SHIFTING COASTAL WETLAND COMMUNITIES IN NORTH CAROLINA: AN HISTORICAL SPATIAL ANALYSIS OF ALLIGATOR RIVER NATIONAL WILDLIFE REFUGE

by

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ABSTRACT

Coastal wetlands are dynamic landscapes shaped by many factors. However, there is growing concern that sea level rise brought on by climate change, and its associated physical pressures (e.g. saltwater intrusion, increased flooding, accelerated erosion, and increased storm frequency and severity), will amount to significant habitat change and loss for these systems. The Nature Conservancy (TNC) has initiated their Climate Change Adaptation Project in an effort to study and help mitigate for the effects of climate change on the Alligator River National Wildlife Refuge, situated in North Carolina's Albemarle-Pamlico estuarine system. As a component of their project, TNC would like to identify areas of the refuge that have undergone significant changes in habitat type so they can better focus their adaptation strategies. Through the examination and classification of historical aerial photography, this study informs TNC of the overall changes in habitat that have occurred on the refuge. An overlay analysis on data from 1932 to 2009 was completed using GIS to calculate the total change and rates of change of the vegetative communities on the refuge, and to identify areas of the refuge that have been changing more rapidly. This study also takes a closer look at some fine-scale changes that occurred at two study sites near the shoreline of the refuge, to determine if rising sea levels play a significant role in the dynamics of these coastal wetlands. Results from CART (Classification and Regression Tree) models indicate that sea level rise might indeed be one of the forces driving habitat change on the refuge.

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INTRODUCTION

Coastal wetland landscapes, such as those found in the Coastal Plains of North Carolina, are dynamic landscapes shaped by many factors. Historically, the coastal wetlands of North Carolina have been influenced by the occurrence of fire (Bailey 2007). They have been subjected to changes in fire regimes through fire suppression and more recent trends towards prescribed burning. Humans have also shaped this landscape through past forestry and agricultural practices, as well as continued developmental pressures (Bryant 2008). Of more recent concern are the effects that climate change can have on coastal wetland landscapes. In particular, there is growing concern that sea level rise and its associated physical pressures (e.g. saltwater intrusion, increased flooding, accelerated erosion, and increased storm frequency and severity) will amount to significant habitat change and loss in coastal wetland ecosystems (Corbett 2008). Sea level rise, in combination with the aforementioned human pressures and natural disturbance events, is likely to lead to changes in wetland vegetation over time in what is already a fragile and vulnerable ecosystem (Shirley 2006). Thus, it is important for land managers to examine the historical habitat changes occurring on our coastal wetlands, so they can effectively implement adaptation strategies for protecting them. This project addresses the overall changes that have occurred on the Alligator River National Wildlife Refuge in North Carolina, and also takes a closer look at some finer-scale changes to determine if rising sea levels play a significant role in the dynamics of these coastal wetland landscapes.

One of the most imminent threats to the continued conservation of coastal wetlands is sea level rise brought on by climate change. Accelerated rates of sea level rise threaten coastal areas worldwide with the advent of increased shoreline erosion, more frequent and severe storm systems, and unprecedented rates of habitat loss. Within the US, the coastal region of North

Carolina is particularly vulnerable to sea level rise due to its low-lying elevation and low-relief topography (Thieler and Hammar-Klose 1999). National Ocean and Atmospheric Administration tide gage measurements indicated that the measured rate of relative sea level rise in North Carolina ranges from 0.07 to 0.17 inches per year (Corbett 2008). Wetlands bordering the South Atlantic coastal region are expected to decrease in acreage due to pressure from both human growth and increased rates of sea level rise (Moorhead and Brinson 1995). Worldwide, it has been estimated that with the worst case scenario of a 1 meter rise in sea level by 2080, 46% of the world's wetlands will be lost (Nicholls et al. 1999). In the same study, it was also found that the Atlantic coast of the US was one of a handful of regions globally that is most vulnerable to coastal wetland loss. That vulnerability is due in part to the low tidal range of the region. While these results show that we should be concerned about the future of coastal wetlands in the face of sea level rise, they have some amount of uncertainty. Thus, it is crucial for there to be continued research of wetland response to sea level rise on local, regional, and global scales.

The processes that govern the elevation of coastal wetlands, such as sediment accretion, can interact with changes in sea level to affect their overall productivity (Morris et al. 2002). For instance, the relative mean sea level determines both the flooding frequency and salinity content of soils. An optimal elevation at the appropriate flood level and salinity gradient exists for coastal wetlands such as salt marshes, and the vegetation will constantly modify its elevation to keep equilibrium with the current sea level. It can be expected then, that as sea levels continue to rise, marsh habitat will migrate inland to seek higher elevations and keep up productivity.

Background

Alligator River National Wildlife Refuge

The Albemarle-Pamlico peninsula, part of Dare and Hyde counties in eastern North Carolina, is home to the Alligator River National Wildlife Refuge (Figure 1).

Figure 1: The Albemarle-Pamlico peninsula, which is home to the Alligator River National Wildlife Refuge.

The refuge was established in 1984 by the U.S. Fish and Wildlife Service (USFWS) mostly through donated lands (Bryant 2008). It is a peninsula surrounded by three bodies of water - Alligator River to the west, Albemarle Sound to the north, and Pamlico Sound to the east. The refuge is situated in the Albemarle-Pamlico estuarine system, which is comprised of shallow, brackish waters and low tidal flux due to a lack of connection to the open ocean (Wells and Kim 1989). The system is buffered by the Outer Banks barrier island chain, which only has four permanent inlets.

Today, the refuge totals 154,000 acres of vastly uninhabited wetland and wildlife habitat. It also surrounds the Dare County Bombing Range used by the Navy and Air Force. Because of its unique environment, the refuge is of high conservation importance. Coastal wetlands, such as those found on the refuge, are also among the most biologically productive ecosystems that exist (Michener 1997). The refuge's wetland communities – including pocosins, hardwood swamps, Atlantic White Cedar (*Chamaecyparis thyoides*) swamps, and brackish marshes – house many rare and endangered species (Bryant 2008). For instance, the refuge is one of the last remaining strongholds for the East Coast black bear (*Ursus americanus*) population, and it is one of the first successful sites for the reintroduction of the red wolf (*Canis rufus*). Also, many birds make their homes on the refuge, including the endangered red-cockaded woodpecker (*Picoides borealis*) and the many migratory species that frequent it on a seasonal basis.

The refuge, like other lands throughout the coastal plains of North Carolina, has been shaped by both natural and artificial fire regimes, human disturbance, and sea level rise. Additionally, the refuge has an extensive network of ditches and drainage canals, remnants of past agricultural and forestry practices (Bryant 2008). These ditches and canals serve as inlets for saltwater intrusion, especially during severe storm events. Saltwater intrusion, which is the

movement of saline water into naturally occurring freshwater, has the potential to alter the composition of the wetland communities present on the refuge. In a study on the effects of saltwater intrusion on wetland forests in the Gulf of Mexico, it was found that inundation of saltwater caused tree mortality in bottomland hardwood swamps and other coastal forests. (Pezeshki 1990).

The refuge sits at an extremely low elevation and has little topological relief. It is also almost completely surrounded by water. Therefore, just a slight increase in sea level will likely have some impact on vegetative communities throughout much of the refuge. In fact, a rise in sea level accompanied by changes in the frequency and severity of tropical storms and hurricanes could have significant effects on coastal wetland processes (Michener 1997). In response to the practical management needs of the region, one of the goals of this study is to determine the patterns of habitat change on the refuge in response to sea level rise.

Climate Change Adaptation Project

The Nature Conservancy (TNC) of North Carolina, in partnership with USFWS, is conducting ongoing research for their Climate Change Adaptation Project. The project is located on the Alligator River National Wildlife Refuge, and its goal is to mitigate for the effects of climate change by helping the natural communities on the refuge adapt to rising sea levels and other negative consequences of climate change. These effects can include, but are not limited to, a retreating forest boundary, die-back of forest, saltwater intrusion, salt and brackish marsh migration inland, changes in the soil biogeochemistry, and an overall loss in diversity of habitat. TNC plans to implement several adaptation strategies, which include (1) buffering shorelines from storm surge and erosion, (2) reforestation with tree species that can tolerate inundation with

salt water, (3) protecting upland habitat to facilitate the movement of plant species, (4) and establishing a baseline for soil carbon and monitoring carbon sequestration in response to different management strategies (The Nature Conservancy 2010). These strategies aim to jumpstart adaptation or succession that would naturally take place, and give the vegetation a chance to keep pace with rising seas.

It has been recognized that a major concern of long-term coastal planning is to assess and predict the change in habitat likely to occur from accelerated rates of sea level rise due to climate change (Thieler and Hammar-Klose 1999). While it is difficult to separate other environmental variables from sea level rise that could potentially alter habitat, an assessment of the long-term habitat trends will allow coastal and marine managers to effectively make informed decisions on how to protect the most sensitive and ecologically important coastal areas. The results from the analyses that follow will inform TNC of those trends, and allow them to focus their efforts on areas of the refuge undergoing rapid change, as compared to areas that are relatively stable. Also, an analysis of the fine-scale changes along the shoreline will help discern if any of the effects of sea level rise are visible. By identifying areas, particularly along the shoreline, where the habitat patterns have significantly changed, TNC will be able to reflect those dynamics in their plans to restore the hydrology and natural habitats on the refuge.

Study Objectives

The study objectives for this project are as follows:

1. Discern what shifts have occurred over time in the habitat composition on the refuge, and what type of habitat has changed the most.

2. Determine where the greatest amounts of change are happening. For instance, are there certain areas of the refuge that have been particularly unstable over the time period for this study?

3. Gain a better understanding of the habitat patterns on the shoreline to test the hypothesis that sea level rise is contributing to change on the refuge. Does the rate of change vary as a function of distance from shore? Is there evidence of forest retreat?

STUDY SITES

This project aims to study both the large-scale changes that have occurred on the entire refuge in recent years, and the fine-scale changes that have been happening on the shoreline since the 1930s. In order to observe these changes, multiple study sites have been selected. The first study site, the Albemarle-Pamlico Peninsula, is primarily composed of the Alligator River National Wildlife Refuge (Figure 1). It also contains some USFWS administrative areas, the Dare County Bombing Range, and the Manns Harbor and Stumpy Point residential areas. It is lies mostly within mainland Dare County's boundaries, and a small portion of Hyde County's boundaries to the south-west. The Albemarle-Pamlico Peninsula study site will be used in the analysis to quantify large-scale habitat changes that have occurred on the entire peninsula over time.

The other two study sites were chosen in order to capture fine-scale change near the shoreline of the peninsula (Figure 2). These sites were selected based on a previous doctoral thesis work conducted by Dr. Benjamin Poulter, in which habitat was classified and analyzed for change over time (Poulter 2005). By choosing the same sites that Poulter used, this project effectively expands on work that has already been conducted. Both sites are located on the

Albemarle-Pamlico Peninsula. The first site, Long Shoal Marshes, is in the southern portion of the refuge in Dare County. The dominant habitat found there is pond pine forest and brackish marsh. The second site, Manns Harbor, is in the north-east section of the refuge, and is named for the residential area that it encompasses. It is also in Dare County. Like Long Shoal Marshes, it is characterized by pond pine forest and brackish marsh habitat. All of the sites on the peninsula have been heavily fragmented by drainage canals in the past, and are composed of deep peat soils.

Figure 2: Long Shoal Marshes and Manns Harbor study sites, which are located on the Albemarle-Pamlico peninsula. Imagery depicted is from 2005.

METHODS

Aerial Photography Data Collection and Processing

This research project examines the habitat changes that have occurred on Alligator River National Wildlife Refuge from 1932 to 2009. The method used for quantifying the rates of habitat change happening on the refuge was to analyze and classify a series of historical aerial photography using ArcGIS 9.3 (ESRI 2008). Aerial images, such as those captured by satellite remote sensing, have been proven useful in tracking changes in vegetation at multiple scales (Stow 2004). These types of images allowed the classification of the refuge's habitat types over several years to see how the communities have shifted over a long period of time.

Several sources of data were used to compile the collection of necessary aerial photos. Digital Orthophotographic Quarter Quads (DOQQs) were obtained as infrared color, black and white, and true color imagery. DOQQ imagery is at a relatively high resolution (i.e. 1 meter), but the relative quality of data varies from year to year. Also, sets of imagery from the National Agricultural Imagery Program (NAIP) were obtained for the study site. Lastly, historical aerial photos for 1947 were obtained from the GIS office of Dare Country. The Dare County data comprises about 95% of the refuge. These historical aerial photos are useful for the historical component of this project because they are prior to the time period when the refuge was ditched and drained for agriculture and forestry, and only a small amount of roads were present. Thus, they give a good idea of what the refuge looks like under more 'natural' conditions.

In addition to the aerial photography, previously classified habitat shapefiles were obtained from two sources. First, a layer of habitat types for the Albemarle-Pamlico Peninsula study site for 1998 was obtained from USFWS. Second, Poulter provided layers for the two other study sites - Long Shoal Marshes and Manns Harbor - for the years 1932, 1969, and 1998. The

data inventory below shows all of the classified habitat shapefiles and imagery used for this

project, along with their sources (Table 1).

Table 1: Data inventory of classified habitat and imagery used in the study.

Year	Description	Source
Classified Habitat Shapefiles		
1932	Long Shoal Marshes and Manns Harbor only	Benjamin Poulter
1969	Long Shoal Marshes and Manns Harbor only	Benjamin Poulter
1998	Long Shoal Marshes and Manns Harbor only	Benjamin Poulter
1998	Dare Co. and Hyde Co.	USFWS
Aerial Photography		
1947	Aerial photos of Dare Co. only	Dare County GIS Office
1993	1 meter orthophotography aerial images of Dare Co. and Hyde Co.	http://www.ncdot.gov/it/gis/Data Distribution/1993AerialPhotography/default.html
1998	Digital Ortho County Mosaic of 7.5' quads of Dare Co. and Hyde Co.	http://datagateway.nrcs.usda.gov
2000	Digital Ortho County Mosaic of 7.5' quads of Dare Co. and Hyde Co.	http://datagateway.nrcs.usda.gov
2005	NAIP Mosaic of Dare Co. and Hyde Co.	http://datagateway.nrcs.usda.gov
2009	NAIP Mosaic of Dare Co. and Hyde Co.	http://datagateway.nrcs.usda.gov

Habitat Classification

Classification for the Albemarle-Pamlico Peninsula

The years 1993, 1998, 2000, and 2005 were classified for the Albemarle-Pamlico

peninsula change analysis. The data prior to 1993 was of too poor quality to classify vegetation

for the entire peninsula. There were two main reasons for the exclusion of data prior to 1993.

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The first reason was that the data was obtained in an un-georeferenced format. The 1947 data was particularly troublesome because it came in tiles, some of which had no recognizable features to use as ground control points (GCP's). Because of the difficulty of locating GCP's for many of the tiles on the 1947 data, the reliability of the quality of the data was uncertain. Also, the data that could be georeferenced did not cover the entire study area. The second reason is simply that historical aerial photos prior to modern photo and satellite capturing technology (ca. 1990s) is not of high enough resolution to distinguish all of the necessary habitat categories.

In classifying the data, the habitats were grouped into broad wetland communities present on the Albemarle-Pamlico peninsula. The classification was modeled after the habitat shapefile that was obtained from USFWS. The USFWS shapefile, which represents a compilation of aerial images from 1998-99, was used both in the analysis for the year 1998 and as a guide for classifying the other years of data. In other words, the 1998 habitat shapefile was used as a guide for classifying the 1993, 2000, and 2005 data to check that the interpretation agreed with that of USFWS. This insured that the classification was consistent. Also, because the USFWS habitat classification for 1998-99 was ground-truthed and checked by professionals and managers very familiar with the refuge, it is an accurate representation of on-the-ground habitat types.

The habitat categories were digitized as polygon shapefiles using ArcGIS 9.3 (ESRI 2008). The classification done by USFWS for the 1998-99 aerial photography produced 14 habitat communities (in addition to the open water, administrative, residential, cropland, and managed wetland categories). Groupings similar to those of USFWS were used for this project. However, since some of the data was of lesser quality in terms of resolution, it was necessary to classify more general categories. Based on the previous minimum mapping unit used for the 1998-99 map and a similar classification done for the Everglades (Rutchey 2009), a minimum

mapping unit of 50m² was used for this classification. Digitizing was conducted between 1:1,000 and 1:6,000 scales. Below is a table with the habitat categories that were ultimately classified (Table 2).

Table 2: Albemarle-Pamlico peninsula habitat classification categories.

Habitat Categories	Class ID
Open Water	1
Administrative	2
Residential	3
Cropland	4
Managed Wetlands	5
Brackish Marsh	6
Shrub/Marsh Transition	7
Shrub Pocosin	8
Pond Pine Pocosin	9
Mixed Forest	10
Hardwood Swamp	11
Atlantic White Cedar Forest	12
Loblolly Pine Forest	13
Bay Forest	14
Non-alluvial Hardwood Forest	15

The open water category includes both freshwater creeks and ponds as well as brackish and salt-water from the bordering Albemarle and Pamlico sounds. Administrative lands include areas of land owned by the USFWS for their offices and administration, as well as the Dare County Bombing Range lands. The residential areas are comprised mostly of the land around Manns Harbor, in the northeast section of the refuge, and Stumpy Point, on the eastern shore of the refuge. There are some areas of the refuge still being used for crop production that are classified as cropland. In addition, some areas of cropland are being actively managed as wetlands, and are flooded for part of the year. The level of water is managed to encourage the growth of water-loving plants that provide a food source for waterfowl that come to the refuge on a seasonal basis.

All of the marsh on the refuge was classified as brackish marsh, although it is likely that some of the marsh areas have relatively less or more salinity depending on whether they are further inland or not, respectively. Brackish marsh is generally found along sounds and estuaries in areas that aren't regularly influenced by tidal flooding. The dominant plant species include black needlerush (*Juncus romerianus*), saltmeadow grass (*Spartina patens*), salt grass ((*Distichlis spicata*) giant cordgrass (*Spartina cynosuroides*), and the invasive reed (*Phragmites australis*). Shrub/marsh transition is generally the area of transition between marsh and pocosin. It is a combination of marsh vegetation and live shrubs. Shrub pocosin is characterized by a dominant understory of shrubs with stunted or dead trees. Pond pine pocosin has taller vegetation than shrub pocosin, and is dominated by pond pine, bay, and red maple trees with either a shrub or cane understory. Several types of forest were distinguishable in the aerial photos, such as those dominated by Atlantic white cedar (*Chamaecyparis thyoides*), loblolly pine (*Pinus taeda)*, and bay (*Laurus nobilis)*. All other forested lands that weren't distinguishable were classified as mixed forest. Atlantic white cedar forests are typically mixed in with other habitats such as pond pine pocosin, cypress-gum, and non-alluvial hardwood communities. Also, while the dominant species is white cedar, black gum is commonly found there as well. Hardwood swamps are characterized by a mixture of larger to medium-sized hardwood tree species such as bald cypress (*Taxodium distichum)* and black gum (*Nyssa sylvatica)*. Non-alluvial hardwood forests have similar vegetation as hardwood swamps and contain many species of oak; however, they are found on poorly drained mineral soils at the margins of pocosin, cypress gum, or Atlantic white cedar habitats. The final classified maps for all four years can be found in the appendix (Figures 1A - 4A).

Classification for Long Shoal Marshes and Manns Harbor

     The habitat classification that was conducted for Long Shoal Marshes and Manns Harbor was modeled after Poulter's habitat classification from his previous studies. The years 1947, 1993, 2000, 2005, and 2009 were classified for the Long Shoal Marshes and the years 1993, 2000, 2005, and 2009 were classified for the Manns Harbor study site. The 1947 data was not classified for Manns Harbor because the aerial photos for that year did not cover the entire study area. These were compiled with Poulter's classified habitat data for the years 1932, 1969, and 1998 to perform the analysis. The 1947 photography that was obtained from Dare County came in tiles in an ungeoreferenced format, so it was georeferenced using the georeferencing tool in ArcGIS. An average of 4 GCP's were used to georeference each tile.

     The same digitizing methodology as in the Albemarle-Pamlico peninsula classification was used, but the digitizing resolution and minimum mapping unit were changed to capture more fine-scale changes. The digitizing was conducted between 1:500 and 1:3,000 scales to stay consistent with Poulter's methodology. A minimum mapping unit of 10m² was used. The habitat classification for this part of the analysis contained the following categories, which are slightly different than the vegetative categories used in the broad-scale analysis (Table 3).

Table 3: Long Shoal Marshes and Manns Harbor habitat classification categories.

Habitat Categories	Class ID
Residential	1
Open Water	2
Dense Forest	3
Ditch	4
Brackish Marsh	5
Road	6
Sand	7
Shrub Pocosin	8
Sparse Forest	9

This classification includes roads and ditches, but doesn't distinguish forest types. Instead, the forest is classified as simply dense or sparse. Dense forest consists of 80 percent or more canopy closure, while sparse forest consists of less than 80 percent canopy closure. Residential lands are only in the Manns Harbor study site. Some areas of sand, between marsh and open water, were visible when classifying at a smaller scale. The remaining categories - open water, brackish marsh, and shrub pocosin - are defined the same as in the Albemarle-Pamlico peninsula classification. The final classified maps for all years for Long Shoal Marshes and Manns Harbor can be found in the appendix (Figures 5A - 19A).

Geospatial Analysis

Each of the classified habitat layers for all of the study sites - the entire peninsula, Long Shoal Marshes, and Manns Harbor - were analyzed in ArcGIS 9.3 (ESRI 2008) for changes in total area of each vegetative class, as well as the rates of those changes over time. In addition, an overlay analysis was completed to find change over time for all of the study sites.

Change over Time: Albemarle-Pamlico peninsula

The rates of gains and losses of habitat types demonstrate the underlying pattern among habitats on the refuge, and help discern what shifts in habitat have occurred with the onset of climate change and human settlement. This portion of the project was aimed at understanding the broad scale changes that have occurred on the entire refuge over the past 12 years. It uses the habitat datasets from 1993, 1998, 2000, and 2005.

To assess areas of the refuge that had more or less relative amounts of change, a Python script, written using version 2.5.5, (Python Software Foundation 2006) was created to complete an overlay analysis using ArcGIS 9.3 (ESRI 2008). The overall purpose of this analysis was to highlight areas of most rapid change versus areas of highest stability between four time periods spanning 12 years. To do this, the script compares habitat data over time by overlaying all four habitat datasets and evaluating the number of times a particular pixel has changed from one habitat class to another. In this way, the output only gives the total number of times a point has changed, not the types of transitions that occurred.

The analysis steps for the overlay analysis were as follows. All polygon feature classes and raster datasets were in the UTM, Zone 18, NAD 1983 projected coordinate system. First, each habitat class was given a unique class ID code. Then, the polygon feature classes for each year were converted to raster datasets with 30 meter cells. Next, the change was detected between each year sequentially. To do this, conditional statements were used to reclassify each pixel based on whether its habitat classification changed from year to year. For instance, if a pixel changed from pond pine pocosin to brackish marsh between 1993 and 1998, it was given a value of '1'. If the pixel stayed in the same habitat class from one year to the next, it was given a value of '0'. These steps were repeated three times - once from 1993 to 1998, once from 1998 to

2000, and once from 2000 to 2005. This created three rasters with binary outcomes of either '1'

for change or '0' for no change. The three rasters were added together to get a total change

raster. This raster contained values for the total number of times each pixel changed. Thus, a

pixel that stayed the same for all three transition periods would have a value of '0'. A pixel that

changed once would have a value of '1', a pixel that changed twice would have a value of '2',

and a pixel that changed all three times would have a value of '3'.

Change over Time: Long Shoal Marshes and Manns Harbor

To assess whether or not changes in shoreline have an effect on habitat, a similar analysis

to that above was conducted for the Long Shoal Marshes and Manns Harbor study sites. The

analysis was conducted on habitat feature classes for 1932, 1947 (Long Shoal Marshes only),

1969, 1993, 1998, 2000, 2005, and 2009, for a total of 77 years' worth of measured change at

seven transition steps for Long Shoal Marshes, and six transition steps for Manns Harbor.

A Python script, written using version version 2.5.5 (Python Software Foundation 2006)

was created to complete an overlay analysis using ArcGIS version 9.3 (ESRI 2008). The overall

purpose of this script was to capture the changes between each transition period, as well as the

overall change for all 77 years. All polygon feature classes and raster datasets were in the UTM,

Zone 18, NAD 1983 projected coordinate system. First, each habitat class was given a unique

class ID code. Then, the polygon feature classes for each year were converted to raster datasets.

Because the classification was conducted at finer level, the polygon feature classes were

converted to rasters with one meter cell resolution instead of 30 meter cell resolution. As in the

Albemarle-Pamlico peninsula overlay analysis, conditional statements were used to reclassify

each pixel based on whether its habitat class changed from year to year. Adding the rasters then gave the total number of changes for the entire study period.

In addition to getting the total number of changes that occurred between all of the transition periods, the goal of this analysis was to gain a better understanding of the types of transitions that occurred from year to year. A total of seven transition rasters were produced for Long Shoal Marshes (1932-1947, 1947-1969, 1969-1993, 1993-1998, 1998-2000, 2000-2005, and 2005-2009), and a total of six transition rasters (1932-1969, 1969-1993, 1993-1998, 1998-2000, 2000-2005, and 2005-2009) were produced for Manns Harbor. Also, a total transition raster was produced for both study sites, spanning from 1932-2009. A 'zipcode' approach was used with the Single Output Map Algebra tool in ArcGIS 9.3 (ESRI 2008) to add the rasters for each transition period. This gave a unique transition code for each type of transition that occurred over the entire time span. For instance, dense forest was given a code of '3' and brackish marsh was given a code of '5'. So, for a pixel that changed from dense forest to brackish marsh, a code of '35' would be assigned. This was done in Single Output Map Algebra with the following formula:

$$[1932\_code]*10 + [2009\_code] = 3*10 + 5 = 35$$

The output of this part of the analysis gave a value for each one meter pixel of the type of transition that occurred from the beginning to the end of the study period. This result was then used to determine the type of change as a function of the distance from shore.

Determining Change as a Function of Distance from Shore

To determine the effect of distance from shoreline on vegetative change, a statistical analysis was conducted for the Long Shoal Marshes and Manns Harbor study sites. A CART

(Classification and Regression Tree) model was created using the 'rpart' package from R

Statistical Software version 2.9.2 (R Core Development Team 2009). The response variable for

the model was the 1932-2009 transition raster created from the previous geospatial analysis.

Three predictor variables were used in the CART model. First, a Euclidian distance from

shoreline grid was created based on the 1932 shoreline, which was extracted from the classified

habitat data. The second predictor was a Euclidian distance from ditch grid that was created from

the most recent ditch data from 2009. Lastly, LIDAR elevation data at 20 foot resolution was

used (obtained from the North Carolina Floodplain Mapping Program). These predictor variables

were chosen based on Poulter's previous work, where he found that other predictor variables

(such as slope, aspect, and soil type) were generally homogenous within a study site (Poulter

2005).

Next, using ArcGIS 10.0 (ESRI 2010), a set of 1,000 random points was sampled through

all three predictor variables and the response variable for both the Long Shoal Marshes and

Manns Harbor study sites. This gave a value of distance from shoreline, distance from a ditch,

elevation, and transition type for each random point. These sample points were used in R to run

the CART analysis. Only some of the transition types were of interest to the study, while the rest

were excluded from the CART model. The transition types used in the CART model were forest

to forest, forest to marsh, marsh to marsh, and marsh to open water. For both models, a 10-fold

cross-validation was run to see if the output tree needed to be 'pruned' or 'trimmed' in order to

reduce the predictive error.

RESULTS

Albemarle-Pamlico Peninsula

Habitat Change over Time

The results from the Albemarle-Pamlico peninsula change over time analysis are designed to give TNC an idea of relative change between the four habitat datasets (1993, 1998, 2000, and 2005). They highlight areas that are undergoing rapid change in contrast to areas that are not undergoing much change. Thus, the change is a comparison between the available data, so it may or may not actually be a significant amount of change. The results from this analysis should be used only as guidelines for the management of critical habitat. While the rapidly changing areas are certainly good starting points for management and research, they provide no information as to the actual cause of the change. Lastly, the analysis does not account for digitizing errors. Slight changes in the boundaries of polygons from year to year show up as areas that have changed rapidly. This could be because of digitizing errors, or because those boundaries have actually changed over time. In the interest of not leaving out potentially valuable information on gradually shifting boundaries, these 'sliver' polygons were not removed from the final dataset.

The areas of each habitat class broken down by year for the Albemarle-Pamlico peninsula study site are detailed in the following table (Table 4).

Habitat Category	Area (km²)			
	1993	1998	2000	2005
Administrative	19.22	19.22	19.22	19.20
Atlantic White Cedar Forest	38.38	37.01	35.58	24.42
Bay Forest	6.16	5.86	5.72	4.12
Brackish Marsh	51.38	55.89	54.80	55.88
Cropland	16.57	16.58	16.57	16.58
Hardwood Swamp	70.37	68.90	73.53	73.35
Loblolly Pine Forest	21.02	19.47	19.89	17.78
Managed Wetlands	4.23	4.23	4.23	4.23
Mixed Forest	110.40	111.86	105.69	102.25
Non-alluvial Hardwood Forest	36.73	37.71	37.93	42.48
Open Water	7.57	8.09	7.51	7.62
Pond Pine Pocosin	289.59	286.99	279.74	309.59
Residential	19.35	19.12	19.15	19.24
Shrub Pocosin	112.93	111.47	119.68	89.37
Shrub/Marsh Transition	30.75	29.98	33.03	45.17
TOTAL	834.64	832.37	832.26	831.28

The total area of the peninsula has decreased from 1993 to 2005 by 3.36 km². That makes for an overall 0.28 km² per year loss of land for the 12 year time span. The most likely explanation for this loss of land is the process of shoreline erosion around the periphery of the refuge at the land water interface. The rates of change for each habitat class and time period are summarized in the following table (Table 5).

Table 5: Rates of habitat changes for Albemarle-Pamlico peninsula.

Habitat Category	Rate of change (km²/year)			
	1993-1998	1998-2000	2000-2005	1993-2005
Administrative	0.00	0.00	0.00	0.00
Atlantic White Cedar Forest	-0.27	-0.71	-2.23	-1.16
Bay Forest	-0.06	-0.07	-0.32	-0.17
Brackish Marsh	0.90	-0.54	0.22	0.37
Cropland	0.00	0.00	0.00	0.00
Hardwood Swamp	-0.29	2.32	-0.04	0.25
Loblolly Pine Forest	-0.31	0.21	-0.42	-0.27
Managed Wetlands	0.00	0.00	0.00	0.00
Mixed Forest	0.29	-3.09	-0.69	-0.68
Non-alluvial Hardwood Forest	0.20	0.11	0.91	0.48
Open Water	0.10	-0.29	0.02	0.00
Pond Pine Pocosin	-0.52	-3.63	5.97	1.67
Residential	-0.05	0.01	0.02	-0.01
Shrub Pocosin	-0.29	4.11	-6.06	-1.96
Shrub/Marsh Transition	-0.15	1.53	2.43	1.20
TOTAL	-0.46	-0.05	-0.20	-0.28

The vegetation categories that have decreased in total area over the 12 year time period include Atlantic white cedar forest, bay forest, loblolly pine forest, mixed forest, and shrub pocosin. The vegetation categories that have gained area include brackish marsh, hardwood swamp, non-alluvial hardwood forest, pond pine pocosin, and shrub/marsh transition. With the exception of shrub pocosin, all of the habitat categories that have increased in area over time are wetland habitats that experience some amount of increased soil moisture and/or flooding throughout the year. This is indicative that the peninsula is losing upland and dryer forested habitat to wetland habitat.

These results are also demonstrated by the following time series figures, showing the total area of each habitat category versus the year (Figures 3 -7).
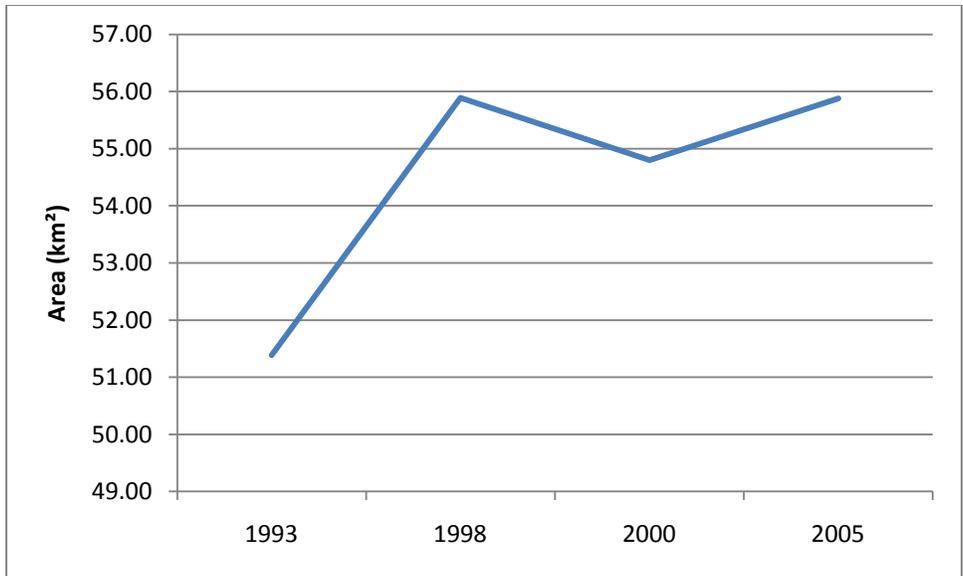
Figure 3: Changes in the area of brackish marsh over time for the Albemarle-Pamlico peninsula.
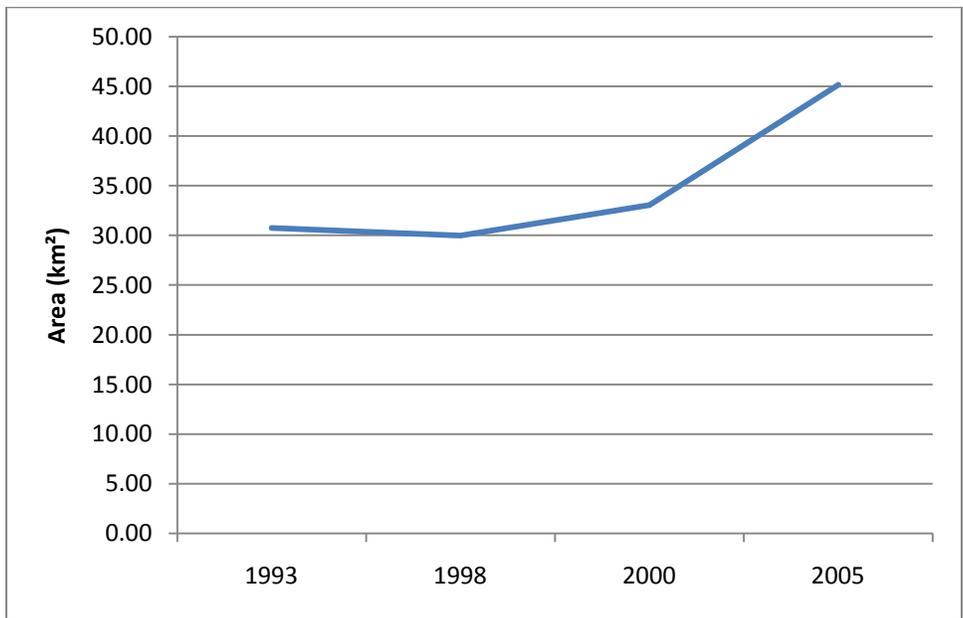

Figure 4: Changes in the area of shrub/marsh transition over time for the Albemarle-Pamlico peninsula.
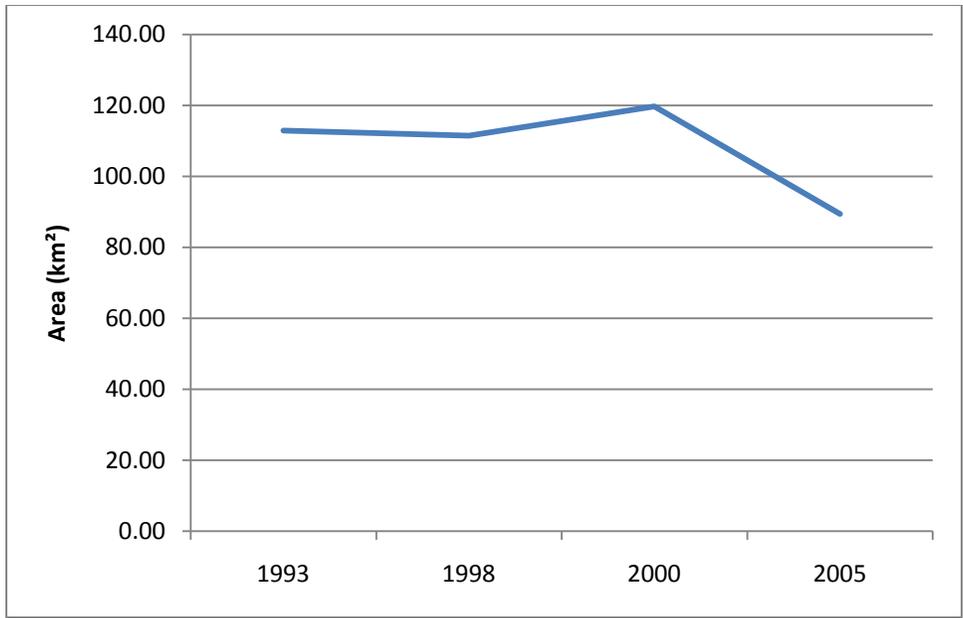
Figure 5: Changes in the area of shrub pocosin over time for the Albemarle-Pamlico peninsula.
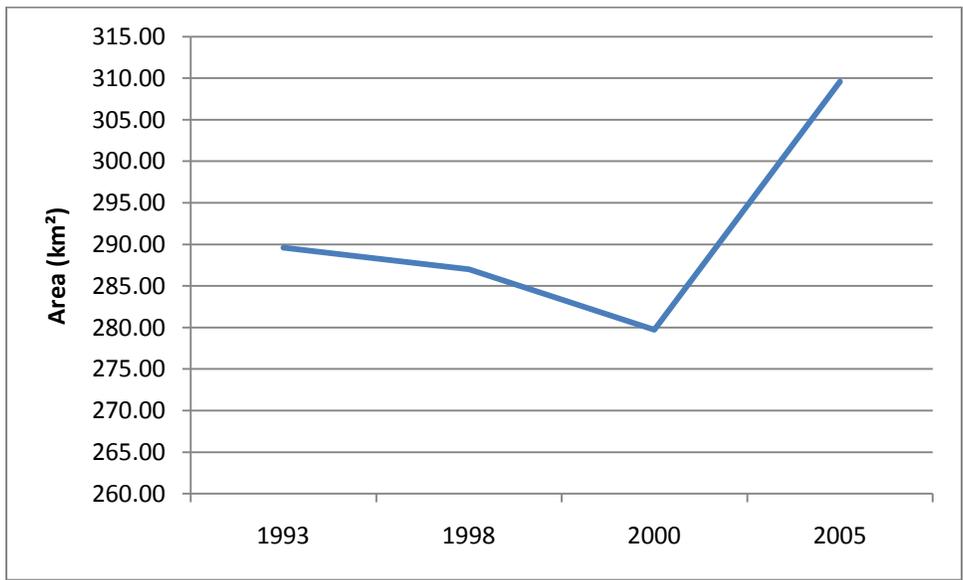

Figure 6: Changes in the area of pond pine pocosin over time for the Albemarle-Pamlico peninsula.
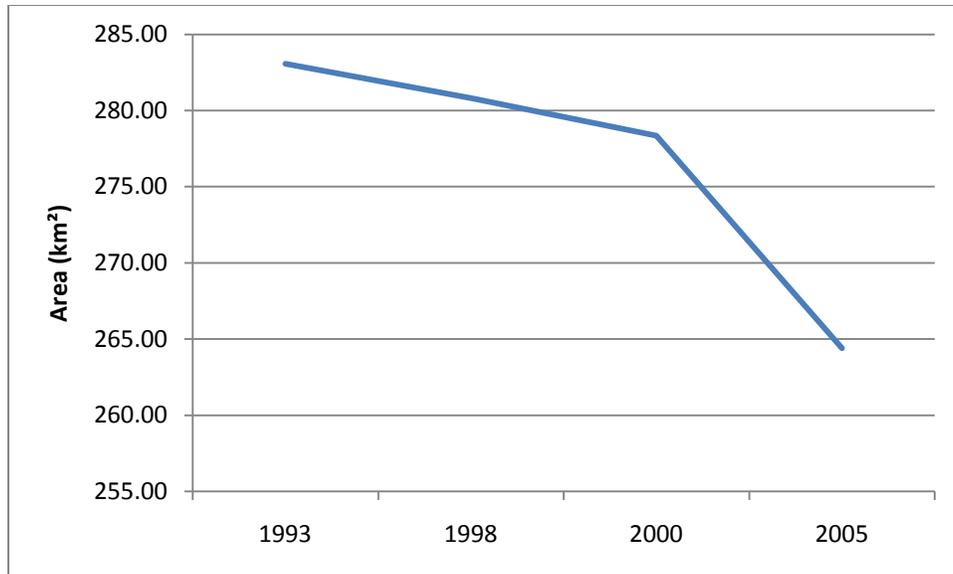
24

Figure 7: Changes in the area of total forested land over time for the Albemarle-Pamlico peninsula.

Rapidly Changing Areas

To get a better idea of the distribution of change happening on the refuge, a total change map of the Albemarle-Pamlico peninsula analysis was created (Figure 8). The total change map indicates the total number of times a pixel has changed habitat types. A value of '3' is the highest amount of relative change that could occur over the study period, while a value of '0' indicates that no habitat change occurred. The amount of change is fairly well distributed. There appears to be much change of varying degrees occurring on the western portion of the peninsula. This side of the refuge has been heavily impacted by ditches, roads, and canals in the past, and it is likely that these structures have fragmented the landscape and caused the hydrology (and thus the habitat) to change over time. The largest patches of change occur along the shoreline in the northern section of the peninsula and in the southern portion of the refuge near the Long Shoal Marshes study site, as well as an inland section of the northeastern side of the refuge.
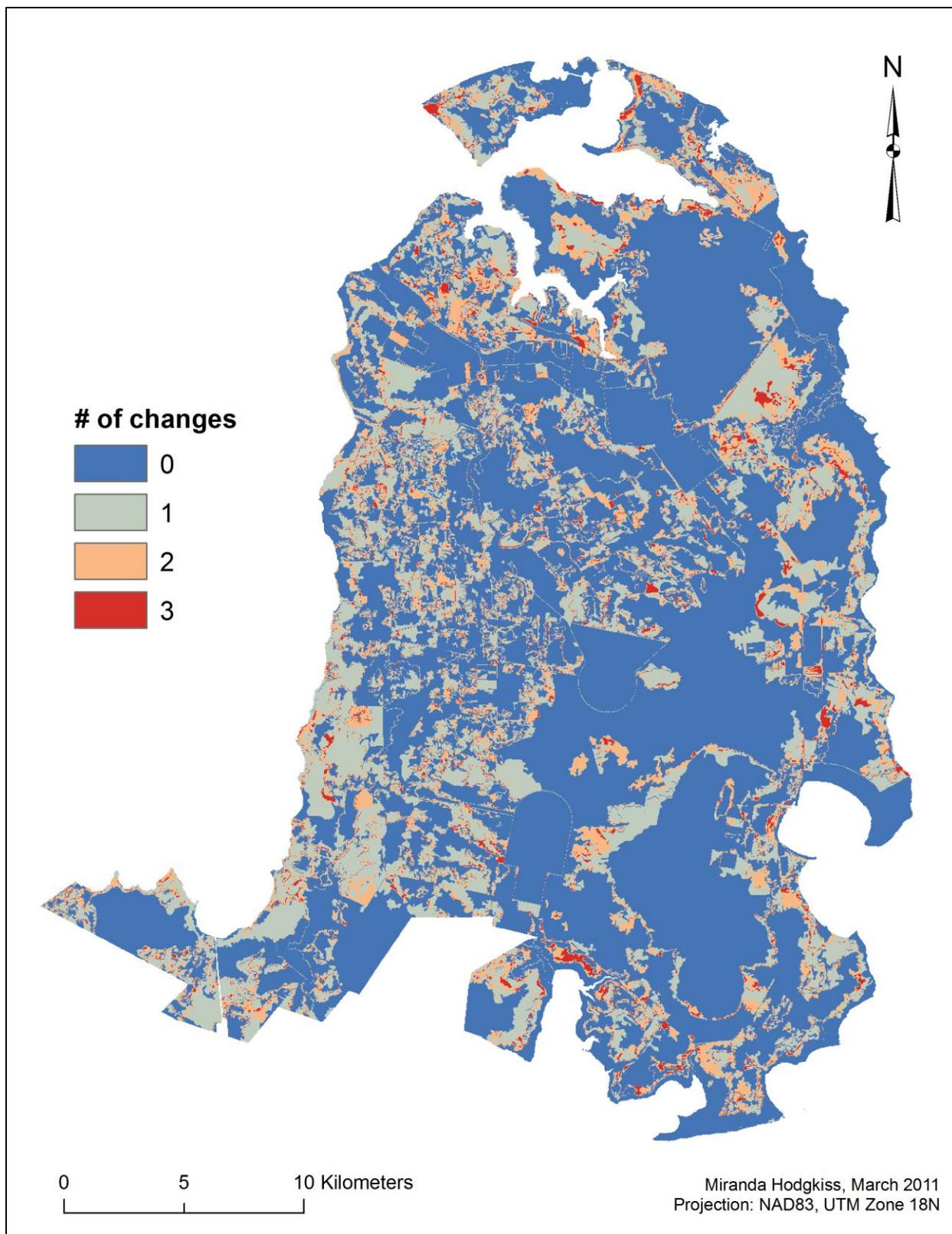
Figure 8: Map of total change for the Albemarle-Pamlico peninsula.

Long Shoal Marshes

Habitat Change over Time

The areas of each habitat class broken down by year for the Long Shoal Marshes study site are detailed in the following table (Table 6). The total area for all of the time periods remained the same because the extent of each habitat shapefile was clipped to the extent of the Long Shoal Marshes study area when conducting the overlay analysis. The areas of brackish marsh, dense forest, and shrub pocosin have all increased from 1932 to 2009. Sparse forest was the only habitat that decreased, quite significantly, over time. In addition, the total area of open water increased, which indicates that total land area is being lost to open water.

Table 6: Habitat changes for Long Shoal Marshes.

Habitat Category	Area (km²)							
	1932	1947	1969	1993	1998	2000	2005	2009
Brackish Marsh	2.79	3.11	2.41	2.83	2.93	3.09	3.49	3.57
Dense Forest	1.46	1.46	5.47	2.35	2.48	2.31	2.40	2.33
Ditch	0.00	0.00	0.03	0.04	0.04	0.05	0.04	0.03
Open Water	2.60	2.50	2.65	2.75	2.78	2.77	2.82	2.82
Road	0.00	0.00	0.02	0.02	0.02	0.02	0.01	0.01
Shrub Pocosin	1.51	1.22	0.41	3.10	3.27	3.33	2.83	2.84
Sparse Forest	4.03	4.10	1.40	1.29	0.88	0.81	0.80	0.78
TOTAL	12.4							

To get an idea of the pace of change, the rates of change for each habitat class and time period were also calculated (Table 7). Overall, from 1932-2009, shrub pocosin had the highest positive rate of change of 0.017 km²/year, followed by dense forest and then brackish marsh. Sparse forest had a fairly high negative rate of change of -0.042 km²/year. These same results are also demonstrated by the following time series figure, showing the total area of each habitat category versus the year (Figure 9).

Table 7: Rates of habitat changes for Long Shoal Marshes.

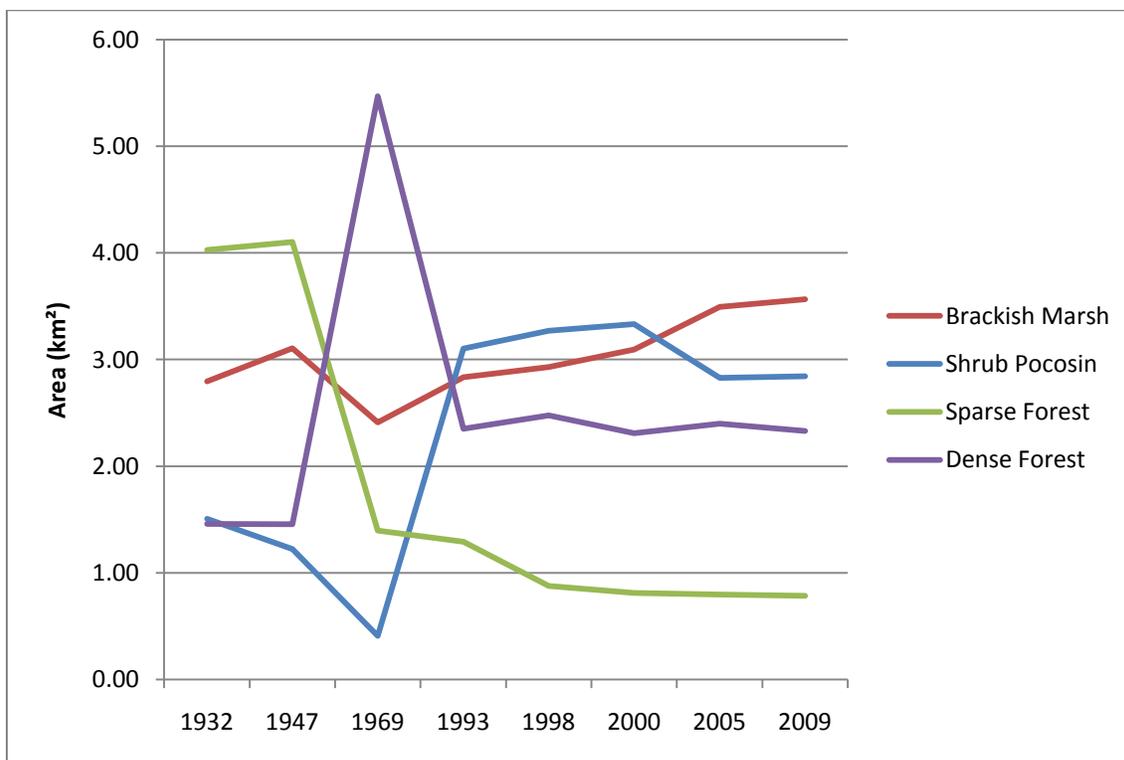| Habitat Category	Rate of change (km²/year)							
	1932-1947	1947-1969	1969-1993	1993-1998	1998-2000	2000-2005	2005-2009	1932-2009
Brackish Marsh	0.021	-0.032	0.018	0.019	0.081	0.080	0.018	0.010
Dense Forest	0.000	0.182	-0.130	0.025	-0.084	0.018	-0.017	0.011
Ditch	0.000	0.002	0.000	-0.001	0.008	-0.004	-0.002	0.000
Open Water	-0.007	0.007	0.004	0.006	-0.004	0.011	0.000	0.003
Road	0.000	0.001	0.000	0.000	0.000	-0.001	0.000	0.000
Shrub Pocosin	-0.019	-0.037	0.112	0.033	0.032	-0.101	0.004	0.017
Sparse Forest	0.005	-0.123	-0.004	-0.083	-0.032	-0.003	-0.003	-0.042
TOTAL	0.000							

Figure 9: Changes in the area of selected habitat types over time for Long Shoal Marshes.
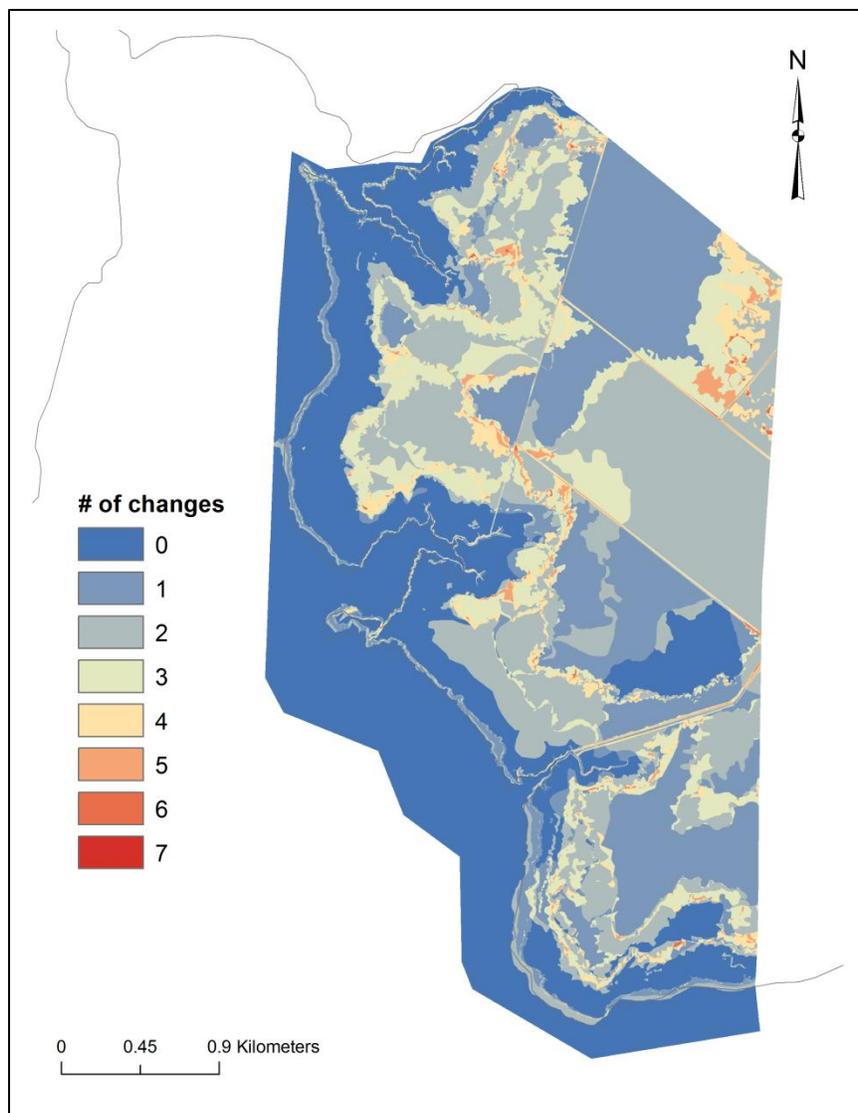
Figure 10: Map of total change for Long Shoal Marshes.

As in the analysis for the entire Albemarle-Pamlico Peninsula, the total number of times a

particular pixel of habitat changed over time was determined for Long Shoal Marshes (Figure

10). There were relatively few areas that changed more than five or six times. Areas of change

seem to be concentrated mostly directly around the shoreline, or further inland. The changes

inland can possibly be attributed to the formation of roads and ditches sometime between 1947

and 1969. The fragmentation of the landscape by roads and ditches is likely a large contributor to habitat change.

In addition to evaluating the total number of changes, the types of habitat transitions were evaluated for both Long Shoal Marshes and Manns Harbor. The figure below depicts a time series of transition maps for Long Shoal Marshes, for the set of transition types selected because of their relevance to this study (Figure 11). From 1932-1947, there were some small patches of change from sparse forest to brackish marsh, sparse forest to dense forest, and dense forest to sparse forest. However, there was little change along the shoreline for that time period. From 1947-1969, a large amount of sparse to dense forest conversion occurred in the northern inland section of the study area. Also, fair amounts of brackish marsh to shrub pocosin and brackish marsh to sparse forest occurred. There was also a good amount of brackish marsh to open water conversion concentrated all along the shoreline. From 1969-1993, there was a large amount of dense forest to shrub pocosin transition, and sparse forest to shrub pocosin transition. There was little change from 1993-1998 and from 1998-2000. From 2000-2005, there were a fair amount of shrub pocosin to brackish marsh transition. And, little change occurred from 2005-2009. Overall, the most noticeable differences from 1932 to 2009 were a significant amount of sparse forest to dense forest transition, sparse forest to shrub forest transition, and dense forest to shrub pocosin. Also, there was a notable shift from brackish marsh to open water along the coastline. The following tables give the total area of the habitat change from year to year, and the rate of change for each habitat transition from year to year (Tables 8 and 9).
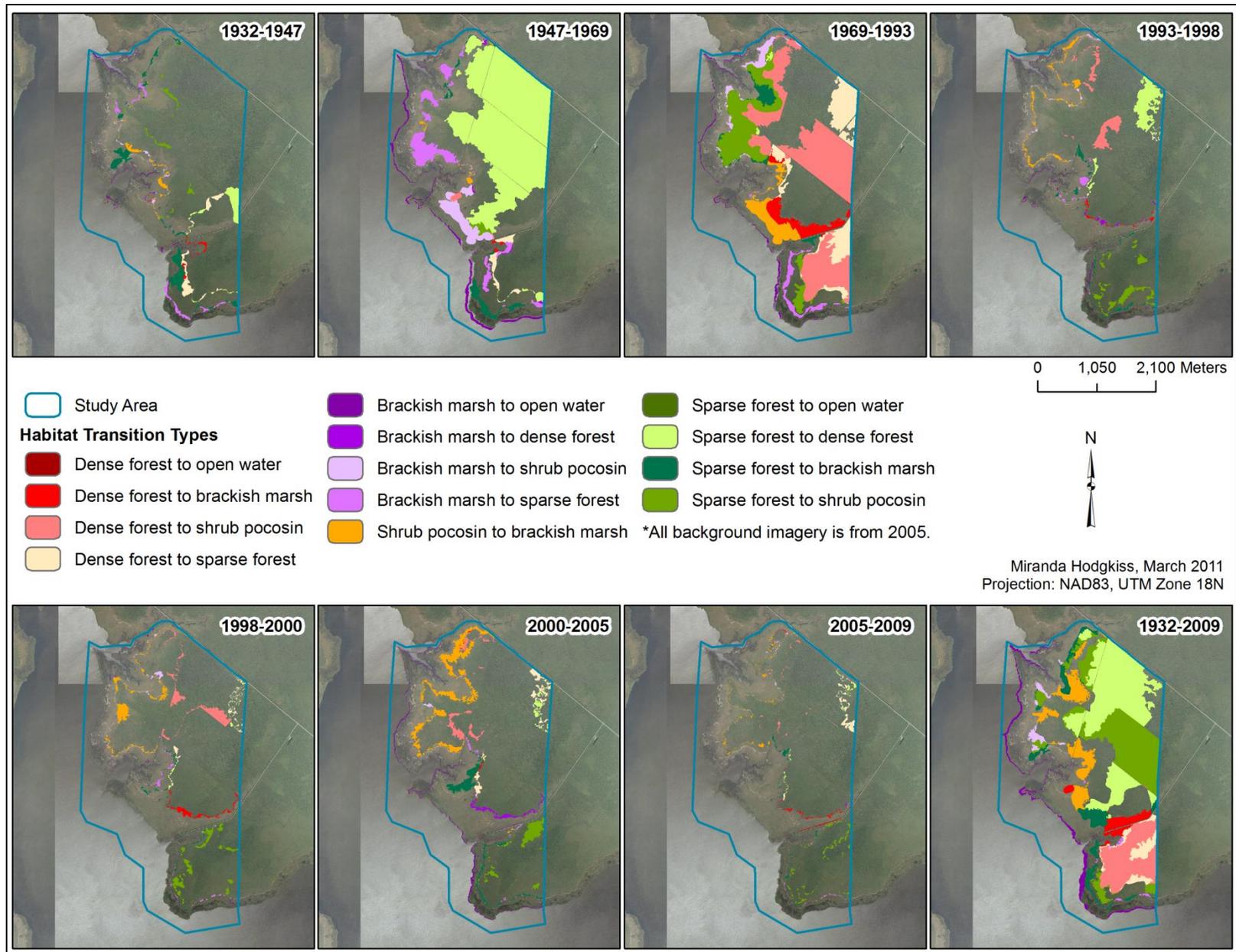
Figure 11: Selected vegetation transitions for Long Shoal Marshes.

Table 8: Areas of each habitat transition type per time period for Long Shoal Marshes.

Habitat Transition Type		Area (m²)							
Year 1	Year 2	1932-1947	1947-1969	1969-1993	1993-1998	1998-2000	2000-2005	2005-2009	1932-2009
Dense Forest	Open Water	0	0	977	1	813	0	0	0
Dense Forest	Brackish Marsh	25,487	11186	293,454	19,532	51,657	9,685	27,778	199,106
Dense Forest	Shrub Pocosin	2,188	22489	2,050,706	186,397	153,861	102,169	21,856	752,943
Dense Forest	Sparse Forest	96,893	83572	769,135	5,856	39,885	100,384	62,976	213,907
Brackish Marsh	Open Water	39,674	182690	106,055	45,984	14,509	92,168	9,091	246,113
Brackish Marsh	Dense Forest	3,401	17714	1,594	17,385	161	53,079	3,813	0
Brackish Marsh	Shrub Pocosin	17,337	270329	136,407	20,054	24,402	9,201	13,155	90,287
Brackish Marsh	Sparse Forest	69,390	426946	126,906	33,319	27,672	16,993	10,292	22,333
Shrub Pocosin	Brackish Marsh	49,226	22488	327,028	97,450	121,987	364,890	43,074	517,022
Sparse Forest	Open Water	0	0	0	3	0	0	0	2,040
Sparse Forest	Dense Forest	117,666	3459067	17,054	283,575	16,647	35,354	19,386	1,769,394
Sparse Forest	Brackish Marsh	228,260	143515	154,892	82,413	33,757	159,393	29,979	393,306
Sparse Forest	Shrub Pocosin	61,333	36813	911,743	144,815	121,929	134,676	63,623	1,370,946

Table 9: Rates of change for each habitat transition type per time period for Long Shoal Marshes.

Habitat Transition Type		Rate of change (m²/year)							
Year 1	Year 2	1932-1947	1947-1969	1969-1993	1993-1998	1998-2000	2000-2005	2005-2009	1932-2009
Dense Forest	Open Water	0.00	0.00	40.71	0.20	406.50	0.00	0.00	0.00
Dense Forest	Brackish Marsh	1,699.13	508.45	12,227.25	3,906.40	25,828.50	1,937.00	6,944.50	2,585.79
Dense Forest	Shrub Pocosin	145.87	1,022.23	85,446.08	37,279.40	76,930.50	20,433.80	5,464.00	9,778.48
Dense Forest	Sparse Forest	6,459.53	3,798.73	32,047.29	1,171.20	19,942.50	20,076.80	15,744.00	2,778.01
Brackish Marsh	Open Water	2,644.93	8,304.09	4,418.96	9,196.80	7,254.50	18,433.60	2,272.75	3,196.27
Brackish Marsh	Dense Forest	226.73	805.18	66.42	3,477.00	80.50	10,615.80	953.25	0.00
Brackish Marsh	Shrub Pocosin	1,155.80	12,287.68	5,683.63	4,010.80	12,201.00	1,840.20	3,288.75	1,172.56
Brackish Marsh	Sparse Forest	4,626.00	19,406.64	5,287.75	6,663.80	13,836.00	3,398.60	2,573.00	290.04
Shrub Pocosin	Brackish Marsh	3,281.73	1,022.18	13,626.17	19,490.00	60,993.50	72,978.00	10,768.50	6,714.57
Sparse Forest	Open Water	0.00	0.00	0.00	0.60	0.00	0.00	0.00	26.49
Sparse Forest	Dense Forest	7,844.40	157,230.32	710.58	56,715.00	8,323.50	7,070.80	4,846.50	22,979.14
Sparse Forest	Brackish Marsh	15,217.33	6,523.41	6,453.83	16,482.60	16,878.50	31,878.60	7,494.75	5,107.87
Sparse Forest	Shrub Pocosin	4,088.87	1,673.32	37,989.29	28,963.00	60,964.50	26,935.20	15,905.75	17,804.49

CART Model Results

CART models use recursive partitioning, where the goal is to split the data at each "partition" in order to divide the two outcomes into relatively similar groups. The length of the branch in the output tree indicates the relative amount of difference it explains. At each split, the value chosen for the environmental predictor is the one that accounts for the maximum amount of deviance in the response variable. For both Long Shoal Marshes and Manns Harbor, a 10-fold cross validation (where 10 ancillary trees are created to test the error rate of the predicted model) was completed to determine if tree-pruning was necessary. CART models are inherently over-fitted, as they try to explain all of the differences in the data by ultimately splitting the final ends of the tree into homogenous groups. Since this is not a predictive model, however, and rather an explanatory model fitted to a particular study location, it was determined that pruning the trees would be unnecessary.

Below is the CART model tree output for Long Shoal Marshes, which describes the behavior of the response variable (transition type), based on the predictor variable inputs (Figure 12). Because the model attempts to explain all of the data, some of the transition types are repeated in multiple parts of the model.
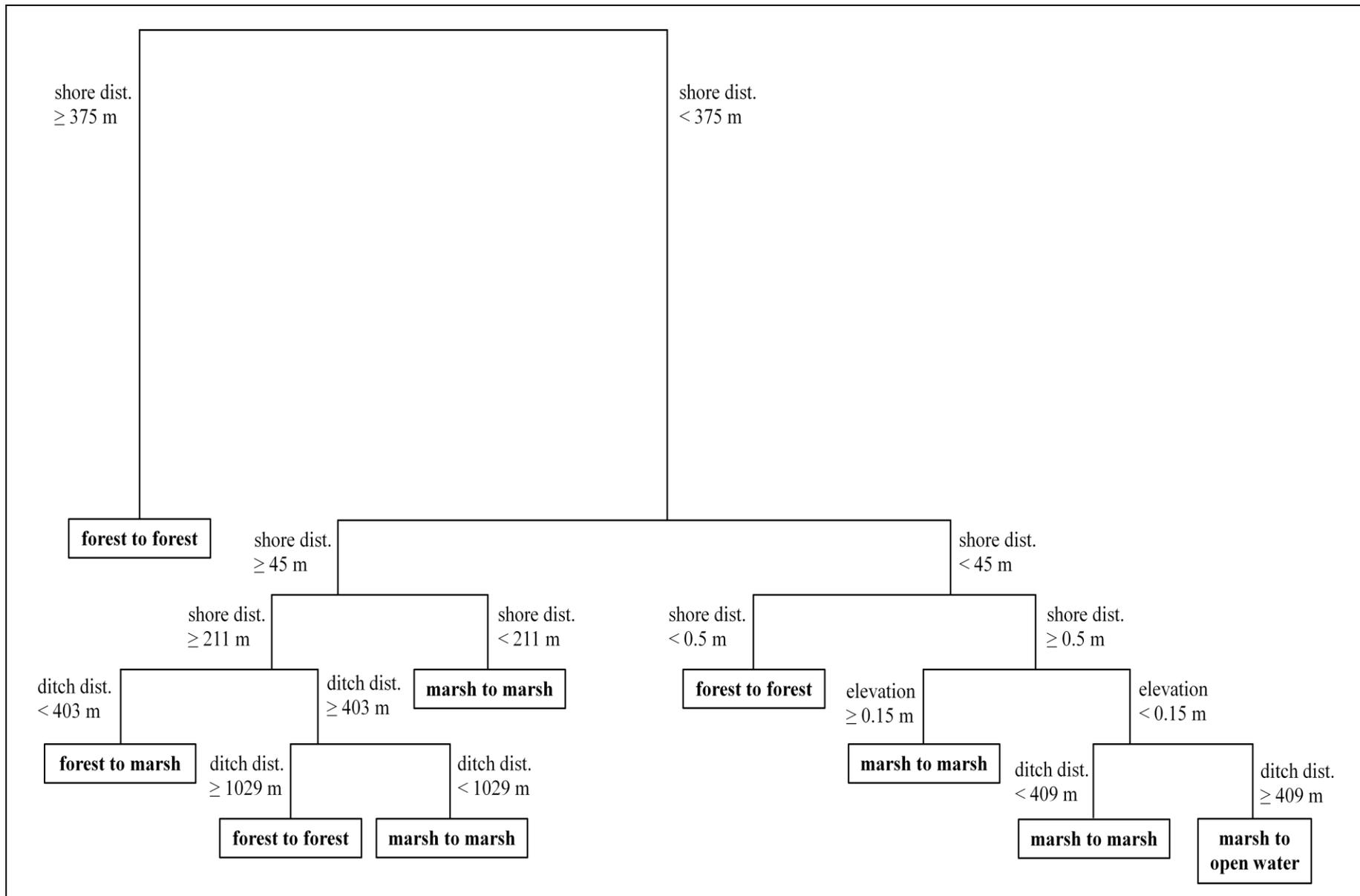
Figure 12: CART model tree output for Long Shoal Marshes.

The most explanatory predictor in the CART Model for Long Shoal Marshes is distance from shore, which splits the data at either greater than/equal to 375 meters, or less than 375 meters. Below are descriptions of where each habitat transition type is predicted to occur for this study site.

Forest to forest:

This transition is found in three branches of the tree. It is likely to be found at 375 meters or more from shore. It is also likely to be found between 211 and 375 meters from shore if it is also greater than 1,029 meters from a ditch. And, it is likely to be found in some places at less than 0.5 meters from shore, which indicates that there are some areas of forested land on the shore of the Long Shoal Marshes study site that haven't yet been converted to any other habitat type.

Forest to marsh:

This transition is found in only one branch of the tree, where it is predicted to occur between 211 and 375 meters from shore and less than 403 meters from a ditch.

Marsh to marsh:

This transition is found in four branches of the tree. First, it is predicted to occur between 211 and 375 meters from shore if it is also between 403 and 1,029 meters from a ditch. Second, it is likely to occur between 45 and 211 meters from shore. Third, it is likely to occur between 0.5 and 45 meters from shore and greater than 0.15 meters in elevation. And last, it is likely to occur between 0.5 and 45 meters from shore, less than 0.15 meters in elevation, and less than 409 meters from a ditch.

Marsh to open water

This transition is found in only one branch of the tree. It is predicted to occur between 0.5 and 45 meters from shore, less than 0.15 meters in elevation, and 409 meters or greater from a ditch.

The following diagram illustrates the CART model results, but only for the most explanatory branches of the tree to show where one would be most likely to find a particular transition type for Long Shoal Marshes (Figure 13). In other words, the section of the tree which is schematically represented below contained the highest number of sampling points for its particular transition type overall. All of the transitions are predicted by distance from shore, and each transition group fits into exhaustive but mutually exclusive ranges of distance from shore. The forest to marsh and marsh to open water transitions are also both predicted by distance from ditch, and the marsh to open water transition is additionally predicted by elevation.
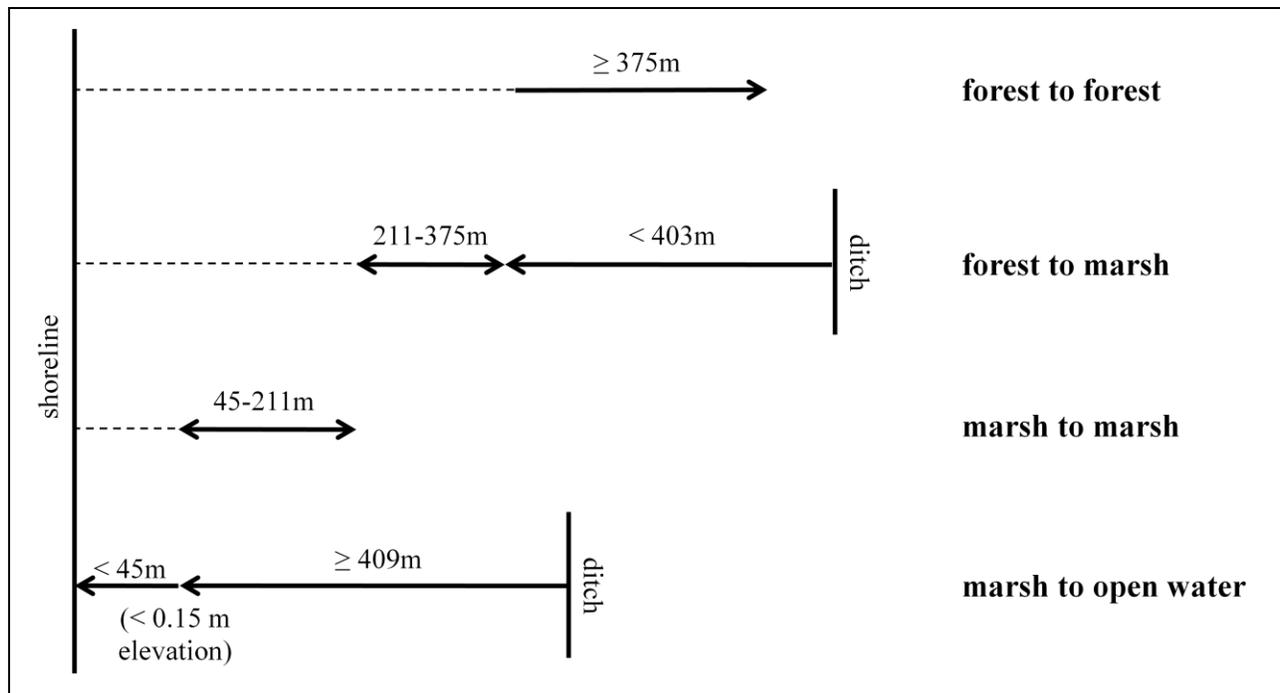
Figure 13: Schematic diagram of CART model results for Long Shoal Marshes. Only the most explanatory branches of the CART tree are represented.

Manns Harbor

Habitat Change over Time

The areas of each habitat class broken down by year for the Manns Harbor study site are detailed in the following table (Table 10). The total area for all of the time periods remained the same because the extent of each habitat shapefile was clipped to the extent of the Manns Harbor study area when conducting the overlay analysis. The overall area of brackish marsh and shrub pocosin increased, while the area of dense forest and sparse forest decreased. Also, the area of open water increased, indicating that the total amount of land area has decreased for the entire time period. However, there were some decreases in the amount of open water from 1998-2000 and again from 2000-2005. The rates of change in habitat types for each time period were also calculated (Table 11). The largest positive rate of change occurred in brackish marsh with a rate of 0.056 km²/year. The largest negative rate of change occurred in dense forest with a rate of

-0.108 km²/year. These same results are also demonstrated by the following time series figure, showing the total area of each habitat category versus the year (Figure 14).

Table 10: Habitat changes for Manns Harbor.

Habitat Category	Area (km²)						
	1932	1969	1993	1998	2000	2005	2009
Brackish Marsh	8.64	9.38	10.28	10.42	10.94	12.86	12.93
Dense Forest	16.83	18.88	9.20	9.20	8.85	9.17	8.53
Ditch	0.10	0.15	0.12	0.17	0.14	0.13	0.13
Open Water	7.45	7.85	8.36	8.57	8.52	8.37	8.73
Residential	0.84	0.80	1.56	1.56	1.61	1.70	1.73
Road	0.19	0.18	0.20	0.21	0.23	0.29	0.24
Sand	0.10	0.08	0.02	0.02	0.02	0.00	0.00
Shrub Pocosin	0.00	0.23	3.94	3.86	4.28	3.12	3.12
Sparse Forest	4.07	0.67	4.53	4.20	3.63	2.57	2.79
TOTAL				38.2			

Table 11: Rates of habitat changes for Manns Harbor.

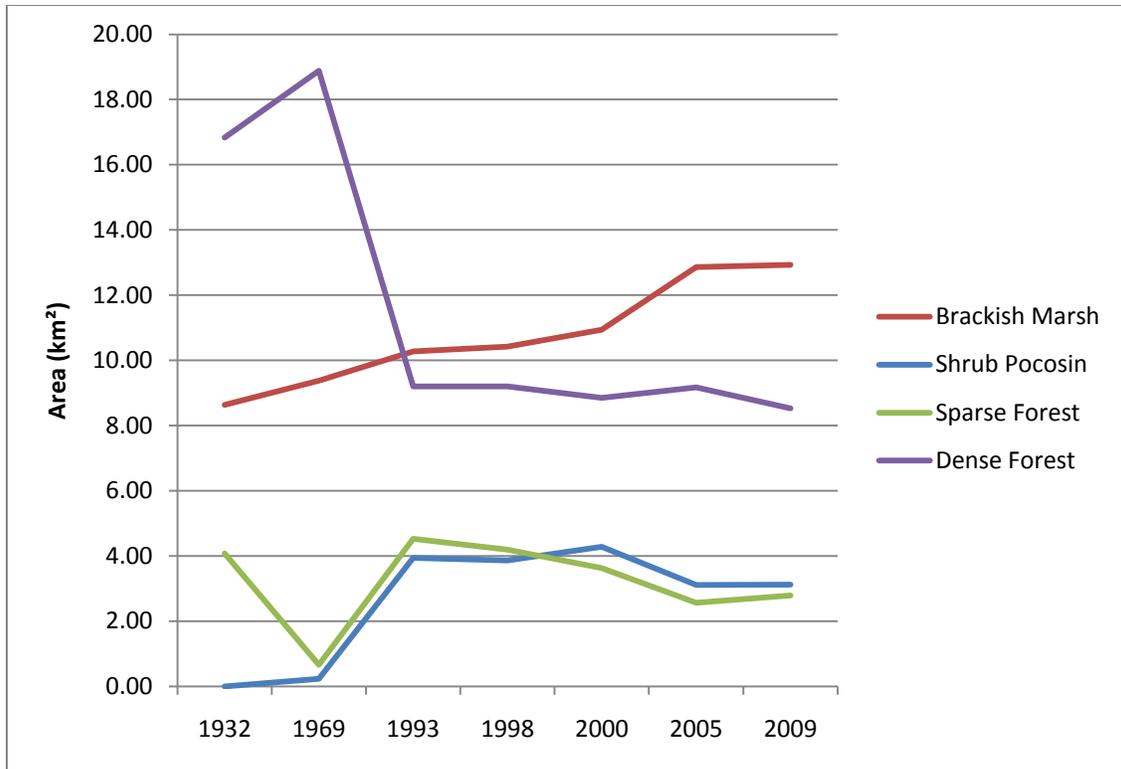| Habitat Category	Rate of change (km²/year)						
	1932-1969	1969-1993	1993-1998	1998-2000	2000-2005	2005-2009	1932-2009
Brackish Marsh	0.020	0.037	0.029	0.258	0.385	0.016	0.056
Dense Forest	0.055	-0.403	-0.001	-0.174	0.065	-0.161	-0.108
Ditch	0.001	-0.001	0.010	-0.013	-0.003	0.001	0.000
Open Water	0.011	0.021	0.042	-0.027	-0.029	0.090	0.017
Residential	-0.001	0.032	0.001	0.023	0.019	0.007	0.012
Road	0.000	0.001	0.003	0.007	0.012	-0.011	0.001
Sand	-0.001	-0.002	0.001	-0.003	-0.002	0.000	-0.001
Shrub Pocosin	0.006	0.154	-0.015	0.211	-0.234	0.002	0.041
Sparse Forest	-0.092	0.161	-0.067	-0.284	-0.212	0.056	-0.017
TOTAL				0			

Figure 14: Changes in the area of selected habitat types over time for Long Shoal Marshes.

Below is a figure showing the total number of times a particular pixel of habitat changed over the study time period for Manns Harbor (Figure 15). There were few areas that changed more than five times. The most amount of change seems to be happening in the southernmost portion of the study area.
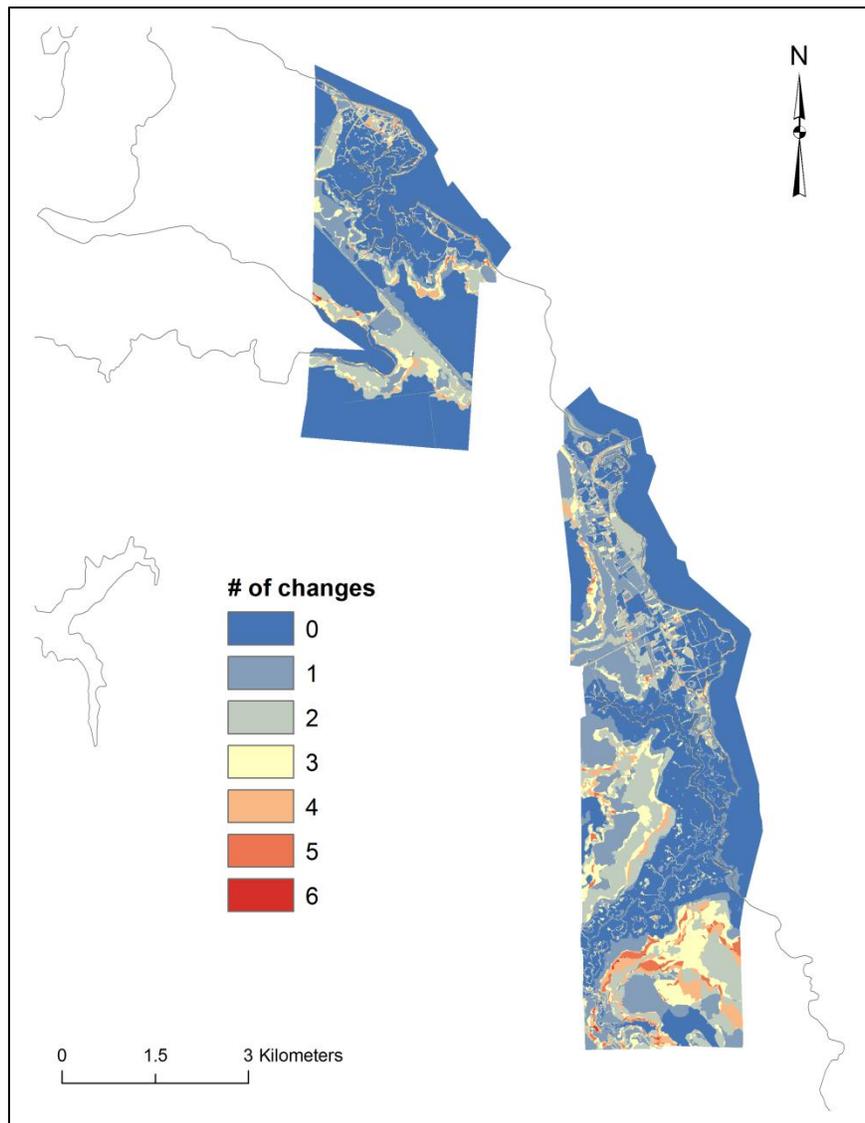
Figure 15: Map of total change for Manns Harbor.

The figure below depicts a time series of transition maps for Manns Harbor, for the set of

transition types selected because of their relevance to this study (Figure 16). Most of the large

patches of change occurred from 1932-1969, and from 1969-1993. From 1932-1969, there was a

large amount of sparse forest to dense forest transition. Then from 1969-1993, there was a large

amount of dense forest transition to brackish marsh, shrub pocosin, and sparse forest. The most

change along the shoreline where brackish marsh was converted to open water also appeared to happen between 1932 and 1993. The following tables give the total area of the habitat change from year to year, and the rate of change for each habitat transition from year to year (Tables 12 and 13).
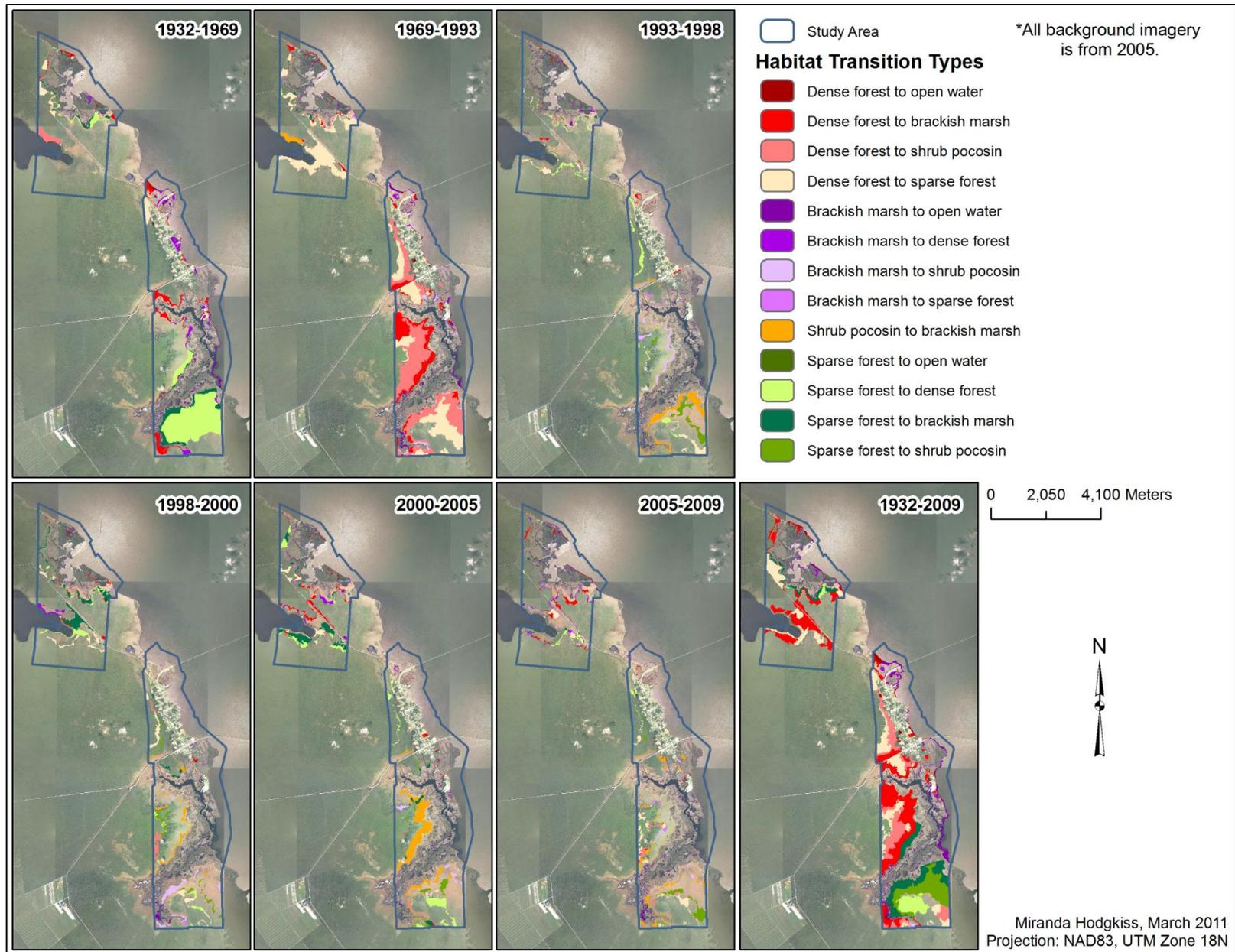
Figure 16: Selected vegetation transitions for Manns Harbor.

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Table 12: Areas of each habitat transition type per time period for Manns Harbor.

Habitat Transition Type		Area (m²)						
Year 1	Year 2	1932-1969	1969-1993	1993-1998	1998-2000	2000-2005	2005-2009	1932-2009
Dense Forest	Open Water	81,117	100,429	31,112	20,994	19,777	34,009	292,153
Dense Forest	Brackish Marsh	713,795	1,637,928	128,472	144,718	381,657	332,037	3,984,798
Dense Forest	Shrub Pocosin	231,496	3,774,144	23,115	202,203	91,663	158,007	1,721,971
Dense Forest	Sparse Forest	463,114	3,930,945	422,244	537,292	279,063	540,035	2,405,992
Brackish Marsh	Open Water	445,545	539,860	317,259	192,720	190,290	430,420	1,002,500
Brackish Marsh	Dense Forest	382,812	142,962	78,078	142,761	183,449	201,991	138,547
Brackish Marsh	Shrub Pocosin	0	158,217	304,013	384,323	144,562	120,853	27,345
Brackish Marsh	Sparse Forest	13,838	43,036	84,201	35,417	38,797	144,557	6,773
Shrub Pocosin	Brackish Marsh	0	0	609,280	282,010	1,150,620	459,794	0
Sparse Forest	Open Water	121	309	3,526	2,152	787	5,936	21,005
Sparse Forest	Dense Forest	3,220,452	45,126	475,837	379,896	723,635	177,710	697,289
Sparse Forest	Brackish Marsh	667,561	65,687	57,465	606,733	605,789	53,493	1,608,840
Sparse Forest	Shrub Pocosin	0	863	416,122	336,038	235,358	364,420	1,372,767

Table 13: Rates of change for each habitat transition type per time period for Long Shoal Marshes.

Habitat Transition Type		Rate of change (m²/year)						
Year 1	Year 2	1932-1969	1969-1993	1993-1998	1998-2000	2000-2005	2005-2009	1932-2009
Dense Forest	Open Water	2,192	4,185	6,222	10,497	3,955	8,502	3,794
Dense Forest	Brackish Marsh	19,292	68,247	25,694	72,359	76,331	83,009	51,751
Dense Forest	Shrub Pocosin	6,257	157,256	4,623	101,102	18,333	39,502	22,363
Dense Forest	Sparse Forest	12,517	163,789	84,449	268,646	55,813	135,009	31,247
Brackish Marsh	Open Water	12,042	22,494	63,452	96,360	38,058	107,605	13,019
Brackish Marsh	Dense Forest	10,346	5,957	15,616	71,381	36,690	50,498	1,799
Brackish Marsh	Shrub Pocosin	0	6,592	60,803	192,162	28,912	30,213	355
Brackish Marsh	Sparse Forest	374	1,793	16,840	17,709	7,759	36,139	88
Shrub Pocosin	Brackish Marsh	0	0	121,856	141,005	230,124	114,949	0
Sparse Forest	Open Water	3	13	705	1,076	157	1,484	273
Sparse Forest	Dense Forest	87,039	1,880	95,167	189,948	144,727	44,428	9,056
Sparse Forest	Brackish Marsh	18,042	2,737	11,493	303,367	121,158	13,373	20,894
Sparse Forest	Shrub Pocosin	0	36	83,224	168,019	47,072	91,105	17,828

CART Model Results

Below is the CART output for Manns Harbor (Figure 17), followed by the schematic diagram of the most explanatory branches of the tree (Figure 18). The most explanatory predictor in the CART Model for Long Shoal Marshes is distance from shore, which splits the data at either greater than/equal to 276 meters, or less than 276 meters. Below are descriptions of where each habitat transition type is predicted to occur for this study site.

Forest to forest:

This transition type occurred in three branches of the tree. It is predicted to occur at 785 meters or more from shore. It is also predicted to occur between 276 and 785 meters from shore if it is also less than 1,063 meters from a ditch. And, it is also likely to occur less than 0.5 meters from shore. Again, as for the Long Shoal Marshes site, this indicates that there are some areas of forested land on the shore of Manns Harbor that haven't yet been converted to any other habitat type.

Forest to marsh:

This transition type is described by two branches of the tree. First, it is predicted to occur between 276 and 785 meters from shore and 1,063 meters or more from a ditch. Also, it is predicted to occur between 184 and 276 meters from shore and less than 803 meters from a ditch.

Marsh to marsh:

 This transition type is also described by two branches of the tree. First, it is predicted to occur between 184 and 276 meters from shore, and also 803 or more meters from a ditch. Second, it is predicted to occur between 0.5 and 184 meters from shore.

Marsh to open water

This transition type is not accounted for in the final CART model for Manns Harbor. This is likely due to the fact that it had a small sample size (79 sample points), making it difficult for the model to predict any differences in this data.

In the schematic diagram, all of the transitions are predicted by distance from shore. However, unlike for Long Shoal Marshes, each transition group does not fit into either exhaustive or mutually exclusive ranges of distance from shore. The forest to forest and forest to marsh transitions overlap in their distance from shore, and there is a gap from 184 meters to 276 meters where none of the transition types are predicted to occur. Part of the reason for these less clear distinctions is because the Manns Harbor CART model did not perform as well in creating response variable groups that were completely homogenous. For instance, one branch of the tree had forest to marsh as the predominant transition response with 121 samples, but it also included 110 forest to forest samples in that same branch. Another reason for the less consistent relationships for this study site may be because there were other factors (such as human development and occurrence of fire) that weren't accounted for in the CART model predictor variables.

Figure 17: CART model tree output for Manns Harbor.

Figure 18: Schematic diagram of CART model results for Manns Harbor. Only the most explanatory branches of the CART tree are represented.

DISCUSSION

Implications of Climate Change and Sea Level Rise

The results above indicate that sea level rise is likely one of the variables driving habitat changes on the refuge, especially at the Long Shoal Marshes study site. At that site, the types of habitat transitions were clearly predicted by distance from shore. Also, the breakdown of habitat transitions by distance from shore falls in line with what is expected under a sea level rise scenario. One study of vegetation dynamics of Upper Coastal Plain depression wetlands found that the hydrologic regime was the strongest correlate of vegetation type (De Steven and Toner 2004). Thus, if changes in sea level do affect vegetation, then the types of transitions one would expect to see happen close to shore would be those most influenced by hydrology and salinity gradients. This was seen by the fact that the marsh to open water and the forest to marsh

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transitions occurred closer to shore than areas that remained forest at the Long Shoal Marshes site.

Overall, both sites have been losing forest and gaining marsh over time. This natural succession process has been observed in tidal freshwater forests in the Gulf of Mexico and South Atlantic coasts (e.g. Doyle 2010, Desantis 2007). When sea level rises, the marsh will respond by migrating inland and seeking higher elevations. Additional pressures from increased salinity and wetter soils cause a die back of the forest to occur. In a very flat area like the refuge, small increases in sea level can have far-reaching consequences, causing significant loss of forested land. On the refuge, as well as other coastal areas of North Carolina, the loss of forest coupled with increased marsh habitat has become problematic mostly because the invasive species, *Juncus romerianus* (or black needlerush), has a tendency to outcompete all of the other native marsh plant species. This leaves an overall ecosystem reduced in biodiversity and unable to support native habitat.

Lastly, this study has found evidence of shoreline erosion at both study sites. In looking at the overall habitat areas over time, there was a loss of marsh to open water, especially along the shoreline. This is indicative that the shoreline is being eroded over time as the sea level becomes too high for marsh vegetation to produce enough sediment to keep pace and survive.

Management of the North Carolina Coastal Plains

Results show that for even the same study area, the Alligator River National Wildlife Refuge, the range of conditions can vary widely. It is important to consider this variability in climate change planning and management. TNC and USFWS, who have already begun working together to implement some climate change and habitat adaptation projects, must remain

cautious of the differences found throughout the refuge. A strategy that works in one area may not be as effective in another. Thus, when implementing climate change adaptation projects, managers of the refuge should consider what mechanisms (e.g. sea level rise, human pressure and development, or fire) are driving changes in habitat before devising solutions to help those communities adapt.

As land on the refuge disappears due to sea level rise, there is even more incentive to preserve and restore wetlands that might help to slow the effects of sea level rise. For instance, wetlands are known for their ability to stabilize shorelines and protect coastal communities (Gedan 2011). Wetland vegetation can interact with the water and sediment along the coast to slow the flow of water, facilitate deposition of sediment (and development of peat), and help to make the shoreline more solid.

Recommendations

This project began with the idea of guiding TNC on additional areas that they should focus on for their habitat adaptation strategies. In evaluating the results of this project, it is imperative to keep in mind that the results from the large-scale change portion of this project only give an idea of the relative amounts of change for the entire refuge. However, the results from the small-scale analysis indicate that the best study site for implementing additional climate change adaptation projects would be at Long Shoal Marshes. It is recommended that TNC begin by focusing on that site, and that they conduct further research into what mechanisms might be driving the vegetative changes at Manns Harbor before expending too many resources there. Additionally, TNC should validate the results of this study by cross-checking the most recent vegetation classification with field data. Although it is not possible to check the historical

vegetation classification, the accuracy obtained from field verification on recent data would give an indication of the accuracy of the other years that were classified.

The results from this project provide a good basis for understanding the historical habitat changes on the refuge from the early 1930s until 2009. Increasingly better quality aerial photos are becoming more widely available. Also, data is now being collected on a more frequent basis. In order to assess more recent trends occurring on the refuge, it is recommended that TNC continue with this study in the future by re-evaluating the results with additional analyses as more data becomes available. Also, the small-scale analysis only takes into account two study sites. There may be other study sites on the refuge that weren't considered for this project, but that could be investigated in the future depending on the availability of data.

With the inevitability of sea level rise, managers of coastal areas such as the Alligator River National Wildlife Refuge have been forward-thinking in planning for climate change adaptation. With the rich amount of natural resources and conservation potential that these wetland communities provide it is important to plan for the future, but in a way that accurately reflects historical factors driving habitat change.

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APPENDIX

Habitat Types
- Administrative
- Atlantic White Cedar Forest
- Bay Forest
- Brackish Marsh
- Cropland
- Hardwood Swamp
- Loblolly Pine Forest
- Managed Wetlands
- Mixed Forest
- Non-alluvial Hardwood Forest
- Open Water
- Pond Pine Pocosin
- Residential
- Shrub Pocosin
- Shrub/Marsh Transition

0   4   8 Kilometers

Miranda Hodgkiss, March 2011
Projection: NAD83, UTM Zone 18N

Figure 1A: 1993 habitat classification for the Albemarle-Pamlico peninsula.

Figure 2A: 1998 habitat classification for the Albemarle-Pamlico peninsula.

Figure 3A: 2000 habitat classification for the Albemarle-Pamlico peninsula.

Figure 4A: 2000 habitat classification for the Albemarle-Pamlico peninsula.

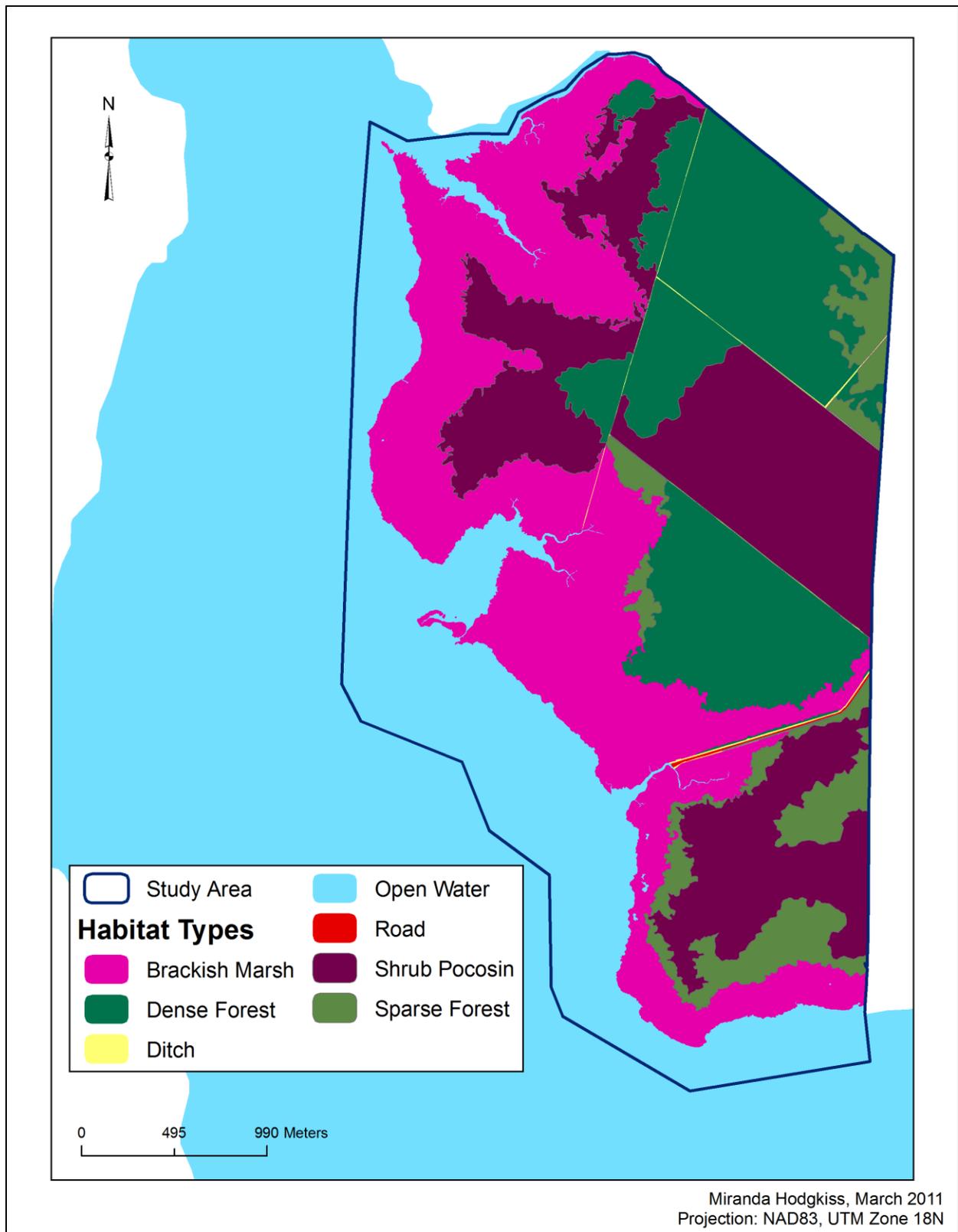Miranda Hodgkiss, March 2011
Projection: NAD83, UTM Zone 18N

A-4

Figure 5A: 1932 habitat classification for Long Shoal Marshes.

Figure 6A: 1947 habitat classification for Long Shoal Marshes.

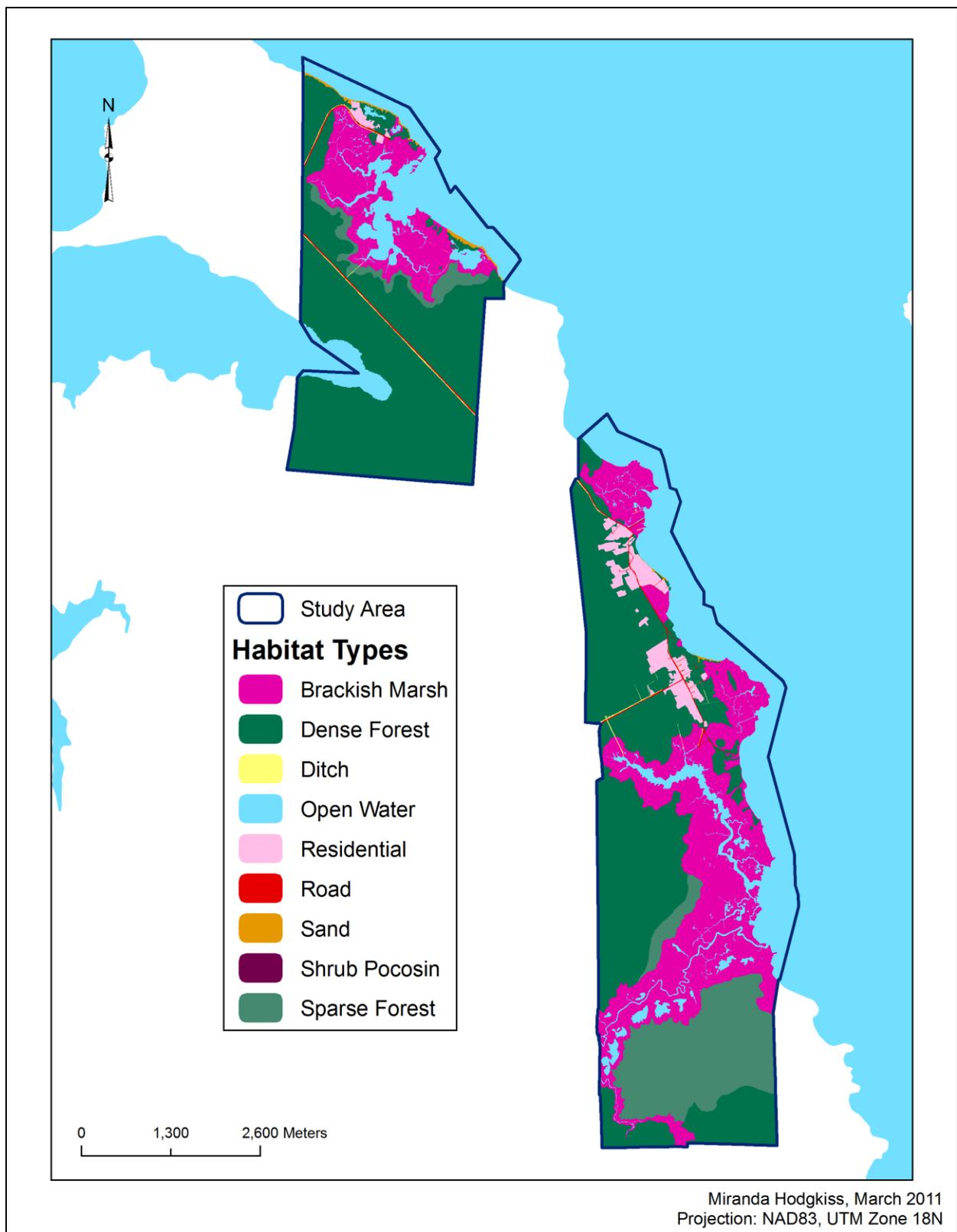**Figure 7A: 1969 habitat classification for Long Shoal Marshes.**
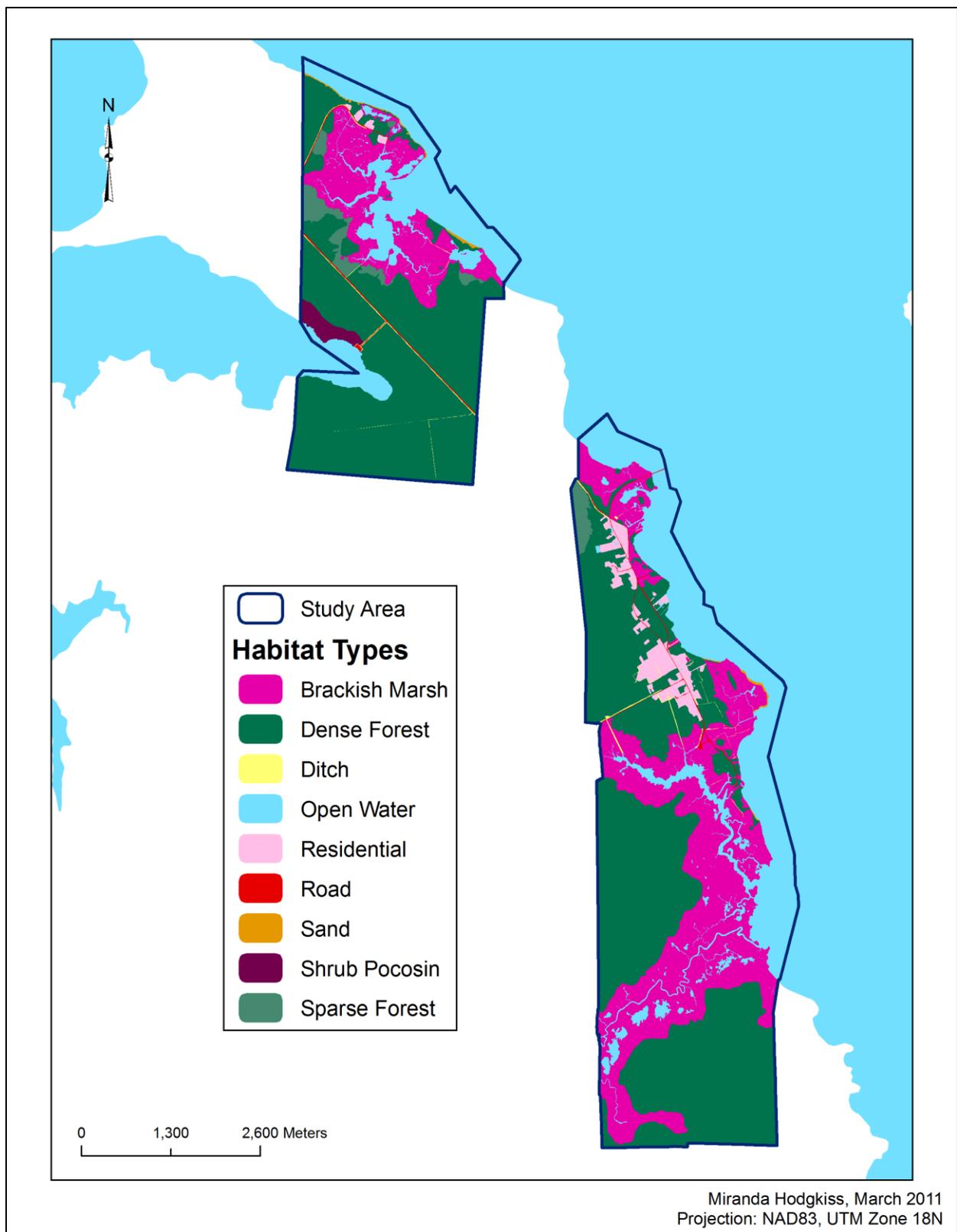
Figure 8A: 1993 habitat classification for Long Shoal Marshes.

Figure 9A: 1998 habitat classification for Long Shoal Marshes.

Figure 10A: 2000 habitat classification for Long Shoal Marshes.

Figure 11A: 2005 habitat classification for Long Shoal Marshes.

Figure 12A: 2009 habitat classification for Long Shoal Marshes.

Figure 13A: 1932 habitat classification for Manns Harbor.

Legend:

Study Area

Habitat Types
- Brackish Marsh
- Dense Forest
- Ditch
- Open Water
- Residential
- Road
- Sand
- Shrub Pocosin
- Sparse Forest

0   1,300   2,600 Meters

Miranda Hodgkiss, March 2011
Projection: NAD83, UTM Zone 18N

Figure 14A: 1969 habitat classification for Manns Harbor.

Figure 15A: 1993 habitat classification for Manns Harbor.

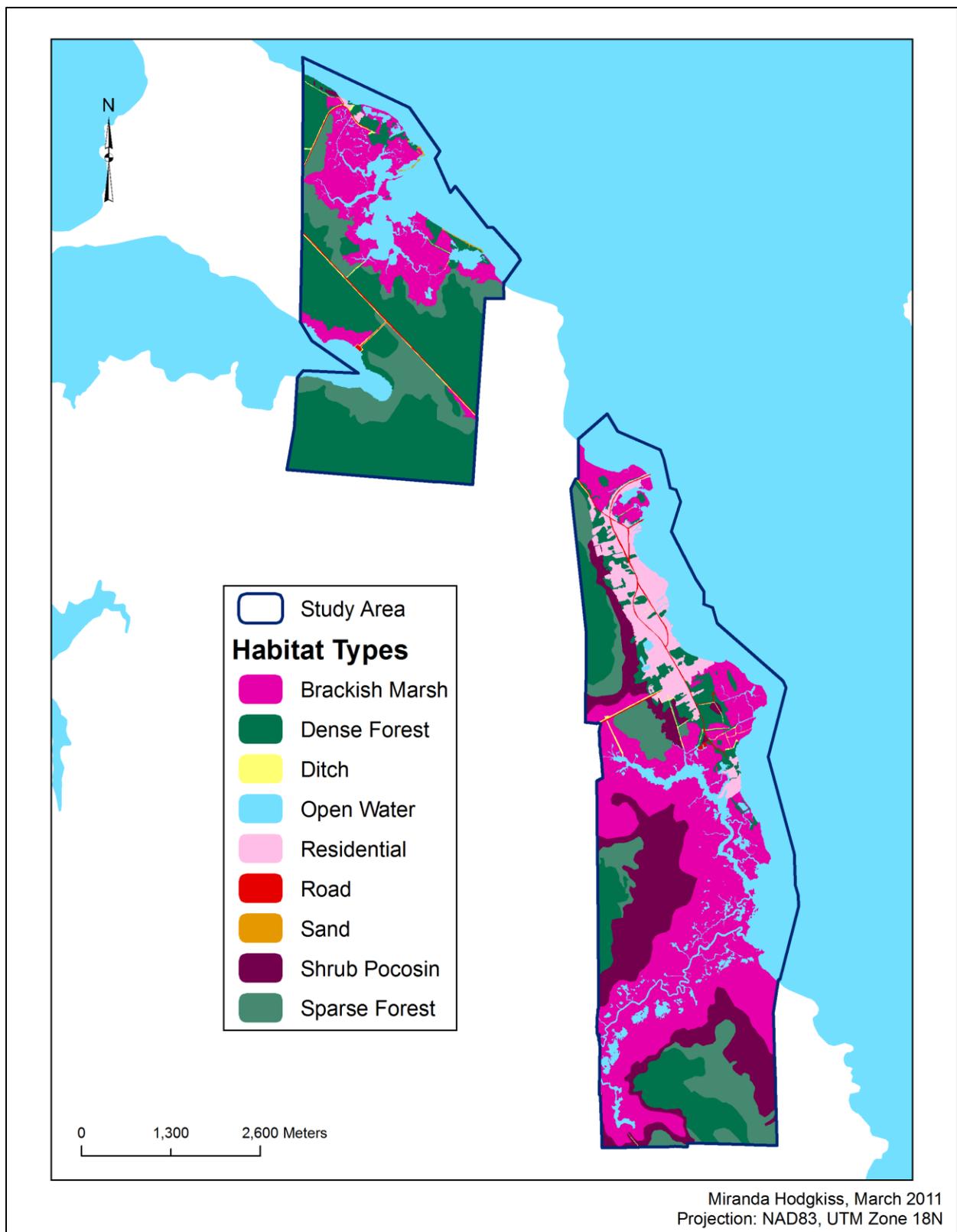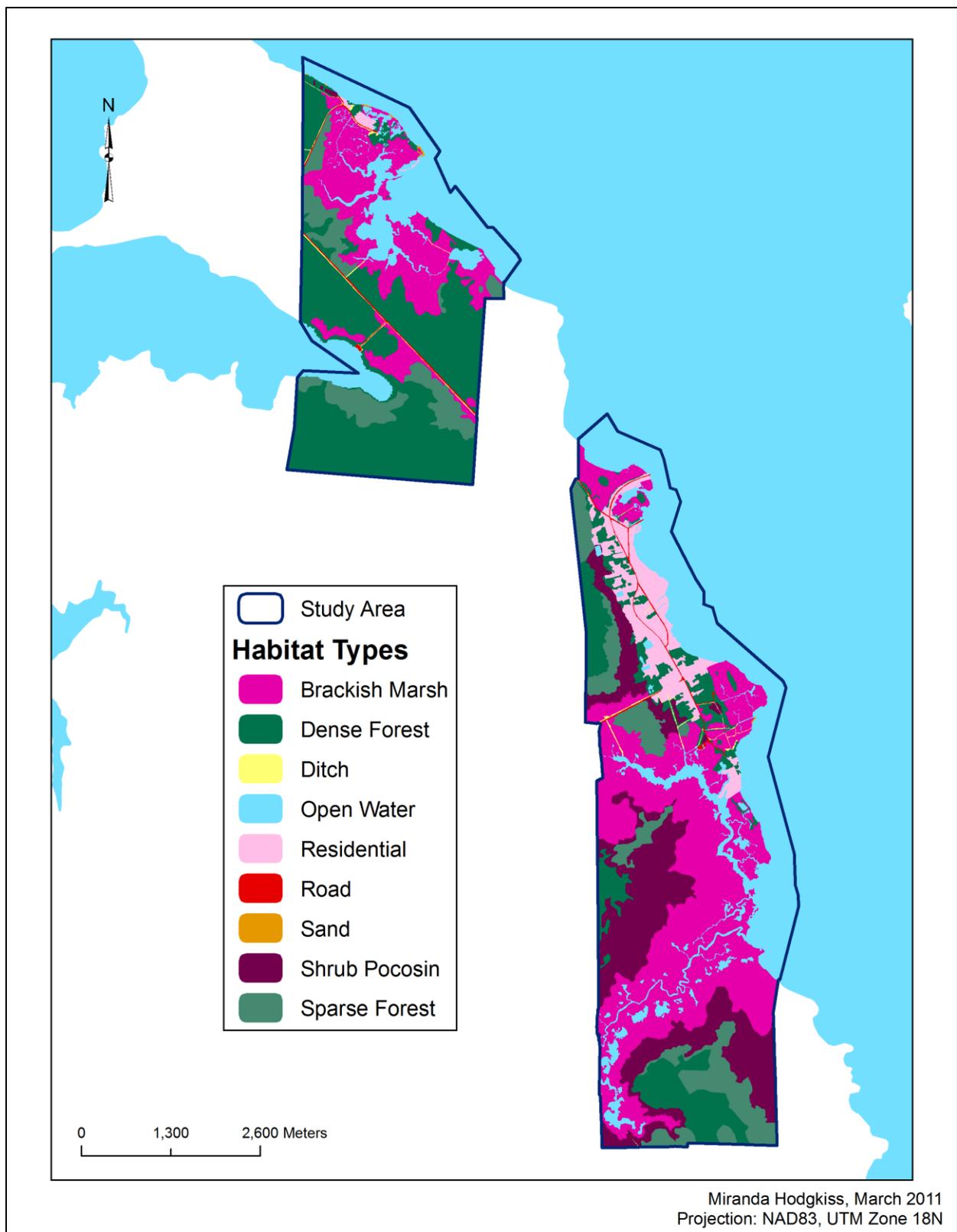**Figure 16A: 1998 habitat classification for Manns Harbor.**

Legend:

Study Area

Habitat Types
- Brackish Marsh
- Dense Forest
- Ditch
- Open Water
- Residential
- Road
- Sand
- Shrub Pocosin
- Sparse Forest

0   1,300   2,600 Meters

Miranda Hodgkiss, March 2011
Projection: NAD83, UTM Zone 18N

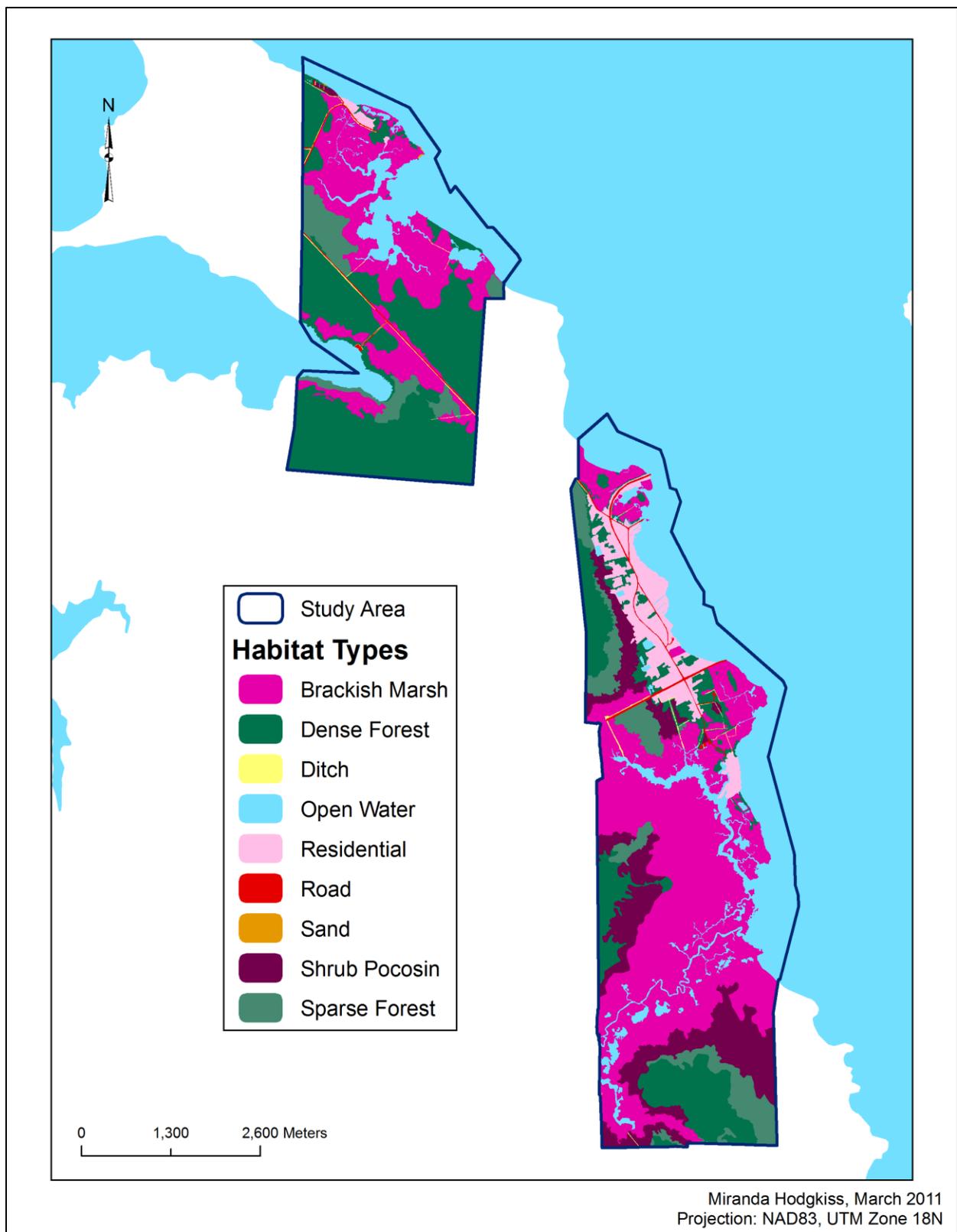**Figure 17A: 2000 habitat classification for Manns Harbor.**

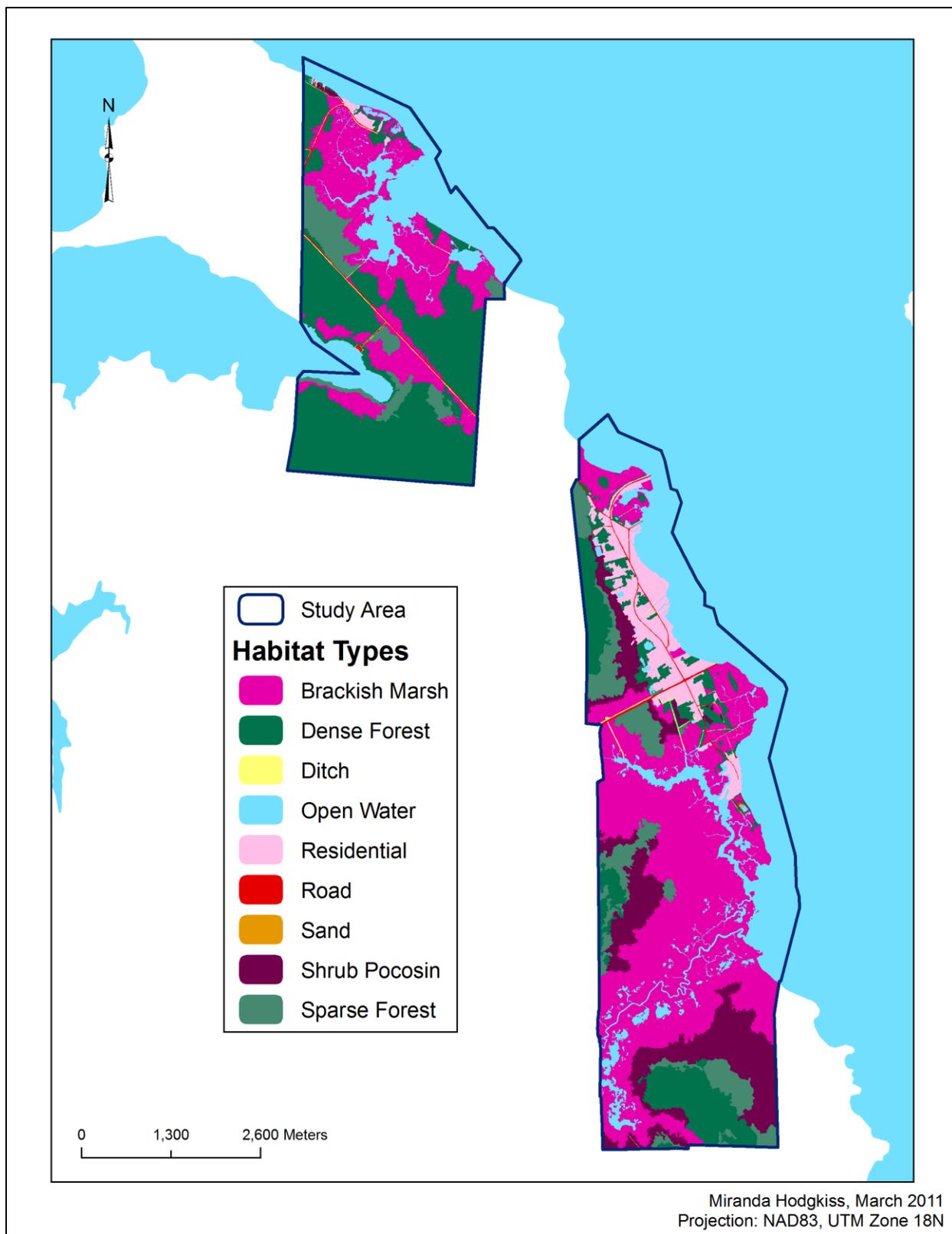**Figure 18A: 2005 habitat classification for Manns Harbor.**

Figure 19A: 2009 habitat classification for Manns Harbor.