | | | 1% |
| 2.5 G 7/6 | | | | 17% | 1% |
| 5 GY 4/8 | | 5% | 3% | | 2% |
| 2.5 GY 6/8 | | 2% | | | 1% |
| 2.5 G 6/8 | 2% | | | | 1% |
| 7.5 GY 7/8 | | 2% | 3% | | 2% |
| 2.5 G 7/8 | | 2% | 3% | | 2% |
| 5 GY 6/10 | | | 3% | | 1% |
| | 33% | 35% | 28% | 5% | 100% |

**Table 46: Leaf Color sorted by chroma, neutral gray to saturated**

Red mangrove leaves had the least saturated color, that is, were the most neutral grey.

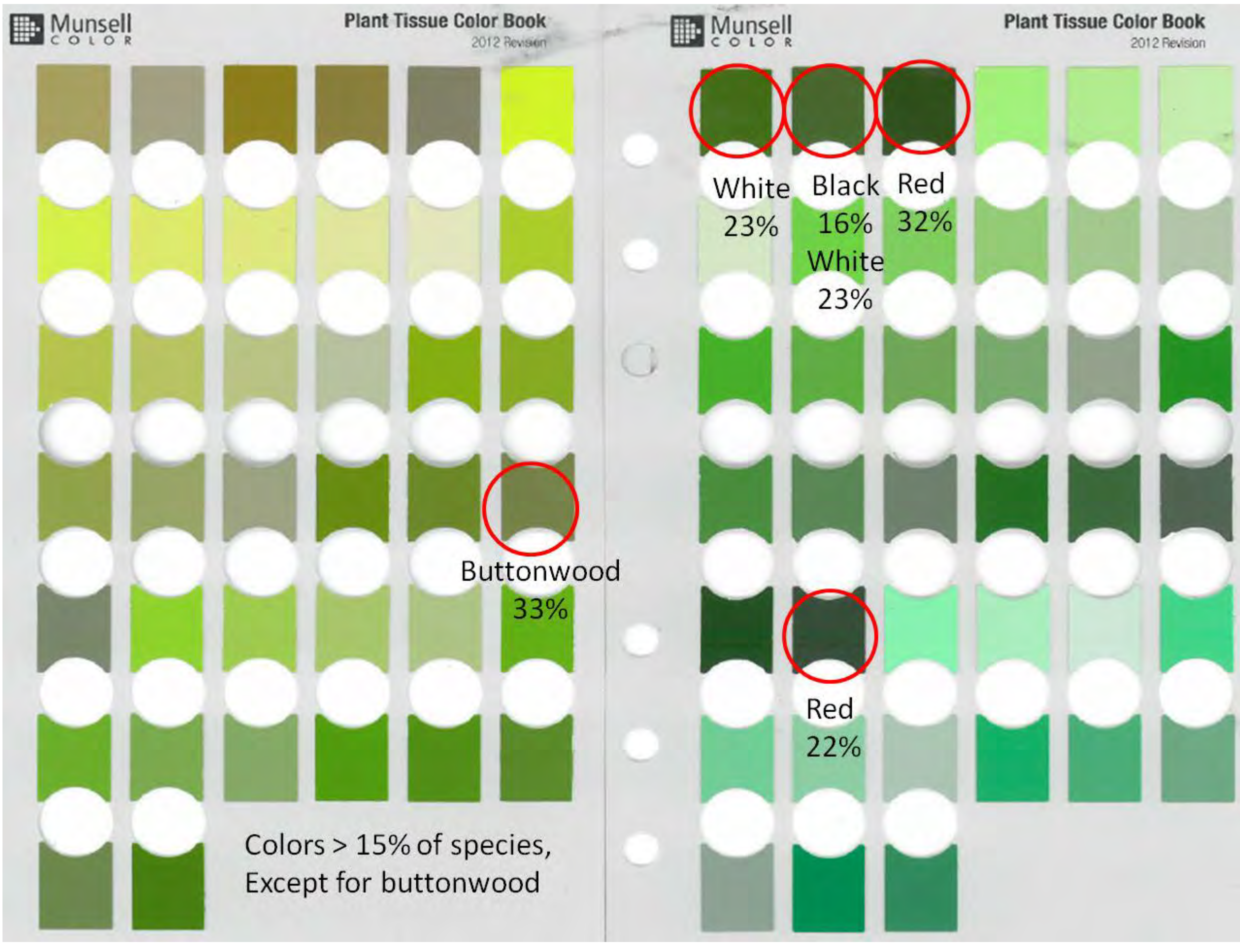



**Figure 43: Most commonly used Munsell plant tissue chart pages**

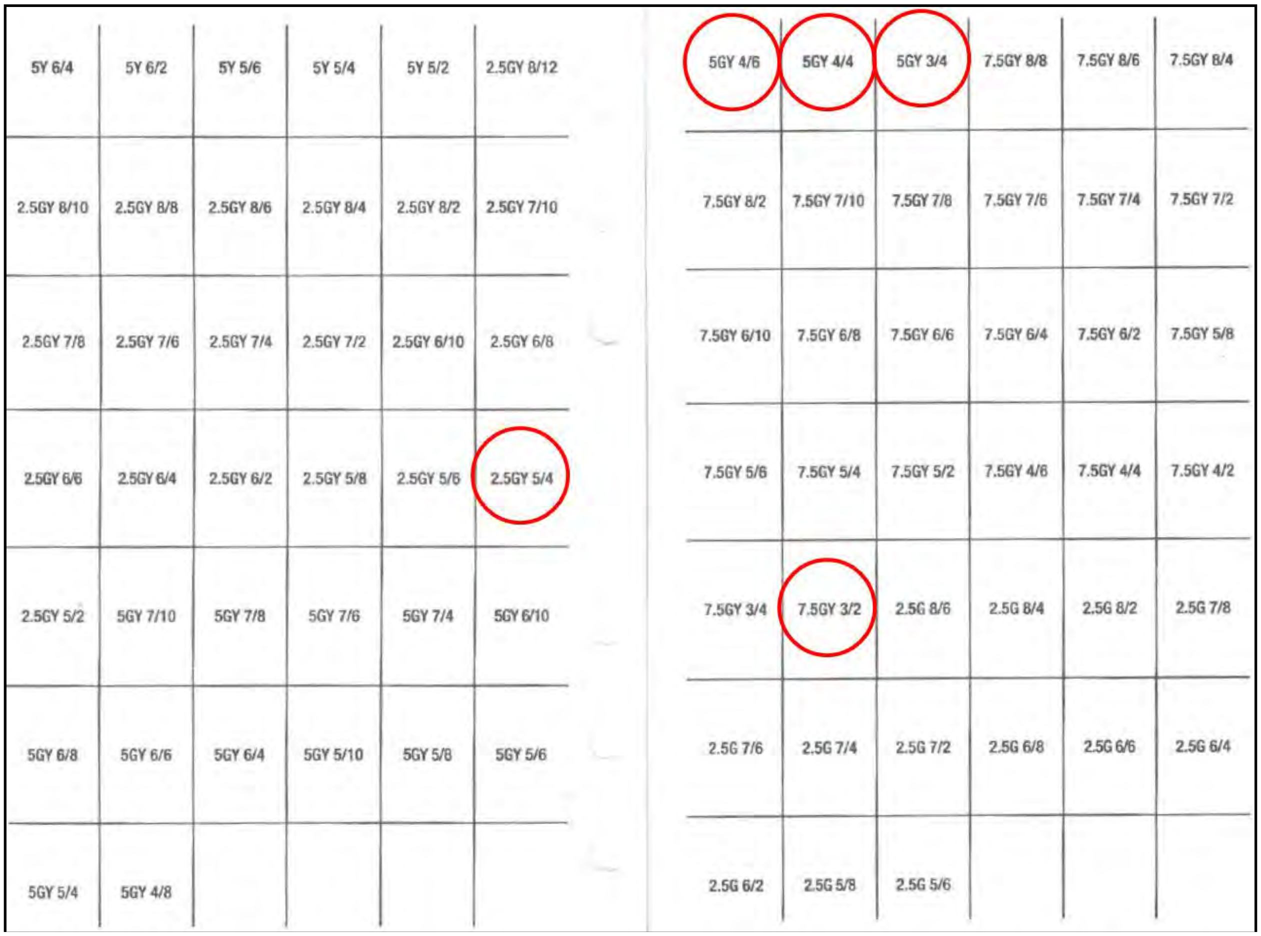


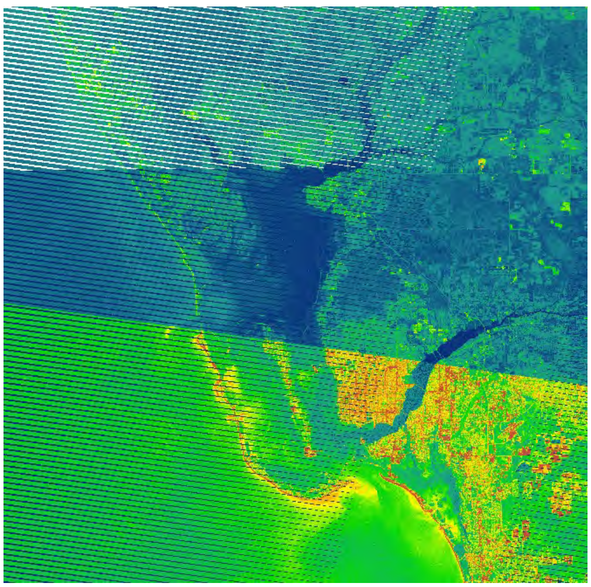

**Figure 44: Most commonly used Munsell plant tissue chart codes**

# Spectral Modeling to Determine Mangrove Condition

## Landsat Data Retrieval and Preparation

LandSat data can be procured for free from the USGS Earth Explorer website at http://earthexplorer.usgs.gov/. Locating the needed views on Landsat is by Path and Row. For the Charlotte Harbor National Estuary Program study area (including its saltwater wetlands), there are two scenes: Path 016, Row 041 and Path 016, Row 042. For the Charlotte Harbor area, winter provides the best views unobstructed by clouds. In addition, Path 017, Row 041 was downloaded for the Tampa to complete the rectangular view of the CHNEP study area for future use.

The Landsat mission was initially launched on July 23, 1972 with a satellite which was later renamed Landsat 1. Data were acquired at 60 square meter resolution. Subsequent launches followed. Landsat 4, the first with 30 meter resolution, was launched July 1982. Landsat 5 followed March 1984 and continued operation until January 2013. January 9, 1985 imagery was the first Landsat 5 imagery available to be unobstructed by clouds.



Landsat 7 was launched April 15, 1999, the same year infrared photography was acquired for the Charlotte Harbor area and on which most plant community mapping appears to have been based. Images acquired December 26, 1999 is the first imagery free of cloud cover. Landsat 7 continues to be operational despite Scan Line Corrector (SLC) failure in 2003. Therefore Landsat 7 images collected in late 2014 and early 2015 are not sufficient to utilize in this study. The image to the left shows Landsat 7 data taken December 19, 2014. Despite limited cloud cover, the SLC failure is apparent with the horizontal lines across the image. Because the two scenes were not mosaicked, there is a color change in the middle of the image.

The Landsat 8 mission was launched February 11, 2013. January 28, 2015 provided the best, most recent imagery for use in the project. It was also the date USGS used for their 2015 mangrove update in the area. Level 1 GeoTIFF data products downloaded from the site included LC801604120150281.tar.gz, LC801604220150281.tar.gz and LC801704120150511.tar.gz. The files are unzipped twice to reveal a set of raster files for each of the 11 bands contained within the scene. http://landsat.usgs.gov/Landsat8_Using_Product.php.

The following tables documents the bands, wavelength and purposes for the Landsat 8 mission and comparison of Landsat 5, 7 and 8 data.

**Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)**

| Band | Wavelength | Useful for mapping |
|---|---|---|
| Band 1 – coastal aerosol | 0.43 - 0.45 | coastal and aerosol studies |
| Band 2 – blue | 0.45 - 0.51 | Bathymetric mapping, distinguishing soil from vegetation and deciduous from coniferous vegetation |
| Band 3 - green | 0.53 - 0.59 | Emphasizes peak vegetation, which is useful for assessing plant vigor |
| Band 4 - red | 0.64 - 0.67 | Discriminates vegetation slopes |
| Band 5 - Near Infrared (NIR) | 0.85-0.88 | Emphasizes biomass content and shorelines |
| Band 6 - Short-wave Infrared (SWIR) 1 | 1.57 - 1.65 | Discriminates moisture content of soil and vegetation; penetrates thin clouds |
| Band 7 - Short-wave Infrared (SWIR) 2 | 2.11 - 2.29 | Improved moisture content of soil and vegetation and thin cloud penetration |
| Band 8 - Panchromatic | 0.50 - 0.68 | 15 meter resolution, sharper image definition |
| Band 9 – Cirrus | 1.36 - 1.38 | Improved detection of cirrus cloud contamination |
| Band 10 – TIRS 1 | 10.60 – 11.19 | 100 meter resolution, thermal mapping and estimated soil moisture |
| Band 11 – TIRS 2 | 11.5 - 12.51 | 100 meter resolution, Improved thermal mapping and estimated soil moisture |

**http://landsat.usgs.gov/best_spectral_bands_to_use.php**

**Landsat 5, 7 and 8 Band Comparisons**

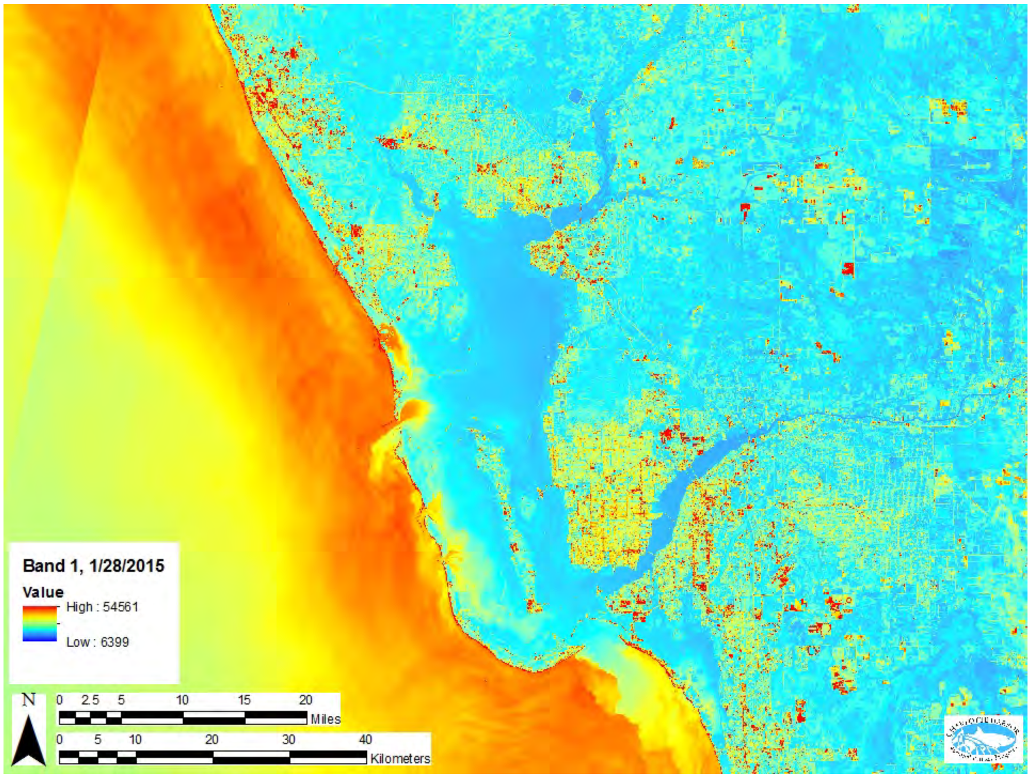
| **Landsat 5** (1984-2013) | **Wavelength (micrometers)** | **Landsat 7** (1999-2002) | **Wavelength (micrometers)** | **Landsat 8** (2013- ) | **Wavelength (micrometers)** |
|---|---|---|---|---|---|
| | | | | Band 1 - Coastal aerosol | 0.43 - 0.45 |
| Band 1 | 0.45-0.52 | Band 1 | 0.45-0.52 | Band 2 - Blue | 0.45 - 0.51 |
| Band 2 | 0.52-0.60 | Band 2 | 0.52-0.60 | Band 3 - Green | 0.53 - 0.59 |
| Band 3 | 0.63-0.69 | Band 3 | 0.63-0.69 | Band 4 - Red | 0.64 - 0.67 |
| Band 4 | 0.76-0.90 | Band 4 | 0.77-0.90 | Band 5 - Near Infrared (NIR) | 0.85 - 0.88 |
| Band 5 | 1.55-1.75 | Band 5 | 1.55-1.75 | Band 6 - SWIR 1 | 1.57 - 1.65 |
| Band 6 | 10.40-12.50 | Band 6 | 10.40-12.50 | Band 10 - Thermal Infrared (TIRS) 1 | 10.60 - 11.19 |
| Band 7 | 2.08-2.35 | Band 7 | 2.09-2.35 | Band 7 - SWIR 2 | 2.11 - 2.29 |
| | | Band 8 | .52-.90 | Band 8 - Panchromatic | 0.50 - 0.68 |
| | | | | Band 9 - Cirrus | 1.36 - 1.38 |
| | | | | Band 11 - Thermal Infrared | 11.50 - 12.51 |

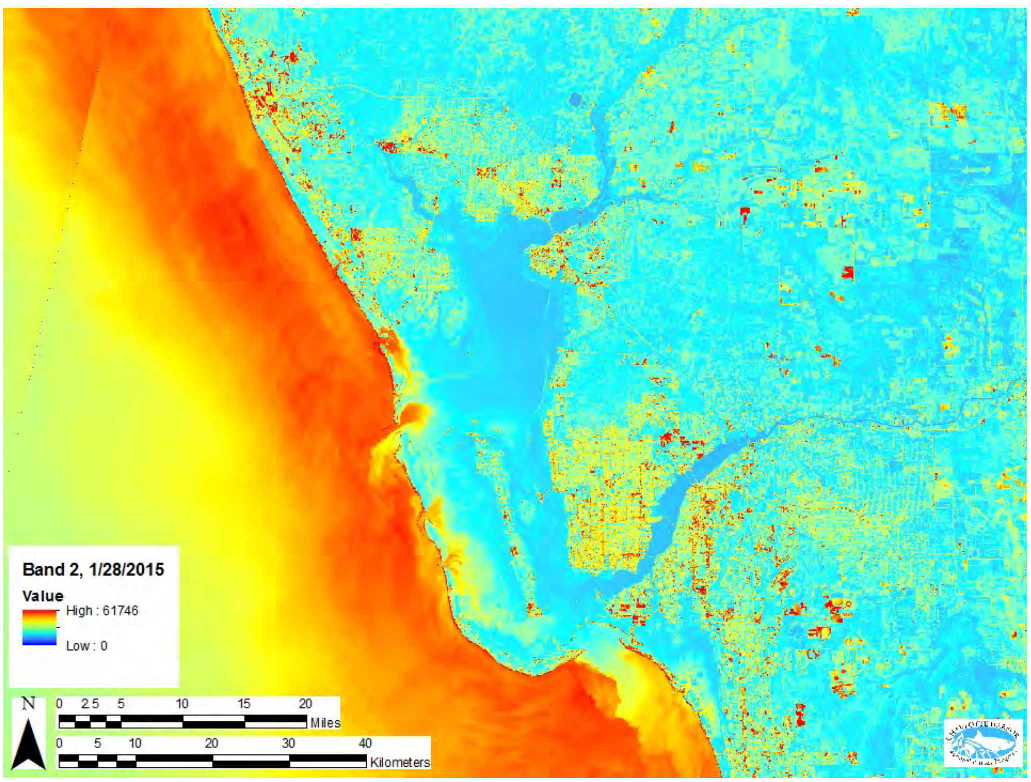
| | |
|---|---|
| (TIRS) 2 | |


**Figure 45: Landsat Mission timelines (USGS website)**

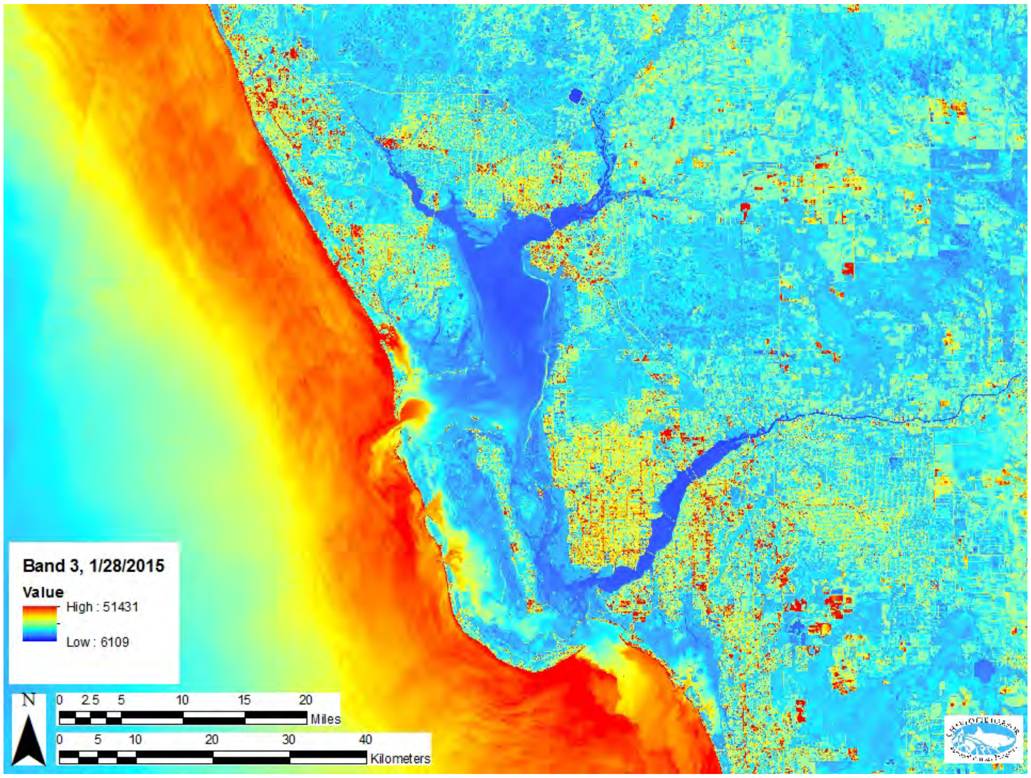
Landsat 5 provided the longest period of record for any Landsat mission to date. Landsat 4 predated Landsat 5 by less than 3 years and provides the same 30 meter resolution and the same wavelength band ranges as Landsat 5. Landsat 1-3 provides for a 60 meter resolution rather than the 30 meter resolution from later missions and is therefore less desirable.

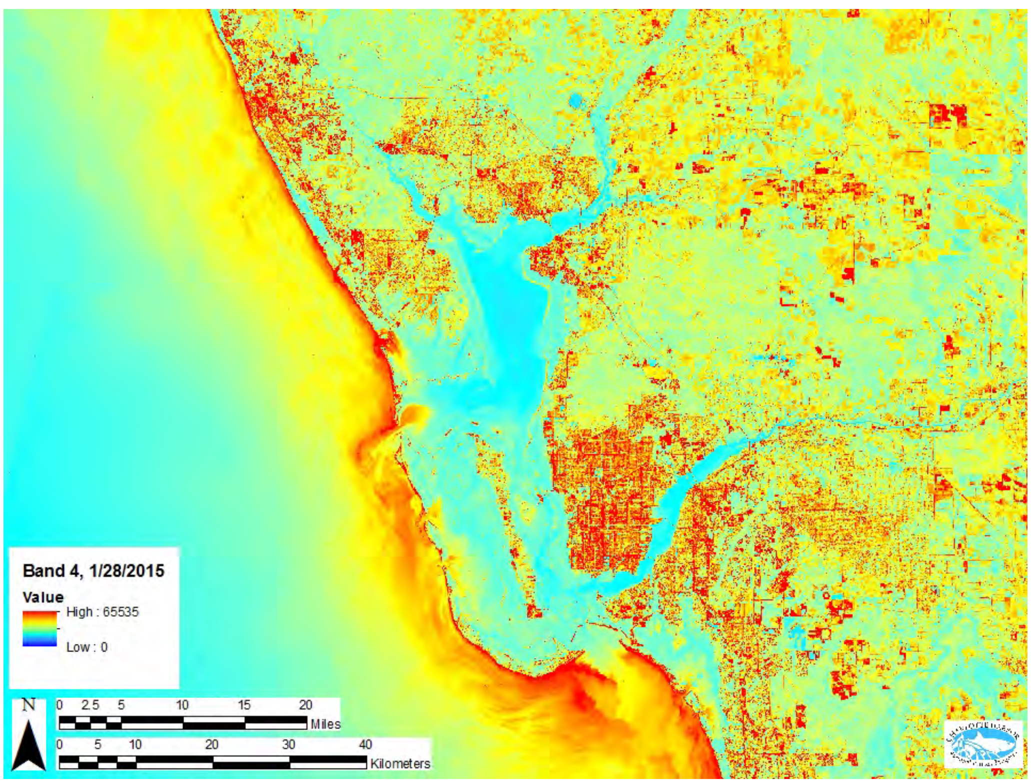
The following Map series displays each band individually from Landsat 8 (January 28, 2015) and several composite images. Please note that the scale is presented in Digital Numbers, as described below.



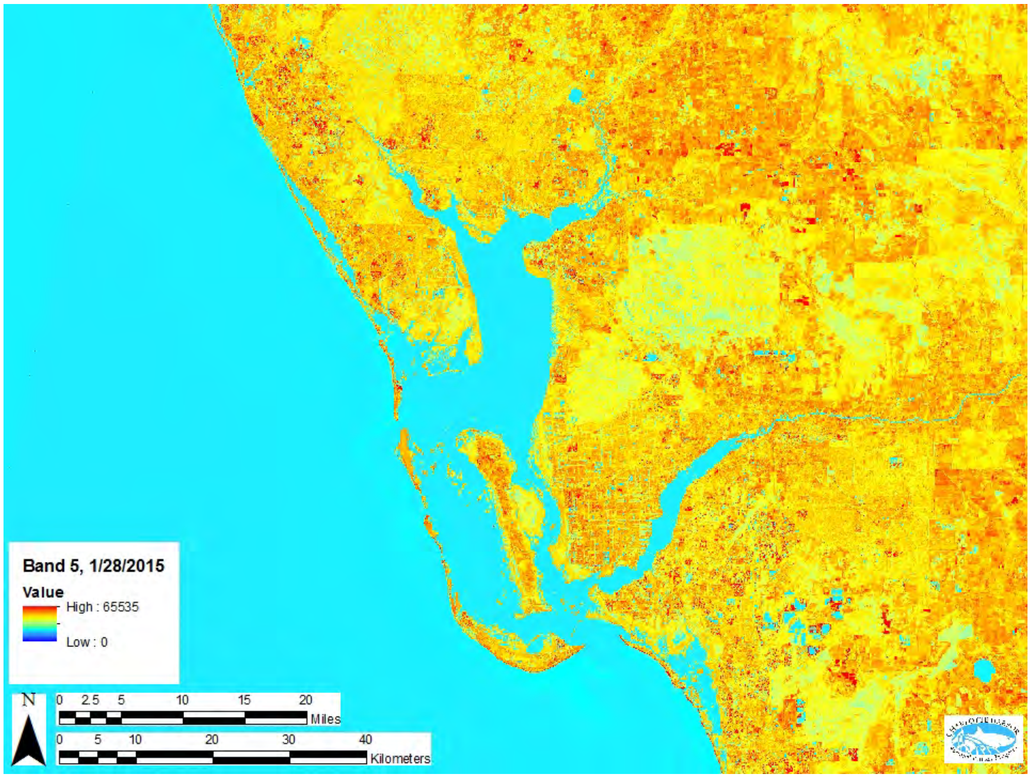



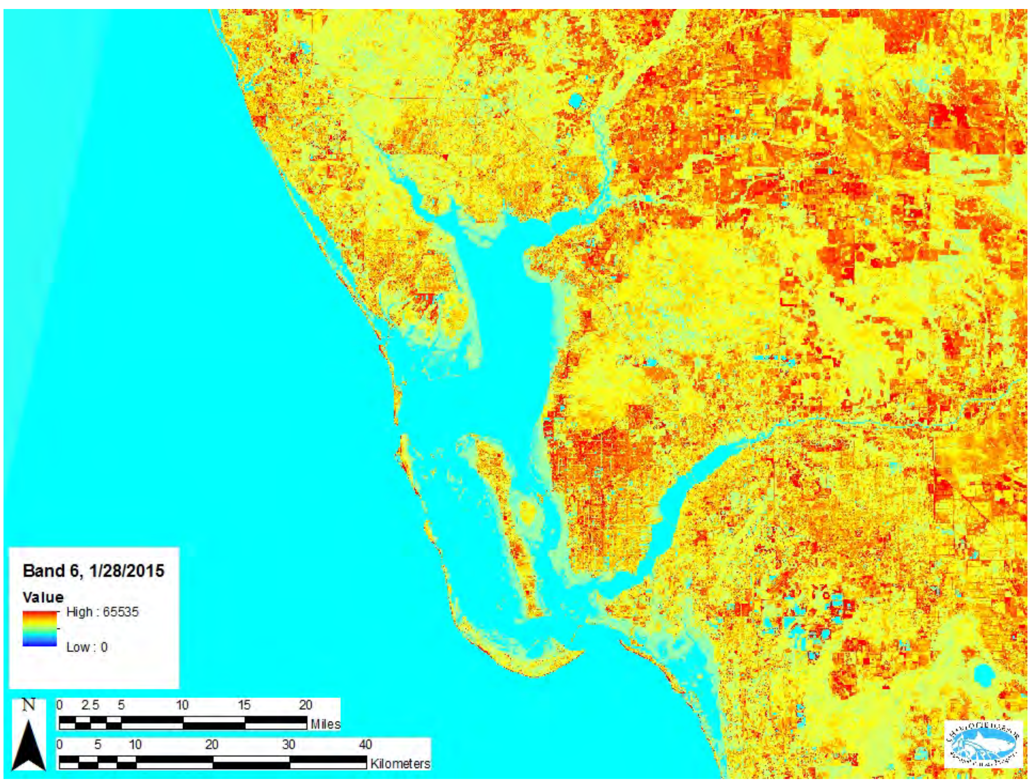

**Map 20: Bands 1 (coastal aerosol) and 2 (blue)**



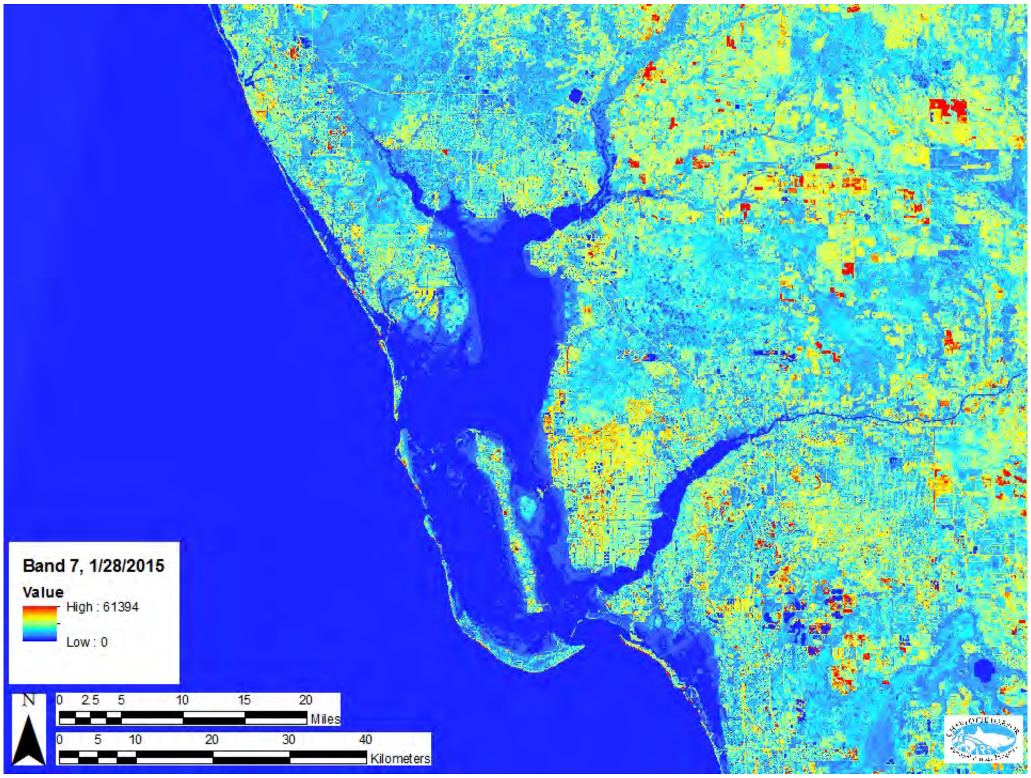



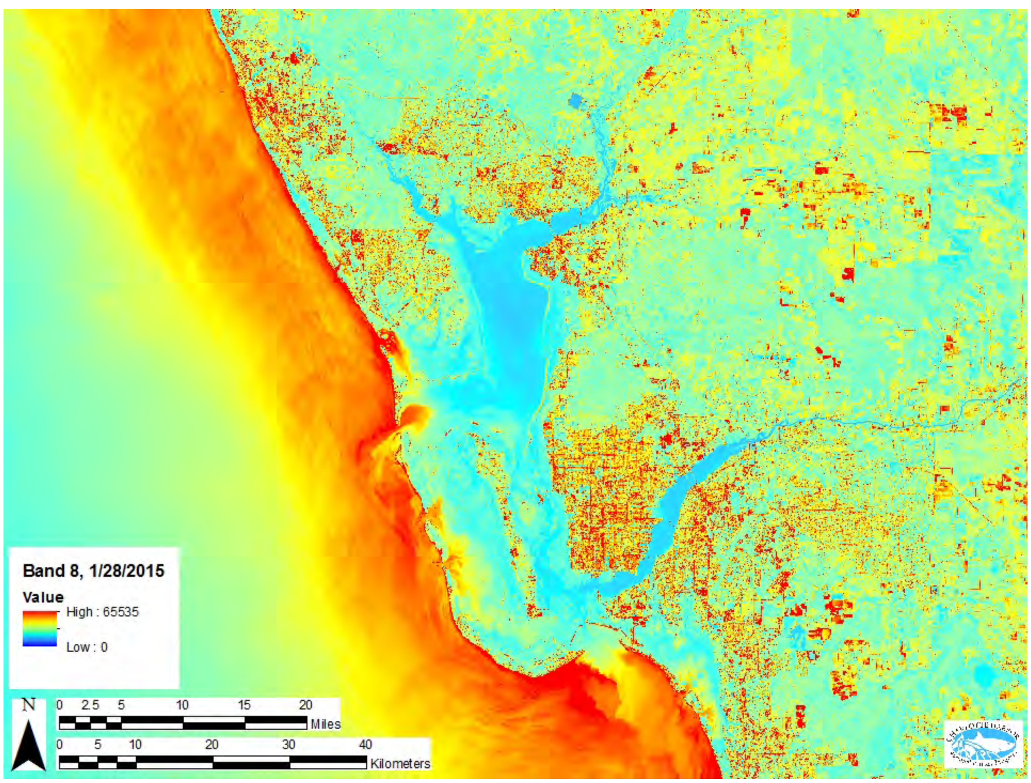

**Map 21: Bands 3 (green) and 4 (red)**



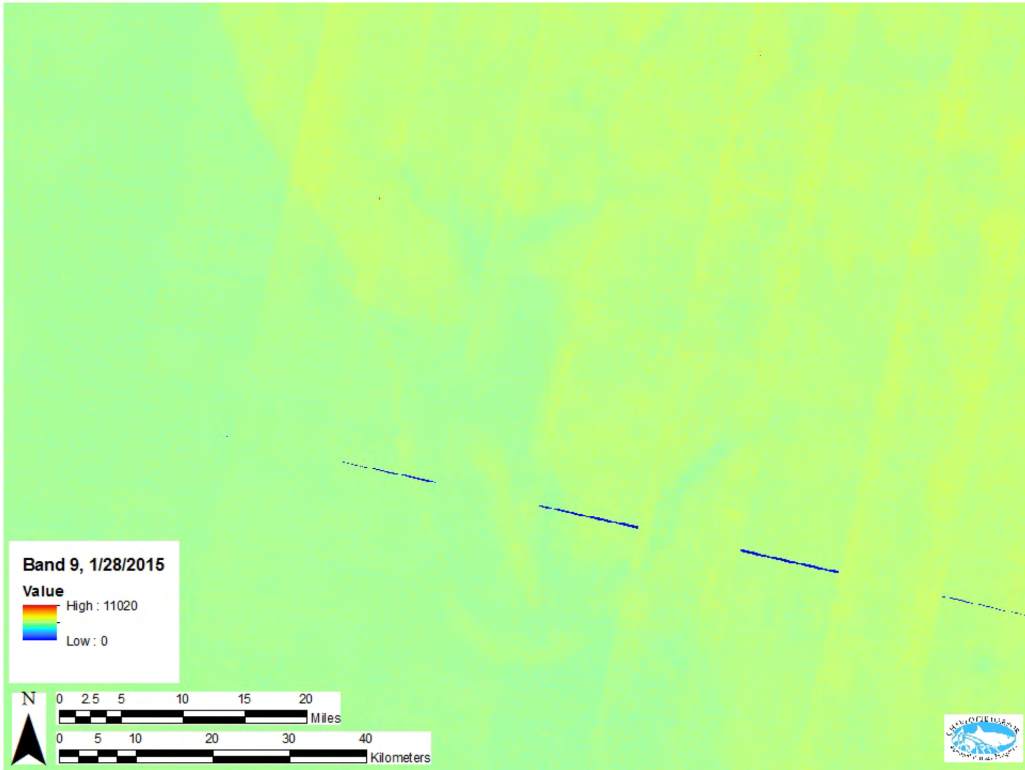



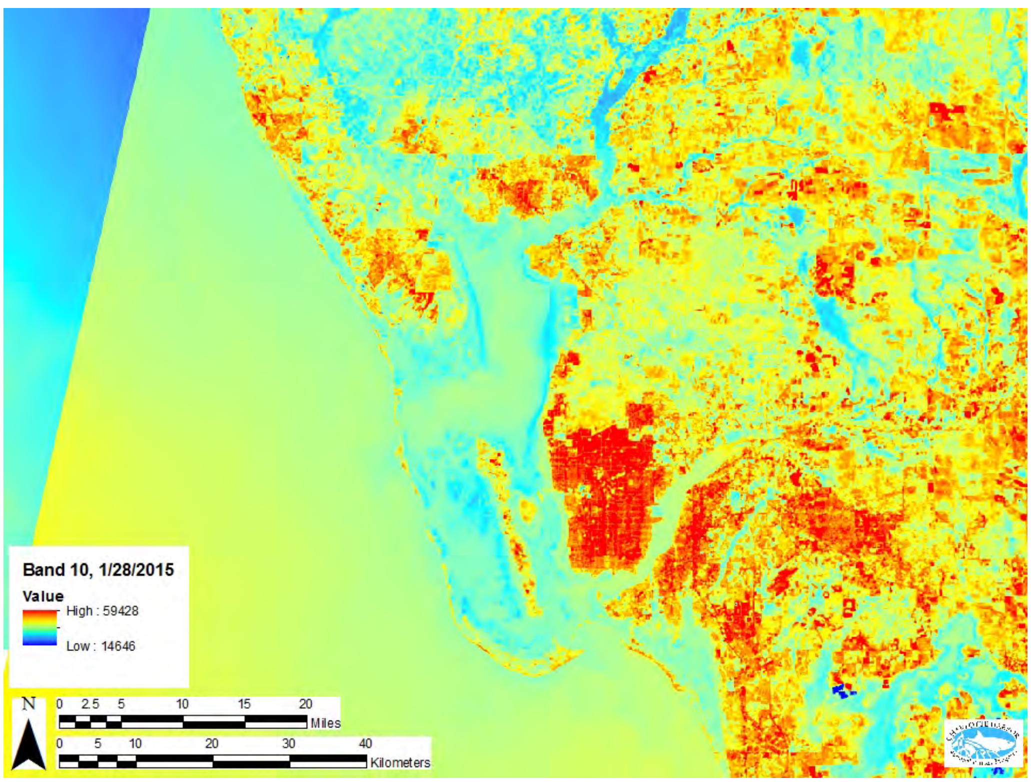

**Map 22: Bands 5 (near infrared, NIR) and 6 (short wave infrared1, SWIR1)**



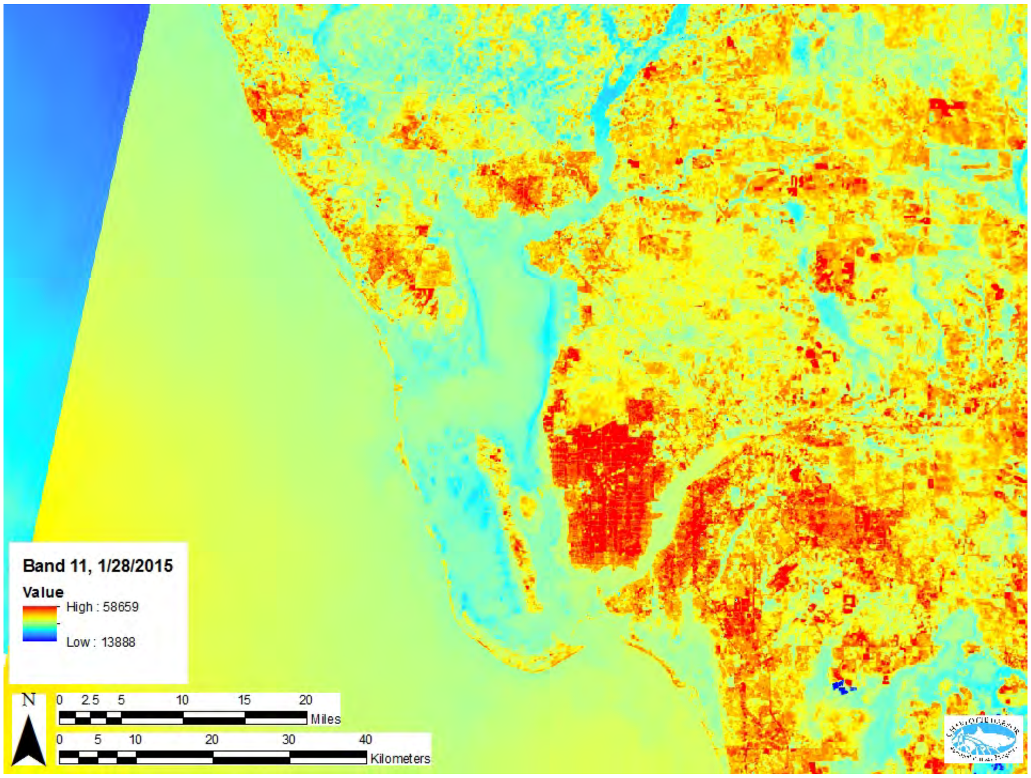



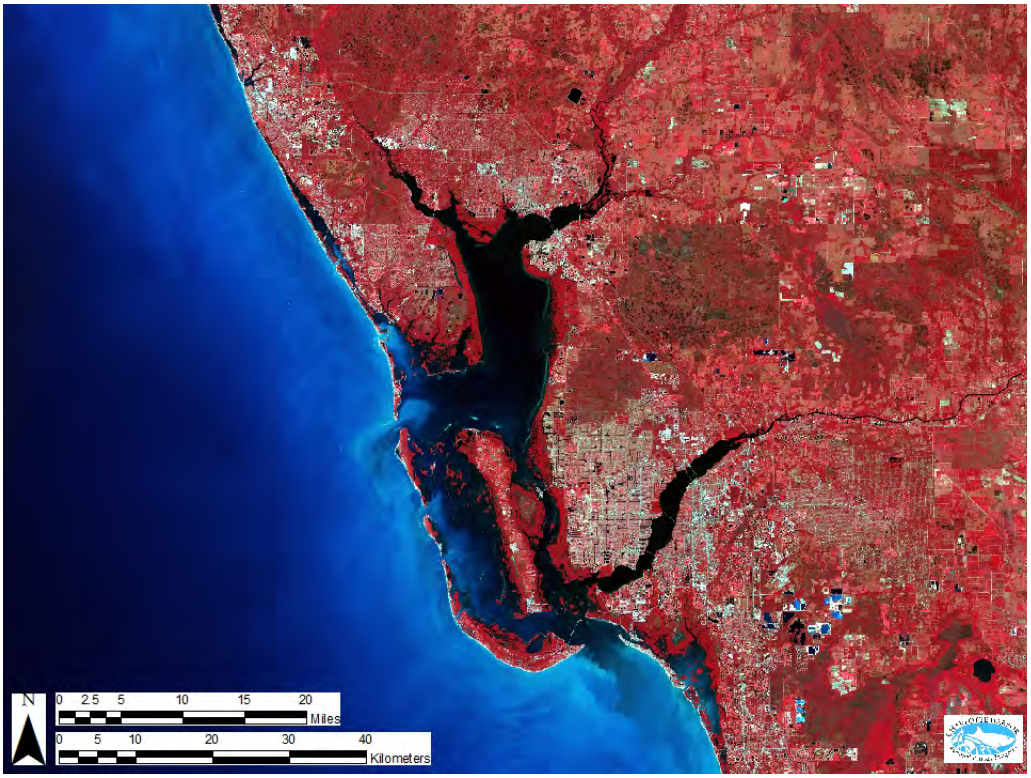

**Map 23: Bands 7 (short wave infrared 2, SWIR2) and 8 (Pan-Chromatic)**



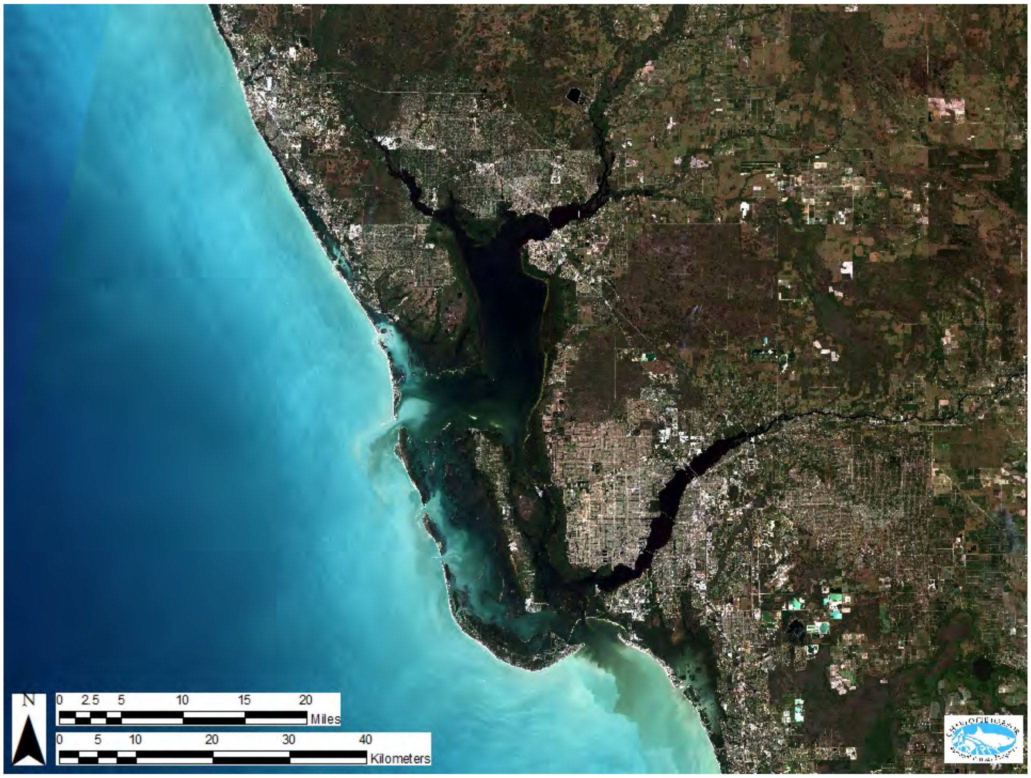



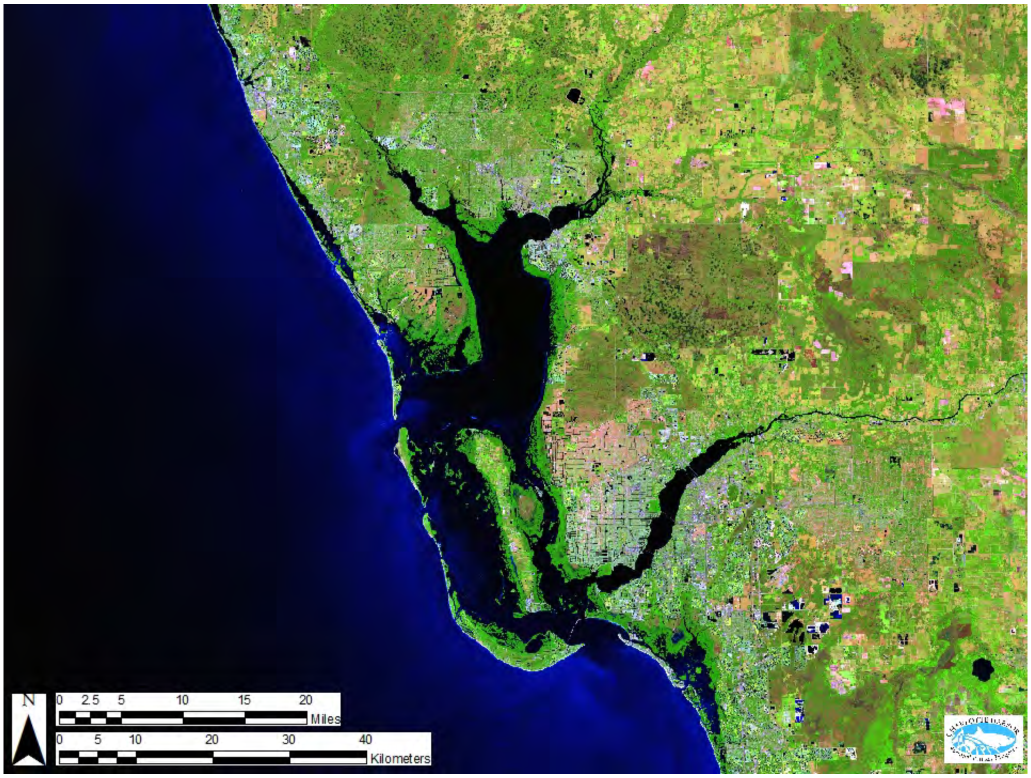

**Map 24: Bands 9 (cirrus) and 10 (Thermal Infrared 1, TIRS1)**



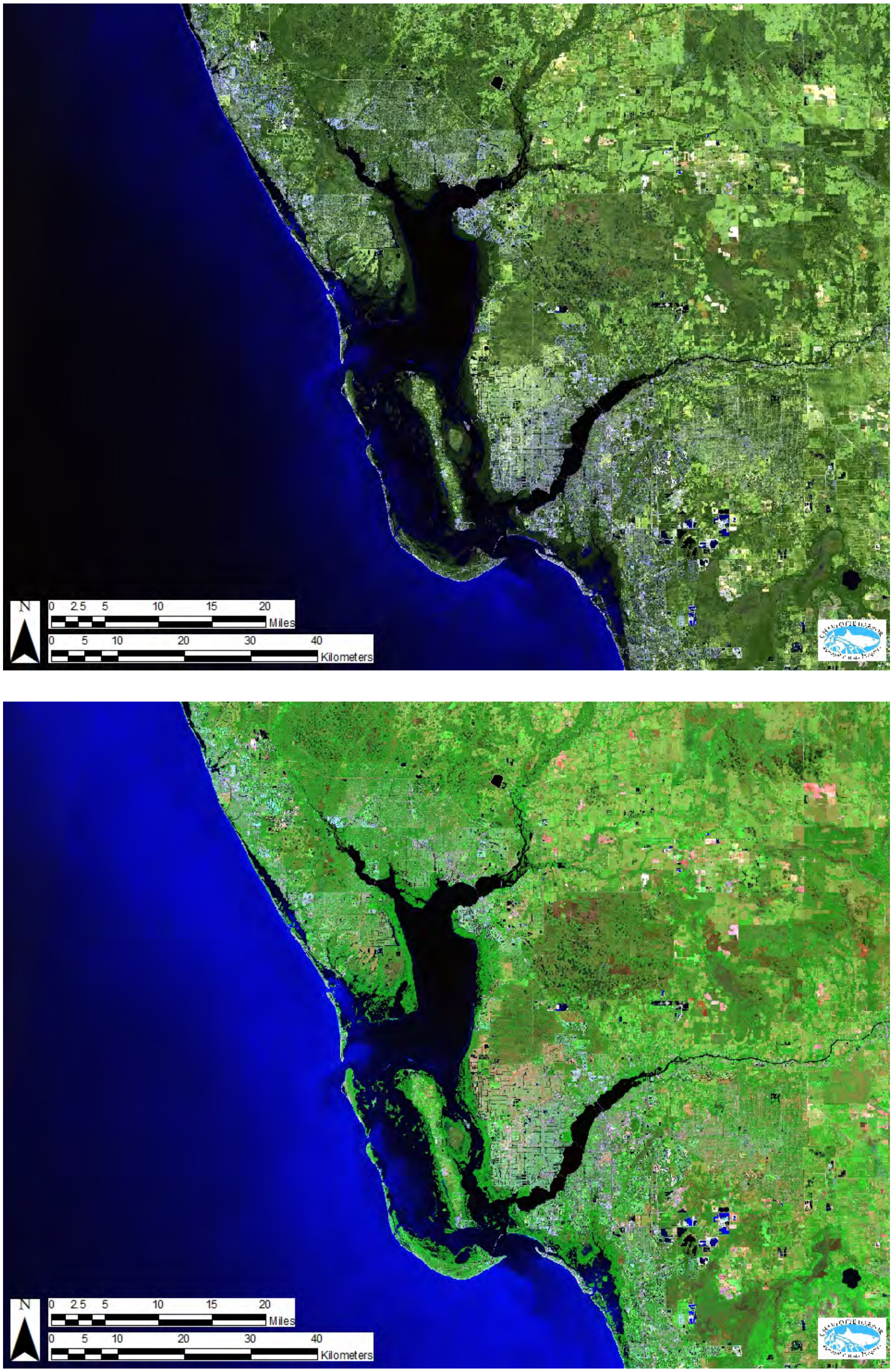




**Map 25: Band 11 (Thermal Infrared 2, Tirs2) And False Infrared (Bands 5, 4, 3)**

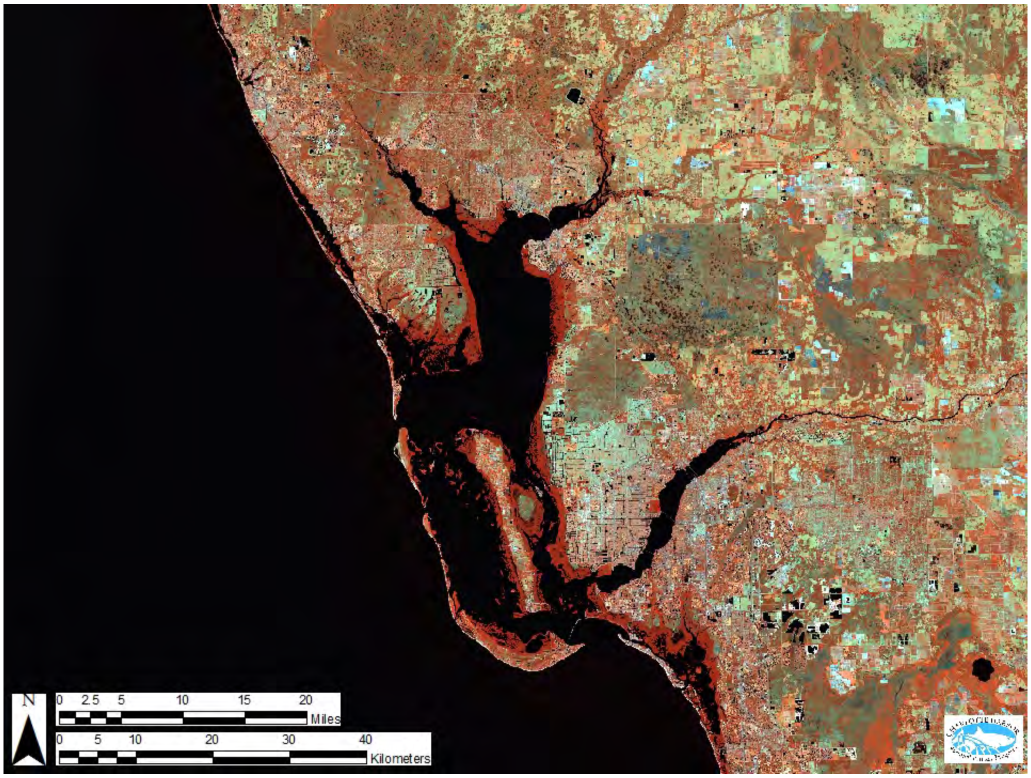



**Map 26: Natural Color (Bands 4, 3, 2 )and False Color 1 (Bands 6, 5, 4)**




**Map 27: False Color 2 (Bands 7, 6, 4) and False Color 3 (Bands 7, 5, 3)**



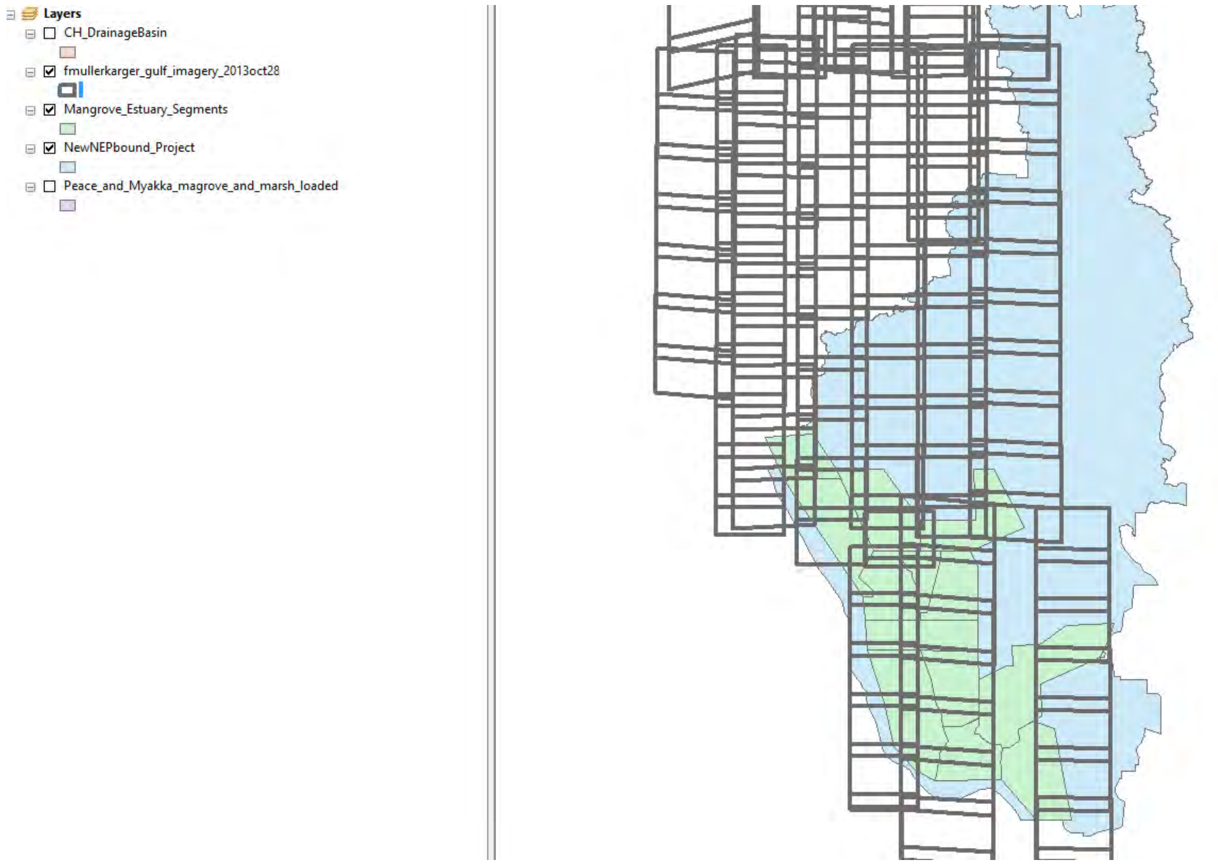

**Map 28: Mangroves as dark orange (Bands 5, 6, 7)**

The thermal infrared images include cooler water in the Gulf, because the outline scene was collected on May 11, 2015. Band 9 Cirrus demonstrates that January 28, 2015 had little to no cloud cover.

The composite of Bands 5, 6 and 7 was recommended by Pagalinawan (2015).

Pastor-Guzman *et al* (2015) recommend Sentinel-2 data, deployed in 2015, as an improved satellite data set for mangrove monitoring at high spatial and temporal resolutions. The date 2016-01-15 appears to have a coverage available for the CHNEP, within two scenes. However, the date had heavy cloud cover. 2015-12-16 has lighter cloud cover but was unavailable for the entire study area. https://scihub.copernicus.eu/. Based on the timing of this study, Sentinel-2 data were not practical to use but may be for future mangrove health analysis studies.

High resolution Worldview-2 data were reviewed for possible use in late 2015. No complete dataset of the CHNEP mangrove areas were available. However, these high-resolution data could have utility in the future for fine mapping of mangrove and other habitats.




**Map 29: World View-2 Coverage of CHNEP and Mangrove Estuary Segments in Late 2015**

## Top of Atmosphere Conversion

Data from the Landsat 5 and 7 missions are provided in percentage reflectance for each of the bands. The Georeferenced TIFF files that make up the individual Landsat 8 band possess pixel values. These digital number (DN) values are in 16-bit unsigned integer format and can be rescaled to the Top Of Atmosphere (TOA) reflectance and/or radiance using radiometric rescaling coefficients provided in the product metadata file (MTL file). See [http://landsat.usgs.gov/Landsat8_Using_Product.php](http://landsat.usgs.gov/Landsat8_Using_Product.php).

The following equation is used to convert level 1 DN values to TOA reflectance:

$$\rho\lambda' = M\rho * Qcal + A\rho$$

where:
$\rho\lambda'$ = Top-of-Atmosphere Planetary Spectral Reflectance, without correction for solar angle. (Unitless)
$M\rho$ = Reflectance multiplicative scaling factor for the band (REFLECTANCEW_MULT_BAND_n from the metadata).
$A\rho$ = Reflectance additive scaling factor for the band (REFLECTANCE_ADD_BAND_N from the metadata).

Qcal = Level 1 pixel value in DN (USGS 2015).

For the 2015-01-28 scenes used for Charlotte Harbor, scaling factors listed in the MTL file which downloaded with the Landsat Bands is:

$M\rho = 0.00002$

$A\rho = - 0.1$.

Applying the conversion equation to the pixel DN values is commonly referred to as "unpacking" the data.

Discussion of the Landsat values will refer to Band 1 (B1) through Band 7 (B7) TOA reflectance. Reflectance is unitless.

Data from the Landsat 1 through Landsat 7 missions requires no TOA conversion and is transmitted as percent reflectance at the various wavelength bands. The Landsat 8 refinement allows for more precession for analysis.

## Mangrove v. Not Mangrove calls using Landsat 8

An initial Landsat Analysis of mangroves was provided by USGS (Jordan Long and Chandra Giri 2015). Additional comparisons include Landsat analysis from Florida Fish and Wildlife Commission (2003) and hand-drawn maps from the water management districts (2008 and 2009).

Initial project evaluation of the data suggests that B7-SWIR2 is most useful for identifying mangroves as a wet forest type and B5-NIR is needed to separate open water from the mangrove fringe while B4-Red eliminates impervious surfaces that can be confused with mangroves.

$$B7 > .97 \text{ and } B7 < 1.12 \text{ and } B5 > 1.8 \text{ and } B4 < 1.7.$$

In comparison with site data, both equations are 75% accurate, the same accuracy as the water management district maps. Both USGS and FWC Landsat techniques were at a lower accuracy, 67.78% and 69.64% respectively.

# Final Mangrove Map Series and Analysis

## Landsat Interpretation Refinement

Early in the project's evaluation of spectral data and before the site investigation was complete, the working equation B7 >0.97 and B7<1.12 and B5>1.8 and B4<1.7 was used. The equation was 75% accurate, the same as water management district land use mapping of mangroves. The accuracy was greater than other Landsat mapping efforts including USGS and FWC at 68 and 70% respectively.

Sources of error in the CHNEP equation were scrutinized and alternatives tested.

- Site investigation data suggested that four black mangrove sites existed in B7 between 1.16 and 1.166. However, one of the two non-mangrove sites (CR-01) fell into the range. With the modification to B7 >.97 and B7<1.166 and B5>1.8 and B4<1.7, the accuracy improves to 80%.
- Evaluation of the site data suggested that the B5 >1.8 term be modified to B5>1.6. In doing so, the equation improves to 82% accuracy. However, stream bank vegetation such as Brazilian pepper and oaks are misidentified as mangroves.

By opening up the equation to B7 >.97 and B7<1.166 and B5>1.8 and B4<1.7, additional bank-side vegetation including oak hammock and Brazilian pepper are included in the call.

The alternate approach was to evaluate the results of FLUCCS mapping and site investigations. The means and standard deviations of Landsat 8 visual color and infrared bands were applied to geomorphic types and species and species mixes as identified during FLUCCS mapping and through site investigations.

## Mangrove Geomorphology and Species using Landsat 8

Geomorphology and species data from the FLUCCS maps described earlier and from the site investigations were compared to associated Landsat 8 pixel values.

Mangrove Species using FLUCCS maps and Landsat 8

The Landsat 8 band values were obtained for each mapped mangrove species and species mix. The values for each band and each mangrove species overlapped significantly. Though false color infrared imagery is an excellent tool to identify broad areas of red, black and white mangroves. Though one would assume that Landsat 8's near infrared (B5-NIR), short wave infrared 1 (B6-SWIR1), or short wave infrared 2 (B7-SWIR7) bands would provide a similar tool, but they did not.

As we did with the USGS data, we looked at pixels that were equal to or over 0.222394 acres.

The following tables provide the mean and standard deviation for each mangrove species and mangrove species mix that were mapped.

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Red Mangrove | Mean | 0.072 | 0.056 | 0.041 | 1.149 | 2.586 | 1.290 | 1.049 |
| | Std. Deviation | 0.002 | 0.002 | 0.003 | 0.022 | 0.171 | 0.085 | 0.041 |
| Black Mangrove | Mean | 0.072 | 0.057 | 0.043 | 1.174 | 2.358 | 1.279 | 1.066 |
| | Std. Deviation | 0.002 | 0.002 | 0.002 | 0.021 | 0.135 | 0.048 | 0.028 |
| White Mangrove | Mean | 0.077 | 0.062 | 0.053 | 1.265 | 2.560 | 1.746 | 1.283 |
| | Std. Deviation | 0.002 | 0.002 | 0.003 | 0.038 | 0.189 | 0.117 | 0.077 |
| Button-wood | Mean | 0.072 | 0.057 | 0.048 | 1.190 | 2.827 | 1.648 | 1.188 |
| | Std. Deviation | 0.001 | 0.001 | 0.002 | 0.017 | 0.155 | 0.040 | 0.018 |
| Red-Black-White Mix | Mean | 0.073 | 0.057 | 0.042 | 1.168 | 2.427 | 1.300 | 1.070 |
| | Std. Deviation | 0.002 | 0.002 | 0.002 | 0.020 | 0.143 | 0.059 | 0.033 |
| Black-White-Buttonjwood Mix | Mean | 0.075 | 0.060 | 0.048 | 1.239 | 2.402 | 1.616 | 1.237 |
| | Std. Deviation | 0.003 | 0.003 | 0.005 | 0.051 | 0.330 | 0.221 | 0.126 |
| Red-White Mix | Mean | 0.079 | 0.065 | 0.052 | 1.301 | 2.355 | 1.893 | 1.392 |
| | Std. Deviation | Insufficient number of samples with full pixels | | | | | | |
| Total | Mean | 0.073 | 0.057 | 0.043 | 1.170 | 2.425 | 1.311 | 1.076 |
| | Std. Deviation | 0.002 | 0.002 | 0.002 | 0.026 | 0.153 | 0.092 | 0.050 |

**Table 47: Mangrove Species Reflectance means and standard deviations**

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Red Mangrove | Mean | 99% | 98% | 95% | 98% | 107% | 98% | 98% |
| | Std. Deviation | 109% | 106% | 104% | 86% | 112% | 92% | 82% |
| Black Mangrove | Mean | 99% | 99% | 101% | 100% | 97% | 98% | 99% |
| | Std. Deviation | 101% | 94% | 83% | 81% | 88% | 52% | 57% |
| White Mangrove | Mean | 105% | 108% | 125% | 108% | 106% | 133% | 119% |
| | Std. Deviation | 129% | 132% | 115% | 147% | 124% | 127% | 154% |
| Buttonwood | Mean | 98% | 100% | 112% | 102% | 117% | 126% | 110% |
| | Std. Deviation | 30% | 41% | 86% | 65% | 101% | 43% | 36% |
| Red-Black-White Mix | Mean | 100% | 100% | 99% | 100% | 100% | 99% | 100% |
| | Std. Deviation | 93% | 90% | 80% | 78% | 93% | 64% | 66% |
| Black-White-Buttonwood Mix | Mean | 103% | 105% | 114% | 106% | 99% | 123% | 115% |
| | Std. Deviation | 164% | 175% | 192% | 199% | 216% | 239% | 252% |
| Red-White Mix | Mean | 108% | 113% | 123% | 111% | 97% | 144% | 129% |
| | Std. Deviation | Insufficient number of samples with full pixels | | | | | | |
| Total | Mean | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| | Std. Deviation | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table 48: Mangrove Species Reflectance as a percentage of total mean**

The greatest differentiation detected is on the short wave infrared 1 (B6-SWIR1) band. Here red mangroves (1) and black mangroves (2) are not distinct from one another. White mangroves (3) and buttonwoods (4) are not distinct from one another. Red mangroves and black mangroves are distinct from white mangroves and buttonwoods. Red-black-white mangrove mixes was more similar to red mangroves and black mangroves. Black-white-buttonwood mixes (6) were more similar to white mangroves (3) and buttonwoods (4) in the short wave infrared 1 (B6-SWIR1) band.

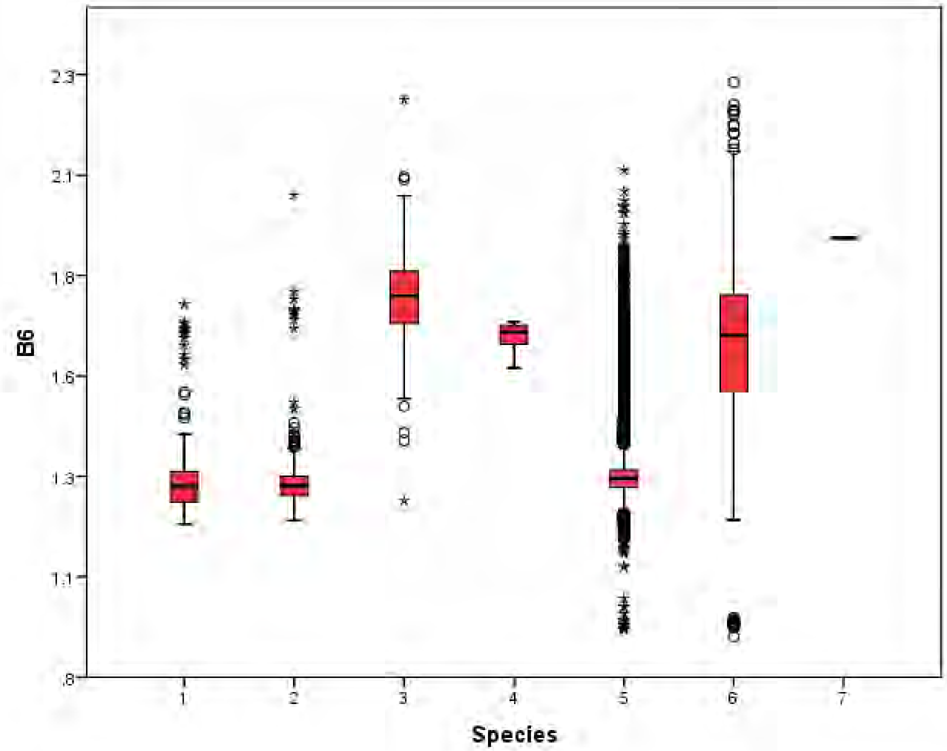



**Figure 46: Boxplot of short wave infrared 1 (B6-SWIR1) band values by species and mixes**

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Red Mangrove | Lower | 0.070452 | 0.054195 | 0.038068 | 1.126679 | 2.415540 | 1.204503 | 1.007595 |
| | Upper | 0.074229 | 0.057888 | 0.043238 | 1.170781 | 2.757211 | 1.374545 | 1.090107 |
| Black Mangrove | Lower | 0.070677 | 0.055061 | 0.040712 | 1.153328 | 2.223583 | 1.231473 | 1.037986 |
| | Upper | 0.074150 | 0.058350 | 0.044859 | 1.195077 | 2.492616 | 1.327318 | 1.094804 |
| White Mangrove | Lower | 0.074606 | 0.059560 | 0.050254 | 1.227318 | 2.370942 | 1.628633 | 1.205548 |
| | Upper | 0.079049 | 0.064157 | 0.055992 | 1.302807 | 2.748903 | 1.862778 | 1.360207 |
| Buttonwood | Lower | 0.071591 | 0.056300 | 0.045420 | 1.173347 | 2.671609 | 1.607740 | 1.170534 |
| | Upper | 0.072631 | 0.057726 | 0.049722 | 1.207016 | 2.981518 | 1.687278 | 1.206157 |
| Red-Black-White Mix | Lower | 0.071579 | 0.055556 | 0.040352 | 1.147695 | 2.283701 | 1.241187 | 1.036886 |
| | Upper | 0.074791 | 0.058675 | 0.044321 | 1.187844 | 2.569675 | 1.359728 | 1.103479 |
| Black-White-Buttonwood Mix | Lower | 0.072253 | 0.056993 | 0.043562 | 1.188062 | 2.072471 | 1.395423 | 1.110828 |
| | Upper | 0.077927 | 0.063085 | 0.053135 | 1.290687 | 2.732118 | 1.837497 | 1.363351 |
| Red-White Mix | Lower | 0.078888 | 0.064065 | 0.051738 | 1.294167 | 2.316765 | 1.869682 | 1.379282 |
| | Upper | 0.079752 | 0.064935 | 0.052982 | 1.307033 | 2.393235 | 1.915918 | 1.404318 |

**Table 49: Lower and Upper extent to define each species and species mix, based on FLUCCS**

Since the Red-white mix did not have a sufficient number of samples to render a standard deviation, the average standard deviation for all species types and mixes were divided by 4.

Mangrove Geomorphology using FLUCCS maps and Landsat 8

Again, short wave infrared 1 (B6-SWIR1) band values showed the greatest divergence for mangrove geomorphology of any of the bands.

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Overwash | Mean | 0.071 | 0.055 | 0.039 | 1.139 | 2.497 | 1.227 | 1.022 |
| | Std. Deviation | 0.001 | 0.001 | 0.001 | 0.008 | 0.287 | 0.043 | 0.020 |
| Fringe | Mean | 0.073 | 0.057 | 0.042 | 1.167 | 2.429 | 1.302 | 1.071 |
| | Std. Deviation | 0.002 | 0.002 | 0.002 | 0.021 | 0.144 | 0.070 | 0.038 |
| Riverine | Mean | 0.073 | 0.057 | 0.042 | 1.169 | 2.520 | 1.345 | 1.086 |
| | Std. Deviation | 0.002 | 0.002 | 0.004 | 0.035 | 0.139 | 0.119 | 0.063 |
| Basin | Mean | 0.074 | 0.058 | 0.044 | 1.184 | 2.338 | 1.283 | 1.072 |
| | Std. Deviation | 0.002 | 0.002 | 0.002 | 0.020 | 0.125 | 0.039 | 0.026 |
| Hammock | Mean | 0.077 | 0.062 | 0.050 | 1.248 | 2.436 | 1.669 | 1.261 |
| | Std. Deviation | 0.001 | 0.002 | 0.003 | 0.039 | 0.144 | 0.171 | 0.100 |
| Scrub | Mean | 0.075 | 0.060 | 0.048 | 1.231 | 2.391 | 1.549 | 1.206 |
| | Std. Deviation | 0.003 | 0.003 | 0.004 | 0.049 | 0.306 | 0.236 | 0.129 |
| Altered | Mean | 0.075 | 0.060 | 0.047 | 1.198 | 2.594 | 1.521 | 1.159 |
| | Std. Deviation | 0.002 | 0.002 | 0.003 | 0.031 | 0.142 | 0.180 | 0.081 |
| Total | Mean | 0.073 | 0.057 | 0.043 | 1.170 | 2.425 | 1.311 | 1.076 |
| | Std. Deviation | 0.002 | 0.002 | 0.002 | 0.026 | 0.153 | 0.092 | 0.050 |

**Table 50: Mangrove Geomorphology Reflectance means and standard deviations**

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Overwash | Mean | 97% | 96% | 91% | 97% | 103% | 94% | 95% |
| | Std. Deviation | 85% | 82% | 56% | 32% | 188% | 46% | 39% |
| Fringe | Mean | 100% | 100% | 99% | 100% | 100% | 99% | 100% |
| | Std. Deviation | 93% | 90% | 85% | 82% | 94% | 75% | 75% |
| Riverine | Mean | 99% | 99% | 100% | 100% | 104% | 103% | 101% |
| | Std. Deviation | 129% | 132% | 145% | 136% | 91% | 129% | 125% |
| Basin | Mean | 101% | 102% | 103% | 101% | 96% | 98% | 100% |
| | Std. Deviation | 105% | 98% | 84% | 79% | 82% | 42% | 51% |
| Hammock | Mean | 105% | 108% | 118% | 107% | 100% | 127% | 117% |
| | Std. Deviation | 83% | 110% | 137% | 153% | 94% | 185% | 200% |
| Scrub | Mean | 102% | 104% | 112% | 105% | 99% | 118% | 112% |
| | Std. Deviation | 148% | 159% | 176% | 190% | 200% | 255% | 257% |
| Altered | Mean | 103% | 104% | 111% | 102% | 107% | 116% | 108% |
| | Std. Deviation | 140% | 138% | 134% | 121% | 93% | 194% | 161% |
| Total | Mean | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| | Std. Deviation | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table 51: Mangrove Geomorphology as a percentage of total mean**

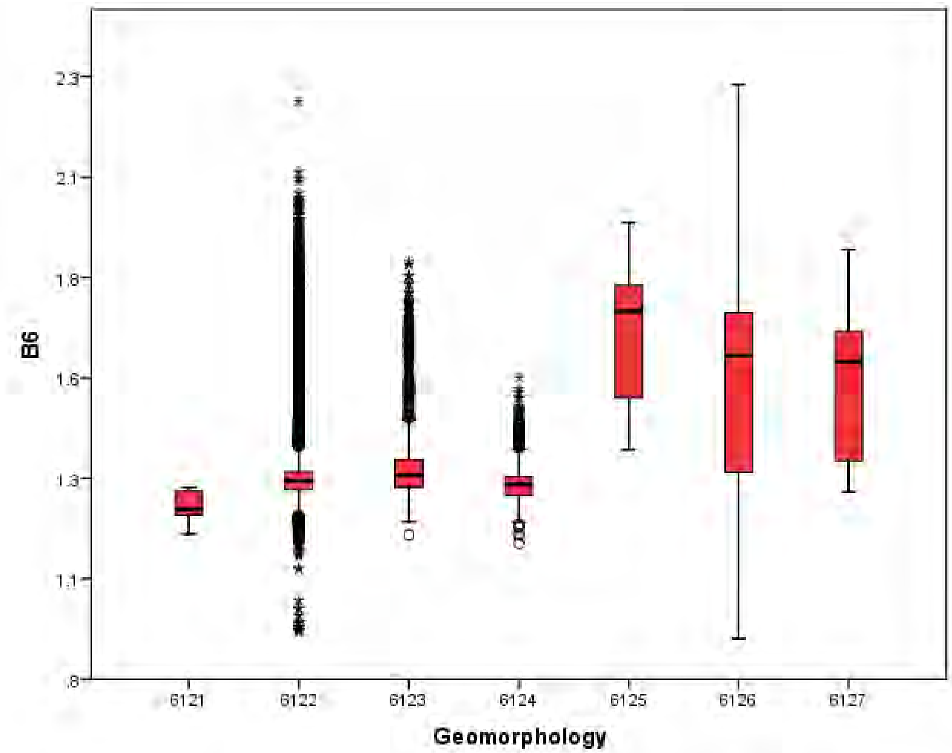



**Figure 47: Boxplot of short wave infrared 1 (B6-SWIR1) band values by geomorphology**

Overwash Island (6121), Fringe (6122), Riverine (6123), and Basin (6124) all had similar short wave infrared 1 (B6-SWIR1) band values. These geomorphic types diverged from Hammock (6125), Scrub (6126) and Altered (6127) in the short wave infrared 1 (B6-SWIR1) band. The elevated values of Hammock (6125), Scrub (6126) and Altered (6127) mimicked the elevated values of white mangroves (3), buttonwoods (4) and black-white-buttonwood mixes (6). The equation B7 >1.0 and B7<1.2 and B4<1.7 and B6>1.4 and B6<1.8 and B5>2 and B5<2.6 was tested to see if scrub mangroves appeared. This was tested with the earlier refined Landsat interpretation equation B7 >.97 and B7<1.166 and B5>1.6 and B4<1.7.

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Overwash | Lower | 0.069296 | 0.053190 | 0.037171 | 1.130737 | 2.209866 | 1.183992 | 1.002400 |
| | Upper | 0.072224 | 0.056056 | 0.039969 | 1.147197 | 2.783600 | 1.269142 | 1.041933 |
| Fringe | Lower | 0.071502 | 0.055479 | 0.040192 | 1.146285 | 2.285388 | 1.232703 | 1.032878 |
| | Upper | 0.074711 | 0.058611 | 0.044416 | 1.188297 | 2.572784 | 1.372086 | 1.108444 |
| Riverine | Lower | 0.070466 | 0.054453 | 0.038745 | 1.133766 | 2.381331 | 1.226164 | 1.023104 |
| | Upper | 0.074915 | 0.059061 | 0.045972 | 1.203578 | 2.659428 | 1.464588 | 1.148660 |
| Basin | Lower | 0.072332 | 0.056511 | 0.041708 | 1.163436 | 2.212757 | 1.243943 | 1.045967 |
| | Upper | 0.075949 | 0.059916 | 0.045875 | 1.204112 | 2.462971 | 1.322113 | 1.097098 |
| Hammock | Lower | 0.075512 | 0.059626 | 0.046874 | 1.208440 | 2.292310 | 1.497557 | 1.160892 |
| | Upper | 0.078377 | 0.063460 | 0.053666 | 1.286938 | 2.579334 | 1.839865 | 1.361671 |
| Scrub | Lower | 0.072259 | 0.056876 | 0.043219 | 1.181641 | 2.085193 | 1.312959 | 1.077074 |
| | Upper | 0.077353 | 0.062420 | 0.051987 | 1.279673 | 2.697496 | 1.784973 | 1.334228 |
| Altered | Lower | 0.072969 | 0.057104 | 0.043794 | 1.166766 | 2.451539 | 1.341841 | 1.078200 |
| | Upper | 0.077802 | 0.061915 | 0.050441 | 1.228800 | 2.735894 | 1.700892 | 1.239817 |

**Table 52: Mangrove Geomorphology Upper and Lower Reflectance Limits**

The ranges for geomorphology and species were tested in the ArcGIS environment. Riverine, basin, hammock and scrub geomorphic types were overstated. Fringe geomorphology was understated. Red-white mix, red, black-white-buttonwood mix and black mangrove are overstated. Red-black-white mix appears to be understated. Moreover, some large confirmed mangrove areas were not captured.

Mangrove Species calls using Site Investigation Values and Landsat 8

Landsat 8 band values were compared to results of the site investigations. Some of the mixed mangroves systems were combined. For example, the red-black-white mix included mixes where buttonwoods were also present or the white mangrove was not present. Black-white-buttonwood mixes included those where the buttonwood was not present. Both near infrared (B5-NIR-5) and short wave infrared 1 (B6-SWIR1) offered some differences between some mangrove species and others. In the Figures 48 and 49, below, species are as follows: (1) Red Mangrove, (2) Black Mangrove, (3) White Mangrove; (5) Red/Black/White, (6) Black/White/Buttonwoods.

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Red Mangrove | Mean | 0.076 | 0.060 | 0.046 | 1.237 | 2.516 | 1.536 | 1.204 |
| | Std. Deviation | 0.006 | 0.007 | 0.007 | 0.102 | 0.304 | 0.194 | 0.147 |
| Black Mangrove | Mean | 0.077 | 0.061 | 0.047 | 1.278 | 1.776 | 1.171 | 1.033 |
| | Std. Deviation | 0.001 | 0.001 | 0.003 | 0.079 | 0.509 | 0.158 | 0.069 |
| White Mangrove | Mean | 0.076 | 0.060 | 0.045 | 1.223 | 2.189 | 1.438 | 1.164 |
| | Std. Deviation | Insufficient number of samples with full pixels | | | | | | |
| Red-Black-White Mix | Mean | 0.074 | 0.059 | 0.044 | 1.184 | 2.355 | 1.280 | 1.059 |
| | Std. Deviation | 0.003 | 0.003 | 0.003 | 0.038 | 0.276 | 0.113 | 0.057 |
| Black-White-Buttonwood Mix | Mean | 0.077 | 0.062 | 0.049 | 1.261 | 2.444 | 1.571 | 1.236 |
| | Std. Deviation | 0.005 | 0.007 | 0.009 | 0.120 | 0.074 | 0.279 | 0.181 |
| Total | Mean | 0.075 | 0.059 | 0.045 | 1.205 | 2.282 | 1.297 | 1.075 |
| | Std. Deviation | 0.003 | 0.003 | 0.004 | 0.064 | 0.377 | 0.162 | 0.087 |

**Table 53: Mangrove Species Reflectance means and standard deviations**

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Red Mangrove | Mean | 101% | 102% | 104% | 103% | 110% | 118% | 112% |
| | Std. Deviation | 207% | 207% | 173% | 160% | 81% | 120% | 168% |
| Black Mangrove | Mean | 103% | 104% | 106% | 106% | 78% | 90% | 96% |
| | Std. Deviation | 43% | 45% | 77% | 124% | 135% | 97% | 79% |
| White Mangrove | Mean | 101% | 101% | 102% | 101% | 96% | 111% | 108% |
| | Std. Deviation | Insufficient number of samples with full pixels | | | | | | |
| Red-Black-White Mix | Mean | 99% | 99% | 98% | 98% | 103% | 99% | 99% |
| | Std. Deviation | 86% | 84% | 84% | 60% | 73% | 70% | 65% |
| Black-White-Buttonwood Mix | Mean | 103% | 104% | 109% | 105% | 107% | 121% | 115% |
| | Std. Deviation | 186% | 214% | 215% | 188% | 20% | 173% | 208% |
| Total | Mean | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| | Std. Deviation | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table 54: Mangrove Species Reflectance as a percentage of total mean**

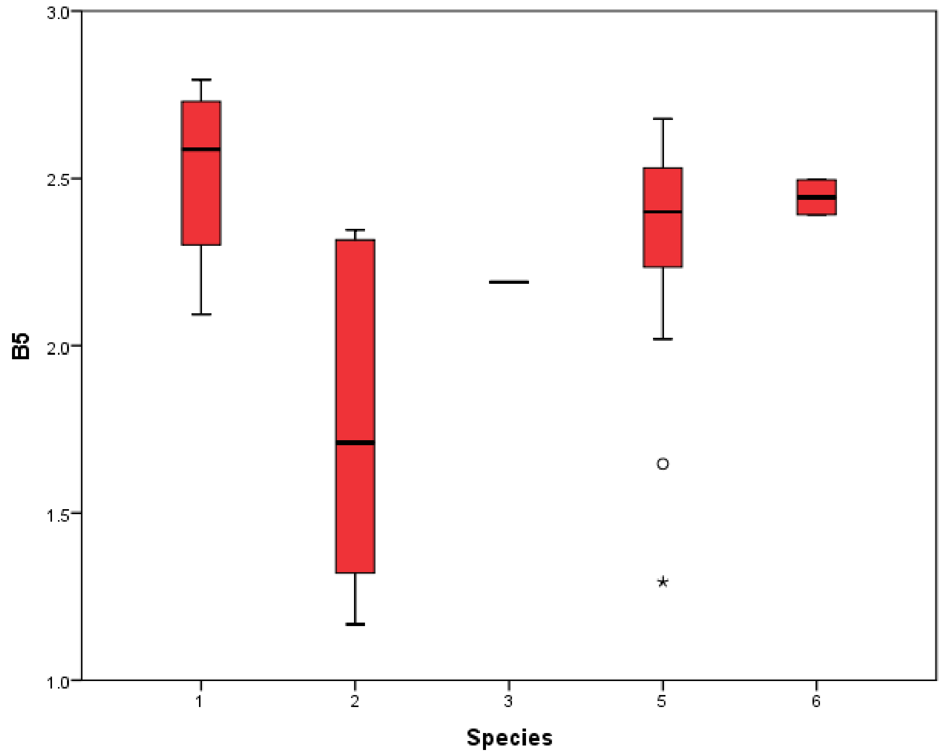



**Figure 48: Data distribution of near infrared reflectance by species type (B5)**

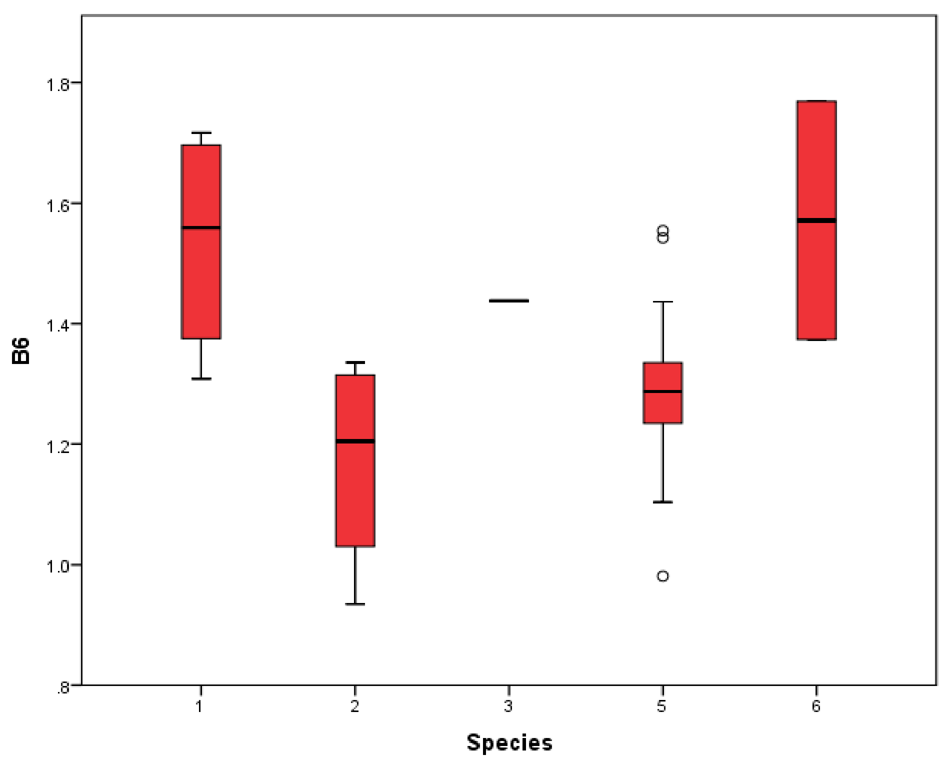



**Figure 49: Data distribution of shortwave infrared reflectance by species type (B6)**

| | | B1 | B3 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Red Mangrove | Lower | 0.069526 | 0.053653 | 0.039059 | 1.135060 | 2.211121 | 1.341949 | 1.056917 |
| | Upper | 0.081714 | 0.066927 | 0.053341 | 1.338740 | 2.819879 | 1.729751 | 1.351083 |
| Black Mangrove | Lower | 0.075775 | 0.059948 | 0.044249 | 1.199127 | 1.266670 | 1.013517 | 0.963328 |
| | Upper | 0.078325 | 0.062827 | 0.050606 | 1.357423 | 2.284680 | 1.328683 | 1.101822 |
| White Mangrove | Lower | 0.075066 | 0.059040 | 0.044227 | 1.206848 | 2.094970 | 1.397568 | 1.141765 |
| | Upper | 0.076534 | 0.060640 | 0.046293 | 1.238752 | 2.283430 | 1.478432 | 1.185435 |
| Red-Black-White Mix | Lower | 0.071806 | 0.055864 | 0.040122 | 1.145702 | 2.079417 | 1.167159 | 1.002426 |
| | Upper | 0.076874 | 0.061241 | 0.047043 | 1.222083 | 2.631260 | 1.393159 | 1.116118 |
| Black-White-Buttonwood Mix | Lower | 0.071497 | 0.055011 | 0.039739 | 1.141275 | 2.369537 | 1.291993 | 1.054256 |
| | Upper | 0.082443 | 0.068729 | 0.057501 | 1.381125 | 2.517463 | 1.850607 | 1.417144 |

**Table 55: Lower and Upper extent to define each species and species mix**

White mangrove forests did not possess enough samples to develop a standard deviation. Using the average for all mangroves yielded an overstatement of white mangrove forests. Therefore the project team agreed to divide the average standard deviation by 4 to apply as the white mangrove forest spectral call.

<u>Mangrove Geomorphology calls using Site Investigation Values</u>

The reflectance means and standard deviations for each of the Landsat 8 bands are sown below for each geomorphic type.

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Overwash | Mean | 0.075 | 0.059 | 0.046 | 1.227 | 1.895 | 1.112 | 0.977 |
| | Std. Deviation | 0.000 | 0.001 | 0.004 | 0.073 | 0.549 | 0.114 | 0.039 |
| Fringe | Mean | 0.075 | 0.059 | 0.044 | 1.196 | 2.408 | 1.332 | 1.091 |
| | Std. Deviation | 0.003 | 0.003 | 0.004 | 0.050 | 0.191 | 0.140 | 0.086 |
| Riverine | Mean | 0.073 | 0.057 | 0.042 | 1.165 | 2.404 | 1.327 | 1.070 |
| | Std. Deviation | 0.003 | 0.003 | 0.002 | 0.022 | 0.404 | 0.151 | 0.058 |
| Basin | Mean | 0.076 | 0.060 | 0.045 | 1.240 | 1.968 | 1.194 | 1.034 |
| | Std. Deviation | 0.002 | 0.002 | 0.004 | 0.086 | 0.505 | 0.135 | 0.059 |
| Scrub | Mean | 0.075 | 0.060 | 0.046 | 1.215 | 2.414 | 1.445 | 1.155 |
| | Std. Deviation | 0.004 | 0.005 | 0.006 | 0.088 | 0.107 | 0.218 | 0.141 |
| Total | Mean | 0.075 | 0.060 | 0.045 | 1.213 | 2.304 | 1.312 | 1.084 |
| | Std. Deviation | 0.004 | 0.005 | 0.007 | 0.088 | 0.388 | 0.185 | 0.107 |

**Table 56: Mangrove Geomorphology Reflectance means and standard deviations**

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Overwash | Mean | 99% | 100% | 102% | 101% | 82% | 85% | 90% |
| | Std. Deviation | 10% | 27% | 55% | 82% | 141% | 62% | 37% |
| Fringe | Mean | 100% | 99% | 98% | 99% | 105% | 101% | 101% |
| | Std. Deviation | 75% | 68% | 60% | 57% | 49% | 76% | 80% |
| Riverine | Mean | 97% | 95% | 92% | 96% | 104% | 101% | 99% |
| | Std. Deviation | 63% | 50% | 25% | 25% | 104% | 82% | 54% |
| Basin | Mean | 101% | 101% | 100% | 102% | 85% | 91% | 95% |
| | Std. Deviation | 46% | 49% | 61% | 98% | 130% | 73% | 56% |
| Scrub | Mean | 100% | 100% | 101% | 100% | 105% | 110% | 107% |
| | Std. Deviation | 87% | 94% | 89% | 99% | 28% | 118% | 131% |
| Total | Mean | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| | Std. Deviation | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table 57: Mangrove Species Geomorphology as a percentage of total mean**

In Figures 50 and 51 below, the FLUCCS codes are as follows: 6121 – Overwash Island, 6122 – Fringe, 6123 – Riverine, 6124 – Basin, 6126 – Scrub.

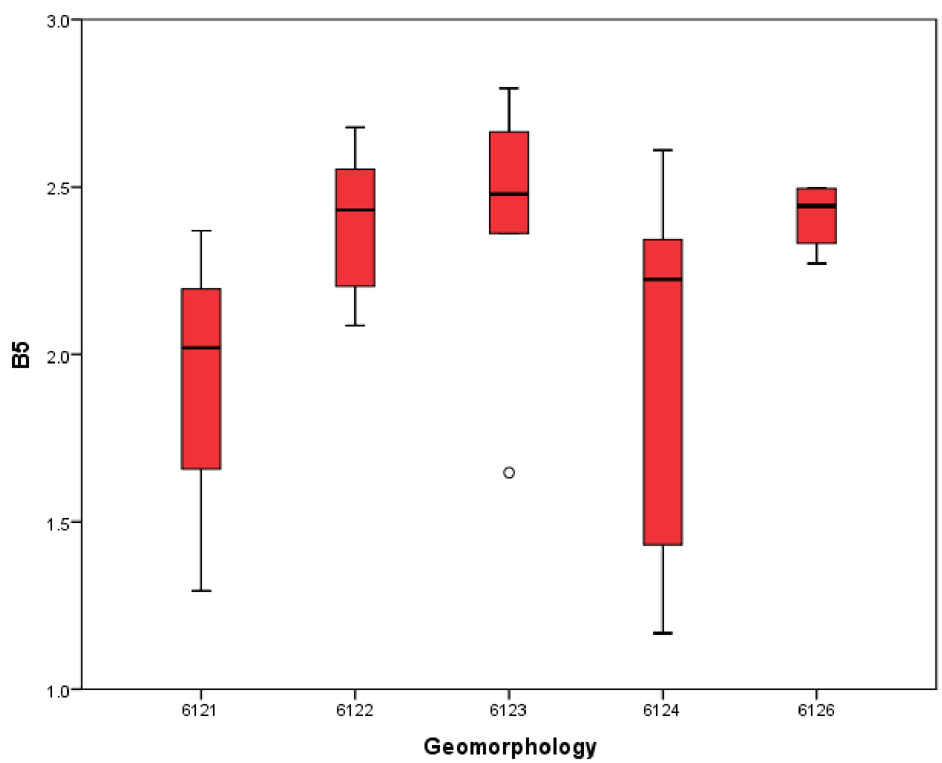



**Figure 50: Data distribution of near infrared reflectance by geomorphology type**

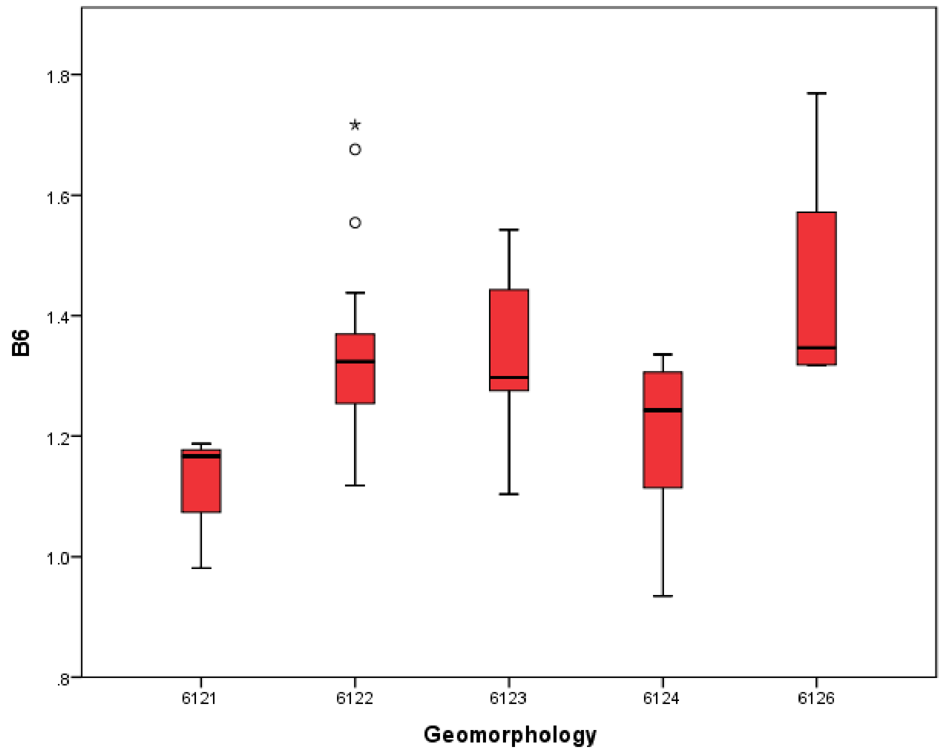



**Figure 51: Data distribution of shortwave infrared reflectance by geomorphology type**

| | | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Overwash | Lower | 0.074137 | 0.058050 | 0.042173 | 1.154402 | 1.620368 | 0.997847 | 0.937308 |
| | Upper | 0.074970 | 0.060790 | 0.049814 | 1.299865 | 2.169099 | 1.225619 | 1.015892 |
| Fringe | Lower | 0.071688 | 0.055839 | 0.040331 | 1.146090 | 2.216630 | 1.191868 | 1.005465 |
| | Upper | 0.078203 | 0.062724 | 0.048627 | 1.245841 | 2.598818 | 1.471401 | 1.176535 |
| Riverine | Lower | 0.070307 | 0.054476 | 0.040059 | 1.143152 | 2.000178 | 1.175473 | 1.012857 |
| | Upper | 0.075780 | 0.059518 | 0.043548 | 1.186648 | 2.808289 | 1.477727 | 1.128010 |
| Basin | Lower | 0.073992 | 0.057665 | 0.041188 | 1.153640 | 1.463050 | 1.059338 | 0.975020 |
| | Upper | 0.077981 | 0.062592 | 0.049669 | 1.326026 | 2.472617 | 1.328629 | 1.093947 |
| Scrub | Lower | 0.071379 | 0.054857 | 0.039456 | 1.127075 | 2.306863 | 1.335941 | 1.084200 |
| | Upper | 0.078971 | 0.064363 | 0.051844 | 1.302425 | 2.520237 | 1.553559 | 1.224800 |

**Table 58: Lower and Upper extent to define each geomorphic type**

## Mangrove Geomorphology and Species Recalibration

The combination of FLUCCS-based Landsat band ranges and site investigation-based Landsat ranges were used. The version or combination of versions which seemed to perform the best was selected to represent the geomorphic type first and then the species or species mix. Where types intersected, the type that was most constrained was selected to overlay the layer which was less constrained. The following tables describe the order, source and final band ranges for the Landsat interpretation.

| Geomorphology | Source | | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|
| Basin | FLUCCS | Lower | 1.163436 | 2.212757 | 1.243943 | 1.045967 |
| | | Upper | 1.204112 | 2.462971 | 1.322113 | 1.097098 |
| Fringe | Site | Lower | 1.146090 | 2.216630 | 1.191868 | 1.005465 |
| | | Upper | 1.245841 | 2.598818 | 1.471401 | 1.176535 |
| Fringe | FLUCCS | Lower | 1.146285 | 2.285388 | 1.232703 | 1.032878 |
| | | Upper | 1.188297 | 2.572784 | 1.372086 | 1.108444 |
| Overwash | Site | Lower | 1.154402 | 1.620368 | 0.997847 | 0.937308 |
| | | Upper | 1.299865 | 2.169099 | 1.225619 | 1.015892 |
| Riverine | Site | Lower | 1.143152 | 2.000178 | 1.175473 | 1.012857 |
| | | Upper | 1.186648 | 2.808289 | 1.477727 | 1.128010 |
| Scrub | Site | Lower | 1.127075 | 2.306863 | 1.335941 | 1.084200 |
| | | Upper | 1.302425 | 2.520237 | 1.553559 | 1.224800 |
| Hammock | FLUCCS | Lower | 1.163436 | 2.212757 | 1.243943 | 1.045967 |
| | | Upper | 1.204112 | 2.462971 | 1.322113 | 1.097098 |

**Table 59: Lower and Upper extent to define each geomorphic type**

| Species | Source | | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|
| White Mangrove | Site, Average SD/2 | Lower | 1.206848 | 2.094970 | 1.397568 | 1.141765 |
| | | Upper | 1.238752 | 2.283430 | 1.478432 | 1.185435 |
| Red Mangrove | FLUCCS, SD/2 | Lower | 1.137704 | 2.500957 | 1.247013 | 1.028223 |
| | | Upper | 1.159756 | 2.671793 | 1.332034 | 1.069479 |
| Black Mangrove | FLUCCS Basin, SD/1.3 | Lower | 1.168129 | 2.241628 | 1.252963 | 1.051867 |
| | | Upper | 1.199418 | 2.434100 | 1.313093 | 1.091199 |
| Red-Black-White Mix | Site | Lower | 1.145702 | 2.079417 | 1.167159 | 1.002426 |
| | | Upper | 1.222083 | 2.631260 | 1.393159 | 1.116118 |
| Red-Black-White Mix | FLUCCS | Lower | 1.147695 | 2.283701 | 1.241187 | 1.036886 |
| | | Upper | 1.187844 | 2.569675 | 1.359728 | 1.103479 |
| Red Mangrove | FLUCCS | Lower | 1.126679 | 2.415540 | 1.204503 | 1.007595 |
| | | Upper | 1.170781 | 2.757211 | 1.374545 | 1.090107 |
| Black-White-Buttonwood Mix | Site and FLUCCS BWT and scrub | Lower | 1.188062 | 2.369537 | 1.395423 | 1.110828 |
| | | Upper | 1.279673 | 2.517463 | 1.553559 | 1.224800 |

**Table 60: Lower and Upper extent to define each geomorphic type**

The source of the black mangrove calls was based on basins in the FLUCCS mapping. We used infrared photography to help identify basins based on the location of black mangroves forests. At most black mangrove site investigation locations, open water were part of the Landsat pixel because of the need to visit die-off locations. Therefore, a modification of the FLUCCS mapped basin locations was used as a surrogate for black mangroves.

The geomorphic call was combined with the species call to develop a Level 5 FLUCCS category. This was done by multiplying the level 4 geomorphic code by 10 (6121-overwash island becomes 61210), then adding the species code (61210-overwash island plus 1-red mangrove) to form the final level 5 code (61211- Red mangrove overwash island forest). There were occasions that a species call did not have an associated geomorphic call and vice versa. In cases where 1-red mangrove, 3-white mangrove or 5-mixed mangrove did not have a geomorphic type, they were called fringe. In cases where a geomorphic type did not have a species call. Overwash became overwash red, Riverine became riverine mixed.

## Predicted and Observed Species Identification

As stated previously, USGS and FWC Landsat analyses of mangroves were 66% and 67% correct related to the site investigations. The original CHNEP calculation of B7 >.97 and B7<1.166 and B5>1.8 and B4<1.7 was 75% correct compared to site data. The original calibrated Landsat interpretation was 68% correct. When spectral analysis from the site data was added for black mangrove basin forests and then basins with no species call was added as a mixed overwash island, accuracy improved to 75%. When the original equation was added as a mixed fringe forest, total accuracy improved to 82% (B4 modified to <1.3 instead of <1.7). Throughout the operation, the two non-mangrove sites were continued to be called as non-mangroves. The addition of the original calculation is best used at the small scale.

## Landsat Interpretation of Geomorphology and Species

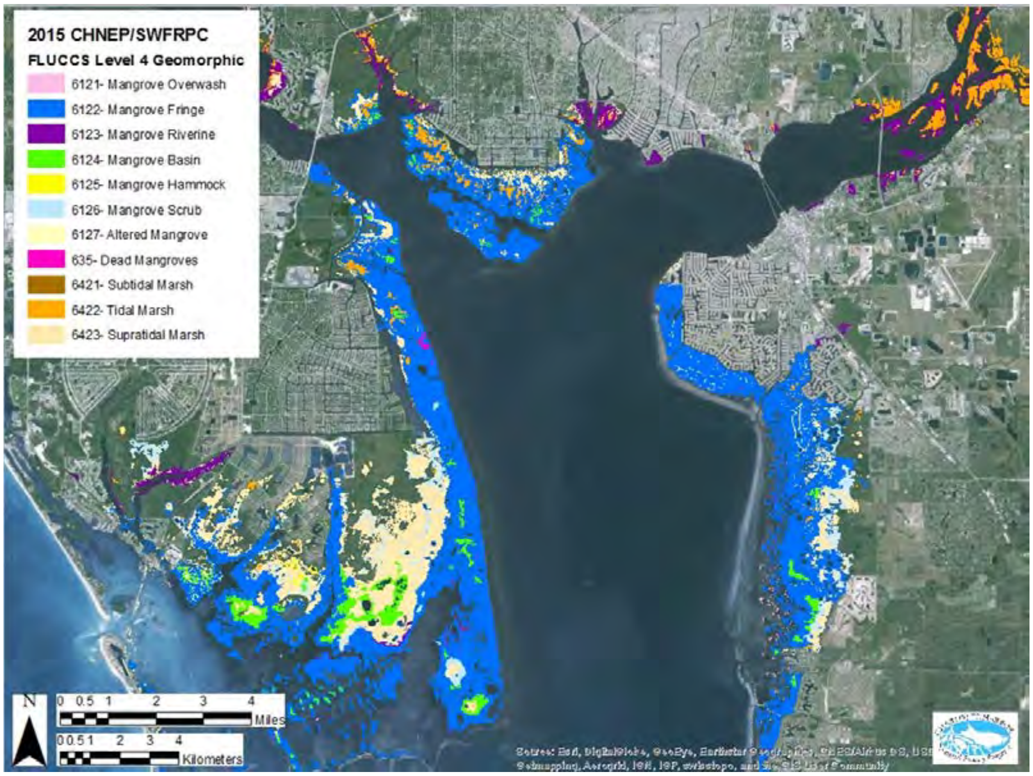
The 2015 FLUCCS map prepared through this effort and the previous 2011 Salt Marsh mapping effort was presented earlier in this document. This map was compared with the final Landsat interpretation by geomorphology, mangrove species and FLUCCS level 5.

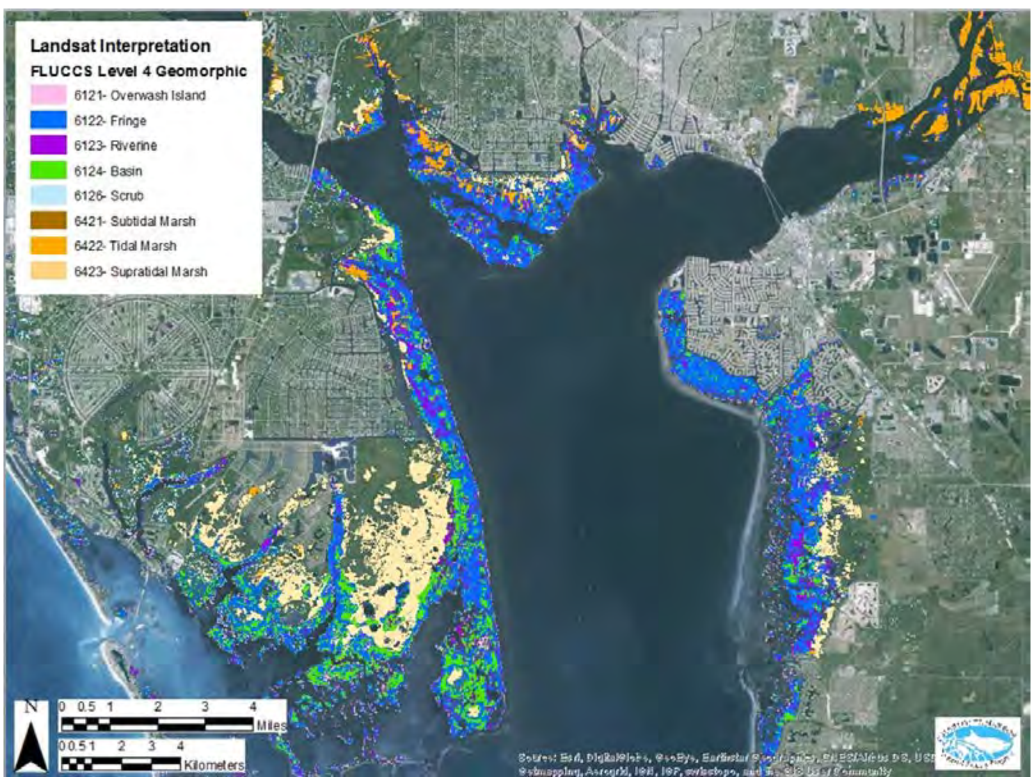
During mapping, geomorphology was determined by reviewing 2015 aerial photographs, relative Lidar elevations, 1999 infrared photography and site experience. This map was used, in combination with site investigation data, to define the band ranges for the Landsat interpretation of geomorphology. We cannot conclude that the Landsat interpretation is right and the FLUCCS mapping is wrong or vice versa. We can conclude that the Landsat Interpretation would provide an excellent guide for future refined mapping efforts.

The final Landsat interpretation appears more refined, answer many questions which emerged, and raised new questions of geomorphology and geomorphic changes.

- Several more basin mangove forests, shown in green, were identified. For example, many appear behibnd a coastal berm that we confirmed in the field along the west wall, yet Lidar was not sensitive enough to indicate basins.
- A line of mangroves  of declining health appear at the landward extent of the Fringe on Cape Haze, with no good explanation. It appears from the Landsat interpretation that extensive basins appear at the landward edge of Fringe mangroves throughout the study area, many with declining condition.
- Landsat interpretation indicate Overwash Islands within flooded basins.
- Landsat interpretation indicate Riverine mangroves within the opper reaches of tidal creeks, originally defined as Fringe.

**Figure 52: Line of mangroves of declining condition mapped as Fringe but interpreted as Basin (Photo credit: Maj. Dick Morell, Charlotte County Civil Air Patrol)**

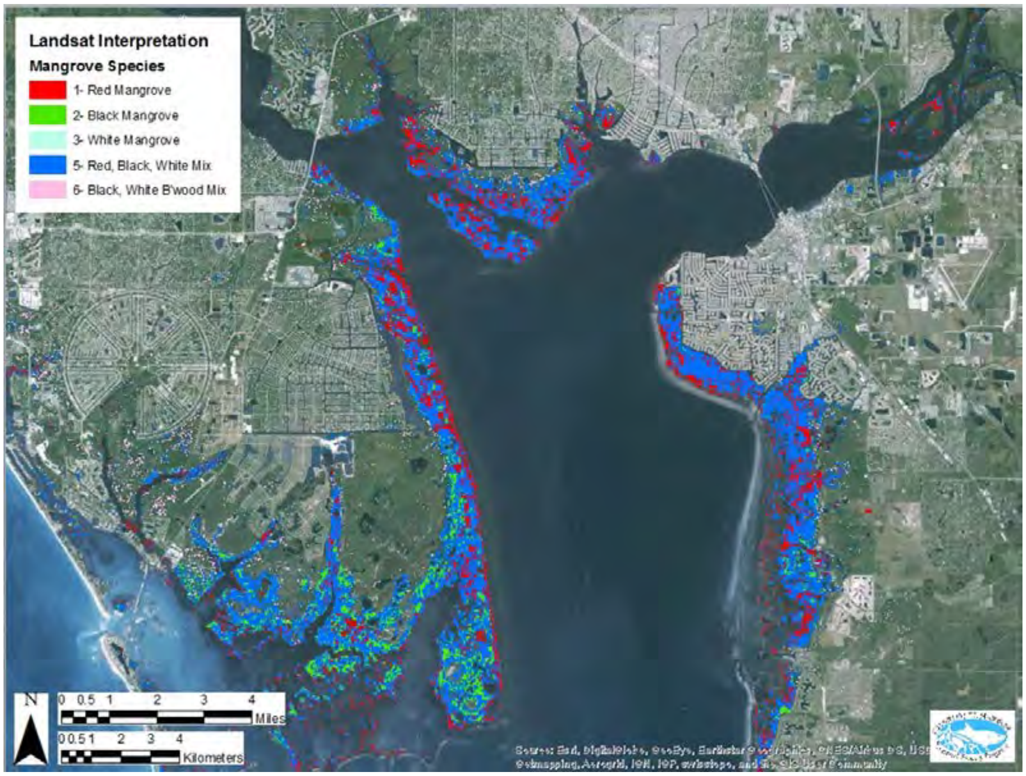



**Map 30: 2015 CHNEP/SWRPC Geomorphic Maps compared with Landsat Interpretation**

Mangrove species for the purposes of Landsat interpretation included red mangroves, black mangroves, white mangroves, red-black-white mangrove mix and black-white-buttonwood mix. For buttonwood and other mangrove mixes, not enough data were available to create a Landsat interpretation. The black-white-buttonwood mix is synonymous with mangrove scrub.

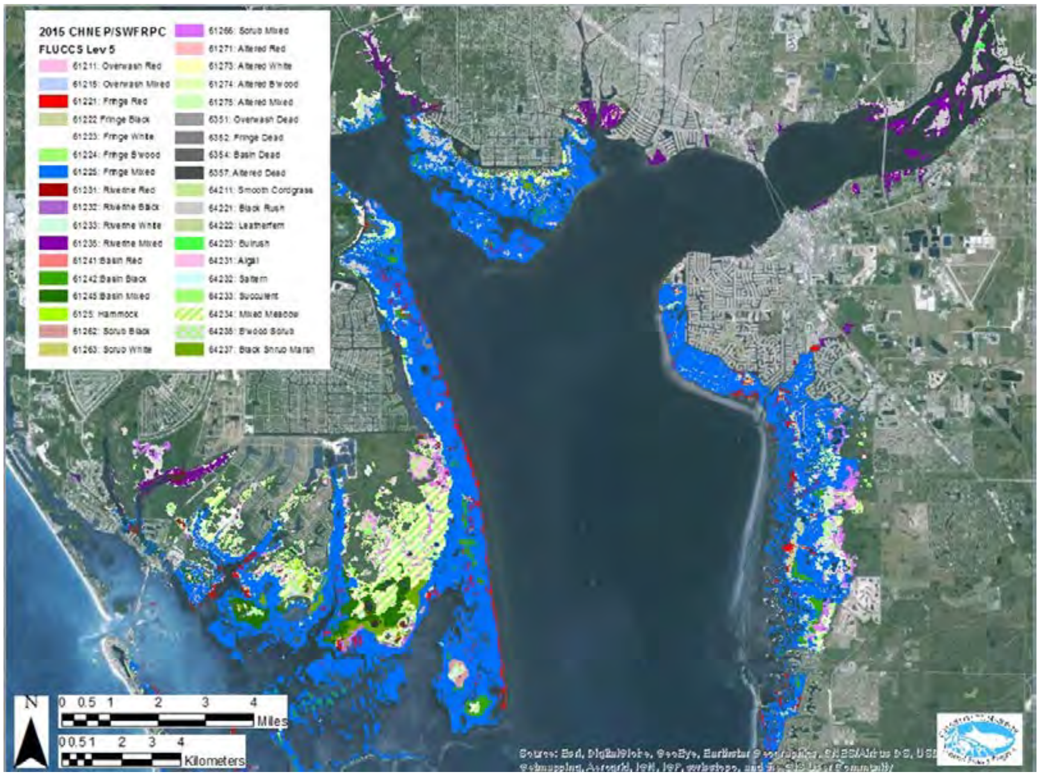
The red mangrove depiction probably has some level of mix, though dominated by red mangrove.

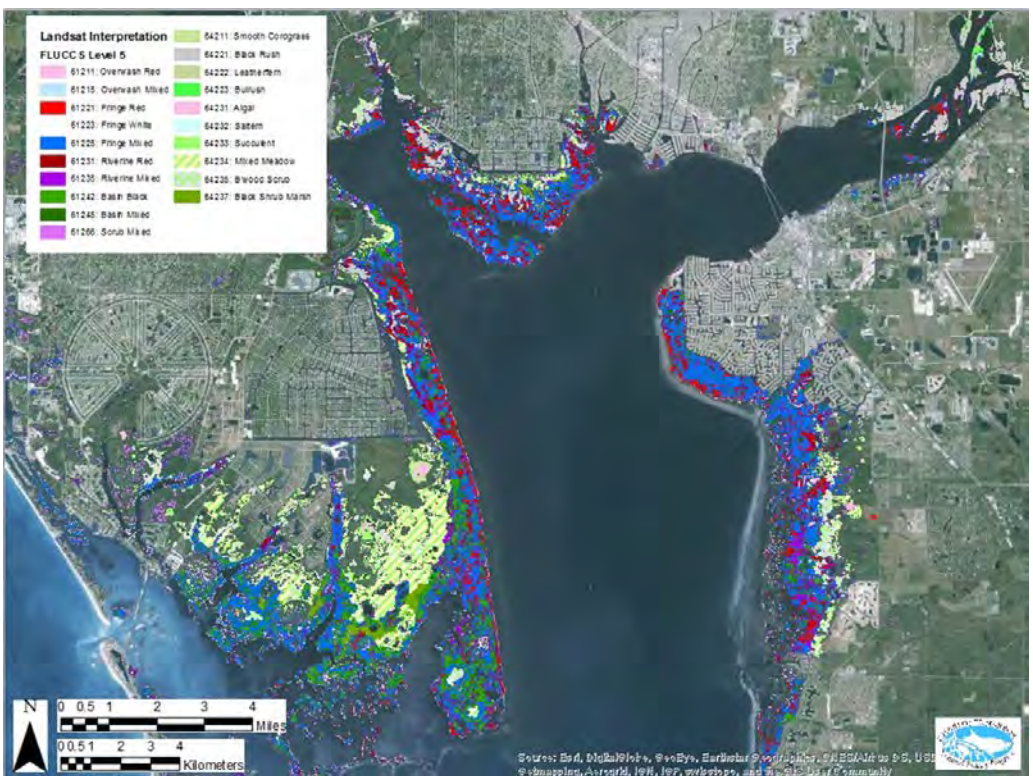



**Map 31: Landsat Interpretation of Mangrove Species**

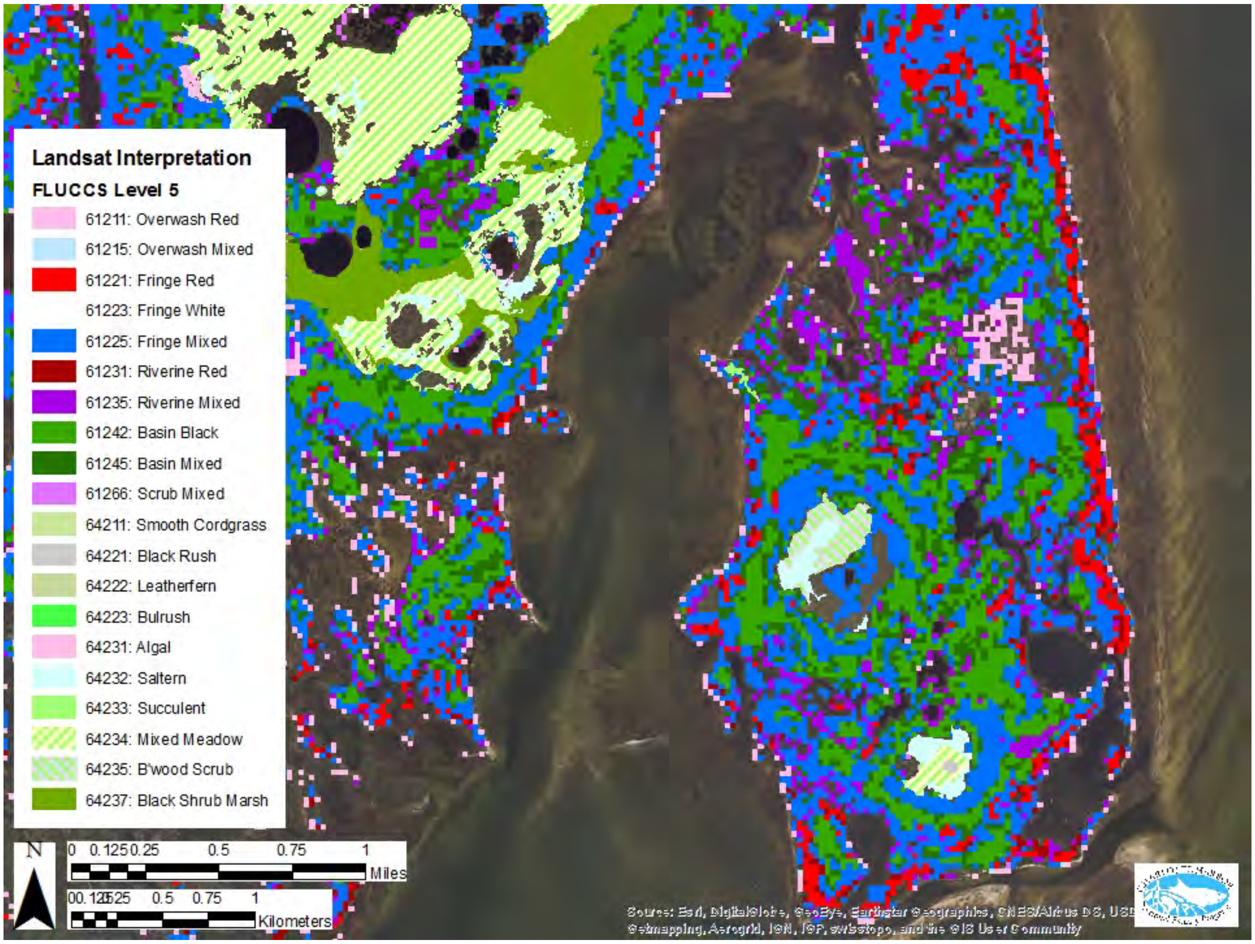
The final Landsat interpretation was presented as a FLUCCS level 5 map with both geomorphology and species identified. The following observations have been made.

- Underlying hydrology is better defined in the Landsat Interpretation. Much of what is hidden by mangrove tree canopy within aerial photography is exposed by mangrove response to that hydrology.
- Mangrove scrub is probably underrepresented in the Landsat interpretation. Mangrove scrub has much the same signature as many dry prairies. Scattered bushes with grasses underneath can occur in mangrove scrub and adjacent dry prairie. This was a problem with both FLUCCS mapping and Landsat interoperation.




**Map 32: 2015 CHNEP/SWRPC FLUCCS Level 5 Maps compared with Landsat Interpretation**




**Map 33: Close-up of Cape Haze Landsat Interpretation**

Upon close-up, the large size of the Landsat pixels is more apparent. For finer scale mapping, these may be used as a guide to augment aerial photograph interpretation.

Most overwash islands included water in association with the mangrove. This carries forward with shoreline mangroves reading as overwash islands. In some cases, such as the large pink area on the right side of the above map, red mangrove islands within an open lakes area, may operate more as overwash islands rather than fringe. Areas represented as mixed riverine indicate underlying tidal creeks.

The ridge and valley features around the two salt marshes on the peninsula are features that were not seen in the aerial photography.

## Mangrove Condition

Pastor-Guzman *et al* (2015) compared 20 hyperspectral and broad band vegetation indices to relative mangrove canopy chlorophyll measured at 12 sites along the northwest coast of the Yucatan Peninsula, Mexico. The sites were 30m by 30m to represent Landsat spatial resolution. The purpose of the work was to develop indicators of mangrove condition using remotely sensed data. Of the indices, normally distributed vegetation index green (NDVIgreen) was the most sensitive to canopy chlorophyll at the site level (R2 = 0.805.) The formula for NDVIgreen uses the near infrared and green bands. We found the NVDIgreen index to be an excellent indicator of mangrove condition in the Charlotte Harbor area.

The formula for NDVIgreen using Landsat 8 bands is:

$$NDVIgreen = (NIR-Green)/(NIR+Green)$$

Where:

NIR (Near Infrared) corresponds to Landsat 8 band 5
Green corresponds to Landsat 8 band 3.
The result is a value between 0 and 1.

The formula for NDVIgreen using Landsat 5 and 7 bands is:

$$NDVIgreen = (NIR-Green)/(NIR+Green)$$

Where:

NIR (Near Infrared) corresponds to Landsat 8 band 4
Green corresponds to Landsat 8 band 2.
The result is a value between -1 and 1.

Pastor-Guzman *et al* (2015) further explain that the linear model to construct a mangrove canopy chlorophyll map is:

$$y =-54.545 + 149.396x$$

Where:

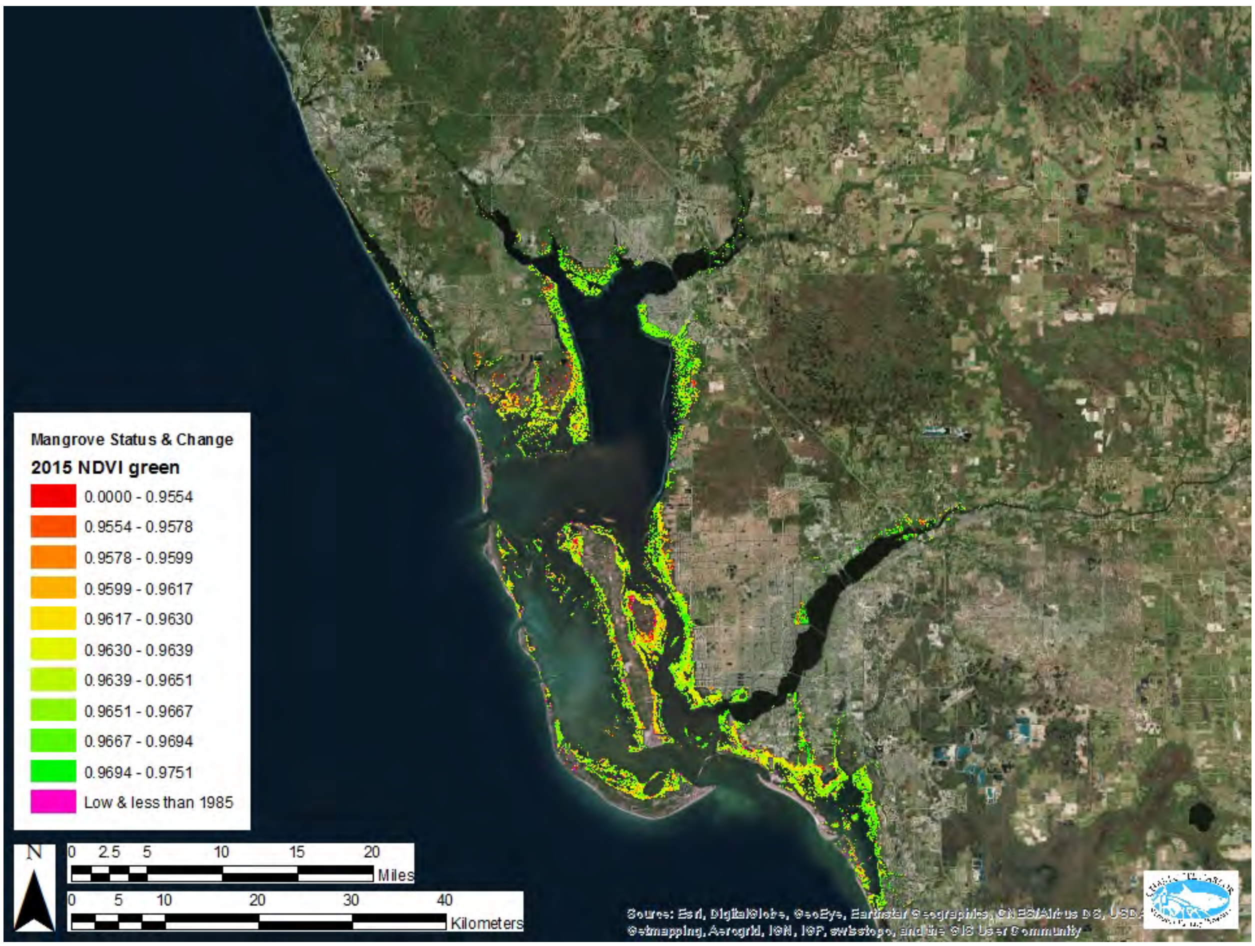
x = pixel value of the Landsat 8 NDVIgreen calculation.

Applying the equation to the Landsat 8 NDVIgreen values yielded a generally narrower range of canopy chlorophyll values for Charlotte Harbor compared to the Yucatan. Because the equation could not be applied to earlier Landsat missions and more work needed to be done to confirm the relationships between Charlotte Harbor mangrove canopy chlorophyll and NDVIgreen, the Principal Investigator settled on simply using NDVIgreen the indicator of mangrove condition.

The B7-NIR band for Landsat 8 is between 0.85 and 0.88 micrometers wavelength, compared to 0.76 and 0.9 for Landsat 4 and 5. The Landsat 4 and 5 missions together provide a period of record from July 16, 1982 through June 5, 2012. Between the differences in wavelength and data formats, direct comparisons are difficult. The next section describes the method used to compare NDVIgreen between Landsat missions in order to detect change in mangrove condition from before the Landsat 8 launch in 2013.

For this study, the terms “mangrove health,” “mangrove condition,” “canopy chlorophyll,” “Green Normalized Difference Vegetation Index,” “NDVIgreen” and NDVIg” are all synonymous with the equation (NIR−Green)/(NIR+Green) where NIR is Landsat 8 Band 5 and Landsat 5 Band 4 and where Green is Landsat 8 Band 3 and Landsat 5 Band 2. NIR is the abbreviation for Near Infrared.

The results for 2015 are presented by map with red indicating a low NDVIgreen and green indicating a high NDVIgreem. Even at a small scale patterns may be seen with waterward mangroves in better condition than landward mangroves in general.




**Map 34: 2015 Mangrove Condition**

## Comparing Mangrove Condition between Landsat Missions

January 9, 1985 (Landsat 5), December 26, 1999 (Landsat 7) and January 28, 2015 (Landsat 8) scenes for Charlotte Harbor were downloaded. NDVI green was run for each dataset. The geo-referencing for the December 26, 1999 data is off by several meters.

ArcGIS was used to evaluate the frequency distribution of NDVIgreen in Charlotte Harbor mangroves. The 2015 mangrove condition ranged from 0.906 to 0.976 (of a potential range of 0 to 1), with a mean of 0.965. In part because of the Landsat 7 georeferencing problem, 1999 mangrove condition appears to range from -1 to +1 (of the same potential range), with a mean of 0.3. The 1985 data appear more in line with the 2015 data. The 1985 mangrove condition ranged from -0.714 to 0.619 (within a potential range of -1 to +1), with a mean of 0.345.

Frequency distribution and descriptive statistics of NVDIgreen for the three datasets is shown below. The range and the kurtosis (tallness) of the 1999 data is greater than that of the 2015 and 1985 data, rendering the comparison from 1985 to 1999 to 2015 more difficult. Therefore the 1985 and 2015 datasets were used to evaluate changes of mangrove condition.

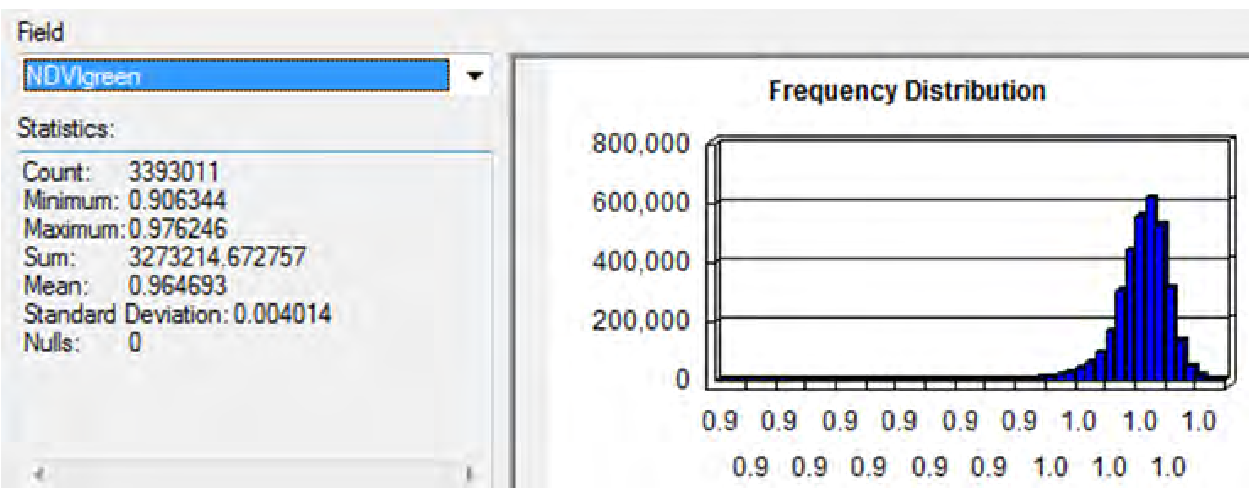



**Figure 53: Frequency Distribution of NDVI green based on mangroves on January 28, 2015**

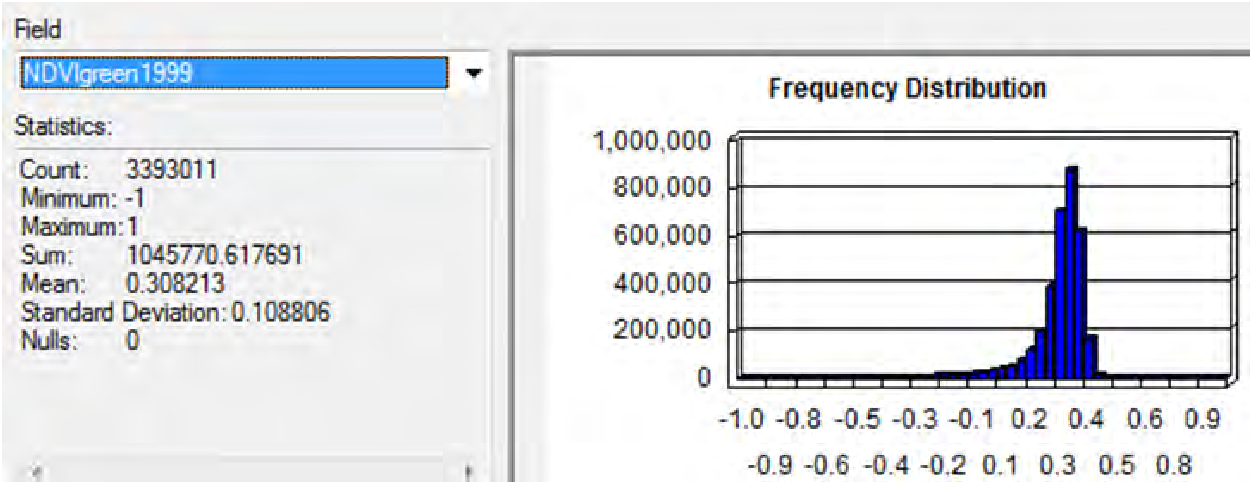



**Figure 54: Frequency Distribution of NDVI green based on mangroves on December 26, 1999**

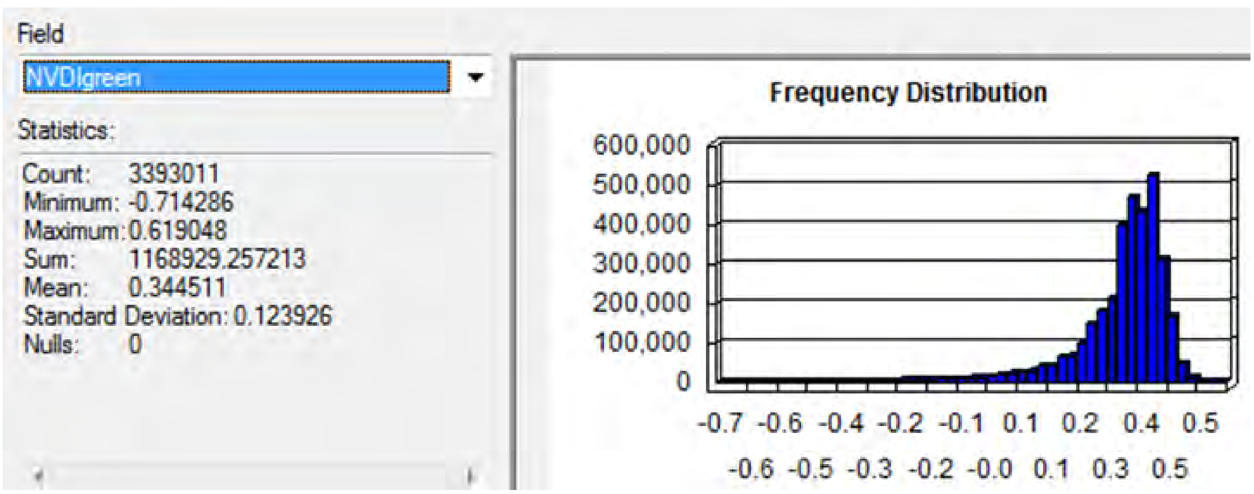



**Figure 55: Frequency Distribution of NDVI green based on mangroves on January 9, 1985**

NDVIgreen values were divided into 10 groups to compare 2015 and 1985. For example, values ranging from 0.906344 to 0.935519 were designated as Group 1 and values over 0.935519 and up to 0.942812 were designated as Group 2 for 1985 and so on.

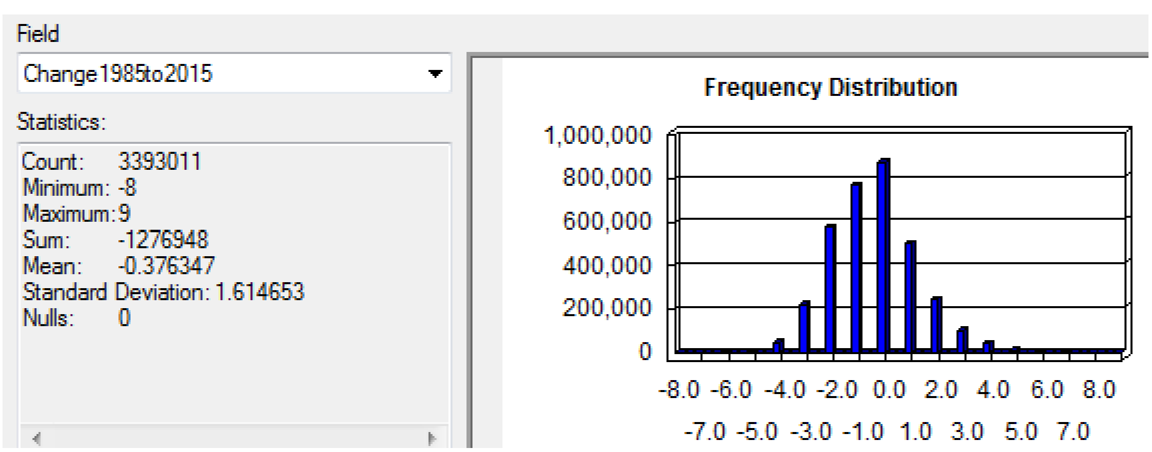
| | 2015 | 1985 | 2015 | 1985 |
|---|---|---|---|---|
| Group | Number | | Description | |
| | 0.906344 | -0.71429 | Min | |
| 1 | 0.935519 | -0.18489 | Mean-Min/2, to form tail | |
| 2 | 0.942812 | -0.05254 | Mean-Lower Tail/3 | |
| 3 | 0.950106 | 0.079812 | Mean-Lower Tail/3 | |
| 4 | 0.957399 | 0.212161 | Mean-Lower Tail/3 | |
| 5 | 0.964693 | 0.344511 | Mean | |
| 6 | 0.967004 | 0.383383 | Max-Mean/4 | Tail-Mean/3 |
| 7 | 0.969314 | 0.422256 | Max-Mean/4 | Tail-Mean/3 |
| 8 | 0.971625 | 0.461128 | Max-Mean/4 | Tail-Mean/3 |
| 9 | 0.973935 | 0.5 | Max-Mean/4 | Visual Tail |
| 10 | 0.976246 | 0.619048 | Max | Max |

**Table 60: 2015 and 1985 NDVIgreen groups**

Change between the two Landsat missions was determined by subtracting the 1985 group score from the 2015 group score. If a mangrove forest was in the best relative condition in 1985 it got a score of 10. If the same forest was in the worst relative condition, in 2015 it got a score of 1. Therefore the change score would be -9. If the mangrove system improved from worst in 1985 to best in 2015, it would receive a score of +9.

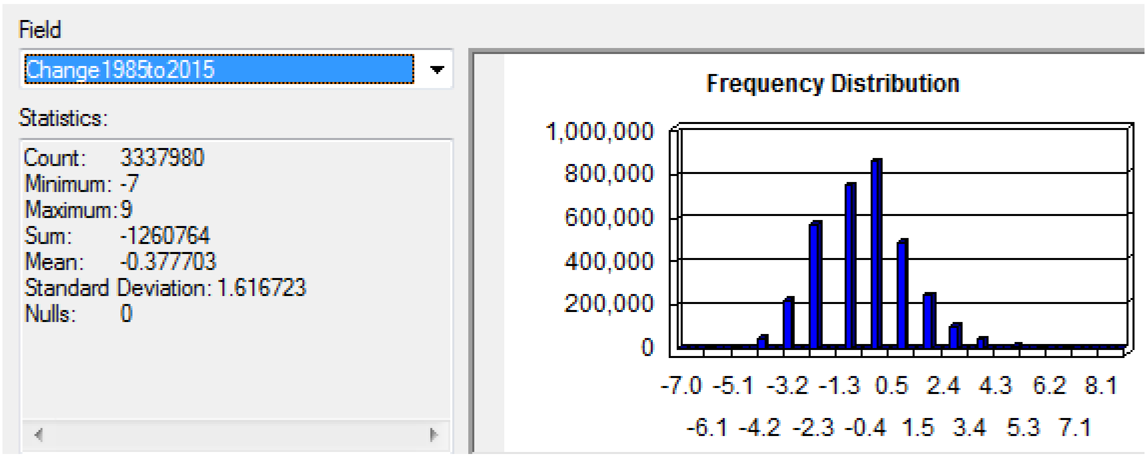
Because the groups were determined by generally fitting the bell curves of the data from the two missions, it would be unrealistic to state whether mangroves of the Charlotte Harbor region on average have improved or declined. However, areas of mangrove that had been in relatively good condition and are now in a relatively stressed condition can be identified.

Regardless of the method to determine mangrove extent using Landsat 8 (USGS or CHNEP version 1), distribution of mangrove condition change is comparable.



CHNEP, version 1 Mangrove Distribution

**Figure 56: Changes of Mangrove Condition between 1985 and 2015.**




USGS 2015 Mangrove Distribution

**Figure 57: Changes of Mangrove Condition between 1985 and 2015**

Year 2015 mangroves of a mildly stressed or worse condition (NDVIgreen<=0.91770) which had declined in the 30 year period (1985to2015Change < 0) were identified. Mangroves which met both conditions (stressed and in worse condition than in 1985) were only 3.66% of mangrove area.

## Mangrove Condition Trends

The previous section discussed how the NDVIg data were converted on a scale of 1 to 10 for both 2015 and 1985. The score for 1985 was subtracted from that of 2015. Therefore if the score of mangrove condition was relatively high in 1985 and relatively low in 2015, the final trends score would be negative. If mangrove condition was relatively high in 2015 compared to 1985, the final trends score would be positive. Because the Landsat missions provided different data and the distribution form one to another was matched, the final score would be close to zero, whether overall condition improved or declined. However, comparing different mangrove estuary segments, geomorphologies and species for relative differences yield patterns related to mangrove condition trends. The advantage of the process, is that any mapping error should return a change of zero if the area is stable. If mangrove shoreline grew between 1985 and 2015, those pixels should show increasing mangrove condition.

In all cases, the final scores were normalized by acreage. The final trend scores ranged from -9 to 9, or the theoretical range of the method. The following table illustrates the acreage within each mangrove estuary segment that attained each score between -9 and 9.

| Condition Trend Score | -9 | -8 | -7 | -6 | -5 | -4 | -3 | -2 | -1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tidal Peace River | | | 0 | 0 | 1 | 5 | 17 | 86 | 281 | 671 | 627 | 343 | 91 | 13 | 3 | 1 | 0 | 0 | |
| Dona and Roberts Bays | | | | 0 | 0 | 0 | 1 | 4 | 8 | 23 | 25 | 8 | 2 | 0 | 0 | | | | |
| Tidal Myakka River | | | 0 | 0 | 1 | 4 | 30 | 144 | 468 | 1,042 | 675 | 354 | 117 | 15 | 1 | 0 | 0 | | |
| East Wall | | 0 | 0 | 1 | 4 | 18 | 110 | 518 | 1,218 | 1,671 | 1,180 | 529 | 137 | 23 | 3 | 0 | 0 | 0 | |
| Tidal Caloosahatchee | | | 1 | 1 | 5 | 32 | 120 | 340 | 591 | 760 | 509 | 293 | 131 | 35 | 3 | 1 | 0 | 0 | 0 |
| Cape Haze | | 0 | 0 | 1 | 5 | 31 | 191 | 716 | 1,630 | 3,291 | 1,357 | 459 | 101 | 18 | 2 | 0 | 0 | | |
| West Wall | | | 0 | 0 | 2 | 19 | 95 | 298 | 574 | 814 | 518 | 173 | 30 | 5 | 0 | 0 | 0 | | |
| Lemon Bay | | | 0 | 0 | 1 | 12 | 47 | 131 | 204 | 282 | 136 | 49 | 12 | 2 | 1 | 0 | 0 | | |
| Lower Charlotte Harbor | | 0 | 0 | 1 | 3 | 14 | 62 | 157 | 281 | 375 | 161 | 48 | 16 | 4 | 1 | 0 | 0 | | |
| Matlacha Pass | | 0 | 0 | 3 | 15 | 181 | 914 | 2,466 | 3,011 | 3,226 | 1,342 | 435 | 141 | 28 | 4 | 1 | 0 | | |
| Estero Bay | 0 | 1 | 3 | 11 | 21 | 90 | 541 | 2,072 | 3,120 | 2,439 | 872 | 344 | 117 | 34 | 7 | 1 | 0 | | |
| San Carlos Bay | 0 | 0 | 5 | 7 | 18 | 130 | 735 | 1,752 | 1,669 | 1,173 | 312 | 104 | 41 | 12 | 3 | 0 | 0 | 0 | |
| Pine Island Sound | 0 | 3 | 13 | 27 | 70 | 320 | 1,241 | 2,345 | 2,275 | 1,560 | 456 | 160 | 61 | 28 | 11 | 4 | 0 | | |
| Total | 0 | 5 | 24 | 53 | 147 | 855 | 4,104 | 11,029 | 15,329 | 17,327 | 8,170 | 3,299 | 995 | 216 | 39 | 9 | 1 | 0 | 0 |

**Table 62: Condition Trend Acreage by Mangrove Estuary Segment**

| Name | Acres | Score |
|---|---|---|
| Tidal Peace River | 2,138 | 0.53 |
| Dona and Roberts Bays | 71 | 0.38 |
| Tidal Myakka River | 2,851 | 0.33 |
| East Wall | 5,413 | 0.01 |
| Tidal Caloosahatchee | 2,824 | -0.05 |
| Cape Haze | 7,801 | -0.15 |
| West Wall | 2,528 | -0.22 |
| Lemon Bay | 876 | -0.43 |
| Lower Charlotte Harbor | 1,121 | -0.47 |
| Matlacha Pass | 11,768 | -0.74 |
| Estero Bay | 9,673 | -0.76 |
| San Carlos Bay | 5,962 | -1.24 |
| Pine Island Sound | 8,574 | -1.33 |
| Total | 61,601 | -0.58 |

**Table 63: Condition Trend Scores by Mangrove Estuary Segment**

A total of 61,601 mangrove acres was identified based on FLUCCS level 5 mapping that occurred in northern portion of the CHNEP study area coupled with water management district and 2011 SWFRPC salt marsh maps.

Since the average score was -0.58, one might look at the condition of the segments below that average as those segments with decline.

The basins where mangroves appear to have improved between 1985 and 2015 are:

- Tidal Peace River
- Dona and Roberts Bays
- Tidal Myakka River and
- East Wall.

These basins are all characterized by tidal rivers and tidal creeks where sea-level rise can expand mangrove habitat. These segments are also in the northern portion of the study area where reduction of hard freezes over time can improve mangrove condition.

The basins where mangroves have declined include:

- Pine Island Sound
- San Carlos Bay
- Estero Bay and
- Matlacha Pass.

These basins all have black mangrove and mixed mangrove basins which have been drowned or are being drowned, probably due to sea-level rise. These are also areas which were not as susceptible to hard freezes in the 1980s.

Of the over 61,000 acres of mangroves in CHNEP study area, over 21,000 acres were mapped to FLUCCS Level 5, providing information on mangrove geomorphology and species. The mapping to level 5 included three of the four most improved segments, therefore the average score for this area is higher than for the entire CHNEP study area at 0.00.

| Name | Acres | Score |
|---|---|---|
| Riverine | 1,540 | 0.73 |
| Overwash Island | 68 | 0.13 |
| Fringe | 17,334 | -0.03 |
| Altered | 524 | -0.15 |
| Basin | 1,252 | -0.16 |
| Hammock | 43 | -0.36 |
| Scrub | 1,093 | -0.40 |
| Total | 21,853 | 0.00 |

**Table 64: Condition Trend Scores by Mangrove Geomorphology**

Riverine and Overwash mangroves appear to be the geomorphic type that has increased mangrove condition between 1985 and 2015. Hammocks and Scrubs have shown a decrease in NDVIg which we are using to measure mangrove condition. Between 1985 and 2015, investments have been made to remove exotic trees, including *Melaleuca quinquenervia*, from scrub and hammock areas. This may be the reason behind the changes detected through this tool. Otherwise basin mangrove forests and altered mangrove hedges have demonstrated the greatest reductions.

| Name | Acres | Score |
|---|---|---|
| Red Mangrove | 1,250 | 0.18 |
| Black Mangrove | 1,129 | 0.08 |
| RBW Mix | 18,189 | 0.01 |
| RW Mix | 5 | -0.25 |
| White Mangrove | 250 | -0.34 |
| BWT Mix | 1,019 | -0.41 |
| Buttonwood | 10 | -0.60 |
| Total | 21,852 | 0.00 |

**Table 65: Condition Trend Scores by Mangrove Geomorphology**

Red mangroves showed the greatest increase in measured condition. Sea-level rise and reduction of hard freezes both favor red mangrove habitat.

## Mangrove Condition Status and Trends Summary

Riverine Mangroves

We have found that riverine mangroves are in good condition and have increased chlorophyll since 1985. Through spectral analysis, mangroves within upper tidal creeks exhibit the same characteristics of mangroves within major riverine systems. Most such mangroves exhibited both excellent condition in 2015 and improved condition since 1985.

Climate change may promote improved condition in these mangroves through two mechanisms. The first is sea-level rise which may provide more habitat for mangroves as they extend up rivers and tidal creeks.

A second climate change mechanism is less frequent and less severe killing freezes in riverine areas which are most prone to freeze because of more inland locations compared to other mangrove geomorphic types. The January 9, 1985 dataset predates the hard freeze that occurred January 20-22, 1985. However the area was still was recovering from the effects of the 1981 and 1983 hard freezes. The latest hard freeze of note prior to the 2015 dataset was in 2010.

Mangroves within tidal creeks that exhibited poor condition in 2015 (whether significant changes occurred since 1985 or not) were affected by a road or berm crossing. We predicted and then confirmed that there were no culverts at several of these locations by visiting the sites.

Scrub Mangroves

“Those mangroves look pekid.” –Kim Dryden, USFWS, in reference to scrub mangroves.
“Those mangroves don’t want to be here but they have to be somewhere.” –Ariel Lugo, in reference to scrub mangroves.

Scrub mangroves naturally have low chlorophyll levels. The short stature of scrub mangroves is a result of the stressed conditions in which they grow. Moreover, scrub mangroves often exhibit a less dense canopy allowing marsh grasses and herbaceous succulents to contribute to the spectral signature. This is where a change analysis is useful. Rather than simply discounting poor mangrove condition as natural, reviewing changes over time can reveal additional stresses placed on scrub mangroves.

In general, we found most scrub mangroves to exhibit low but unchanged chlorophyll levels.

Basin Mangroves

Basin mangroves appear to be inundated over time. Tattar and Scott 2004 identified sea-level rise as the mechanism. Site investigation confirmed this. We found current pneumatophore heights submerged at normal high tides.

Karst collapse and peat losses can lead to a basin becoming deeper through time. Further, as mangroves die and root masses are lost, that volume loss can lead to substrate collapse, further deepening relative basin water levels.

The results of this prevent anything but red mangroves from colonizing the location. In these cases, spectral analysis indicates a change of geomorphology from basin to overwash island.

Overwash Islands

In reviewing historic and modern aerial photographs, various overwash Islands have increased or decreased in size, depending on sediment supply and oyster bar growth. Overwash islands appear to be the most ephemeral and variable of the mangrove forest geomorphic types. Overwash Islands tend to be relatively small and lose their identity as they connect and merge into fringe. Within Landsat imagery, they often include open water. Therefore, condition is difficult to ascertain using Landsat techniques.

Overwash islands will often serve as bird rookeries. For this reason, the project team needed to bypass overwash island sites and could not assess them.

Fringe Mangroves

Fringe mangroves have been impacted by berms and ditches and exhibit a range of condition. Hurricane impacts continue to be found within the path of Hurricane Charley. In addition to riverine mangroves, fringe mangroves have been the most impacted by urban development. Prior to the Henderson Act, developments were allowed to the mean high water. After 1984, all mangroves were considered jurisdictional and therefore fringe mangroves could enjoy this level of protection.

Spectral analysis indicates that fringe mangroves are more complex than previously considered. Tidal creeks and lesser hydrologic flows through the fringe result in a complex spectral signature in the fringe, including riverine signatures for upper tidal creeks.

The fringe mangroves are the first barriers to storms and other impacts. They provide a primary coastal defense infrastructure.

## Comparing Mangrove Condition to Site Investigation Findings

There was no statistically significant correlation between individual tree health at the sites and Landsat-based NDVIgreen values.

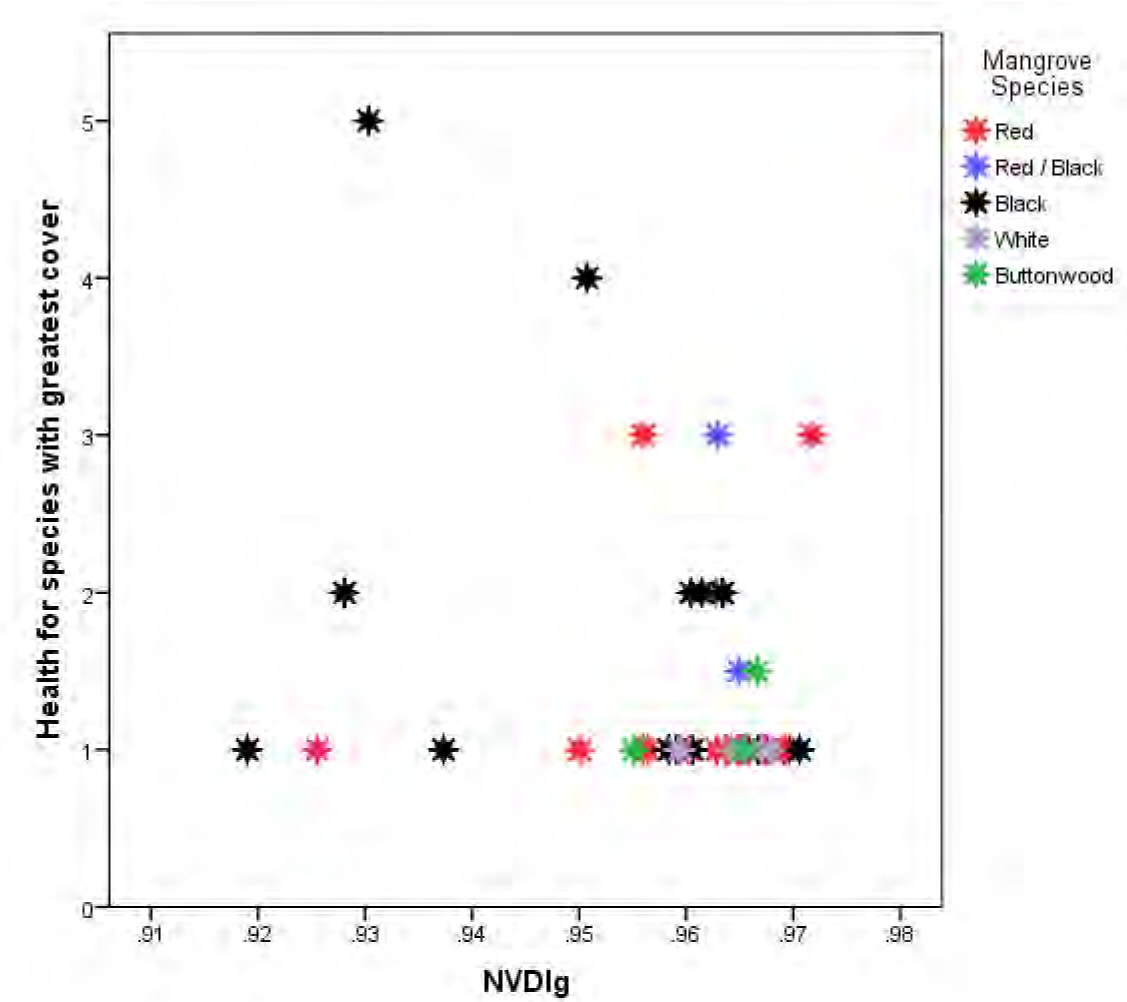



**Figure 58: Limited relationship between mangrove health at the site and Landsat NDVIg values**

One would expect an inverse relationship between mangrove tree health and NDVIgreen. The sites with good health in black mangroves and a low NDVIg value were basin black mangrove forest die-off sites. Although the forest structure was dominated by dead mangroves, the small young trees were documented as in good health for the site data. In addition, the two red mangrove forests with good health but low NDVIg values were overwash islands where part of the pixel picked up open water. Our sites were smaller than a pixel.

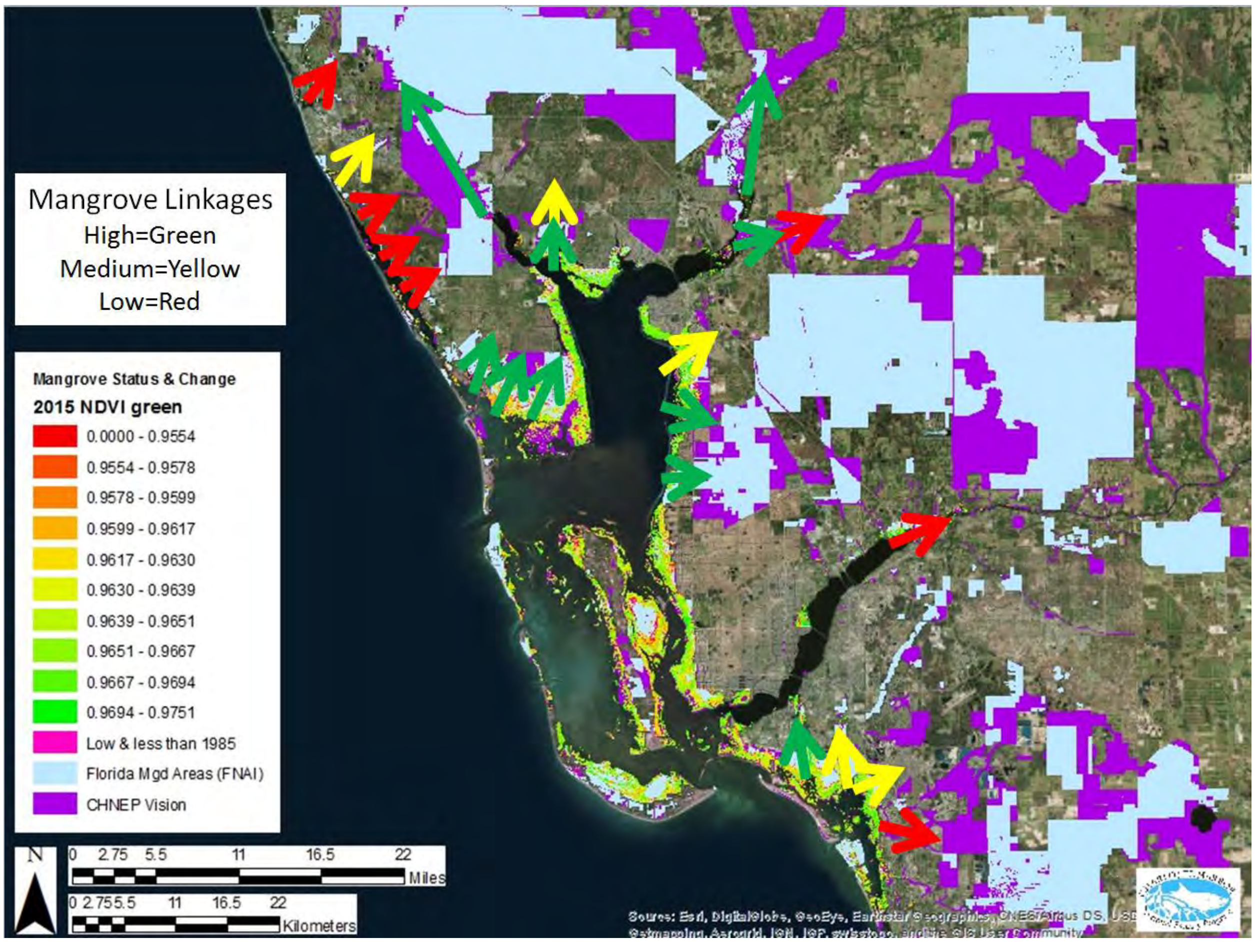
In reviewing mangrove forests with relatively low NDVIg values, problems with the forest were identified. This tool, coupled with the change assessment between 1985 and 2015, provided an excellent screening for mangrove restoration opportunities.

## Mangroves and Landscape Linkages

Habitat linkages between mangrove ecosystems and to adjacent native habitats are important for the continued health of mangrove forests systems.

Based on the above analysis of mangrove condition status and trends, mangrove geomorphology, species distribution and condition can change over time. Maintaining landscape linkages allow for forest movement through time in response to climate change and sea-level rise.

The following map combines mangrove condition, Florida managed areas (mapped by the Florida Natural Areas Inventory) and CHNEP's land acquisition and restoration vision map.




**Map 35: Mangrove and Landscape Linkages**

Linkages of high connectivity to public lands are shown in green and linkages with low connectivity are shown in red. All others are in yellow. The following table describes these linkages based on the county, location, level of connection, path of connection and potential extent. Some connections are good until a barrier is reached. Then mangrove migration is less likely.

| County | Location | Level of Connection | Path of Connection | Potential extent |
|---|---|---|---|---|
| Sarasota | Myakka River Riparian Corridor | High | North to Myakka River State park | High |
| Sarasota | Shakett Creek | Low | North along Riparian Corridor | Low, but assisted with Cow Pen Slough hydrologic Restoration. |
| Sarasota | Alligator Creek | Medium | North along Alligator Creek. | Over time, mangroves may reach Alligator Creek Conservation Area. |
| Sarasota | Forked Creek | Low | North along Forked Creek. | Low, but potential protection of Forked Creek Corridor. |
| Sarasota | Gottfried Creek | Low | North and East to Myakka River | Low, but potential protection of Gottfried Creek Corridor up-creek from Lemon Bay Park. |
| Sarasota | Ainger Creek | Low | North and East to Myakka River State Forest. | Low |
| Charlotte | Cape Haze State Preserve | High | North into Cape Haze, through several creeks including Coral, Catfish, Whidden. | High Initially. Can be expanded with acquisitions to remain High |
| Charlotte | Tippecanoe Bay | High | North into Charlotte Harbor Preserve State Park | High then Medium. Could be expanded north of SR 776 |
| Charlotte-DeSoto | Peace River | High | North up river and tributary creeks. | High. |
| Charlotte | Shell Creek | Low | East toward headwaters | High then Low when blocked by reservoir structure |
| Charlotte | Alligator Creek | Medium | Along Alligator Creek and under US41 to headwaters. | Much of the corridor is managed by the State and the County and then blocked with US 41.. |
| Charlotte | Charlotte Harbor State Buffer Preserve | High | East to extensive Public Lands include the Yucca Pens Unit and Cecil Webb Wildlife Management Areas, Babcock Ranch, and Fisheating Creek | High. Perhaps the best in the CHNEP and southwest Florida if roadway barriers can be addressed |
| Lee | Yucca Pen Creek | High | East to extensive Public Lands include the Yucca Pens Unit, Cecil Webb Wildlife Management Areas, Babcock Ranch, and Fisheating Creek | High. Perhaps the best in the CHNEP and southwest Florida if roadway barriers can be addressed |
| Lee | Caloosahatchee Creeks | Low | Up tidal creeks and the Caloosahatchee. | Low, with the exeption of Lee County 20/20 properties. |
| Lee | Cow Pen Slough/Deep Lagoon | High | Though Estero Bay Preserve State Park and into Cow Pen Slough and Deep Lagoon. | Much of the corridor is managed by the State and the County. |
| Lee | Hendry Creek | Medium | Though Estero Bay Preserve State Park. | Initially High but block by urban lands uses |
| Lee | Halfway Creek Flowway | Medium | East on State lands and then along Estero River and Halfway Creek Corridors, much of which is under conservation easement. | Initially High but narrow with several road barriers until connection to the Corkscrew Regional Ecosystem Watershed |
| Lee | Spring Creek Flowway | Low | East on State lands and then along Spring Creek corridor. | Initially High but narrow with several road barriers until connection to the Corkscrew Regional Ecosystem Watershed |

# Catalog of Mangrove Restoration Opportunities

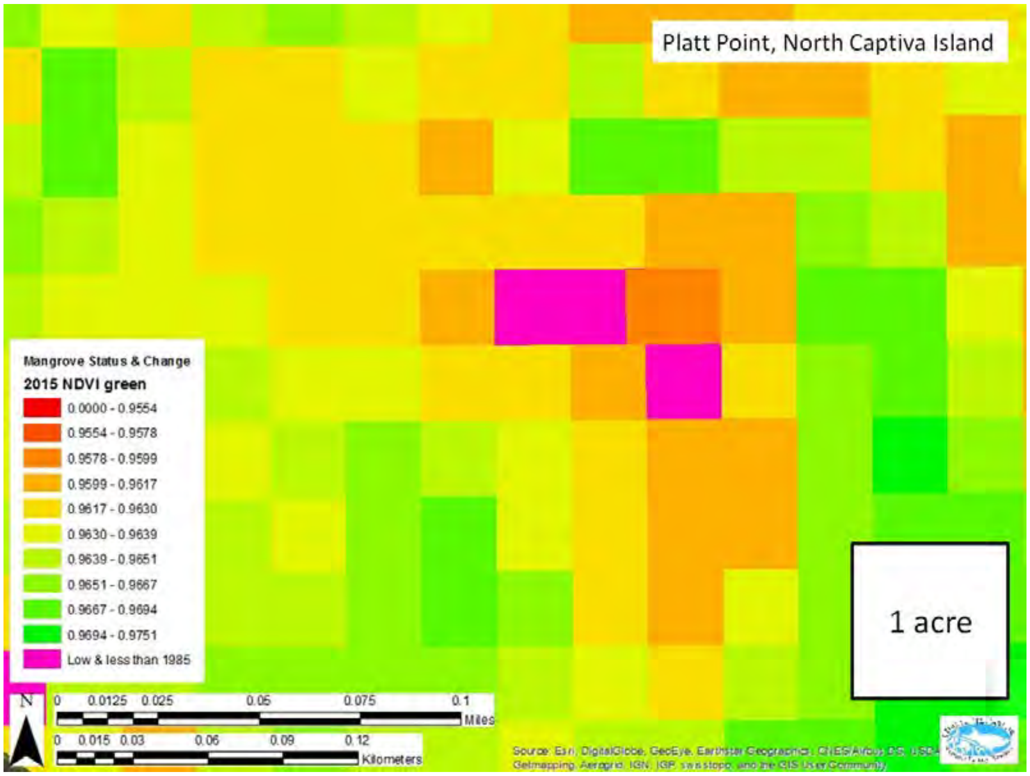
A catalog of mangrove restoration opportunities was developed. The project team assembled to identify restoration opportunities included four mangrove biologists and a regional planner, all with on-site experience in the Charlotte Harbor area. The project team reviewed maps of mangrove condition status and trends, determined the validity of the condition assessment and reviewed the landscape for potential causes of low or declining mangrove condition. In addition to mangrove condition maps, high-resolution aerial photography and 1950's era aerial photography were used. Restoration opportunities were identified without regard to financial or other constraints.

A total of 227 sites were identified based on poor or declining mangrove condition. Potential restoration projects were identified at 90 sites. Another 121 sites that exhibited poor condition were likely to have been from natural causes (or causes external to the study area). There were 13 sites that were caused by man-made actions or activity that had had no option for remedy. The final 3 sites had restoration projects that were funded and being implemented.

## Methods

The team used the Landsat NDVIGreen assessment to identify mangrove forests which were in poor and declining condition, many of which were at risk for future mangrove die-off. In particular, areas of low NDVI green which had declined since 1985 attracted our attention. We illustrated areas with poor condition with red and orange. Those with low and declined condition were illustrated with magenta. Though each Landat pixel is approximately one-quarter acre in size, the bright colors augmented our review of mangrove forests throughout the CHNEP study area.

The mangrove condition maps based on NDVIgreen became a tool to review large areas quickly. The team reviews the study area at roughly 5000 scale, where a single pixel is apparent. For example, Platt Point on North Captiva included areas of low 2015 NDVIgreen, some of which had declined since 1985. These pixels were apparent at 5000 scale. At 1000 scale within the high resolution aerial photography, the mangrove forest appeared in good condition. Upon further investigation at 500 scale, poor conditions became apparent. Bare branches became apparent in the portion of the forest NDVIg was low.





**Map 36: NDVIg indicated poor condition that could not be seen on the aerial**


**Map 37: NDVIg indicated poor condition that could be seen at 500 scale**

NDVIg was sensitive enough to identify mangrove trimming and dock construction that had occurred between 1985 and 2015.

Upon confirmation of poor mangrove condition, causes were suggested and restoration concepts were developed. Through the course of the review, four categories of potential responses were developed:

- Potential restoration project which could improve the condition of the mangrove forest,
- Natural causes or causes outside the study area which could not be addressed with a local restoration project,
- Local man-made cause for which there is no remedy, and
- A restoration project in progress (or has been funded) which may address the problem.

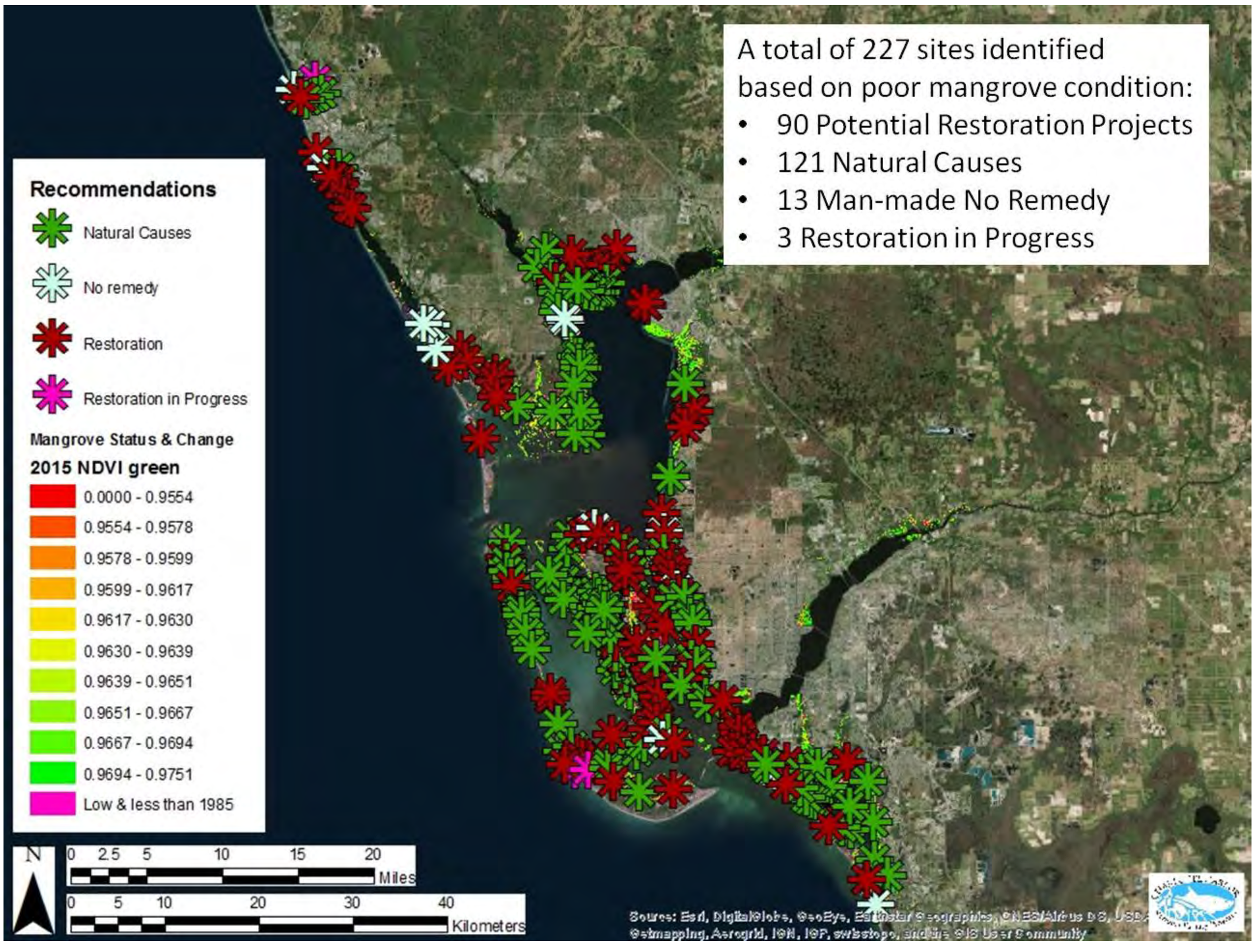
Restoration projects most often included culverts for roads or berms which restricted hydrology. Berm reductions and bridges were also suggested. Often, successful implementation would include ditch blocks. In addition, some but not all mosquito control ditches and spoil piles interrupted hydrologic flow and reduced mangrove condition.

Natural causes included salt marsh recovery, sea-level rise, overwash dynamics, tidal creek impairment, lightning strikes and storm damage from Hurricane Charley. Although CHNEP's most recent shoreline survey in 2013 indicated that mangroves had all but recovered from 2004 Hurricane Charley, use of NDVIgreen confirmed lingering condition issues after over a decade.

Sea level rise appears responsible for many sites of mangrove decline and loss, confirming Tattar and Scott (2004).

Some areas of poor mangrove condition were the result of man-made activity. However, no likely remedy was apparent. Within the CHNEP study area, several spreader waterways were constructed at mean high water, through the salt marsh or behind salt marshes, depending on the governing wetland regulations of the time. These waterways are currently used for recreational navigation but also disrupt hydrologic flow that healthy mangroves require.

At Clam Bayou in Sanibel and Shakett Creek in Venice, poor and declining mangrove condition was identified in specific areas. Restoration projects have been implemented or funded. Continued monitoring of these locations is recommended.




**Map 38: Distribution of Recommended Actions**

Finally, it is important to note that the NDVIg suggests good mangrove condition in some areas where restoration could have been recommended. For example, several areas with mosquito control ditches had good mangrove condition. In such cases, restoration was not suggested.

| Segment | Natural Causes | No remedy | Restoration | Restoration in Progress | Total |
|---|---|---|---|---|---|
| Cape Haze | 6 | | 6 | | 12 |
| Dona and Roberts Bays | 3 | 1 | 1 | 1 | 6 |
| East Wall | 1 | | 6 | | 7 |
| Estero Bay | 14 | 1 | 5 | | 20 |
| Lemon Bay | 1 | 4 | 8 | | 13 |
| Lower Charlotte Harbor | 1 | 1 | 1 | | 3 |
| Matlacha Pass | 13 | 2 | 23 | | 38 |
| Pine Island Sound | 53 | | 19 | 2 | 74 |
| San Carlos Bay | 6 | 2 | 13 | | 21 |
| Tidal Caloosahatchee | | | 1 | | 1 |
| Tidal Myakka River | 9 | | 4 | | 13 |
| Tidal Peace River | 5 | | 3 | | 8 |
| West Wall | 9 | 2 | | | 11 |
| Total | 121 | 13 | 90 | 3 | 227 |

**Table 66: Distribution of Restoration Opportunities by Mangrove Estuary Segment**

As described in the mangrove status and change section, the mangrove estuary segments where mangroves have declined the most include:

- Pine Island Sound
- San Carlos Bay
- Estero Bay and
- Matlacha Pass.

Two-thirds of recommended restoration projects have been recommended for these 4 segments, which contain 59% of CHNEP's mangrove forests.

The listing of restoration projects are distributed both by total mangrove acreage (Kendall's Tau b, .01 level) and by mangrove conditions trends score (Kendalls' Tau b, .05 level).

## Restoration Opportunities

Ninety restoration opportunities were identified. The following table includes a project name, basic description and the mangrove estuary segment the project is in. The table is sorted by segment so that potential projects can be identified more quickly. Locations of concern ascribed to natural causes, no remedy and restoration in progress are listed in the shape file entitled "Restoration Opportunities" and within a database and spreadsheet contained within the final deliverables.

| MHA Restoration Opportunities | | |
|---|---|---|
| **Name** | **Description** | **Segment** |
| Catfish Creek Mosquito Control Ditch restoration | Mosquito control ditches and spoil mounds segment the mangroves increase stress. Extensive mortality along the ditches. Ditches crossing the natural direction of flow cause greater stress than ditches in the direction of flow. | Cape Haze |
| East Catfish Creek Hydrologic Restoration | Culvert under CR 771 appears connected with borrow pit rather than creek. Reconfigure culvert to redirect flows to the creek. Reconfigure stormwater management at Coral Creek Airport to improve freshwater flows. | Cape Haze |
| Gasparilla Mosquito Control Ditches | Areas around tropical hardwood hammocks were ditched with spoil pile, so much no longer reads as mangrove. Some of the red mangrove ditches appear to have healthy mangrove. | Cape Haze |
| Placida Point | Significant mosquito control ditching and spoil mounds render the site unrecognizable as mangrove throughout. Basin black mangroves heavily impacted. Restoration of entire site recommended. | Cape Haze |
| Rotonda Wastewater Treatment update | Wastewater treatment plant needs to be updated to Advanced Wastewater Treatment with deep well injection and reuse to improved estuarine water quality. | Cape Haze |
| West Coral Creek dam | After update of wastewater treatment plant, excavate sediment and open dam. | Cape Haze |
| Dona Pass Island | Boat wake. Construct shoreline stabilization, batter boards. | Dona and Roberts Bays |
| John Quiet Berm Hydrologic Restoration | Create connection between old tidal creek north of the berm and black basin mangrove forest south of the berm | East Wall |
| Pirate Harbor Berm Hydrologic Restoration | Create connection between declining mangroves to the north and north Pirate Harbor canal. This berm ad John Quiet berm are bracketing the mangroves in this section, causing decline of mangroves facing the saltern and the basin black mangrove forests. | East Wall |
| Ponce De Leon Park Culverts | Culvert road that crosses old tidal creek. Add additional culverts along road to facilitate tidal exchange in the fringe. | East Wall |
| Ponce DeLeon Northwest Corner Hydrologic Restoration | Improve water flows into the northwest corner. Possibly tap into canal water to reestablish tidal connection. There are two different possibilities. To the east or to the north. | East Wall |
| San Edmondo Road | Break through the berm between mangroves and canal. | East Wall |
| Tern Bay | Evaluate stormwater outfalls of Tern Bay so that freshwater | East Wall |

| MHA Restoration Opportunities | | |
|---|---|---|
| **Name** | **Description** | **Segment** |
| Stormwater Management System | distribution into the mangrove fringe is more natural. | |
| Bayside Estates Canal Mangroves | Break the berm along the canal to allow flow. | Estero Bay |
| Big Hickory Island Mangrove Heart Attack | Culvert or bridge CR 865. Create tidal channel using 1950s aerials for guidance. | Estero Bay |
| Island Park Mitigation Mangrove South | Investigate for herbicide application overwash from Melaleuca treatment. | Estero Bay |
| Ostego Bay Preserve | Culvert canal berm to restore hydrologic flows. | Estero Bay |
| Port Carlos Cove | Channel to the East is restricted and could be reopened. | Estero Bay |
| Alamander Street Mangroves | Remove spoil berms and retain tidal connection. Appears to have been historically a low marsh. | Lemon Bay |
| Compartmented Mangroves | Mosquito control ditches and berms compartmentalized mangroves. Remove mounds. May be suitable place for hydroblasting. Leave chelles for flow, using 1948 aerials for guidance. | Lemon Bay |
| Manasota Bridge Mangroves | Remove spoil berms and retain tidal connection. Appears to have been historically a low marsh. | Lemon Bay |
| Manasota Bridge Residence mangrove trimming | Mangrove trimming. Leave the mangroves alone in the future. | Lemon Bay |
| Red Lake Island | Increase span of bridge, perhaps with large box culverts. Increase connection to Intracoastal waterway. | Lemon Bay |
| South Venice Lemon Bay Preserve | Evaluate road crossing for additional culvert openings. | Lemon Bay |
| Spyglass point | Remove or culvert berms that are segmenting the mangrove fringe. | Lemon Bay |
| Venice Intracoastal Mangroves | Shoal mangroves are subjected to boat wake. Shoreline stabilization to protect mangrove against boat wake. | Lemon Bay |
| North Spreader Cutoff | Remove spoil berm associated with the dredging of the north spreader cutoff. | Lower Charlotte Harbor |
| Barrabes Ave Mangroves | Area boxed in with mosquito ditches. Remove spoil. | Matlacha Pass |
| Canal off of Gator Slough | Fill canal off of the Spreader. Reduce extreme flows from Gator Slough Canal System. Charlotte Harbor Fatwoods Initiative could help. | Matlacha Pass |
| Embers Parkway mangroves | Remove spoil berm associated with the dredging of the north spreader cutoff. | Matlacha Pass |
| Gamebird Lane Mangroves | Source reduction on agricultural field runoff | Matlacha Pass |
| Little Pine Island North of Road | There are issues with fill throughout the island, resulting in stressed and degrading mangrove in a band around the island. Remove berm fill at canal. | Matlacha Pass |
| Little Pine Island South of Road | There are issues with fill throughout the island, resulting in stressed and degrading mangrove in a band around the island. Remove berm fill at canal. | Matlacha Pass |

| MHA Restoration Opportunities | | |
|---|---|---|
| **Name** | **Description** | **Segment** |
| Little Pine Island Tidal Creek | Tidal creek has closed in, resulting in stressed mangroves. | Matlacha Pass |
| Manatee Drive Mangroves | Break through berm on north side of canal. | Matlacha Pass |
| Masters Landing | Improving connection of mosquito control ditch to Matlacha Pass would improve mangrove health on the property. | Matlacha Pass |
| Matlacha Powerline mangroves | Remove spoil piles and improve tidal flows in mangroves. Culvert powerline road. | Matlacha Pass |
| Matlacha Powerline mangroves South | Source Reduction in Agricultural runoff. | Matlacha Pass |
| North east of Thirsting Lake and east of Cypress Lake | Mangroves have been boxed in. Remove Spoil creating the box. | Matlacha Pass |
| North of Smokehouse Bay | Area boxed in with mosquito ditches. Remove spoil. | Matlacha Pass |
| Pine Island Central East Die-off | Large mangrove die-off probably resulting from barrow pits, roads and sea level rise. Could come in from waterward side and construct hydrologic connection. | Matlacha Pass |
| Pinetree Drive Mangroves | Break through berm on southern side of canal. | Matlacha Pass |
| Powerline Mangrove Heart Attack North | Culverting the fill path underlying powerline and remove extra fill. | Matlacha Pass |
| Powerline Mangrove Heart Attack South | Culverting the fill path underlying powerline and remove extra fill. | Matlacha Pass |
| Sandal Lane Mosquito Control Ditch | Backfill mosquito control ditches with spoil berm material. | Matlacha Pass |
| Smokehouse Fringe | Could connect stress area to ditches to improve hydrology. Low priority. | Matlacha Pass |
| South of Pine Island Road | Add culverts of Pine Island Road at this location. | Matlacha Pass |
| Southern Spreader Waterway north | Remove Spreader Waterway Berm. Had been saltern and low marsh. | Matlacha Pass |
| Thirsting Lake | System may be going anoxic. If so, improve circulation through tidal creek leading to lake. Spreader diverted water from lake system. | Matlacha Pass |
| Tropical Point | Mangroves have been boxed in by mosquito control ditches and roads. Restore hydrologic connections. | Matlacha Pass |
| Cayo Costa Back Bay | Tidal creek channel has silted in. Removing silt will assist in improving flows. Resident reports area is becoming increasingly stagnant. Spoil on north end of canal to the south may have contributed. Evaluate the spoil for removal. | Pine Island Sound |
| Chino Island Hydrologic Restoration | Tidal channel cut off by berm construction related to canal. | Pine Island Sound |
| Clam Bayou Connection | Consider opening inlet. | Pine Island Sound |

| MHA Restoration Opportunities | | |
|---|---|---|
| **Name** | **Description** | **Segment** |
| Demere Key Fringe Donut North | Demere Key Road culverts added | Pine Island Sound |
| Demere Key Fringe Donut South | Demere Key Road culverts added | Pine Island Sound |
| East Impoundment mangrove stress | Additional culverts needed on Wildlife Drive. Consider several small ones. | Pine Island Sound |
| Estuary Court Mangroves | Boxed in mangrove. Reopen small tidal creek. Consider culverts and stormwater retention in adjacent subdivision. | Pine Island Sound |
| Fish Camp Berm | Break berm to allow hydrologic connection | Pine Island Sound |
| Fish Camp Berm North | Break berm to allow hydrologic connection | Pine Island Sound |
| Galt Fringe | Develop a hydrologic connection to open water that had been cut off by old air field and berm. | Pine Island Sound |
| Halloway Bayou basin stress | | Pine Island Sound |
| Jug Creek Mangroves | Breach the berm at the north of the marina | Pine Island Sound |
| LCEC Road off of Wildlife Drive | Evaluate Road for culverts to improve flow. | Pine Island Sound |
| Mason Island Fringe | The canal looks like its blocking the connection to the south with a berm. Create hydrologic connection through the berm. | Pine Island Sound |
| Pine Island West Central Fringe Restoration | Runoff prevention and source reduction of herbicides, fungicides. | Pine Island Sound |
| Platt Point, Murdock Bayou Mangroves | Area appears under stress. Evaluate tidal creek flows related to these stressed mangroves. | Pine Island Sound |
| South Seas Utility Island | Roads and trails blocking flow. Evaluate for additional culverts. | Pine Island Sound |
| South Seas Utility Island | Roads and trails blocking flow. Evaluate for additional culverts. | Pine Island Sound |
| Wulfert Point basin stress | Residential development has interrupted flow. Potential addition of herbicides related to lawn care. Mangroves very susceptible to herbicides. Check with city to ensure that they are following new golf course management standards. | Pine Island Sound |
| Bunche Beach East | Culvert John Morris Road, connecting tidal creek to Bunche Beach South. | San Carlos Bay |
| Bunche Beach North | Boxed in mangrove. John Morris Road with its canal short circuited hydrologic flows. Culverts may not be enough. Review overland flows. | San Carlos Bay |
| Bunche Beach South | Culvert John Morris Road, connecting tidal creek to Bunche Beach East. | San Carlos Bay |
| Bunche Beach West | Bridge Summerlin Road at creek west of Connie Mack Island | San Carlos Bay |
| Buttonwood Key | Culverts on causeway. | San Carlos Bay |
| Jewfish Creek | Excessive S-79 Discharges may have physical and turbidity damage to tidal creek. Flow control issue | San Carlos Bay |
| Pine Island Eagle | Restore mosquito control ditches and spoil to allow overland flow | San Carlos Bay |

| MHA Restoration Opportunities | | |
|---|---|---|
| **Name** | **Description** | **Segment** |
| Preserve | into mangroves. This is an opportunity to establish a reference site for mangrove health on Pine Island. | |
| Punta Rassa Creek | Bridge Summerlin over tidal creek | San Carlos Bay |
| Punta Rassa Mangrove Heart Attack | Culvert Summerlin to improve flows. | San Carlos Bay |
| Shell Point Southwest | Use Mosquito ditches to increase flow. | San Carlos Bay |
| Shell Point West | Culvert Shell Point Road. | San Carlos Bay |
| St. Jude Trail | Culvert underneath trail. Restore mosquito control ditches so that the mangroves are no longer boxed in. | San Carlos Bay |
| Tarpon Bay West, North of Gumbo Limbo | Evaluate mosquito ditches, subdivision and road for better connections to Tarpon Bay. | San Carlos Bay |
| Shell Point East | Culvert Shell Point Road. | Tidal Caloosahatchee |
| Cattle Dock Point Road | Remove old road to the point that has been disconnected by the canal. Road berm is reducing hydrologic connection resulting in recent stressed mangroves. | Tidal Myakka River |
| Manchester Canal T-Feature | Relic canal termini. Evaluate if there is a berm and remove. Remove barriers to flows to mangroves. | Tidal Myakka River |
| Manchester Lake Berm Removal | Remove berm on waterward side of channel to improve flows to stressed mangroves. | Tidal Myakka River |
| Manchester Lake Mosquito Control Ditch. | Area south of mosquito control ditch has area of significant but not recent mangrove decline. Remove spoil and fill ditches. | Tidal Myakka River |
| Manchester Canal T-Feature | Relic canal termini. Evaluate if there is a berm and remove. Remove barriers to flows to mangroves. | Tidal Peace River |
| Manchester Canal T-Feature | Relic canal termini. Evaluate if there is a berm and remove. Remove barriers to flows to mangroves. | Tidal Peace River |
| South of West Spring Lake Berm Hydrologic Restoration | Improve circulation to area by adding breaks to the berms to the south and modifying the mosquito control ditches and spoil to the north. | Tidal Peace River |

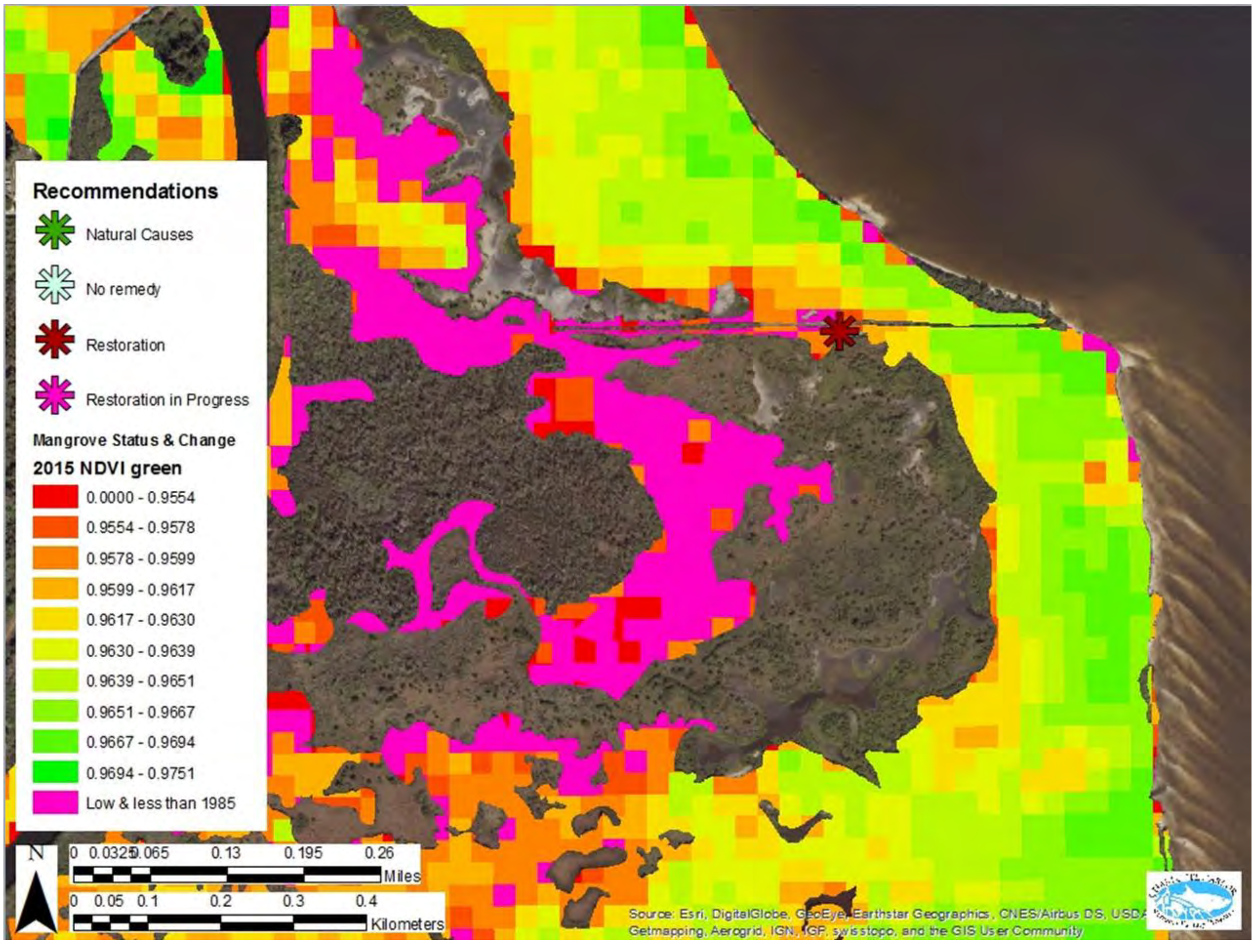
**Table 67: Mangrove Restoration Opportunities**

## Response Examples

Four examples were prepared to illustrate the each of the four restoration categories (restoration, natural causes, no remedy and restoration in progress.

<u>Restoration</u>

Ninety restoration concepts were identified. Each requires additional site investigation to refine designs and engineering.




**Map 39: Restoration Opportunity at Cattle Dock Point Road**

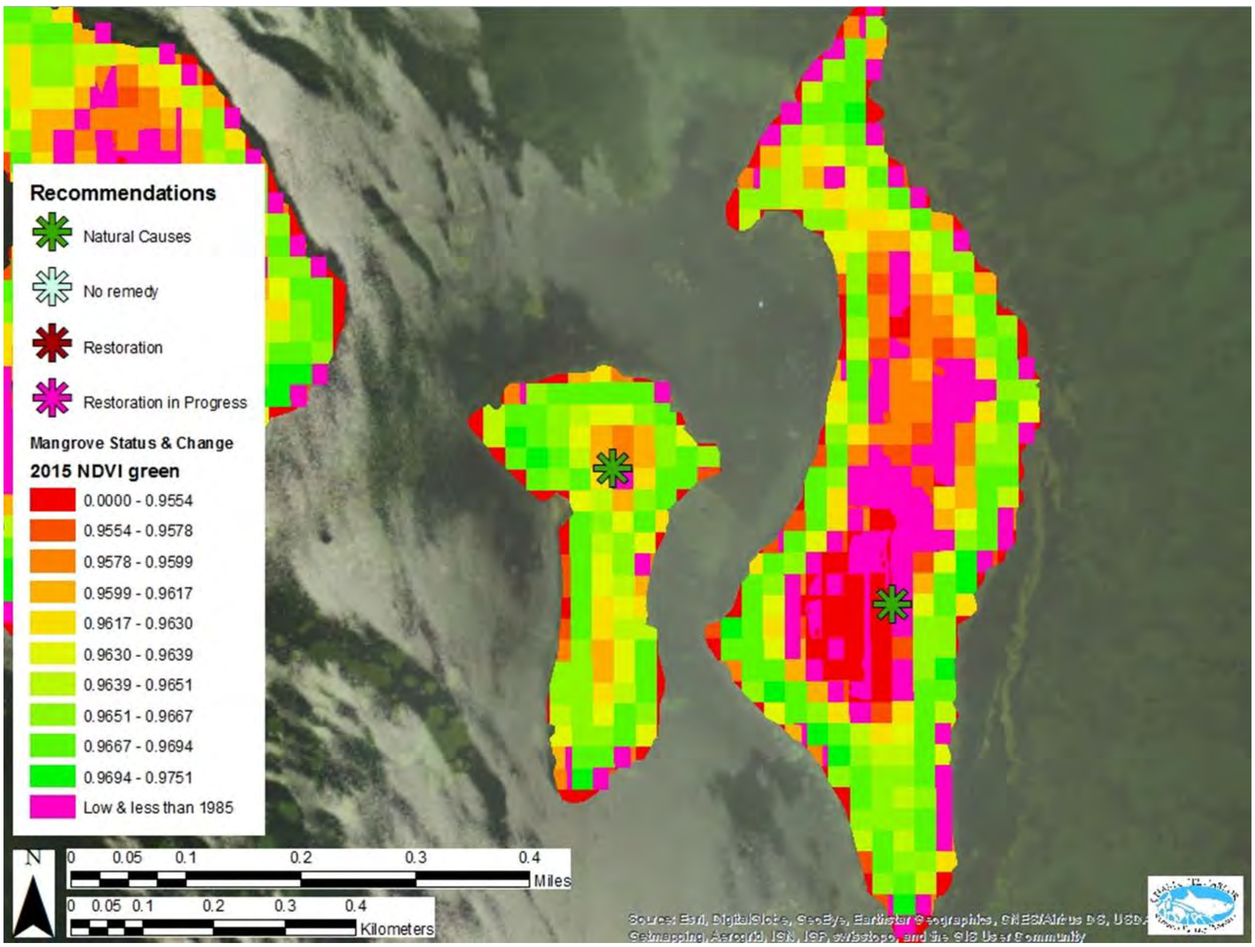
The restoration concept is to remove the old road to the point that has been disconnected by the canal. Road berm is reducing hydrologic connection resulting in recent stressed mangroves. In addition the road is affecting salt marshes. Underlying ownership is the State of Florida, Trustees of the Internal Improvement Trust Fund. The Park Service manages the Charlotte Harbor Preserve State Park. The Southwest Florida Water Management District has cooperatively funded hydrologic restoration projects in this area, with the help of Charlotte County and the Florida Fish and Wildlife Conservation Commission. Expertise within all this agencies would be valuable for restoration design development.


**Figure 59: Photograph of Cattle Dock Point Road**

Natural Causes

Basin forests, often characterized with sylvan expanses of black mangroves, are vulnerable to sea level rise. Many of the mangrove islands within Pine Island Sound include basin mangrove forests which are declining. This phenomenon, along with basin degradation behind the mangrove fringe on Pine Island itself, is a reason the mangrove condition trend score is the lowest for Pine Island Sound.

In the following photograph, the internal basins are magenta, indicating a decline of condition between 1985 and 2015. The shoreline edges which are red or orange may be an artifact of the Landsat pixel including open water. However, the magenta shore indicates a change since 1985, probably a shoreline retreat.




**Map 40: Black Key Basin (island on the right)**

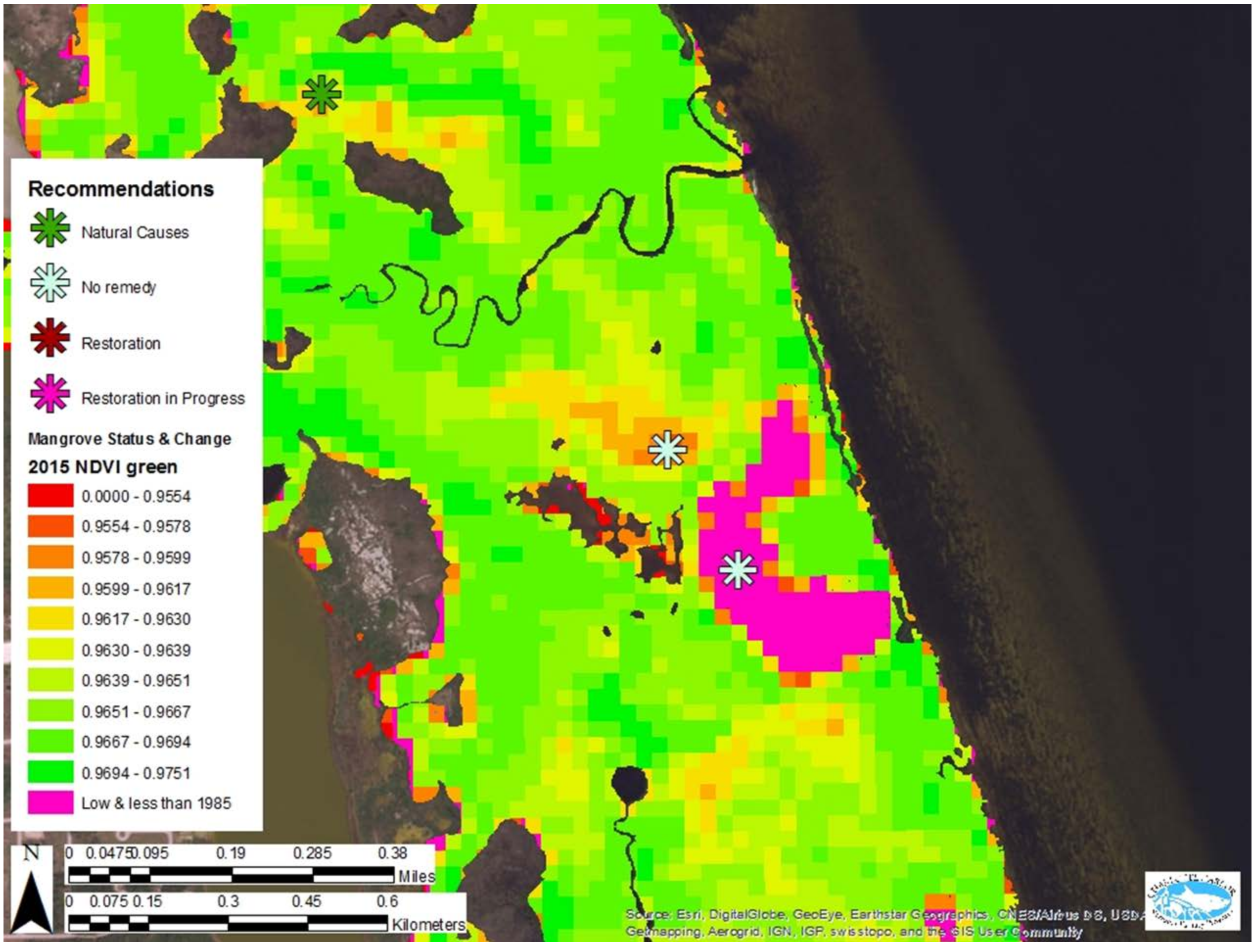
**Figure 60: Black Key Basin Mangrove Die-off and Recovery**

During our site investigation on Black Key, we found healthy black mangrove trees beneath the dead mature black mangrove trees. We believe the saltwort cover protected the peat layer which allows mangrove seedlings to survive.

Black Key is part of the Pine Island National Wildlife Refuge, under management by the US Department of Interior, Fish and Wildlife Service.

No Remedy

Thirteen sites were identified where man-made works severely change hydrology. Repairing the cause would be costly and potentially illegal based on Florida's property laws. Therefore, no remedy is recommended. One such site we named the Great West Wall Die-off.




**Map 41: The Great West Wall Die-off**

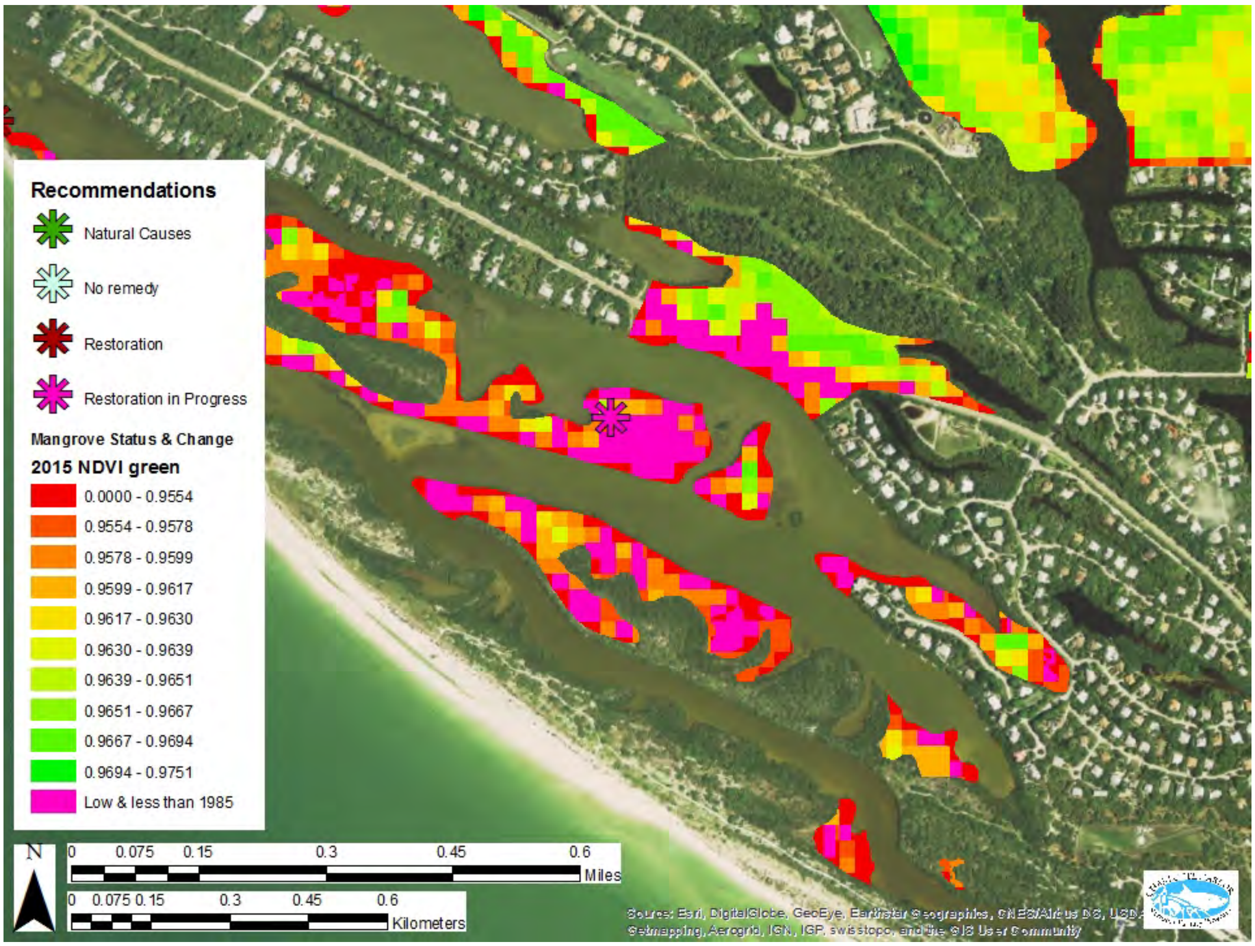
The large area shown in magenta is the location of the Great West Wall Die-off. The area was a salt marsh in the 1950s, with hydrologic connection to the west. A spreader canal was constructed in 1970s, diverting the overland water away from the marsh and Charlotte Harbor. Mangroves colonized the location in 1980s and 1990s. However, these areas were marginal for mangroves. The marginal condition and relatively low elevation allowed sea level rise to drown the mangrove forest. Accumulated mangrove peat was lost through oxidation resulting in open water. Landsat interpretation suggests that the remaining mangroves are functioning as overwash islands as its geomorphic type. This is a story of not only habitat change but fundamental geomorphic changes from off-site impacts.

**Figure 61: Peat Oxidation and Recolonization of Red Mangrove at Die-off Site**

<u>Restoration in Progress</u>

Three sites were identified where restoration was in progress. In these cases, mangroves may not have had a chance to be revived to their 1985 condition.

The City of Sanibel and the Sanibel-Captiva Conservation Foundation (SCCF) partnered on the restoration project. The City of Sanibel added a culvert to assist with flows under Sanibel-Captiva Road (separating declining mangroves from relatively healthy ones.)  SCCF organized mangrove propagule planting.




**Map 42: Clam Bayou Restoration in Progress**

The NDVIg tool which was used to identify declining trends at this location can also be used to track the progress of the restoration. By using a base year after February 2013, Landsat 8 data can be used for a direct pre- and post-restoration condition comparison. Within this work additional steps were needed to compare Landsat 5 data to Landsat 8 data.  A quick review of USGS Earth Explorer suggests that February 10, 2014 provides good early imagery for the CHNEP Study area.

## Implementation

The project team expects that mangrove restoration projects will be implemented through a combination of methods.

Normal capital improvements such as park improvements and road widening can incorporate culverts and ditch blocks to improve mangrove condition. On example is to move a culvert on CR 771 from drainage to a barrow pit to the west branch of Catfish Creek. This can be accomplished with CR771 south of Rotonda Boulevard is widened. The widening of CR 771 north of Rotonda is under construction. Another example is the update of Ponce Park is currently under design. An opportunity exists to add a culvert to restore a tidal creek which was severed before 1950.

Hydrologic restorations are funded through cooperative agreements with the water management districts. The catalog of restoration opportunities will assist the districts and their cooperators select hydrologic restoration projects which will benefit mangroves and, in some cases, salt marshes.

The catalog of restoration opportunities can be used as a bundle to submit for Gulf-wide restore funding. The science behind this work is cutting-edge.

# Project Accomplishments and Uses

The primary accomplishments of the project included:

- A scheme to represent mangrove forest geomorphology using FLUCCS level 4 and mangrove forest species using FLUCCS level 5. The scheme included dead mangroves (635) in addition to live mangrove forests (612). The scheme acknowledged “Altered Mangrove Hedge” as a separate geomorphic type with different forest structure than found in natural forests.
- Refined conceptual models of mangrove forest geomorphology based on site investigations. We found forests of mixed species to be more abundant within each geomorphic type than previously acknowledged. We also used mangrove tree height and cover by species to drive our refined conceptual model for Charlotte Harbor.
- Representation of FLUCCS level 4 and 5 using Landsat 8 spectral analysis. The evaluation consisted of both hand mapping methods and site investigation to establish samples for the band ranges. Bands 4 (red), 5 (near infrared), 6 (shortwave infrared 1) and 7 (shortwave infrared 2) were used to define both geomorphic type and species.
- The use of NDVIgreen to evaluate current mangrove condition and multi-decaldal changes in mangrove condition to assist in restoration planning. We used poor mangrove condition and modeled decline in mangrove condition since 1985 to flag areas to recommend restoration project.
- The identification of NDVIgreen as a way to measure habitat quality for environmental indicators and targets. In 2002, CHNEP developed it environmental indicators and targets based on the Comprehensive Conservation and Management Plan (CCMP). The program had difficulty establishing indictors and targets of mangrove and salt marsh quality. Finally percent exotic invasion was selected. These habitat tend not to have much exotic invasion and a superior indicator is needed. NDVIgreen could be that indicator.
- The identification of NDVIgreen as a way to monitor a functional component of mangrove and salt marsh restoration. Currently, downstream fish community structure is the only functional restoration monitoring component available to CHNEP. The addition of NDVIgreen to evaluation changes in saltwater wetlands pre and post restoration. The free availability of data multiples times per year, every year since the 1980s allows will allow for the evaluation of restoration results, even for projects that have been completed long ago.
- Use the catalog of restoration opportunities and mangrove linkages information to help direct land acquisition priorities for movement corridors, highlighting the importance of river and tidal creek channels with mangroves.
- Use the catalog of restoration opportunities to direct hydrologic restoration. By bundling appropriate restoration opportunities, a substantial and relevant Gulf-wide RESTORE project can the submitted through the state. The science in which it is based is an important criterion for funding. Another opportunity could be financing through blue carbon credits.

Future uses could include:

- Apply NDVIgreen statewide to evaluate mangrove condition and changes of condition.
- Use NDVIgreen to evaluate mangrove restoration projects.
- Use NDVIgreen to help identify RESTORE priorities gulf-wide.
- Use NDVIgreen to evaluate restoration performance, including Everglades Restoration and RESTORE projects.
- Evaluate past restoration projects from 1972 through to present using the process identified in the project to compare past missions to Landsat 8. Evaluate restoration projects directly from 2013 on.
- Calibrate NDVIgreen results for use in ecosystem services evaluation.
- Evaluate latitudinal variation in NDVIgreen.

# Summary

Perception and expectations provide a certain view of the mangroves of Charlotte Harbor held by the public and professionals that reality does not confirm. Classic mangrove is more of a concept than a field condition. Mangrove monocultures are relatively rare and mangrove species mixes are relatively common. Riverine mangrove forests are taller that fringe mangrove forests only at the shoreline. Otherwise both forests possess trees of the same tallest heights. The richness and diversity of Charlotte Harbor's mangrove forests provides for an astonishing view of the realities of mangrove structure, functions, and microhabitats.

Mangrove forest die-off includes a range from natural events including tropical storm wind-throw, lightning strikes, wave erosion, freezing, root predation, defoliation by arthropods, guano burial, and the Quaternary Period cycle of pluvials between ice ages that constitutes natural sea level rise.

Mangrove heart attacks are precipitated by human action or negligence, mediated by impoundment, elimination of tidal creek circulation, coastal hardening, road construction, insufficient culverting, direct fill, channelization with associated spoil ranging from mosquito control ditches to major navigation and drainage channels, chemical spills, herbicide applications, excessive trimming for view and other "aesthetic" purposes, borrow pit construction and fish farms.

Landsat 8 bands 4 (red) through 7 (shortwave infrared 2) can be used to interpret both geomorphology and mangrove species and species mixes. The results offer a sensitive and detailed interpretation which suggests underlying hydrology. This underlying hydrology is difficult to ascertain by aerial photography and Lidar digital elevation models alone. We mapped mangrove geomorphology and species around Charlotte Harbor proper to assist with Landsat interpretation. If a mangrove geomomorphic and species map were to be completed for the entire CHNEP area, the astonishingly reasonable and detailed Landsat results should be used to refine the completed mapping and guide the remaining mapping.

Landsat green and near-infrared bands can be used to identify mangroves of varying conditions. Landsat imagery of two different periods can be used to measure mangrove forest improvement or decline. This use also provides a sensitive expression of mangrove health in areas that are difficult to access on site and which are only revealed via aerial photography at very large scale (for example under 1000 scale). A map of mangrove status and change was used to provide a detailed review the study area and identify 90 restoration opportunities, 121 sites of natural decline, 13 sites where there is no remedy for the decline and 3 sites where restoration is in progress but the mangroves have to yet rebounded to their earlier vigor.

The ability to measure mangrove condition change is a particularly valuable addition to functional restoration monitoring, which until now, has been limited to evaluating fish community structure. Now, the functional effects of hydrologic restoration within mangrove forests can be directly measured to augment structural restoration monitoring techniques.

# Annotated Bibliography

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| Adam | 1990 | Adam, P. 1990. *Saltmarsh ecology*. Cambridge University Press. Cambridge, UK. 461 pp. | A comprehensive review of salt marshes worldwide. Cited in background. |
| Alongi | 2009 | Alongi, DM. 2009. Paradigm shifts in mangrove biology. Chapter 22, pages 615-640 in GME Perillo, E Wolanski, DR Cahoon, and MM Brinson (eds.) Coastal Wetlands: An Integrated Ecosystem Approach. Elsevier Press. | 1. Rates of mangrove net primary productivity rival those of other tropical forests. 2. Mangrove forests appear to be architecturally simple, but factors regulating succession and zonation are complex. 3. Mangrove tree growth is not constant but related to climate patterns. 4. Tree diversity is low, but faunal and microbial diversity can be high. 5. Arboreal communities are important in food webs, exhibiting predatory, symbiotic, and mutualistic relations. 6. Plant–Microbe–Soil Relations are tightly linked and help conserve scarce nutrients. 7. Crabs are keystone species influencing function and structure in many, but not all, mangrove forests. 8. Algae, not just detritus, are a significant food resource. 9. Mangroves are an important link to fisheries.10. Mangroves are chemically diverse and a good source of natural products. |
| Ballou | 1989 | Ballou, TG, and RR Lewis III. 1989. Environmental assessment and restoration recommendations for a mangrove forest affected by jet fuel. Pages 407- 412 in the Proceedings of the 1989 Oil Spill Conference, San Antonio, Texas. API, USEPA and USCG. | Document reviewed a jet fuel spill impacts and cleanup in Ensenada Honda, Naval Station Roosevelt Roads, Puerto Rico. The recommendation placed primary emphasis on natural recovery, with additional actions to increase colonization and/or survival of propagules as needed. |
| Baker | 1971 | Baker, JM. 1971. The effects of oil on plant physiology. Pages 88-98 in E.B. Cowell (ed.), Ecological effects of oil pollution. Applied Science Publishers, London. | Crude oil kills mangroves by coating and clogging pneumatophores; severe metabolic alterations occur when petroleum is absorbed by lipophylic substances on mangrove surfaces |
| Beever | 1979 | Beever, J.W., D. Simberloff, and L.L. King. 1979. Herbivory and predation by the mangrove tree crab, Aratus pisonii. Oecologia 43:317-328. | The mangrove tree crab (Aratus pisonii) is a key member of the arboreal arthropod community of the red mangrove (Rhizophora mangle) swamps of south Florida. Its ecological roles include primary herbivory, predation, and export of biomass and energy in the form of offspring and frass. Although the larval stage is planktonic, distribution of adults and Aratus leaf damage are patchy. |
| Beever | 1988 | Beever III, J.W. 1988. Mangrove trimming. Internal report. Florida Department of | Report to the FDER on the effects of mangrove hedge trimming in Aquatic Preserves |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Natural Resources, Tallahassee, Florida. | |
| Beever | 1989 | Beever III, JW 1989. The effects of fringe mangrove trimming for view in the South West Florida Aquatic Preserves, Part V, and April 1989 to July 1989. Reports of the South West Florida Aquatic Preserves No. 5. | Statistically significant reduction in net primary productivity export (83%), reduction of standing leaf crop (71%), reduction of flower production (95%), reduction of propagule production (84%), and reduction of leaf clusters (70%) resulted from the cutting of the 4.9 meter (16.1 feet) tall fringing red mangrove to 1.7 m (5.4 feet).. Similarly, reduction of net primary productivity export (72%), reduction of standing leaf crop (49%), reduction of propagule production (73%), and reduction of terminal branches (45%) resulted from cutting a 3.4 meter tall fringing white mangrove area to 1.3 m. Habitat utilization by associated large visible fauna was significantly reduced (79%) by mangrove trimming. |
| Beever | 1996 | Beever III, J.W. 1996. The effects of fringe red mangrove and white mangrove trimming for view in the Southwest Florida Aquatic Preserves. Florida Game and Fresh Water Fish Commission, Office of Environmental Services, Punta Gorda, Florida. | Follow up on the negative effects of mangrove hedge trimming. |
| Beever | 2002 | Beever III, J.W. and K Cairns 2002. Mangroves in United States Fish and Wildlife Service. 1999. South Florida multi-species recovery plan. U.S. Fish and Wildlife Service, Atlanta, Georgia. P 3-519 to 3-552. | A chapter in the Multi-Species Recovery Plan for South Florida. This is a synopsis of mangrove knowledge for south Florida in 2002. Including synonymy, distribution, description, community types, wildlife diversity, wildlife species of concern, ecology, zonation, substrate, salinity, reproduction, biomass, productivity, status and trends, management, diking and ditching, trimming, herbicides, oil and oil spills, and fire. Restoration Objective to maintain the structure, function, and ecological processes of mangroves and prevent any further loss, fragmentation, or degradation of this habitat type in South Florida is addressed by Restoration Criteria including Community-level Restoration Actions, preservation plans, management on public lands, and research needs. |
| Beever | 2011 | Beever III, J.W., W. Gray, L. Beever, Beever, Lisa, B., D. Cobb, Walker, Tim 2011. Climate Change Vulnerability Assessment and Adaptation Opportunities for Salt Marsh Types in Southwest Florida. 379 pp. | The salt marsh community of the Southwest Florida Ecosystem is one of the most unique salt marsh systems in the United States. The primary focus of this project is the extent and nature of salt marshes and the adaptation of salt marshes to climate change. This report includes the results of a new study to inventory and determine the areal extent of salt marsh types throughout the Charlotte Harbor National Estuary Program (CHNEP) study area; determine the vulnerability of those marshes to climate change; identify the need and opportunities for avoidance, minimization, mitigation, and adaptation (AMMA) to climate change, and recommend |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | strategies to implement alternate AMMA. |
| Beever | 2013 | Beever III, J.W., and T. Walker 2013. Estimating and Forecasting Ecosystem Services within Pine Island Sound, Sanibel Island, Captiva Island, North Captiva Island, Cayo Costa Island, Useppa Island, Other Islands of the Sound, and the Nearshore Gulf of Mexico. | The output of this project is an assessment of the total ecosystem services provided by all habitat types in the Pine Island Sound, Sanibel Island, and Captiva Island. North Captive Island, Cayo Costa, Useppa Island and other islands within Pine Island Sound and included the tidal extents of Pine island Sound on the western side of Pine Island and the nearshore Gulf of Mexico west and south of the barrier islands. It updated the existing crosswalk reference for the varied definitions of habitat types utilized by the federal government, the state of Florida, regional agencies, local government and other resource management agencies in southwest Florida, to obtain a unified set of defined southwest Florida wetland types. It identified existing referred and gray scientific literature that provides measures of the ecosystem services for each habitat type indentified. It identified and defined the ecosystem services provided by each wetland type. It identified defined reference condition habitats within the study area utilizing existing reference sites and locating new valid reference sites for evaluation. This includes provisioning services; regulating services; supporting services; hydrologic, water quality, water storage, vegetative, biogeochemical cycle, wildlife, fishery, recreational aesthetic, and cultural services. It then generated two alternate future ECOSERVE topographies related to anticipated land use changes resulting form build out of the future land use map for the year 2030 and a future with one-foot of additional sea level rise that could occur in a period from 2027 to 2222, but most likely by 2162 if current rates of sea level rise continue. |
| Beever | 2013 | Beever III, J.W. 2013. Estimate of the Ecosystem Services of Existing Conservation Collier Lands in Collier County Florida. Report to the Collier County Land Acquisition Advisory Committee 37 pp. | The Conservation Collier Program as of May 2014 had 19 preserves with a total acreage of 4,054.7 and a Total Ecosystem Services Value (TEV) of $144,988,312.22 in 2013 dollars. To determine the Total Ecosystems Services Value, 32 ecosystem services were reviewed on a per acre basis. The Mangrove Swamps comprised : 309.49 Acres with a $279,307.71 per acre value for a total of $86,442,943.17 TEV |
| Bosire | 2008 | Bosire, JO, F Dahdough-Guebas, M Walton, BI Crona, RR Lewis III, C. Field, JG Kairo and N Koedam. Functionality of restored mangroves: A review. 2008. Aquatic Botany 89:251-259. | While stand structure in mangrove stands is dependent on age, site conditions and silvicultural management, published data indicates that stem densities are higher in restored mangroves than comparable natural stands; the converse is true for basal area. Disparities in patterns of tree species recruitment into the restored stands have been observed with some stands having linear recruitment rates with time (hence enhancing stand complexity), while some older stands completely lacked the understory. Biodiversity assessments suggest that some fauna species are more responsive to mangrove degradation (e.g. herbivorous crabs and mollusks in general), and thus mangrove restoration encourages the return of such species, in some cases to levels equivalent to those in comparable natural |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | stands. The paper includes a 10-step scheme presenting possible mangrove restoration pathways depending on site conditions (modified after Stevenson *et al*., 1999; Bosire *et al*., 2006) |
| Brockmeyer | 1997 | Brockmeyer, RE Jr., JR Rey, RW Virnstein, RG Gilmore and L Earnest. 1997. Rehabilitation of impounded estuarine wetlands by hydrologic reconnection to the Indian River Lagoon (USA). Wetlands Ecology and Management 4(2):93-109. | When tidal exchange is restored through hydrologic connection, usually by culverts installed through the perimeter dike of impoundments, recovery to more natural conditions is often rapid. In one impoundment where wetland vegetation was totally eliminated, recovery of salt-tolerant plants began almost immediately. In another, cover of salt-tolerant plants increased 1,056% in less than 3 years. Fisheries species that benefitted the most were snook, ladyfish, and striped inlet. |
| Brown | 2006 | Brown, B, and RR Lewis. 2006. Edited by R Lewis, A Quarto, J Enright, E Corets, J Primavera, T Ravishankar, OD Stanley and R Djamaluddin. Five Steps to Successful Ecological Restoration of Mangroves. Yayasan Akar Rumput Laut (YARL) and the Mangrove Action Project. Yogyakarta, Indonesia. 64 p. | This is a graphically appealing manual which outlines the 5 steps to achieve successful mangrove restoration: 1) Understand the autecology (individual species ecology) of the mangrove species at the site; in particular the patterns of reproduction, propagule distribution, and successful seedling establishment, 2) Understand the normal hydrologic patterns that control the distribution and successful establishment and growth of targeted mangrove species, 3) Assess modifications of the original mangrove environment that currently prevent natural secondary succession (recovery after damage), 4) Design the restoration program to restore appropriate hydrology and, if possible, utilize natural volunteer mangrove propagule recruitment for plant establishment, and 5) Only utilize actual planting of propagules, collected seedlings, or cultivated seedlings after determining (through steps a-d) that natural recruitment will not provide the quantity of successfully established seedlings, rate of stabilization, or rate of growth of saplings established as objectives for the restoration project (Lewis and Marshall 1997). Poorly designed projects are compared with well designed projects. Although designed for use in Indonesia, there are excellent applications in the CHNEP study area. |
| Cahoon | 2015 | Cahoon, DR. 2015. Estimating Relative Sea-Level Rise and Submergence Potential at a Coastal Wetland. Estuaries and Coasts (2015) 38:1077–1084. | Because the usefulness of Relative Sea Level Rise (RSLR )is in the ability to tie the change in sea level to the local topography, it is important that RSLR be calculated at a wetland that reflects these local dynamic surface elevation changes in order to better estimate wetland submergence potential. For 89 wetlands where RSLRwet was evaluated, wetland elevation change differed significantly from zero for 80 % of them, indicating that RSLRwet at these wetlands differed from the local tide gauge RSLR. When compared to tide gauge RSLR, about 39 % of wetlands experienced an elevation rate surplus and 58 % an elevation rate deficit (i.e., sea level becoming lower and higher, respectively, relative to the wetland surface). These proportions were consistent across saltmarsh, mangrove, and |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | freshwater wetland types. |
| Carey | 2013 | Carey, J. 2013. Architects of the swamp. Scientific American. December 2013. 74-79. | Many wetland recovery programs have failed by trying to re-create the original ecosystems. Recent successes have focused on one or two limited goals and have let nature take it from there |
| Carlberg | 1980 | Carlberg, S.R. 1980. Oil pollution of the marine environment-with an emphasis on estuarine studies. Pages 367-402 in E. Olausson and I. Cato (eds.), Chemistry and biogeochemistry of estuaries. John Wiley and Sons, New York, New York. | A review of the effects of oil pollution in estuaries including mangrove forests. Used in background. |
| Castañeda-Moya | 2013 | Castañeda-Moya, E, RR Twilley, VH Rivera-Monroy. Allocation of biomass and net primary productivity of mangrove forests along environmental gradients in the Florida Coastal Everglades, USA. Forest Ecology and Management 307 (2013) 226–241. | Vegetation patterns of mangroves in the Florida Coastal Everglades (FCE) result from the interaction of environmental gradients and natural disturbances (i.e., hurricanes), creating an array of distinct riverine and scrub mangroves across the landscape. Root biomass to aboveground wood biomass (BGB:AWB) ratio was 17 times higher in P-limited environments demonstrating the allocation strategies of mangroves under resource limitation. Riverine mangroves allocated most of the biomass and productivity to aboveground (69%) while scrub mangroves showed the highest allocation to belowground (58%). |
| Chapman | 1960 | Chapman, V. J.: Salt marshes and Salt Deserts of the World. Plant Science Monographs (ed. by N. Polunin). With 45 pl., 102 fig. — London: Leonard Hill (Books) Ltd. (Interscience Publ., Inc., New York) 1960. 392 pp. 95 s | The response of plants to salinity, either as single species or collectively as a community, has excited the interest of botanists, be they ecologists or plant physiologists, for many years. A fuller knowledge of the causes underlying the response has become increasingly important in the past two decades because of the need to bring saline soils into cultivation in order to increase the world's agricultural output. Used in background. |
| Cintron | 1984 | Cintron, G, and YS Novelli. 1984. Methods for studying mangrove structure. Pages 91-113 in SC Snedaker and JG Snedaker (eds.), The Mangrove Ecosystem: Research Methods, UNESCO, Paris. 251 p. (with corrections). | Methods to measure structural attributes (diameter, basal area, mean stand diameter, tree height); relative density, dominance and frequency; crown diameter; leaf area index; above-ground biomass are presented. There is an interesting graph of stem density by diameter of stem of mean basal area by five mangrove forest types. |
| Craighead | 1962 | Craighead, F.C., and V.C. Gilbert. 1962. The effects of Hurricane Donna on vegetation of southern Florida. Quarterly Journal of | The wind speed of Hurricane Donna (September 1960) through southern Florida was recorded to be c. 160 to 225 km/h for 36 h. The storm itself had little direct effect on the vegetation in the Everglades National Park but an accompanying tidal wave deposited up to 0.13 m of silt over |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | the Florida Academy of Sciences 25:1-28. | the area. Indirect damage was more severe than the immediate effects of the storms. |
| Crewz | 1991 | Crewz, DW, and RR Lewis. 1991. Evaluation of historical attempts to establish emergent vegetation in marine wetlands in Florida. Florida Sea Grant Technical Paper No.60. Florida Sea Grant College, Gainesville. 79 p + append. | Mangrove growth over time is diagramed, along with mangrove placement in relationship to salt marshes and uplands. Projected effect of sea level rise is diagramed as it relates to slope. Undisturbed are compared to disturbed mangroves as related to slope and exotic invasion. The excellent diagrams could be reproduced in color. Two restoration sites within the study area (both at Punta Rassa) are reviewed. One was a failure and one had mixed results (pages C-4 and C-5.) |
| Dale | 2014 | Dale, PE *et al*. 2014. Multiagency perspectives on managing mangrove wetlands and the mosquitoes they produce. J. Am Mosquito Control Assoc. 30(2):106-115. | A group of Florida researchers, mosquito and coastal managers, and consultants joined together to explore issues of concern to coastal and mosquito management in mangrove forests. The most important issues for everyone included habitat responses to management, community attitude, public education, interaction between agencies, local connectivity, sea-level rise (SLR) loss of wetlands, and conservation. Most urgent were public education, conservation easements, local connectivity, SLR, loss of wetland, restoration, and conservation. |
| Dale | 2014 | Dale, PER, JM Knight and PG Dwyer. 2014. Mangrove rehabilitation: a review focusing on ecological and institutional issues. Wetlands Ecol. Manage. 22:587-604. | Some rehabilitation efforts have had limited success for several reasons including: having insufficient information, using inappropriate methods, not involving local communities, or not following all the steps in the processes that have been identified in the literature. A multi-disciplinary and integrated approach is needed to assist future planning and this needs capacity from a variety of areas in government, research and community. |
| Davis | 1940 | Davis, J. H. 1940. XVI The Ecology and geologic role of mangroves in Florida. Papers form Tortugas Laboratory 32. Carnegie Institution of Washington. | Succession theory views red mangroves as the younger colonizing or pioneer stage which was located more seaward, with black and white mangroves as more mature stages located more landward, and adjacent tropical hardwood forests as the climatic stage. Used in background. Used in background. |
| Davis | 1967 | Davis, J.H. 1967. General maps of natural vegetation of Florida. Circular S-178.Agricultural Experiment Station, Institute of Food and Agricultural Sciences, University of Florida; Gainesville, Florida. | The term "coastal salt marsh " is coined and defined. Used in background. |
| Davis | 1999 | Davis, S.M. 1999. Mangrove Estuary Transition Conceptual Model. Pages 89-102 In The Use of Conceptual Ecological | Unvegetated areas associated with salt marsh communities are labeled white zone; although white zone is also used to identify areas of dried-down periphytic algal freshwater wetlands. Used in background. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Landscape Models as Planning Tools for the South Florida Ecosystem Restoration Programs, Ogden, J.C. and S. M. Davis, 1999, South Florida Water Management District, West Palm Beach, Florida | |
| Day | 1987 | Day, J. W., Jr., W. H. Conner, F. Ley-Lou, R. H. Day, and A. M. Navarro. 1987. The productivity and composition of mangrove forests, Laguna de Terminos, Mexico. Aquatic Botany 27: 267-284. | Productivity and composition of mangrove forests Mangroves have a harder time surviving in soils with salinities of 70-80 ppt. used in background. |
| de la Cruz | 1982 | De la Cruz, AA 1982. The impact of crude oil and oil-related activities on coastal wetlands - a review. Proc. Int. Wetlands Conf., Delhi. | Reviews of the effects of oil spills in mangrove ecosystems. Used in background. |
| Donato | 2011 | Donato, DC, JB Kauffman, D Murdiyarso, S Kurnianto, M Stidham and M Kanninen. 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience. 3 April 2011. DOI:10.1038/NGE01123 | The areal extent of mangrove forests has declined by 30–50% over the past half century as a result of coastal development, aquaculture expansion and over-harvesting. Whole-ecosystem carbon storage were quantified by measuring tree and dead wood biomass, soil carbon content, and soil depth in 25 mangrove forests across a broad area of the Indo-Pacific region. Organic-rich soils ranged from 0.5m to more than 3m in depth and accounted for 49–98% of carbon storage in these systems. Combining the data with other published information, mangrove deforestation generates emissions of 0.02–0.12 Pg carbon per year—as much as around 10% of emissions from deforestation globally, despite accounting for just 0.7% of tropical forest area. |
| Egler | 1952 | Egler, F.E. 1952. Southeast saline Everglades vegetation, Florida, and its management. Veg. Acta. Geobot. 3:213-265. | Egler described the vegetation of the area south and east of the Atlantic Coastal Ridge in southernmost peninsular Florida, noting a conspicuous coastal zonation within the area he called "the Southeast Saline Everglades". Egler's description was based on 1938 and 1940 aerial photographs, and on field work undertaken in 1940 through 1948. He described the vegetation pattern in the coastal Everglades at the time as "fossil", responding slowly to a rapidly changing environment that included a rising sea level, a decline in the level of the surface freshwater aquifer, a reduction in the frequency of fire, and a range of anthropogenic modifications to natural drainage patterns. Egler documented several examples of local vegetation change over the period of his study, including the invasion of the halophytic red mangrove (Rhizophora mangle) into freshwater wetlands far from the coast. At the same time, he anticipated a continued interior- |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | ward shift in the coastal vegetation gradient. |
| Ellison | 2001 | Ellison, AM and EJ Farnsworth. 2001. Mangrove Communities. Pages 423-442 in Bertness, MD, SD Gaines, M Hay (eds). Marine Community Ecology. Sinauer, Associates, Inc. Massachusetts. 550 pp. | The chapter discusses the apparent lack of understory in mangal forests, and relationships with epiphytes, reproduction/pollination, herbivory, marine invertebrates, fungi and pathogens. Disturbance issues include tree-falls, lightening strikes, cyclones, anthropogenic disturbances, sea level rise and other facets of climate change. |
| Ellison | 2012 | Ellison, JC. 2012. Climate change vulnerability assessment and adaptation planning for mangrove systems. World Wildlife Fund. Washington, DC. 142 p. | Contents include the values and threats for mangroves; planning, conducting and interpreting vulnerability assessments; and developing adaptation measures. Adaptation measures include reducing non-climate stressors, managing for accretion in mangroves and plan inland migration areas. The following methods are the most useful for ongoing monitoring of climate change impacts:<br>• mangrove extent and condition<br>• permanent plots<br>• sedimentation rates<br>• relative sea level rise |
| Erftemeijer | 2000 | Erftemeijer, PLA, and RR Lewis III. 2000. Planting mangroves on intertidal mudflats: habitat restoration or habitat conversion? Pages 156-165 in Proceedings of the ECOTONE VIII Seminar “Enhancing Coastal Ecosystems Restoration for the 21st Century”, Ranong, Thailand, 23-28 May 1999. Royal Forest Department of Thailand, Bangkok, Thailand. | Mangrove planting efforts on mudflats were reviewed and balanced against the ecological importance of mudflats in southeast Asia. |
| Estevez | 1981 | Estevez, E.D. 1981. Techniques for managing cumulative impacts in Florida's coastal wetlands. Pages 147-157 in Proceedings of the symposium on progress in wetlands utilization and management. Coordinating council for restoring the Kissimmee River Valley and Taylor Creek-Nubbin Slough Basin. Tallahassee, Florida. | Discussion of mangrove losses and plans for restoration. Lee County has lost 19% of its original mangroves. Used in background. |
| FDOT | 1999 | Florida Department of Transportation. Florida Land | Manual for classifying land use, land cover, and land form in Florida. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Use, Cover and Forms Classification System. Third. Tallahassee: FDOT, 1999 | |
| Finn | 1998 | Finn, M, J Iglehart, P Kangas. 1998. A taxonomy of spatial forms of mangrove die-offs in southwest Florida. Pages 17-35 in Cabbuzzarim PJ (ed.), Proceedings of the Twenty Fourth Annual Conference on Ecosystems Creation and Restoration. HCC, Tampa. | Mangrove die-offs range in size from tens of meters to hundreds of hectares. Both natural and human induced stressors are involved. The paper proposed classification of spatial forms of mangrove die-off's based on aerial views and possible causes are identified using form as a guide. Characteristics such as size, shape, and appearance of dead trees in a die-off are included in the classification and presented as a type of taxonomic key. The three main forms are circular, linear and irregular. Circular die offs include lightening strike die-off and digressional die-off. Linear die offs are classified as near a shoreline and located away from open waterways. They include erosions and depositional, blowdown, boating or automobile accident, alteration (pruning) and improved access die offs. Irregular doff are large too hundreds of hectares. They are caused by hurricanes, cold storms and human impact. A conceptual model is included. |
| FNAI | 1990 | Florida Natural Areas Inventory [FNAI]. 1990. Guide to the natural communities of Florida. Florida Natural Areas Inventory; Tallahassee, Florida. | Description of Florida natural communities. |
| Getter | 1984 | Getter, CD, G Cintron, B Dicks, RR Lewis III, and ED Seneca. 1984. The recovery and restoration of salt marshes and mangroves following an oil spill. Chapter 3, pages 65-113 in J Cairns Jr. ad A Buikema Jr. (eds) Restoration of Habitats Impacted by Oil Spills. Butterworth Publishers, Boston. | The document provides a brief review of the effects of oil spills and cleanup activities on salt marshes and mangrove ecosystems; reviews methods of protecting marine wetlands from being oils; review successful means of cleaning marine wetlands following oil spills; presents techniques for restoring marine wetlands damaged by oil spills and/or cleanup operations; and establishes a set of criteria and guidelines for decisions on means of protecting susceptible areas. The document provides a different graphic illustrating the five mangrove forest types and provides four models of the distribution of oil spill effects. |
| Getter | 2003 | Getter, CD, and RR Lewis. 2003. Spill response that benefits the long-term recovery of oiled mangroves. Pages 1-12 in Proceedings of the 2003 International Oil Spill Conference. Black and white and color images. | Three sites (Florida and Puerto Rico) were visited after they were oiled 23 to 29 years ago. Non-beneficial resource efforts that have degraded mangroves include forest cutting, heavy equipment and personnel traffic, tree burning, onshore use of chemicals, plantings in toxic soils, and most of all, impoundment of basin forests. The only long-term beneficial renounce method appears to be a combination of non-intrusive oil collection and booming techniques in heavily oiled, sheltered areas with closely monitored natural recovery in forests more lightly oiled. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| Giri | 2005 | Giri, C.P., Zhu, Z., and Reed, B.C., 2005, A comparative analysis of the Global Land Cover 2000 and MODIS land cover data sets: Remote Sensing of Environment, v. 94, no. 1, p. 123-132. (Also available online at http://dx.doi.org/10.1016/j.rse.2004.09.005.) | Analysis shows a general agreement at the class aggregate level except for savannas/shrublands, and wetlands. The disagreement, however, increases when comparing detailed land cover classes. Similarly, percent agreement between the two data sets was found to be highly variable among biomes. |
| Giri | 2011 | Giri, C, E Ochieng, LL Tieszen, Z Zhu, A Singh, T Loveland, J Masek and N Duke. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecology and Biogeography 20(1):154-159. | The status and distributions of global mangroves were mapped using recently available Global Land Survey (GLS) data and the Landsat archive. Approximately 75% of world's mangroves are found in just 15 countries, and only 6.9% are protected under the existing protected areas network (IUCN I-IV). The study confirms earlier findings that the biogeographic distribution of mangroves is generally confined to the tropical and subtropical regions and the largest percentage of mangroves is found between 5° N and 5° S latitude. |
| Global Nature Fund. | 2007 | Mangrove Rehabilitation Guidebook. Global Nature Fund. 2007. 68 p. | A Guidebook was published for the Post Tsunami Project in Sri Lanka. Six Steps to Successful Mangrove Restoration include<br>Step 1: Autecology<br>Step 2: Hydrology<br>Step 3: Eliminate Disturbances<br>Step 4: Select an appropriate Restoration Site<br>Step 5: Hydrological Rehabilitation Design<br>Step 6: Mangrove Planting |
| Hartman | 1996 | Hartman, B. J. 1996. Description of major terrestrial and wetland habitats of Florida. Pages xix-xxxii in J.A. Rodgers, Jr., H.W. Kale II, and H.T. Smith eds., Rare and endangered biota of Florida. Volume V. Birds. University Presses of Florida; Gainesville, Florida. | Description of major terrestrial and wetland habitats of Florida. Used in background. |
| Heald | 1970 | Heald, EJ & WE Odum. 1970. The contribution of mangrove swamps to Florida fisheries. *Proc. Gulf Caribbean Fish. Inst.* 22: 130-135. | Description of the detrital mangrove food pathway in the food web for Florida fisheries. |
| Heald | 1971 | Heald, E.J. 1971. The production of organic | Description of the organic detrital mangrove food pathway in southwest Florida estuaries. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | detritus in a south Florida estuary. University of Miami Sea Grant technical bulletin 6. | |
| Hicks | 1975 | Hicks, D.B. and L.A. Burns 1975. Mangrove metabolic response to alterations of natural freshwater drainage to southwestern Florida estuaries. Pp. 238-255 In G. Walsh, S. Snedaker, and H. Teas, Eds. Proc. Intern. Symp. Biol. Manage. Mangroves, Institute of Food and Agricultural Sciences, University of Florida, Gainesville. | Review of how well different mangrove species grow under different salinity regimes. Demonstrates that peak productivity occurs at middle estuarine 15 ppt salinities. |
| Hoff | 2014 | Hoff, R and J Michel (Eds.). 2014. Oil Spills and Mangroves. Planning & Response Considerations. National Oceanographic and Atmospheric Administration, Washington, DC. Various paging. 97 p. total. | The document discusses mangrove ecology, oil toxicity and effects on mangroves, response, mangrove recovery and restoration and mangrove case studies. Oil groups and characteristics, acute and chronic effects and indirect impacts are detailed. Mangroves are highly susceptible to oil exposure. Acute effects of oil (mortality) occur within six months of exposure and usually within a much shorter time frame (a few weeks).Different oil types confer different toxicity effects. The physical effects of oiling (e.g., covering or blocking of specialized tissues for respiration or salt management) can be as damaging to mangroves as the inherent toxicity of the oil. Response techniques that reduce oil contact with mangroves reduce the resultant toxicity as well. Comparing spill impacts at several mangrove sites indicates that variable effects are related to geomorphology and hydrologic kinetics of the mangrove ecosystem that, in turn, control whether oil persists in the mangrove habitat. Recommended responses by oil group are provided. Mangroves can take more than 30 years to recover from severe oil spill impacts. Adequate tidal exchange is critical to restoration success. |
| Honde | 1978 | Honde and Schekter 1978 | Studies of south Florida estuarine food webs have found that 85% of the detrital food base is from red mangroves. This detritus is dominantly leaves but also includes leaf and propagule stalks, small twigs, roots, flowers and propagules. These are fragmented by processors into detritus, decaying organic material coated with and created by algae, fungi, bacteria and protozoa. This detritus is further fragmented, consumed and excreted by a number of primary consumers dominated by small crustaceans. The leaf base material itself is not directly consumed but the algae, fungi, bacteria and protozoal biomass on it is. This results in the excretion of a |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | smaller detrital particle which again becomes the base for a detrital garden of microorganisms. This process is repeated many times utilizing the detrital particle to its full nutritive value to the estuarine ecosystem. Eventually the particle attains a small enough size for use by filter feeders and deposit feeders. |
| Houston | 2015 | Houston, JR, 2015. Shoreline Response to Sea-Level Rise on the Southwest Coast of Florida. Journal of Coastal Research In-Press. | The state of Florida has a unique database of shoreline position measured about every 300 m and dating back to the mid-1800s that presents an opportunity to determine the effects of sea-level rise on shoreline position. The source of the onshore sand transport in southwest Florida is identified. Sea-level rise results in long-term shoreline advance rather than recession for shorelines with sufficient onshore sand movement from beyond closure depth to the active profile, probably during episodic storms. |
| Hutchinson | 2014 | Hutchinson, J, M Spalding and P zu Ermgassen. 2014. The role of mangroves in fisheries enhancement. The Nature Conservancy and Wetlands International. The Netherlands. 52 p. | Fish productivity from mangroves will be highest where mangrove productivity is high, where there is high freshwater input from rivers and rainfall and where mangroves are in good condition. Fish productivity will increase with an increase in total area of mangroves, but notably also with the length of mangrove margin since generally it is the fringes of mangroves where fish populations are enhanced. Mangroves with greater physical complexity both in terms of patterns of channels, pools and lagoons, as well as the structure of roots which are important areas for shelter and for growth of some bivalves will enhance fisheries to a greater extent. |
| Jimenez | 1985 | Jimenez, JA, AE Lugo and G Cintron. 1985. Tree mortality in mangrove forests. Biotropica 17(3):177-185. | Twenty-eight worldwide reports of massive mangrove tree mortalities are reviewed. Disease and other biotic factors do not appear to be primary causes of massive mangrove mortalities. Instead, these factors appear to attack forests weakened by changes in the physical environment. Humans may tilt the balance towards higher mortality rates by introducing chronic stressors that inhibit regeneration mechanisms. |
| Johnson | 2008 | Johnson, LK, and LW Herren. 2008. Re-establishment of fringing mangrove habitat in the Indian River Lagoon. Report to the St. Johns River Water Management District. Main Body Text Only. 60 pages of 161 total. | A PVC encasement methodology thought to improve the success of mangrove plantings was brought to the attention of St. Johns River Water Management District (SJRWMD or District) staff. The Riley encasement method (REM) was developed to facilitate planting along high wave energy shorelines, overcoming limitations of conventional planting methods. Overall survival (number of mangroves surviving divided by the total planted) was 6.5%. Low overall survival may be generally attributable to one or more of the following:<br>1. Large number of locations and plantings (103 plantings in 57 locations).<br>2. High turnover rate with SRC.<br>3. Insufficient site maintenance.<br>4. Lack of adherence to site selection criteria recommended by AC (see Site Selection section of SRP Background). |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | 5. Plantings at different elevations (e.g., Kiwanis Park at Geiger Point in Melbourne and Eau Gallie Bridge are too waterward).<br>6. Modifications to the original REM test the boundaries of the methodology. Note: Bob Riley will provide project advice and sell FDEP his modified PVC for the encasements if the SRC is trained by his company, mangrove.org. The fee would be approximately $3,000.<br>7. Overwhelming/confounding amount of information without a standardized method of recordkeeping.8. Focus of massive plantings and replanting vs. conditioning a site for naturally-recruiting mangroves and then perhaps supplementing with plantings.<br>9. Public education component was extremely strong, however high volunteer involvement and goal to establish 10 sites per year may have outweighed focus of site restoration work. |
| Kauffman | 2012 | Kauffman, JB and DC Donato. 2012. Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper 86. CIFOR, Bogor, Indonesia. | The document includes field and laboratory methods for assessing carbon stocks in mangroves. Of note, dead tree decease status classes, wood density for different mangrove species, and reporting methods are identified. |
| Keim | 2013 | Keim, RF, JA Zoller, DH Braud and BL Edwards. 2013. Classification of Forested Wetland Degradation Using Ordination of Multitemporal Reflectance. In Wetlands 33:1103–1115. | To address difficulties to classify wetland ecosystems using remote sensing because of temporal variability of plant cover and hydrological conditions, multi-temporal classification scheme was developed. Three Landsat bands from each of seven scenes across a 3-year period in each of two phenological conditions were used. The resulting classification represents the desired ecological gradients more robustly than single-image classifications. |
| Kirwan | 2013 | Kirwan, ML, and JP Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504:53-60. | Deterioration of tidal wetlands often begins with plant stress, and the disruption of the stabilizing feedbacks that plants provide. For example, plant mortality associated with the BP Deepwater Horizon oil spill triggered order-of-magnitude increases in marsh edge erosion rates, historically stable channel networks became strongly erosive when crabs disturbed plants and substrate, herbivory caused an accreting marsh on an actively building delta to become strongly erosive, and tree mortality wrought by Hurricane Mitch caused mangrove peat collapse. Even temporary, climatically driven episodes of vegetation die-off sometimes lead to geomorphic change, including rapid subsidence, platform erosion and diminished deposition rates. Thus, factors that influence the growth rate of plants (for example, climate and nutrients) are likely to influence the ability of a marsh to survive sea-level rise. The delivery of salts and sulphates to brackish and freshwater coastal wetlands through sea-level |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | rise may destabilize soil organic matter pools. Groundwater withdrawal and artificial drainage of wetland soils contribute to rapid subsidence such that 8 of the world's 20 largest coastal cities now experience relative sea-level rise rates that greatly exceed any likely climate-driven projection, and most of the world's major river deltas are sinking much faster than the historical rate of sea-level rise. Dams and reservoirs now prevent about 20% of the global sediment load from reaching the coast. Historical adaptation to sea-level rise indicates that the loss of wetlands is not an inevitable outcome of climate change. Although very rapid rates of sea-level rise may drown some marshes regardless of indirect human impacts, numerical models predict that many wetlands will survive in places in which dams and embankments do not restrict sediment transport. |
| Kjerfve | 1990 | Kjerfve, B. 1990. Manual for investigation of hydrological processes in mangrove ecosystems. UNESCO/UNDP Regional Project report. 79 p. | The geomorphic setting of mangrove ecosystems includes deltas estuaries, coastal lagoons and coastal waters. The importance of freshwater flows is highlighted. There is a comprehensive treatment of modeling algorithms describing hydrologic and chemical parameters. Six key data needs prior to proceeding with looking at the hydrology of the basin and associated mangroves:<br>1. Size and extent of drainage basin<br>2. Extent and area of mangroves at the downslope (i.e., toward the sea) end of the basin<br>3. Topography and bathymetry of the mangrove areas<br>4. Hypsometric characteristics to calculate the current tidal prism of the mangrove areas<br>5. Rates of terrestrial input of water, sediment, and nutrients<br>6. Climatic water balance |
| Krauss | 2014 | Krauss, KW, KL McKee, CE Lovelock, DR Cahoon, N Saintilan, R Reef, and L Chen. 2014. How mangrove forests adjust to rising sea level. New Phytologist 202:19-34. | The review provides a general overview of research on mangrove elevation dynamics, emphasizing the role of the vegetation in maintaining soil surface elevations (i.e. position of the soil surface in the vertical plane). The primary ways in which mangroves may influence sediment accretion and vertical land development through surface and sub-surface processes are summarized. For example, roots contribute to soil volume and upward expansion of the soil surface. In addition, how hydrological, geomorphological and climatic processes may interact with plant processes to influence mangrove capacity to keep pace with rising sea level. A variety of studies describe the important, and often under-appreciated, role that plants play in shaping the trajectory of an ecosystem undergoing change are examined. Of particular note, is measured elevation change by mangrove forest type within Rookery Bay. Factors affecting root contributions to vertical soil development include salinity, nutrients, flooding, soil texture, and disturbance (storm damage, harvesting.) Climatic and environmental feedbacks include rainfall variability, response to elevated atmospheric CO2, and |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | response to sea-level rise. |
| Latifovic | 2004 | Latifovic, R., Zhu, Z.-l., Cihlar, J., Giri, C.P., and Olthof, I., 2004, Land cover mapping of North and Central America—Global Land Cover 2000: Remote Sensing of Environment, v. 89, no. 1, p. 116- 127. (Also available online at http://dx.doi.org/10.1016/j.rse.2003.11.002.) | There was good agreement (79%) on the spatial distribution and areal extent of forest between GLC 2000-NCA and the other maps, however, GLC 2000-NCA provides additional information on the spatial distribution of forest types. |
| Lewis | 1975 | Lewis, RR and FM Dunstan. 1975. Possible role of Spartina alterniflora Loisel. in establishment of mangroves in Florida. Pp. 82-100 in RR Lewis (ed.) Proceedings of the Second Annual Conference on Restoration of Coastal Vegetation in Florida. Hillsborough Community College, Tampa, Florida. 203 pp | The evaluation occurred at 3 sites in Tampa Bay and 1 in Indian River Lagoon. Rapid succession of Spartina alterniflora and presence of mangrove seedlings, especially at older areas of Spartina suggests a natural succession pattern that may prove useful to stabilize dredge material. There may be less relevance in the CHNEP study area, given a total of 3 acres within the study area. |
| Lewis | 1980 | Lewis, R.R. III. 1980. Oil and mangrove forests: observed impacts 12 months after the Howard Starr oil spill. Florida Scientist (supplement) 43:23. | Observations on the effects of an oil spill on a mangrove ecosystem. |
| Lewis | 1982 | Lewis, RR. 1982. Low marshes, peninsular Florida. Ch. 7, pp. 147-152 in RR Lewis (ed.), Creation and Restoration of Coastal Plant Communities. CRC Press, Boca Raton, Florida. 219 pp. | The chapter highlights the role of Spartina alterniflora to help re-establish mangroves on spoil islands. |
| Lewis | 1982 | Lewis, RR. 1982. Mangrove forests. Ch. 8, pp. 153-172 in RR Lewis (ed.), Creation and Restoration of Coastal Plant Communities. CRC Press, Boca Raton, Florida. 219 pp. | The chapter outlines the distribution, primary and secondary productivity of mangroves, mangrove loss and global human uses (silvaculture). Florida analysis is centered on Tampa Bay and Biscayne Bay. Table 3 includes attempted plantings of mangroves from the 1880s to 1981, including success rates. Estimated costs and manpower for planting mangroves based on technique is detailed. |
| Lewis | 1983 | Lewis, RR. 1983. Impact of oil spills on mangrove forests. Pp.171-183 in H. J. | Natural recovery of oil damaged mangrove can occur through recolonization of damaged areas by floating mangrove propagules and planktonic larvae of benthic invertebrates. If |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Teas (ed.), Biology and Ecology of Mangroves. Tasks for Vegetation Science 8. Dr. W. Junk, The Hague. 188 p. | concentrations are still very high (30,000-80,000 ppm) the seeds may grow into deformed seedlings or die. Active attempts to replant an oil damaged site have been reported where natural recolonization has been prevented, debris from the dead trees blocking movement of seeds and mortality of seeds in more heavily contaminated areas. |
| Lewis | 1985 | Lewis, RR, RG Gilmore, Jr., DW Crewz and WE Odum. 1985. Mangrove habitat and fishery resources of Florida. Pp. 281-336 in W. Seaman, Jr. (ed.), Florida Aquatic Habitat and Fishery Resources. Florida Chapter, American Fisheries Society, Kissimmee, FL. 543 pp. | The chapter provides a comprehensive description of mangrove area, structure and functions, including comparisons of mangrove area by county and by mapping method. It lists the community types without the hammock forest, but provides comparative illustrations of mangroves by area with relationships to salt marsh systems. |
| Lewis | 1990 | Lewis, RR. 1990. Wetlands restoration/creation/enhancement terminology: suggestions for standardization Pp.417-422 in JA Kusler and ME Kentula (eds.), Wetland Creation and Restoration: The Status of the Science. Island Press, Washington, D.C. xxv + 595 p. | The chapter provides recommended standardization for mitigation, restoration, creation, enhancement and success. |
| Lewis | 1990 | Lewis, RR. 1990. Creation and restoration of coastal plain wetlands in Florida. Pp. 73-101 in JA. Kusler and ME. Kentula (eds.), Wetland Creation and Restoration: The Status of the Science. Island Press, Washington, D.C. xxv + 595 p. | Restoration goals include mitigation, creation/enhancement, stabilization, percentage survival, water quality improvement and establish similar habitat values. Reasons for failure include excessive wave energy, improper planting elevation, no slope/drainage, nursery grown material which is not acclimated to the site, and human impacts. Consideration for a successful mangrove restoration projects and monitoring are recommended. Mangrove occurrence and height related to tidal elevations is graphed. |
| Lewis | 1992 | Lewis, RR. 1992. Coastal habitat restoration as a fishery management tool. Pp. 169-173 in RH Stroud (ed.), Stemming the Tide of Coastal Fish Habitat Loss. Proceedings of a Symposium on Conservation of Coastal Fish Habitat, Baltimore, Md., March 7-9, 1991. National Coalition for Marine Conservation, Inc., Savannah, GA. | Coastal wetlands restoration is an underutilized fishery management tool, particularly for estuarine-dependent fish species whose life histories include a resident period in shallow low-salinity marine habitats. Fish aggregation devises and artificial reefs do not have the same comparable rapid establishment in restored coastal wetlands. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| Lewis | 1999 | Lewis, RR. 1999. Time Zero Report for the Cross Bayou Mangrove Restoration Site, Pinellas County, Florida, USA. 32 p. | The paper details the acquisition of the 10.76 site in response to a 1993 oil discharge into Tampa Bay, called the Cross Bayou Mangrove Restoration Site. It includes performance criteria, as well as monitoring methodology (as described in the consent decree.) |
| Lewis | 2000 | Lewis, RR and W Streever. 2000. Restoration of mangrove habitat. Tech Note ERDC TN-WRP-VN-RS-3.2. U.S. Army, Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. 7 p. | Five critical steps are necessary to achieve successful mangrove restoration:<br>a. Understand the autecology (individual species ecology) of the mangrove species at the site; in particular the patterns of reproduction, propagule distribution, and successful seedling establishment.<br>B. Understand the normal hydrologic patterns that control the distribution and successful establishment and growth of targeted mangrove species.<br>C. Assess modifications of the original mangrove environment that currently prevent natural secondary succession.<br>D. Design the restoration program to restore appropriate hydrology and, if possible, utilize natural volunteer mangrove propagule recruitment for plant establishment.<br>E. Only utilize actual planting of propagules, collected seedlings, or cultivated seedlings after determining (through steps a-d) that natural recruitment will not provide the quantity of successfully established seedlings, rate of stabilization, or rate of growth of saplings established as objectives for the restoration project. |
| Lewis | 2000 | Lewis, RR. 2000. Ecologically based goal setting in mangrove forest and tidal marsh restoration in Florida. Ecological Engineering 15(3-4): 191-198. | The history of goal setting in marsh and mangrove restoration projects includes 3 phases: 1) persistent vegetative cover, 2) compensatory mitigation functional equivalency, 3) Ecological or ecosystem restoration. |
| Lewis | 2003 | Lewis, RR. 2003. Natural and mechanical alterations of mangrove forests. | This review was prepared for Pinellas County. It describes mangrove growth responses to freeze and hurricanes. Tomlinson (1996)'s "architectural tree models" are presented. The inability of Rhizophora to coppice, compared to Avicennia and Laguncularia are highlighted. Trimming considerations related to the three mangrove types are considered. |
| Lewis | 2003 | Lewis, RR. 2003. Mangrove restoration – costs and benefits of successful ecological restoration. Manuscript from presentation at the Mangrove Valuation Workshop, Univerisiti Sains Malaysia, Penang, Malaysia, April 4-8, 2001. Sponsored by the | The costs and benefits of successful mangrove restoration were assessed according to three categories including 1) planting alone, 2) hydrologic restoration with and without planting and 3) excavation or fill with and without planting. The first is the least expensive ($100-200/ha) but usually do not succeed. Reported costs range from $225-216,000/ha. Connected impounded mangroves are the lowest published cost. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Beijer International Institute of Ecological Economics, Stockholm, Sweden. 18 p. | |
| Lewis | 2004 | Lewis, RR. 2004. Time Zero Plus 60 Months Report for the Cross Bayou Mangrove Restoration Site, Pinellas County, Florida, USA. 25 p. | This is the 5 year monitoring report for the Cross Bayou Mangrove Restoration Site. Success criteria were met. |
| Lewis | 2005 | Lewis RR, AB Hodgson, and PL McNeese and CR Kruer. 2005. Rapid ecological assessment (REA) (Phase 1) for mangroves within the runway 07-25 clear zone, Boca Chica Field Naval Air Station Key West (NASKW), Monroe County, Florida. 51 p. | A rapid ecological assessment (REA) of existing mangroves within a proposed runway clear zone at Naval Air Station Key West. The results of the REA emphasize the importance of assessing the existing hydrology of natural mangrove ecosystems, and applying this knowledge to assessing the functional quality of the mangrove habitats for managed marine and estuarine fish species using an understanding of mangrove hydrology. |
| Lewis | 2005 | Lewis RR, AB Hodgson, and GS Mauseth. 2005. Project facilitates the natural reseeding of mangrove forests (Florida). Ecological Restoration 23(4):276-77. | To eliminate the cost of and labor of actively replanting mangrove forests, four steps are recommended: 1) determine why mangroves are not present, 2) correct defective condition or pick another site, 3) refer to local reference mangrove sites for normal topography and tidal elevations, and 4) design the restoration to mimic the normal hydrology. Improving hydrology may save $59,305 in labor costs associated with planting in areas where propagule limitation is unlikely. |
| Lewis | 2005 | Lewis, RR. 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng. 24(4 SI): 403-418. (English) | Previous research has documented the general principle that mangrove forests worldwide exist largely in a raised and sloped platform above mean sea level, and inundated at approximately 30%, or less of the time by tidal waters. More frequent flooding causes stress and death of these tree species. Prevention of such damage requires application of the same understanding of mangrove hydrology. |
| Lewis | 2007 | Lewis, RR and RG Gilmore. 2007. Important considerations to achieve successful mangrove forest restoration with optimum fish habitat. Bull. Mar. Sci. 80(3):823-837. | Tidal hydrology must be carefully designed to incorporate fish habitat, including tidal creeks, to provide access and low tide refuge for mobile nekton because the mangrove forest floor is generally flooded by tidal waters less than 30 percent of the time. A fully successful restoration design must mimic tidal stream morphology and hydrology along an estuarine gradient across a heterogeneous mixture of mangrove ecosystem communities. A case study illustrates the principal of hydrologic connection in the design. |
| Lewis | 2009 | Lewis, RR 2009. Methods and criteria for successful mangrove forest restoration. Chapter 28., pages 787-800 in GME Perillo, E Wolanski, DR Cahoon, and MM Brinson (eds.) Coastal | Greater mangrove restoration success can be achieved with a four-step approach that includes:<br>1. General site selection for restoration sites that includes examination of multiple coastal basins that contain mangroves.<br>2. Specific site selection that looks at the history of changes in areal cover of mangroves and changes in hydrology at specific |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Wetlands: An Integrated Ecosystem Approach. Elsevier Press. | potential restoration sites, and targets hydrologic restoration of these sites.<br>3. Establishing quantitative and measurable success criteria and use uniform criteria between study sites.<br>4. Monitoring and reporting of progress toward achieving these success criteria, including reporting on lessons learned from both successes and failures. |
| Lewis | 2010 | Lewis, RR. 2010. Mangrove field of dreams: if we build it, will they come? SWS research Brief No. 2009-005. 4 p. Wetland Science and Practice 27(1):15-18. | In the Philippines, mangrove restoration failure was attributed to two assumptions regarding restoration: 1) Mangroves can only be restored by planting and 2) Sub-tidal mud flats are suitable for planting, when in fact they likely never supported a mangrove forest in the first place. In addition to the need to understand the existing hydrology as it relates to topography of an adjacent mangrove forest reference area, it is also important to understand the natural recovery processes in damaged mangrove forest areas, also known as “secondary succession.” |
| Lewis | 2011 | Lewis, RR. 2011. How successful mangrove forest restoration informs the process of successful general wetlands restoration. National Wetlands Newsletter 33(4):23-25. | The probability of successful restoration of various wetland types from high to low rank are as follows: 1) Estuarine Marshes, 2) Coastal Marches, 3) Mangrove Forests, 4) Freshwater Marshes, 5) Freshwater Forests, 6) Groundwater Seepage Slope Wetlands, and 7) Seagrass Meadows. The natural secondary succession process in damaged mangrove forests often begins with the appearance of a "nurse species," which is typically a herbaceous plant species such as smooth cordgrass and saltwort. |
| Lewis | 2014 | Lewis, RR and LL Flynn. 2014. Mangrove zone ecology. Oxford Bibliographies in Ecology. www.oxfordbibliographies.com. Oxford University Press, New York. 10 p. | An annotated bibliography grouped by General Overviews, Journals, Databases, Defining the Mangrove Zone, Zonation and Hydrology, General Distribution and Area, Ecological Functions, Value of Mangroves to Humans, Management and Restoration, and Sea Level Rise. |
| Lewis | 2014 | Lewis, RR and B Brown. 2014. Ecological mangrove rehabilitation – a field manual for practitioners. Version 3. Mangrove Action Project Indonesia, Blue Forests, Canadian International Development Agency, and OXFAM. 275 p. (ENGLISH) | Well-laid out manual, for world-wide application. The focus is Ecological mangrove restoration (EMR) and defined as: “an approach to coastal wetland rehabilitation or restoration that seeks to facilitate natural regeneration in order to produce self sustaining wetland ecosystems.” Ecological Mangrove Rehabilitation engages communities to consider social, economic and ecological factors before undertaken mangrove restoration, and relies on monitoring to inform corrective actions over time. Many tools and examples are offered. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| Lewis | 2014 | Lewis RR. 2014. Mangrove forest restoration and the preservation of mangrove biodiversity. Pages 195-200 in Bozzano, M., Jalonen R., Evert, T., Boshier, D., Gallo, L., Cavers, S., Bordacs, S., Smith, P., and Loo, J. (eds). Genetic considerations in ecosystem restoration using native tree species. A thematic study for the State of the World's Forest Genetic Resources. United Nations Food and Agriculture Organization, Rome, Italy. I-xi + 271 p | Mangrove restoration projects should be more designed to ensure successful establishment of a biodiverse plant cover over large areas at minimal cost. This can be achieved, for example, by restoring hydrologic connections to impounded mangrove areas, as has been done in Florida. Use of non-native species of mangroves in management and restoration projects should be avoided. |
| Lewis | 2016 | Lewis, RR, EC Milbrandt, B Brown, KW Krauss, AS Rovai, JW Beever III, and LL Flynn. 2016. Stress in mangrove forests: Early detection and preemptive rehabilitation are essential for future successful worldwide mangrove forest management. Marine Pollution Bulletin, Volume 109, Issue 2, 30 August 2016, Pages 764–771 | Mangrove forest rehabilitation should begin much sooner than at the point of catastrophic loss. Describes the need for "mangrove forest heart attack prevention", and how that might be accomplished by embedding plot and remote sensing monitoring within coastal management plans. The major cause of mangrove is often linked to reduced tidal flows and exchanges. Blocked water flows can reduce flushing not only from the seaward side, but also result in higher salinity and reduced sediments when flows are locked landward. Often, mangroves are lost within a few years; however, vulnerability is re-set decades earlier when seemingly innocuous hydrological modifications are made (e.g., road construction, blocked tidal channels), but which remain undetected without reasonable large-scale monitoring. |
| Lindall | 1977 | Lindall, W.N., and C.H. Saloman. 1977. Alteration and destruction of estuaries affecting fishery resources of the Gulf of Mexico. Marine Fisheries Review 39, paper 1262. | Estimates off fishery habitats of the Gulf of Mexico inlcuding the loss of mangrove forests. |
| Lugo | 1974 | Lugo, AE and SC Snedaker. 1974. The ecology of mangroves. Pp 39-64 In: Annual review of ecological systems, vol 5. | In South Florida, five basic mangrove community types are distinguished by the hydrological and tidal characteristics. These are: 1) the fringe forest, 2) riverine forest, 3)overwash forest, 4 basin forest and 5) dwarf forest. The classification has also been applied to mangroves in Puerto Rico, Mexico and Central America. |
| Lugo | 1976 | Lugo, A.E., M. Sell, and S.C. Snedaker. 1976. | Ecosystem analysis of mangrove ecosystem incorporating conceptual modeling. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Mangrove ecosystem analysis. Pages 113-145 in B.C. Patten (ed.), Systems analysis and simulation in ecology. Academic Press, New York, New York. | |
| Lugo | 1977 | Lugo, A.E., and C. Patterson-Zucca. 1977. The impact of low temperature stress on mangrove structure and growth. Tropical Ecology 18:149-161. | Effects of cold on mangrove growth and survival as an explanation of northern and interior range. |
| Lugo | 1980 | Lugo AE, RR Twilley and C Patterson-Zucca 1980. The role of black mangrove forests in the productivity of coastal ecosystems of south Florida. EPA Report R806079010, Center For Wetlands, University of Florida, Gainesville. | Two year study in southwest Florida proved conclusively that black mangroves connect to marine waters, the protein quality of their export is higher than red mangroves and black mangroves export more organic matter to marine waters in absolute amounts than do red mangroves. This disproved E Heald and D Tabb assertions that black mangroves had no positive role in marine food chains. |
| Lugo | 1981 | Lugo, A.E., Cintrón, G., Goenaga, C., 1981. Mangrove ecosystems under stress. In: Barrett, G.W., Rosenberg, R., Eds., Stress Effects on Natural Ecosystems. John Wiley & Sons Ltd., Great Britain, pp. 129–153. | Any activity that covers the root systems with water or mud for a long period will kill the trees by preventing oxygen transport to the deeper roots. |
| Lugo | 1999 | Lugo, A.E., 1999. Mangrove forests: a tough system to invade, but an easy one to rehabilitate. Mar. Poll. Bull. 37, 427–430. | Mangrove forests are tough ecosystems to invade because few species can tolerate the hydrological and edaphic conditions that prevail in mangrove habitats. The small pantropical mangrove species pool is also the basis for asserting that mangrove forests are easy to rehabilitate, at least in terms of tree species composition. The high complexity of the animal and microbial component of mangrove ecosystems is not addressed in this article. The following questions are useful as a guide for evaluating the invasion of plant species into mangrove habitats: (1) Is the invading species a halophyte? (2) What conditions of the environment is the invading species occupying and how long will those conditions last? (3) What is the geographic location of the invasion, does it penetrate the forest or is it only at the edge? (4) Is the invasion a short-term response to changes in microsite conditions? (5) Is the invasion the result of a long-term shift in the mangrove habitat? |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| Mauseth | 2001 | Mauseth, G.S., J. S. U-Donnelly and R. R. Lewis. 2001. Compensatory restoration of mangrove habitat following the Tampa Bay oil spill. Pages 761-767 in Proceedings of the 2001 International Oil Spill Conference, Volume 1, March 26-29, 2001, Tampa, Florida. USEPA, API, IPIECA, IMO, US Coast Guard. 771 p. | In 1993, a discharge of 300,000 gallons of fuel oil was discharged into the waters of Egmont Key. To compensate for the impacts to epibenthic communities, fish and bird habitats, wetlands and mangrove communities, a 10.67-acre parcel with acquired and title transferred to Pinellas County. The goal was to establish a typical Tampa Bay mangrove forest and roadside buffer free of exotic plant species. Tidal exchange through the site was reestablished to improve water quality and increase export of mangrove detritus and import of high-quality tidal waters. |
| McCleod | 2011 | McCleod, E, GL Chmura, S Bouillon, R Salm, M Bjork, CM Duarte, CE Lovelock, WH Schlesinger and BR Sullivan. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front. Ecol. Environ. 9(10): 552-560. | The carbon © sequestered in vegetated coastal ecosystems, specifically mangrove forests, seagrass beds, and salt marshes, has been termed “blue carbon”. If these systems mangroves have the highest average carbon burial rate based on 34 sites. Several critical questions must be addressed to improve our understanding of the fate of C sequestered in vegetated coastal ecosystems, including: (1) how are sequestration rates affected by ecosystem loss, and what is the fate of existing sediment C stocks? (2) How may sequestration rates and C stocks in sediments be affected by climate change? (3) What recommendations can be made to inform future C sequestration research? |
| McKee | 2011 | McKee, KL. 2011. Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems. Est. Coast. Shelf Sci. 91:475-483. | This study indicates that biotic processes of root production and benthic mat formation are important controls on accretion and elevation change in mangrove ecosystems common to the Caribbean Region. Quantification of specific biological controls on elevation provides better insight into how sustainability of such systems might be influenced by global (e.g., climate, atmospheric CO2) and local (e.g., nutrients, disturbance) factors affecting organic matter accumulation, in addition to relative sea-level rise. Sites in Southwest Florida all showed a positive accretion rate, with the three restored sites among the highest elevation change due to root input. |
| McLeod | 2006 | McLeod, E, and RV Salm. 2006. Managing mangroves for resilience to climate change. IUCN, Gland, Switzerland. 64 p. | Local conditions are described which makes mangrove forests more or less vulnerable to the effects of climate change. Overwash islands are most vulnerable. Riverine mangroves and fringe mangroves with undeveloped areas behind them are the least vulnerable. Ten recommendation to improve resiliency include: 1) Apply risk-spreading strategies to address the uncertainties of climate change. 2) Identify and protect critical areas that are naturally positioned to survive climate change. 3) Manage human stresses on mangroves. 4) Establish greenbelts and buffer zones to allow for mangrove migration in response to sea-level rise, and to reduce impacts from adjacent land-use practices. 5) Restore degraded areas that have demonstrated resistance or resilience to climate change. 6) Understand and preserve connectivity between |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | mangroves and sources of freshwater and sediment, and between mangroves and their associated habitats like coral reefs and seagrasses. 7) Establish baseline data and monitor the response of mangroves to climate change. 8) Implement adaptive strategies to compensate for changes in species ranges and environmental conditions.9) Develop alternative livelihoods for mangrove dependent communities as a means to reduce mangrove destruction. 10) Build partnerships with a variety of stakeholders to generate the necessary finances and support to respond to the impacts of climate change. |
| Montague | 1990 | ıe, C.L. and R.G. Wiegert. ılt marshes. Pages 481-516 in ers and J.J. Ewel, eds. ɛms of Florida. University of Florida Press; Orlando, | Description of the salt marsh communities of Florida |
| Myint | 2008 | Myint, S.W., Yuan, M., Cerveny, R.S., and Giri, C.P., 2008, Categorizing natural disaster damage assessment using satellite-based geospatial techniques: Natural Hazards and Earth System Sciences, v. 8, no. 4, p. 707-719, available only online at http://www.nat-hazards-earth-systsci.net/volumes_and_issues.html. | This study demonstrates that satellite-based geospatial techniques can effectively add spatial perspectives to natural disaster damages, and in particular for this case study, tornado damages. |
| National Wetland Inventory | 1982 | National Wetland Inventory, 1982. Online Washington D.C. | Marshes, swamps, ponds, and bogs are teeming biological nurseries for migratory birds, fish, and aquatic plants. They also provide natural flood and erosion control. These predominantly wet areas, or wetlands as they are commonly called, now represent only about 5 percent of the land surface of the lower 48 States. Out of 221 million acres of wetlands that once existed in the conterminous United States, the U.S. Fish and Wildlife Service (FWS) estimates that only about 103.3 million acres remain. Each year, development, drainage, and agriculture eliminate another 290,000 acres - an area a little less than half the size of Rhode Island. From the 1950's to the 1970's, conversion of wetlands to farmland caused 87 percent of all wetland losses. The FWS has long recognized the importance of America's wetlands because they form breeding and wintering grounds for great numbers of migratory birds. In 1977, the FWS began the National Wetlands Inventory (NWI), a systematic effort to classify and map America's remaining wetlands. |
| Nieves-Rivera | 2005 | Nieves-Rivera, A. M., T. A. Tattar and L. Ryvarden. 2005. Manglicolous | Fungi that cause decay in woody tissues of mangroves in SW Puerto Rico and SW Florida are identified. These fungi can act as saprophytes on dead and dying mangroves and also can |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | basidiomycetes of southwestern Puerto Rico and southwestern Florida (U.S.A.). Hoehnea 32: 49-57. | act as pathogens, that have the capacity to cause wood decay diseases, in living trees. Their key ecological role is carbon recycling of lignified xylem tissues. |
| Odum | 1975 | Odum, W.E., and R.E. Johannes. 1975. The response of mangroves to man-induced environmental stress. Pages 52-62 in E.J.F Wood and RE Johannes (eds.), Tropical Marine Pollution. Elsevier (Oceanography Series), Amsterdam, Netherlands. | Two factors render mangroves susceptible to certain types of pollutants. First, because they are growing under metabolically stressful conditions, any factor that further stresses the tree may be potentially fatal. Second, their modified root systems with lenticels and pneumatophores are especially vulnerable to clogging |
| Odum | 1982 | Odum, WE, McIvor, CC, and Smith, III, TJ 1982. The ecology of the mangroves of South Florida: a community profile: U.S. Fish and Wildlife Service, FWS/OBS-81/24. 154 p. | The document presents a comprehensive treatment of the mangrove forest structure, adaptations, functions, community and management. This appears to be the first presentation of the six mangrove forest types, referencing Lugo and Snedaker (1974)'s Five mangrove forest types (fringe, riverine, overwash basin and dwarf) but adding hammock forest as a sixth type. |
| Odum | 1990 | Odum, W.E. and C.C. McIvor. 1990. Mangroves. Chapter 15, pp. 517-548 In: Ecosystems of Florida. J. Ewel and R. Myers (Eds.), University of Central Florida Press, Orlando, FL, 765 pp. | Review of Florida Mangrove ecosystems. |
| Orians | 1970 | Orians, GH, and EW Pfeiffer. 1970. Ecological effects of the war in Vietnam. Science 168:544-554. | A review listing sources of information, outlining the operational aspects of the defoliation programme, and covering: the effects of defoliants on trees (especially Mangroves), upland forests, animals, and Rubber culture; the effects of accidental defoliation; the deliberate destruction of crops; the effects of the craters made by 500- and 750-lb. bombs dropped in raids by B-52 bombers; and miscellaneous effects of the war (e.g. air pollution in Saigon, fires and uncontrolled hunting). |
| Orr | 2005 | Orr, J. Victoria J. Fabry, Olivier Aumont, Laurent Bopp, Scott C. Doney, Richard A. Feely, Anand Gnanadesikan, Nicolas Gruber, Akio Ishida, Fortunat Joos, Robert M. Key, Keith Lindsay, Ernst Maier-Reimer, Richard Matear, Patrick Monfray, Anne Mouchet, Raymond G. | Effects of acidification of oceans and estuaries including dissolution of calcium rocks and karsts. Discusses chemistry leading to increased acidification of rain and subsequent receiving waters. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Najjar, Gian-Kasper Plattner, Keith B. Rodgers, Christopher L. Sabine, Jorge L. Sarmiento, Reiner Schlitzer, Richard D. Slater, Ian J. Totterdell, Marie-France Weirig, Yasuhiro Yamanaka & Andrew Yool. 2005, Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms , Nature, vol. 437, pp. 681-686 | |
| Parkinson | 1999 | Parkinson, RW, M Perez-Bedmar and HA Santangelo. 1999. Red mangrove (Rhizophora mangle L.) litter fall response to selective pruning (Indian River Lagoon, Florida, U.S.A.) in R.S. Dodd (ed.), Diversity and Function in Mangrove Ecosystems. Hydrobiologia 413: 63–76, | This 33 month study quantified red mangrove (Rhizophora mangle L.) litter fall response to a selective pruning event using fringing forests located along the Indian River Lagoon. Subcanopy light transmission data were used to estimate the impact of pruning on canopy closure and monthly measurements were obtained thereafter to monitor recovery. Following selective pruning, subcanopy light transmission increased by more than 30%. This provided a favorable environment for enhanced mangrove propagule recruitment, but several exotic species, including Brazilian Pepper (Schinus terebinthifolius), also invaded the forest beneath canopy gaps. Subcanopy light transmission within the impact plots has steadily declined since pruning and within 12 months had approached control plot levels. |
| Parkinson | 2015 | Parkinson, RW, PW Harlem and JF Meeder 2015. Managing the Anthropocene marine transgression to the year 2100 and beyond in the State of Florida U.S. Climatic Change (2015) 128:85–98 | The vulnerability of all 35 Florida coastal counties to the ongoing Anthropocene marine transgression was assessed using a bathtub model unconstrained by the artificial end date of year 2100. This regional approach is designed to facilitate the implementation of effective adaptation activities by providing a logical basis for establishing or re-enforcing collaboration based upon a common threat and the utility of shared technical and financial resources. The benefits of a regional perspective in formulating an actionable response to climate change have already been demonstrated in south Florida. It is our intent to facilitate regional adaptation activities in other parts of the state and adjacent southern and southeastern seaboard. Region 4 includes Lee, Charlotte, Sarasota, Manatee, Hillsborough, and Pinellas counties.<br>It is distinguished from adjacent regions by the presence of well-developed barrier islands and large estuarine embayments (i.e., Caloosahatchee River, Charlotte Harbor, Tampa Bay). Like the other two regions in this vulnerability category, it is classified as ‘higher’ (between high and highest) because the geomorphic landscape consists of a mixture of both low lying coastal terrain and an elevated topography associated with relict ridges. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| Pastor-Guzman | 2015 | Pastor-Guzman, J, P Atkinson, J Dash and R Rioja-Nieto. Spatiotemporal Variation in Mangrove Chlorophyll Concentration Using Landsat 8. Remote Sens. 2015, 7, 14530-14558; doi:10.3390/rs71114530. | Pastor-Guzman *et al* compared 20 hyperspectral and broad band vegetation indices to relative mangrove canopy chlorophyll measured at 12 sites along the northwest coast of the Yucatan Peninsula, Mexico. The sites were 30m by 30m to represent Landsat spatial resolution. The purpose of the work was to develop indicators of mangrove condition using remotely sensed data. Of the indices, normally distributed vegetation index green (NDVIgreen) was the most sensitive to canopy chlorophyll at the site level (R2 = 0.805.) The formula for NDVIgreen uses the near infrared and green bands. We found the NVDIgreen index to be an excellent indicator of mangrove condition in the Charlotte Harbor area. |
| Patterson | 1986 | Patterson, SG. 1986. Mangrove community boundary interpretation and detection of aerial changes on Marco Island, Florida: application of digital image processing and remove sensing techniques. US Fish and Wildlife Service, Biological Report 86(10). 87 p. | The document includes early work related to effects of human impacts and the use of color infrared imagery. The work suggests that darker tidal creeks within a mangrove fringe should be classified as riverine mangrove. Finally, the document provides guidance related to aerial photograph (and other imagery) interpretation of mangrove systems by type and species, most notably on page 33. |
| Patterson-Zucca | 1978 | Patterson-Zucca, C. 1978. The effects of road construction on a mangrove ecosystem. MS thesis. University of Puerto Rico, Rio Piedras, Puerto Rico. 77 pp. | Documentation of the negative effects of road construction on mangroves including mangrove forest death |
| Pomeroy | 1981 | Pomeroy, L.R. and R.G. Wiegert. 1981. Ecology of a salt marsh. Ecological Studies Series. Volume 38. Springer-Verlag; New York, New York. | Comprehensive book on salt marshes |
| Pool | 1975 | Pool, D.J., A.E. Lugo, and S.C. Snedaker. 1975. Litter production in mangrove forests of south Florida and Puerto Rico. Pages 213-237 in G. Walsh, S. Snedaker, and H. Teas (eds.), Proceedings of the international symposium on the biology and management of mangroves. University of Florida, Gainesville, Florida. | Information on litter fall and mangrove productivity in Florida and Puerto Rican mangrove swamps. The NPP exported from natural red mangrove fringe, in the form of utilizable mangrove detritus has been measured at 9.9 metric tons/ha/yr. |
| Pool | 1977 | Pool, DJ, SC Snedaker and | The riverine and basin mangrove forests of the southwestern |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | AE Lugo. 1977. Structure of mangrove forests in Florida, Puerto Rico, Mexico and Costa Rica. Biotropica 9(3): 195-212. | coast of Florida had considerably taller trees (6-9 m) and larger basal areas (20.3-38.5 m2/ha) than did scrub mangrove growing on the southeastern Coast of Florida where a low canopy (1.0 m), a low basal area (6.0 m2/ha), and a correspondingly low complexity index (1.5) were measured. |
| Rabinowitz | 1978 | Rabinowitz, D. 1978. Early growth of mangrove seedlings in Panama and an hypothesis concerning the relationship of dispersal and zonation. Journal of Biogeography 5:113-133. | Characteristics of dispersal and establishment for water-borne mangrove propagules, including period and pattern of floating, period of obligate dispersal, time to root firmly, longevity, and vigor, are estimated for six species in Panama (Laguncularia racemosa, Avicennia germinans, A. bicolor, Rhizophora mangle, R. barrisonii, and Pelliciera rhizophorae). Dispersal properties correlate with the spatial distribution of adults within the swamp. Genera whose adults are found on higher ground, on the landward edge of the intertidal zone, have small propagules that require a period of freedom from tidal inundation of approximately five days in order to establish firmly in the substrate. Genera whose adults are found on the seaward edge of the swamp, in deeper water, have large, heavy propagules. |
| Ragotzkie | 1959 | Ragotzkie, R.A., L.R. Pomeroy, J.M. Teal, D.C. Scott, eds. 1959. Proceedings of saltmarsh conference, Marine Institute, University of Georgia, Sapelo Island, Georgia. Marine Institute, University of Georgia; Athens, Georgia. Page 3-588 | Collection of studies on salt marshes of the southeastern United States |
| Ranwell | 1972 | Ranwell, D.S. 1972. Ecology of salt marshes and sand dunes. Chapman and Hall; London, England. | Book containing salt marsh studies worldwide with emphasis on Europe. |
| Rey | 2012 | Rey, JR, DB Carlson and RE Brockmeyer Jr. 2012. Coastal wetland management in Florida: environmental concerns and human health. Wetl. Ecol. Manage. 20(3):197-211. | Wetland management efforts to reduce mosquito populations along Florida's coastal areas date back to the 1920s and have included ditching, dredging and filling, and impounding. The paper discusses management and restoration techniques that minimize environmental impacts, allow for mosquito control, and minimize the need for pesticide use. |
| Rovai | 2012 | Rovai, SR, EJ Soriano-Sierra, PR Pagliosa, G Cintron, Y Schaeffer-Novelli, RP Menghini, C Coelho Jr., PA Horta, RR Lewis III, JC Simonassi, JAA Alves, F Boscatto and SJ Dutra. 2012. Secondary succession impairment in | In this work it was hypothesized that secondary succession on sites that have been managed by single planting of mangrove species is compromised by residual stressors, which could reduce the ecosystem's structural development and lower its functions. Forest structure and environmental characteristics of three planted mangrove stands are compared with reference sites. Structural attributes showed significant differences in the comparison of planted and reference stands. At restoration sites an impaired pattern of secondary succession was |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | restored mangroves. Wetl. Ecol. Manage. 20:447-449. | observed, indicating that single species plantings may be ineffective if characteristics of the site, as well as of the area surrounding it, are not considered. The inadequate management of restoration sites can therefore have implications for both immediate and longterm large-scale ecosystem services. Page 456 includes a graph of various conditions and how successional processes are different than predicted succession. |
| Samson | 2008 | Samson, MS, and RN Rollon. 2008. Growth performance of planted red mangroves in the Philippines: revisiting forest management strategies. Ambio 37(4):234-240. | Overall, there is a widespread tendency to plant mangroves in areas that are not the natural habitat of mangroves, converting mudflats, sandflats, and seagrass meadows into often monospecific Rhizophora mangrove forests. In these nonmangrove areas, the Rhizophora seedlings experienced high mortality. Of the few that survived (often through persistent and redundant replanting), the young Rhizophora individuals planted in these nonmangrove and often low intertidal zones had dismally stunted growth relative to the corresponding growth performance of individuals thriving at the high intertidal position and natural mangrove sites. |
| Sargent | 1987 | Sargent, WB, and PR Carlson. 1987. The utility of Breder traps for sampling mangrove and high marsh fish assemblages. Pages 194-205 in FJ Webb (Ed.) Proceedings of the Fourteenth Annual Conference on Wetlands Restoration and Creation, Hillsborough Community College, Plant City, Florida. 218 p. | The document compares gear for fish assemblage sampling in different environments. |
| Shromer | 1982 | Schomer, N.S., and R.D. Drew. 1982. An ecological characterization of the lower Everglades, Florida Bay, and the Florida Keys. U.S. Fish and Wildlife Service | An ecological characterization of the lower Everglades, Florida Bay, and the Florida Keys inlcuding mangroves, salt marshes and tropical hardwood hammocks.. |
| Shafer | 2008 | Shafer, DJ and TH Roberts. 2008. Long-term development of tidal mitigation wetlands in Florida. Wetlands Ecol. Manage. 16:23-31. | Eighteen Florida mangrove mitigation sites originally sampled in 1988 were revisited in 2005. Even after 13-25 years, stand structure in mangrove mitigation wetlands in Florida still differed from that of natural sites. Mitigation sites had lower basal area and height than natural sites and were more dense and complex than natural sites. The most common patter was an increase in volunteer Laguncularia at site where Rhizophora had been planted. Volunteer recruitment and colonization by Avicennia was observed less frequently. Four or five of the sites are in the CHNEP study area. |
| Sheaves | 2015 | Sheaves, M, R Baker, I | Ten key components of nursery habitat value are grouped into |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Nagelkerken and RM Connolly. 2015. True Value of Estuarine and Coastal Nurseries for Fish: Incorporating Complexity and Dynamics. Estuaries and Coasts (2015) 38:401–414. | three types: (1) connectivity and population dynamics (includes connectivity, ontogenetic migration and seascape migration), (2) ecological and ecophysiological factors (includes ecotone effects, ecophysiological factors, food/predation trade-offs and food webs) and (3) resource dynamics (includes resource availability, ontogenetic diet shifts and allochthonous inputs). By accounting for ecosystem complexities and spatial and temporal variation, these additional components offer a more comprehensive account of habitat value. |
| Snedaker | 1982 | Snedaker, S.C. 1982. Pages 111-125 in Contributions to the ecology of halophytes. D.N. Sen and K.S. Rajpurohit (eds.), Volume 2 The Hague: D.W. Junk. | Black mangroves are shade tolerant and sun intolerant when immature, but become shade intolerant with maturation |
| Snedaker | 1993 | Snedaker, SC. 1993. Impact on mangroves. Pages 282-305 in GA Maul (ed.), Climatic change in the Intra-American Seas: implications of future climate change on the ecosystems and socio-economic structure of the marine and coastal regimes of the Caribbean Sea, Gulf of Mexico, Bahamas and N.E. Coast of S. America. Edward Arnold, London. (see link to download # 18 above). | The "Intra-American Sea" or "Wider Caribbean Region" includes the Gulf of Mexico, south to the east coast of South America. The region includes 14% of the worlds mangroves. Mangroves are more likely to be affected by changes in regional precipitation rather than rising temperature and sea level. Mangrove areas that receive substantial precipitation and freshwater runoff are likely to persist, whereas mangrove areas exposed to full-strength seawater may be overstepped and lost. Because of the importance of intertidal mangroves in shoreline protection, fisheries support and water quality, efforts should be taken by the appropriate authorities and organizations to curb abuses and protect the resource for both ecological and economic purposes. |
| Snedaker | 1995 | Snedaker, S (1995) Mangroves and climate change in the Florida and Caribbean region: scenarios and hypotheses. Hydrobiologia, 295, 43-49. | The principal scenario concerning the potential effects of climate change on mangrove forest communities revolves around sea level rise with emphases on coastal abandonment and inland retreat attributable to flooding and saline intrusion. However, at the decade to century scale, changes in precipitation and catchment runoff may be a more significant factor at the regional level. Specifically, for any given sea level elevation it is hypothesized that reduced rainfall and runoff would necessarily result in higher salinity and greater seawater-sulfate exposure. This would likely be associated with decreased production and increased sediment organic matter decomposition leading to subsidence. In contrast, higher rainfall and runoff would result in reduced salinity and exposure to sulfate, and also increase the delivery of terrigenous nutrients. Consequently, mangrove production would increase and sediment elevations would be maintained. Support for this scenario derives from studies of the high production in saline mangrove impoundments which are |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | depleted in seawater sulfate. This paper also examines other components of climate change, such as UVb, temperature, and storm frequency, and presents a suite of hypotheses and analytical protocols to encourage scientific discussion and testing. |
| Spalding | 2014 | Spalding, M, A McIvor, FH Tonneijk, S Toi and P van Eijk. 2014. Mangroves for coastal defense. Guidelines for coastal managers and policy makers. Wetlands International and The Nature Conservancy. The Netherlands. 42 p. | The key messages are organized by 1) Is my shore at risk?, 2) The role of mangroves in coastal risk reduction, 3) Managing mangroves for coastal defense and 4) Recognizing the multiple values of mangroves. Of particular note: • Wind and swell waves are rapidly reduced as they pass through mangroves, lessening wave damage during storms.<br>• Wide mangrove belts, ideally thousands of meters across, can be effective in reducing the flooding impacts of storm surges occurring during major storms (also called cyclones, typhoons or hurricanes). This can significantly reduce flood extent in low lying areas. Narrower mangrove belts, hundreds of meters wide, will still be able to reduce wind speed, the impact of waves on top of the surge and flooding impact to some degree.<br>• Wide areas of mangroves can reduce tsunami heights, helping to reduce loss of life and damage to property in areas behind mangroves.<br>• The dense roots of mangroves help to bind and build soils. The above-ground roots slow down water flows, encourage deposition of sediments and reduce erosion.<br>• Over time mangroves can actively build up soils, increasing the thickness of the mangrove soil, which may be critical as sea level rise accelerates.<br>• Mangroves don’t always provide a stand-alone solution; they may need to be combined with other risk reduction measures to achieve a desired level of protection. If they are integrated appropriately, mangroves can contribute to risk reduction in almost every coastal setting, ranging from rural to urban and from natural to heavily degraded landscapes.<br>• For mangroves to optimally contribute to risk reduction, their conservation needs to be incorporated into broader coastal zone management planning: they need to be protected and restored, allowing wise use where possible.<br>• Mangroves, and their coastal risk reduction function, can recover in most places where appropriate ecological and social conditions are present or restored.<br>The book includes many useful illustrations such as complex structure versus open structure and soil building. Bulleted guidance for coastal managers will be useful in the catalog of restoration options section. |
| Spier | 2016 | D Spier, HLN Gerum, MA Noernberg, and PC Lana 2016. Flood regime as a driver of the distribution of mangrove and salt marsh | Tidal patterns of the subtropical Paranaguá Estuarine Complex, in southern Brazil, are strongly affected by episodic cold fronts and by the coastal geometry and bottom topography, resulting in high temporal variability and marked gradients in flood regime. This delimits tolerance ranges of |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | species in a subtropical estuary. Journal of Marine Systems 161 (2016) 11–25 | submersion and exposure for representative plant and animal species from local mangroves and salt marshes, through a quantitative analysis of flooding patterns in three estuarine sectors. Results are consistent with flood regime being the leading factor on how species are distributed over the intertidal flats of the PEC. Subleading factors might be related to salinity, sediment composition and nutrient flow. |
| Stohlgren | 2010 | Stohlgren, T.J., Jarnevich, C.S., and Giri, C.P., 2010, Modeling the human invader in the United States: Journal of Applied Remote Sensing, v. 4, no. 1, citation number 043509, available only online at http://dx.doi.org/10.1117/1.3357386. | A preliminary model of the spread of modern humans in the conterminous United States between 1992 and 2001 was based on a subset of National Land Cover Data (NLCD), a time series LANDSAT product. Humans have a highly predictable pattern of urbanization based on climatic and topographic variables. Conservation strategies may benefit from that predictability. |
| Strong | 1994 | Strong, A.M., R.J. Sawicki, and G.T. Bancroft. 1991. Effects of predator presence on the nesting destruction of white-crowned pigeons in Florida Bay. Wilson Bulletin 103:414-425. | In the upper Florida Keys, over 15% or 8,306 ha (20,500 acres) of the original mangrove forests were cleared for residential and commercial construction purposes by 1991 |
| Tabb | 1962 | Tabb, D.C. and A.C. Jones, 1962 Effect of hurricane Donna on the aquatic fauna of North Florida Bay. Trans.Am.Fish.Soc., 91(4):375–8 | Mangroves were killed in Hurricane Donna by direct shearing at 2 to 3 m (6 to 10 ft.) above the ground, complete wash-outs of overwash islands, and obstruction of air exchange through prop roots and pneumatophores by coatings of marl, mud and organics over the lenticels. The burial of these aerial roots was the largest cause of death. The entire aquatic system was subsequently negatively affected by the oxygen depletion caused by the decomposition of large amounts of dead organic material |
| Tattar | 1989 | Tattar, T. A. 1989. Diseases of shade trees. 2nd Edition. Academic Press, NY, 385p. | Chapter 23 describes diebacks and declines of shade trees related to complex diseases. Severe stress can sometimes cause the death of trees without the attack of secondary organisms but in many cases chronic stress lowers the defense mechanisms of trees to allow an attack. High phosphorous-low nitrogen environments and appropriate hydrology help to control stress. Better methods of early detection are needed. |
| Tattar | 2005 | Tattar, T. A., and D. C. Scott. 2004. Dynamics of tree mortality and mangrove recruitment within black mangrove die-offs in southwest Florida. Final Grant Report. University of Massachusetts. 12p. | Major black mangrove die-offs in northern Charlotte Harbor are identified. The black mangrove die-offs were caused by flooding following Hurricane Keith in 1988. This study followed the dimensions of the die-offs from aerial photographs and ground transects. Recruitment by red mangrove in the 12 ha die-off on the Cape Haze peninsula was measured from 1988 to 2004 (pre-Hurricane Charley). Smaller die-offs ( |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| Teal | 1969 | Teal, J.M. and M. Teal. 1969. Life and death of a salt marsh. Ballantine Books; New York, New York. | Description of slat march biology and loss to development in the USA |
| Teas | 1975 | Teas, H., and J. Kelly 1975. Effects of herbicides on mangroves of South Vietnam and Florida. Pages 719-728 in G. Walsh, S. Snedaker, and H. Teas (eds.), Proceedings of the international symposium on the biology and management of mangroves. University of Florida, Gainesville, Florida. | Black mangroves are somewhat resistant to most herbicides but that red mangroves are extremely sensitive. The red mangrove is particularly sensitive due to the small reserves of viable leaf buds. The stress of a single defoliation can be sufficient to kill the entire red mangrove tree. |
| Teas | 1979 | Teas, H. 1979. Silviculture with saline water. Pages 117-161 in A. Hollaender (ed.), The biosaline concept. Plenum Publishing Corporation. | The annual net primary productivity (NPP) of a 1.5 m (5 ft.) tall red mangrove system is 18% of the annual NPP of a mature system which produces 20.5 metric ton C/ha/yr . Teas derived 10.6 metric tons/ha/yr for mature red mangroves and 1.3 metric tons/ha/yr for shrubby 1.5 m (5 ft.) tall red mangrove fringes. The lowest reported NPP export for a mature red mangrove canopy of 7.3 metric tons/ha/yr. Short canopy provides only 12% to 19% of the detrital export of a mature untrimmed red mangrove fringe. Red mangrove is limited by soil salinity above 60 to 65 ppt. |
| Tomlinson | 1986 | Tomlinson, P.B. 1986. The botany of mangroves. Cambridge University Press, New York, New York. | Mangroves are tropical species restricted by frost and vegetative competition to intertidal regions in tropical and subtropical sheltered waterbodies. Mangroves in the subtropical regions of south Florida represent the northern limits of these tropical species that have been able to colonize because of the warm ocean waters and warm currents along the Florida coastline combined with dependably warm winters |
| Tschirley | 1969 | Tschirley, F.H. 1969. Defoliation in Vietnam. Science 163:779 | Mangroves were defoliated by agent orange in Vietnam and are particularly susceptible to it. |
| Turner | 1997 | Turner, RE, and RR Lewis. 1997. Hydrologic restoration of coastal wetlands. Wetlands Ecol. Manage. 4(2):65-72. | Hydrologic modification of coastal wetlands is pervasive, continuing and longstanding in the US. Appreciation for the subtleties of the direct and indirect effects of hydrologic changes on emergent vegetation, soils and co-dependent flora and fauna is contributing to restoration efforts. |
| Turrell | 2007 | Turrell, Hall and Associates and Lewis Environmental Services, Inc. 2007. Clam Bay Restoration and Management Biological Monitoring Report Number 11. Report to the Pelican Bay Services Division, | This document is the Year 8 monitoring report for the Clam Bayou restoration in Naples, Florida. Monitoring components included hydrology, water quality, and biological. Biological monitoring included eleven mangrove monitoring plots and nine seagrass transects. Additional work was completed in 2007, including 1) Clearing of fallen trees within the main waterways<br>2) Exotic and nuisance vegetation removal. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Naples, Florida. 82 p. | 3) Monitoring of the cattail and restoration areas along the berm.<br>4) Inlet bathymetric survey.<br>5) Ongoing monitoring and maintenance of the existing flushing channels.6) Develop Updated Management Plan for the Clam Bay system<br>7) Continued year-round monitoring of the system. |
| Twilley | 201 | Twilley, R.R., E.J. Barron, H.L. Gholz, M.A. Harwell, R.L. Miller, D. J. Reed, J.B. Rose, E.H. Siemann, R.G. Wetzel, and R.J. Zimmerman. 2001. Confronting Climate Change in the Gulf<br>Coast Region: Prospects for Sustaining Our Ecological Heritage. Union of Concerned Scientist, Cambridge, Massachusetts, and Ecological Society of America, Washington D.C., 82 pp. | From Texas to Florida, the Gulf coast region is rich with ecological resources that support the region's economic wealth. Over time, human activities from dam construction to shoreline development have dramatically altered natural landscapes, waterways, and ecological processes. Pressures from human activities remain the most important agents of ecological change in the region today. Over the century ahead, land-use changes are likely to increase as rapid population growth continues. Global climate change, driven by rising levels of carbon dioxide and other heat-trapping greenhouse gases in the atmosphere, will interact with, and magnify, other human stresses on Gulf Coast ecosystems and the goods and services they provide. Confronting Climate Change in the Gulf Coast Region explores the potential risks of climate change to Gulf Coast ecosystems in the context of pressures from land use. Its purpose is to help the public and policymakers understand the most likely ecological consequences of climate change in the region over the next 50 to 100 years and prepare to safeguard the economy, culture, and natural heritage of the Gulf Coast. This summary highlights key findings. |
| UNEP | 2014 | UNEP. 2014. The importance of mangroves to people: a call to action. J van Brochove, E Sullivan and T Nakamura (eds). United Nations Environment Programme World Conservation Monitoring Centre, Cambridge. 128 p. | The document provides management and policy options at the local, regional and global level with the aim of preventing further losses through effective conservation measures, sustainable management and successful restoration of previously damaged mangrove areas. Mangroves typically occur in association with other coastal ecosystems, such as coral reefs, seagrass beds, algal beds, mud flats and sand flats. While mangroves can persist in isolation, their association with other ecosystems enhances important ecological functions such as fisheries provision and biodiversity. The position of mangroves at the land-sea interface means they perform an important role trapping sediments from both the land and the sea. The complex root structures act as a physical and biological filter and reduce the flow of detrimental land-derived nutrients and sediment onto adjacent seagrass beds and coral reefs. World-wide Ecosystem services are described in great detail. |
| USFWS | 1999 | U.S. Fish and Wildlife Service. 1999. South Florida multi-species recovery plan. Atlanta, Georgia. 2172 pp. | The South Florida Ecosystem encompasses 67,346 square kilometers (26,002 square miles)<br>covering the 19 southernmost counties in Florida. This recovery plan is one of the first specifically<br>designed to recover multiple species through the restoration of |

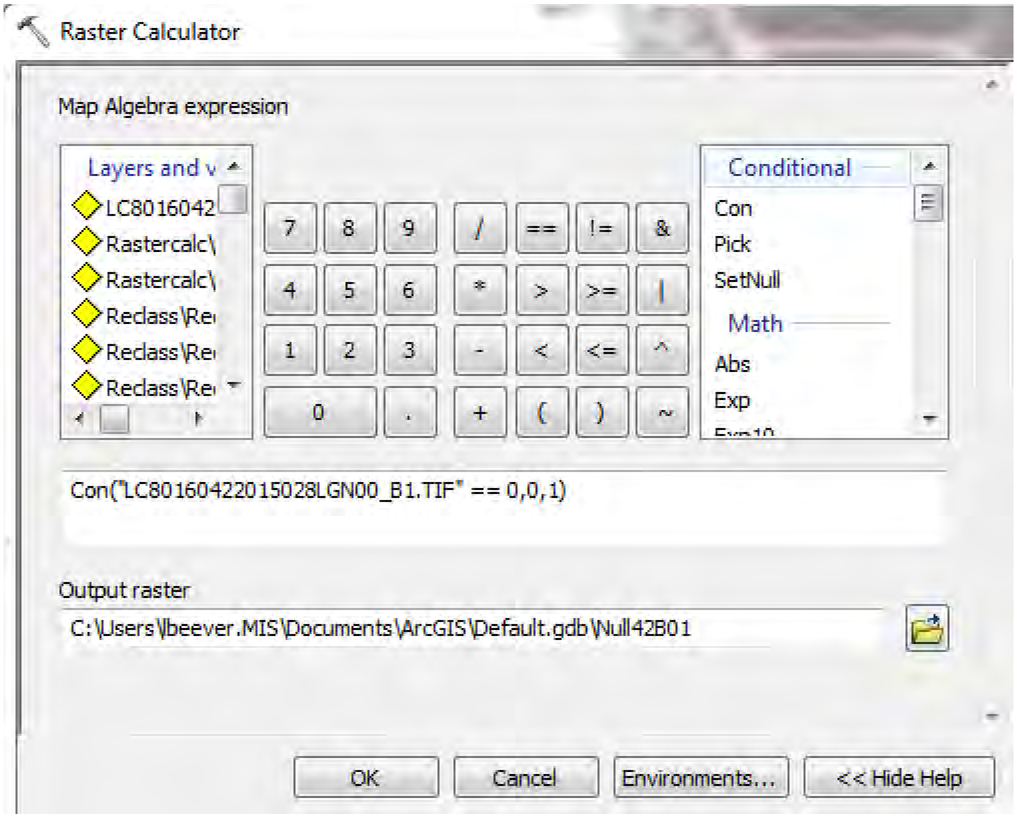
| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | | ecological communities over a large geographic area. The South Florida region supports an extremely diverse array of flora and fauna. Over 600 species are considered either rare or imperiled in South Florida; 68 of those species are federally listed as threatened or endangered, including 8 mammals, 13 birds, 10reptiles, 2 invertebrates and 35 plants. The current status of each of these species is provided in Table 1. Twenty-three of the ecological communities found within this region are inhabited by federally listed species, and are the subject of the ecosystem restoration goals in this recovery plan. These communities include: high pine; Florida scrub, including scrubby flatwoods and scrubby high pine; mesic temperate hammock; tropical hardwood hammock; pine rocklands; mesic and hydric pine flatwoods; dry prairie; cutthroat grass communities; freshwater marshes and wet prairies; forested wetlands including flowing water, pond, and seepage swamps; beach dune, coastal strand, and maritime hammock; coastal salt marsh; mangroves; seagrasses; and nearshore and midshelf reefs. |
| USGS | 2003 | Predicting Future Mangrove Forest Migration in the Everglades Under Rising Sea Level. USGS Fact Sheet FS-030-03. March 2003. 2 p. | An integrated landscape model, SELVA-MANGRO, was developed to simulate the dynamics and distribution of mangrove communities of south Florida. SELVA-MANGRO results show that species and forest cover will change over space and time with increasing tidal inundation across the simulated landscape for all sea-level rise scenarios. The model shows that freshwater marsh and swamp habitats will be displaced as the tidal prism increases over time and moves upslope. |
| USGS | 2003 | Effects of Hydrology on Red Mangrove Recruits. USGS Fact Sheet FS-029-03. March 2003. 2 p. | Red mangrove recruits exposed to tidal fluctuation experienced greater growth than those confined to static water levels. Salinity may have less effect on mangrove growth and development than hydrologic conditions and substrate quality, particularly in freshwater and brackish zones. |
| Walsh | 1973 | Walsh, G.E., R. Barrett, G.H. Cook, and T.A. Hollister. 1973. Effects of herbicides on seedlings of red mangrove, Rhizophora mangle. Bioscience 23:361-364. | Red mangrove tree seedlings are particularly susceptible to herbicide damage. |
| Westing | 1971 | Westing, A.H. 1971. Forestry and the war in South Vietnam. Journal of Forestry 69:777-784. York, New York. | Effects of herbicides on mangroves in Vietnam. |
| Wiegert | 1990 | Wiegert, R.G., and B.J. Freeman. 1990. Tidal marshes of the southeast | Community profile of tidal salt marshes. |

| First Author | Year | Citation | Annotation |
|---|---|---|---|
| | | Atlantic coast: A community profile. U.S. Department of Interior, Fish and Wildlife Service, Biological Report 85(7.29), Washington, D.C. | |
| Wier | 1996 | Wier, A. W., A. Schnitzler, T. A.Tattar, E.J. Klekowski, and A. I. Stern 1996. Wound periderm development in red mangrove, Rhizophora mangle L International J. Plant Sciences 157:63-70. | Wounds from invertebrate feeding have been found to be a major source of seedling mortality in red mangroves. Seedling survival following wounding depends of the formation of wound periderm to compartmentalize and seal wounds from infection. Histological studies of wound periderm formation were conducted on red mangrove seedlings. Photosynthetic mutant seedlings were found to have diminished ability to form wound periderm. |

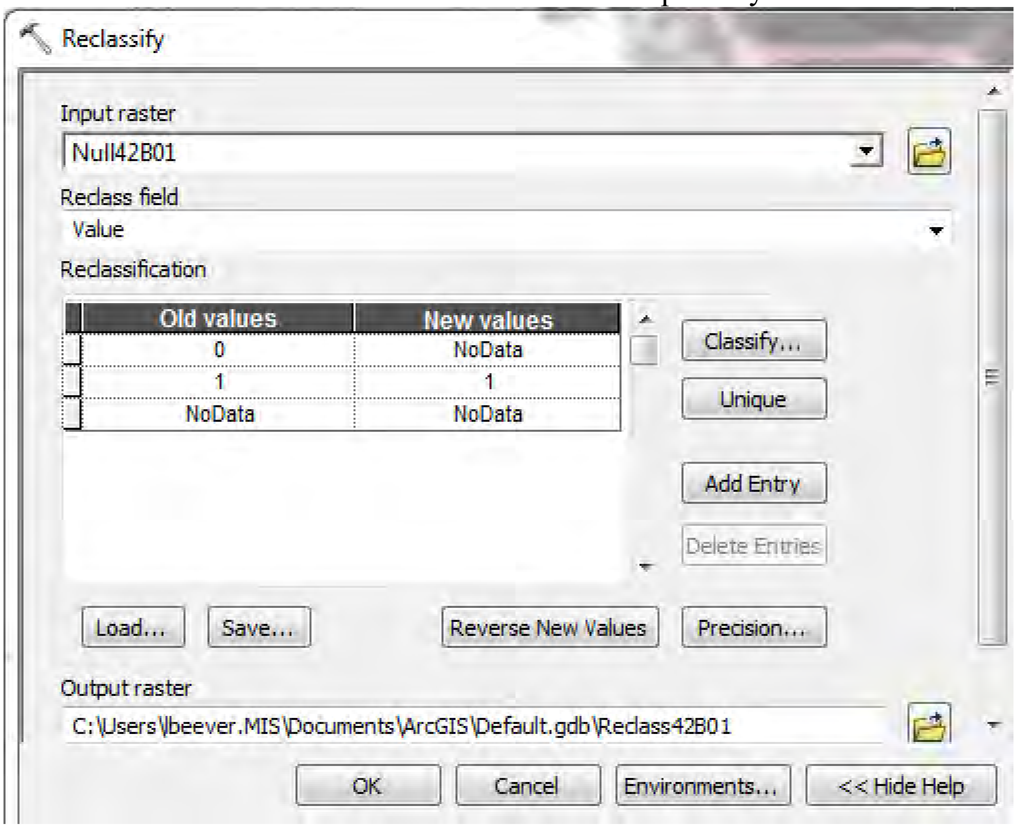
# Appendix A: Raster Manipulation Methods

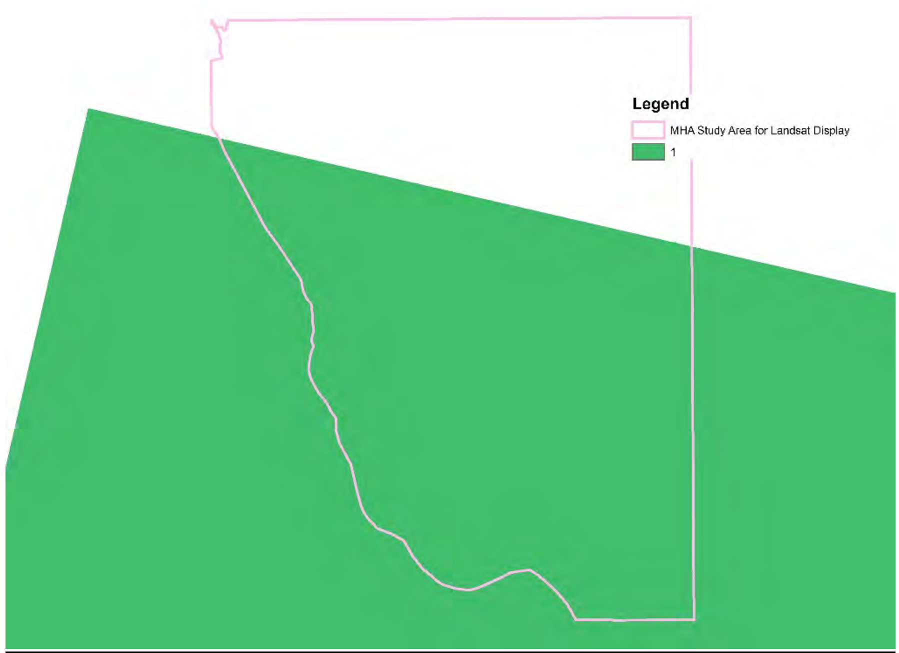
Preparation of the raw Landsat files included the following Carter (2010):

1. <u>Create "Null" file for each scene</u>. Use Spatial Analyst-Map Algebra-Raster Calculator to define the null areas of the scene. For example, Con("LC80160412015028LGN00_B1.TIF" == 0,0,1) yields a file we called Null42B01. The resulting file is shown below.

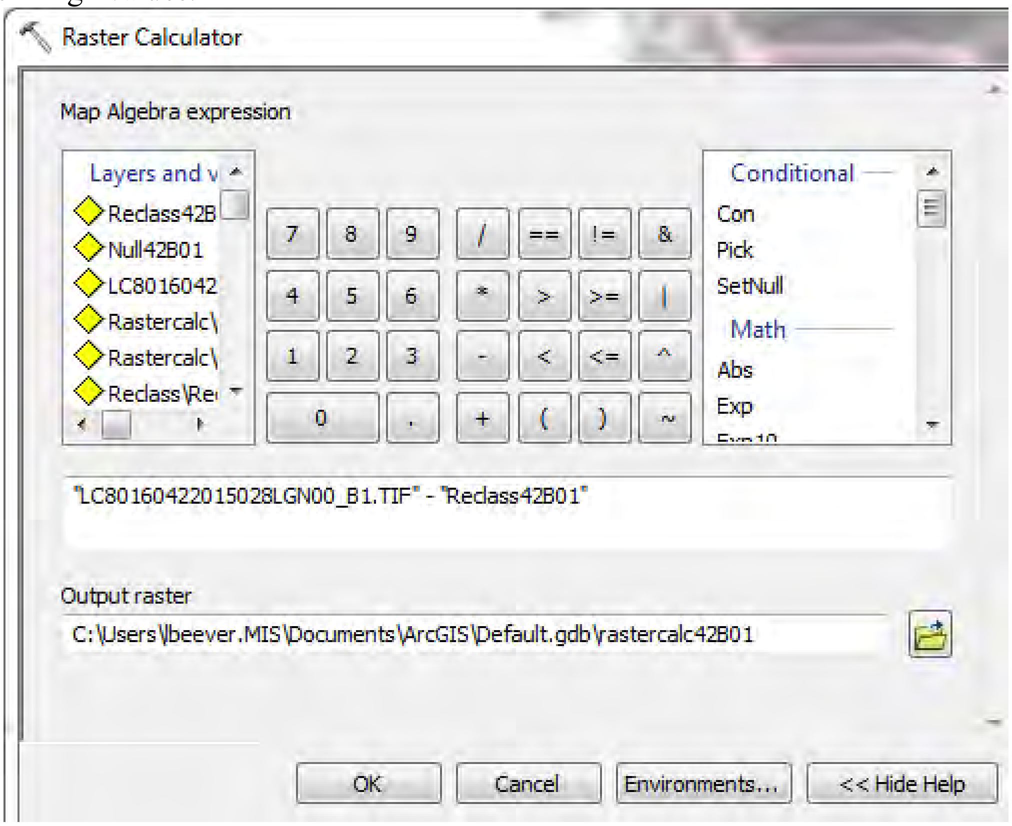



2. Create "Reclass" Files for each scene. Use Spatial Analyst-Reclass-Reclassify to remove the null areas from the "Null42B01". Change "Old value" 0 to NoData, removes the null values. "Old Value" will need to be changed to 1 for later multiplication to result in the same value for the resulting file. We named the resulting field Reclass42B01. The resulting file is shown below. Bands 10 and 11 needed to be run separately for each scene.

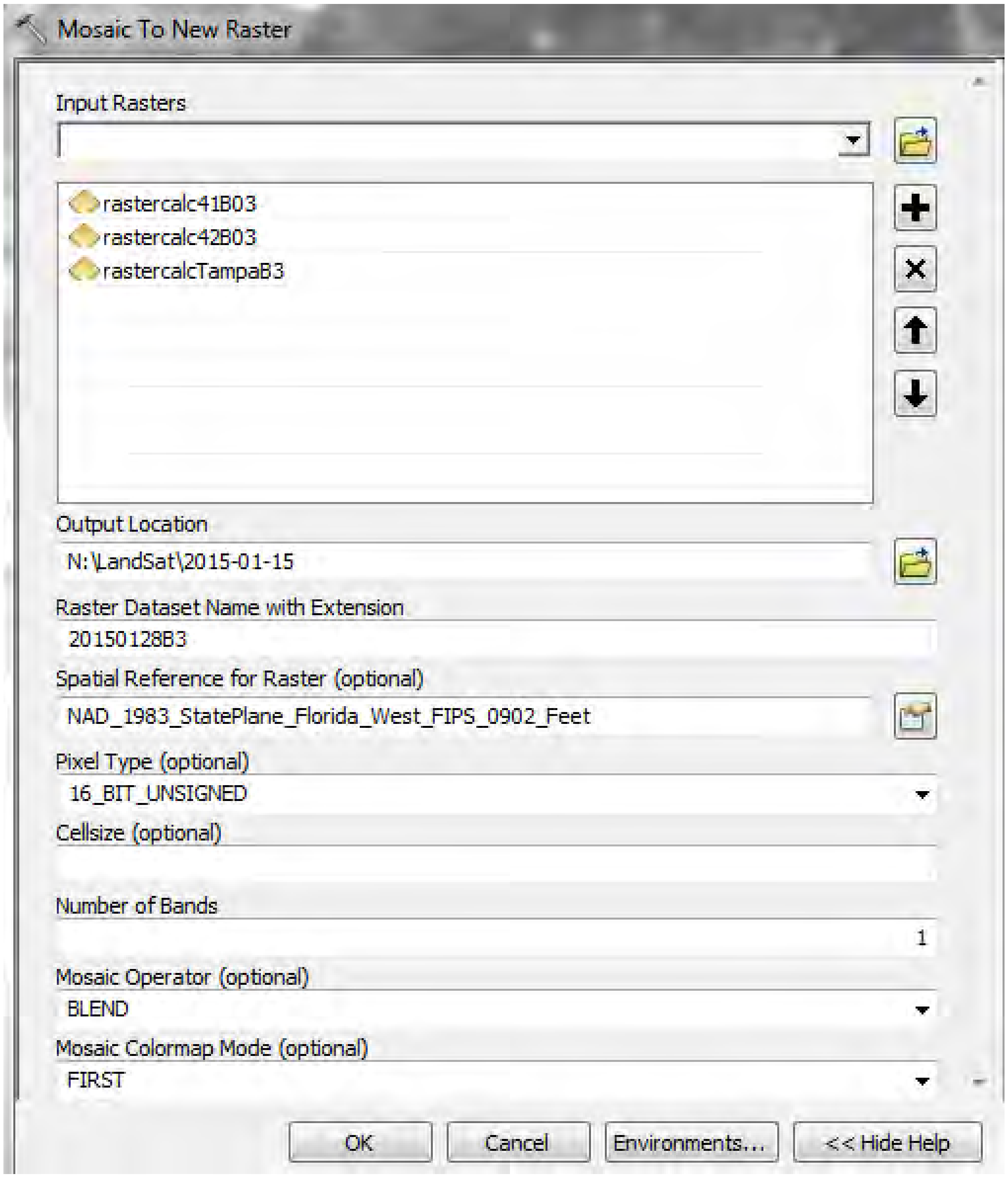


3. Create "Rastercalc" files for each band and scene. Use Spatial Analyst-Map Algebra-Raster Calculator to create a file with the original values and the null area eliminated from the file. Multiply the raw Landsat TIF file by the scene reclassification. We named the resulting field Rastercalc42B01. After this process is completed for both scenes, the file appearance is different at the line between the two because the two files are stretched to different high values.



4. <u>Mosaic "reclass" files for each band.</u> After the operation was completed for the other scene, both scenes were mosaicked using Data Management Tools-Raster-Raster Dataset-Mosaic to New Raster. The single mosaicked image results. A 16-bit new file was selected because the values ranged to a maximum of 56423 (B07), for all bands and scenes.


Mosaic To New Raster
Input Rasters
rastercalc41B03
rastercalc42B03
rastercalcTampaB3
Output Location
N:\LandSat\2015-01-15
Raster Dataset Name with Extension
20150128B3
Spatial Reference for Raster (optional)
NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
Pixel Type (optional)
16_BIT_UNSIGNED
Cellsize (optional)
Number of Bands
1
Mosaic Operator (optional)
BLEND
Mosaic Colormap Mode (optional)
FIRST
OK
Cancel
Environments...
<< Hide Help

5. Create Composites for analysis. Using Data Management Tools-Raster-Raster Processing-Composite Bands, create images using 3 of the 11 bands will be created. There are several common band combinations (See http://landsat.usgs.gov/L8_band_combos.php).

| Image | Red | Green | Blue |
|---|---|---|---|
| | Bands | | |
| Color Infrared: | 5 | 4 | 3 |
| Natural Color: | 4 | 3 | 2 |
| False Color 1: | 6 | 5 | 4 |
| False Color 2: | 7 | 6 | 4 |
| False Color 3: | 7 | 5 | 3 |

| Composite Name | Color Infrared | Natural Color | False Color 1 | False Color 2 | False Color 3 | Analysis Opposite |
|---|---|---|---|---|---|---|
| Combination | 543 | 432 | 654 | 764 | 753 | 762 |
| Band 1 – coastal aerosol | | | | | | |
| Band 2 – blue | | Blue | | | | Blue |
| Band 3 - green | Blue | Green | | | Blue | |
| Band 4 - red | Green | Red | Blue | Blue | | |
| Band 5 - Near Infrared (NIR) | Red | | Green | | Green | |
| Band 6 - Short-wave Infrared (SWIR) 1 | | | Red | Green | | Green |
| Band 7 - Short-wave Infrared (SWIR) 2 | | | | Red | Red | Red |
| Band 8 - Panchromatic | | | | | | |
| Band 9 – Cirrus | | | | | | |
| Band 10 – TIRS 1 | | | | | | |
| Band 11 – TIRS 2 | | | | | | |

1999

| Image | Red | Green | Blue |
|---|---|---|---|
| | Bands | | |
| Color Infrared: | 4 | 3 | 3 |
| Natural Color: | 3 | 2 | 1 |
| False Color 1: | 5 | 4 | 3 |
| False Color 2: | 7 | 5 | 3 |
| False Color 3: | 7 | 4 | 2 |

6. Create "Mask" of Mosaicked files for Composite. Using Spatial Analyst Tools-Extraction-Extract by Mask, the image is clipped for the generalized Mangrove Estuary Segment area for display and analysis.