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Natural Resource Stewardship and Science

Natural Resource Condition Assessment

Cape Hatteras National Seashore

Natural Resource Report NPS/CAHA/NRR—2021/2257



ON THE COVER
A sunset on the Atlantic Coast of CAHA
NPS Photo by Paul Doshkov

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Natural Resource Report NPS/CAHA/NRR—2021/2257

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Executive Summary

The Natural Resource Condition Assessment (NRCA) Program aims to provide documentation about the current conditions of important park natural resources through a spatially explicit, multi-disciplinary synthesis of existing scientific data and knowledge. Findings from the NRCA will help Cape Hatteras National Seashore (CAHA) managers to develop near-term management priorities, engage in watershed or landscape scale partnership and education efforts, conduct park planning, and report program performance (e.g., Department of the Interior's Strategic Plan "land health" goals, Government Performance and Results Act).

The objectives of this assessment are to evaluate and report on current conditions of key park resources, to evaluate critical data and knowledge gaps, and to highlight selected existing stressors and emerging threats to resources or processes. For the purpose of this NRCA, staff from the National Park Service (NPS) and Saint Mary's University of Minnesota – GeoSpatial Services (SMUMN GSS) identified key resources, referred to as "components" in the project. The selected components include natural resources and processes that are currently of the greatest concern to park management at CAHA. The final project framework contains nine resource components, each featuring discussions of measures, stressors, and reference conditions.

This study involved reviewing existing literature and, where appropriate, analyzing data for each natural resource component in the framework to provide summaries of current condition and trends in selected resources. When possible, existing data for the established measures of each component were analyzed and compared to designated reference conditions. A weighted scoring system was applied to calculate the current condition of each component. Weighted Condition Scores, ranging from zero to one, were divided into three categories of condition: low concern, moderate concern, and significant concern. These scores help to determine the current overall condition of each resource. The discussions for each component, found in Chapter 4 of this report, represent a comprehensive summary of current available data and information for these resources, including unpublished park information and perspectives of park resource managers, and present a current condition designation when appropriate. Each component assessment was reviewed by CAHA resource managers, NPS Southeast Coast Network staff, or outside experts.

Existing literature, short- and long-term datasets, and input from NPS and other outside agency scientists support condition designations for components in this assessment. However, in some cases, data were unavailable or insufficient for several of the measures of the featured components. In other instances, data establishing reference condition were limited or unavailable for components, making comparisons with current information inappropriate or invalid. In these cases, it was not possible to assign condition for the components. Current condition was not able to be determined for four of the nine components due to these data gaps.

For those components with sufficient available data, the overall condition varied. Three components were determined to be in good condition: mammals, sea turtles, and dark night skies. However, mammals and dark night skies were at the edge of the good condition range, and any small decline in conditions could shift them into the moderate concern range. Of the components in good condition,

trend could not be assigned for mammals, while sea turtles were determined to be trending towards improvement and dark night skies were considered stable. One component (water quality) was of moderate concern and one was of significant concern (barrier island geomorphology) with no trends assigned. Detailed discussion of these designations is presented in Chapters 4 and 5 of this report.

Several park-wide threats and stressors influence the condition of priority resources in CAHA. Those of primary concern include human development (current and past), invasive species, and climate change. Understanding these threats, and how they relate to the condition of park resources, can help the NPS prioritize management objectives and better focus their efforts to maintain the health and integrity of the park ecosystems.

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Acronyms and Abbreviations

ALR – All-sky Light Ratio

ARD – Air Resources Division

BBS – Breeding Bird Survey

CAHA – Cape Hatteras National Seashore

CALO – Cape Lookout National Seashore

CBC – Christmas Bird Count

CFU – Colony Forming Units

CVS – Carolina Vegetation Survey

DBH – Diameter-at-Breast-Height

DO – Dissolved Oxygen

EPA – Environmental Protection Agency

Esri – Environmental Systems Research Institute

FTU – Formazin Turbidity Units

GIS – Geographic Information System

I&M – Inventory and Monitoring

IPCC – Intergovernmental Panel on Climate Change

IPMT – Invasive Plant Management Team

LWD – Laurel Wilt Disease

MPN – Most Probable Number

NARS – National Aquatic Resource Survey

NCDEQ – North Carolina Department of Environmental Quality

NCDOT – North Carolina Department of Transportation

NCWRC – North Carolina Wildlife Resources Commission

NMFS – National Marine Fisheries Service

NPS – National Park Service

NRCA – Natural Resource Condition Assessment

NSNSD – Natural Sounds and Night Sky Division

NTU – Nephelometric Turbidity Units

NVC – National Vegetation Classification

NWI – National Wetlands Inventory

ORV – Off-road Vehicle

PINWR – Pea Island National Wildlife Refuge

ppt – Parts per Thousand

SECN – Southeast Coast Network

SLR – Sea Level Rise

SMUMN GSS – Saint Mary's University of Minnesota – Geospatial Services

SpC – Specific Conductance

TDN – Total Dissolved Nitrogen

TDP – Total Dissolved Phosphorous

TDS – Total Dissolved Solids

TED – Turtle Excluder Device

USDA – U.S. Department of Agriculture

USFS – U.S. Forest Service

USFWS – U.S. Fish and Wildlife Service

USGS – United States Geological Survey

WCI – Water Clarity Index

WCS – Weighted Condition Score

Chapter 1 NRCA Background Information

Natural Resource Condition Assessments (NRCAs) evaluate current conditions for a subset of natural resources and resource indicators in national park units, hereafter "parks." NRCAs also report on trends in resource condition (when possible), identify critical data gaps, and characterize a general level of confidence for study findings. The resources and indicators emphasized in a given project depend on the park's resource setting, status of resource stewardship planning and science in identifying high-priority indicators, and availability of data and expertise to assess current conditions for a variety of potential study resources and indicators.

NRCAs Strive to Provide…

- *Credible condition reporting for a subset of important park natural resources and indicators*
- *Useful condition summaries by broader resource categories or topics, and by park areas*

NRCAs represent a relatively new approach to assessing and reporting on park resource conditions. They are meant to complement—not replace—traditional issue-and threat-based resource assessments. As distinguishing characteristics, all NRCAs:

- Are multi-disciplinary in scope;[1]
- Employ hierarchical indicator frameworks;[2]
- Identify or develop reference conditions/values for comparison against current conditions;[3]
- Emphasize spatial evaluation of conditions and GIS (map) products; [4]
- Summarize key findings by park areas; and [5]
- Follow national NRCA guidelines and standards for study design and reporting products.

Although the primary objective of NRCAs is to report on current conditions relative to logical forms of reference conditions and values, NRCAs also report on trends, when appropriate (i.e., when the underlying data and methods support such reporting), as well as influences on resource conditions. These influences may include past activities or conditions that provide a helpful context for

[1] The breadth of natural resources and number/type of indicators evaluated will vary by park.

[2] Frameworks help guide a multi-disciplinary selection of indicators and subsequent "roll up" and reporting of data for measures ⇨ conditions for indicators ⇨ condition summaries by broader topics and park areas

[3] NRCAs must consider ecologically-based reference conditions, must also consider applicable legal and regulatory standards, and can consider other management-specified condition objectives or targets; each study indicator can be evaluated against one or more types of logical reference conditions. Reference values can be expressed in qualitative to quantitative terms, as a single value or range of values; they represent desirable resource conditions or, alternatively, condition states that we wish to avoid or that require a follow-up response (e.g., ecological thresholds or management "triggers").

[4] As possible and appropriate, NRCAs describe condition gradients or differences across a park for important natural resources and study indicators through a set of GIS coverages and map products.

[5] In addition to reporting on indicator-level conditions, investigators are asked to take a bigger picture (more holistic) view and summarize overall findings and provide suggestions to managers on an area-by-area basis: 1) by park ecosystem/habitat types or watersheds, and 2) for other park areas as requested.

understanding current conditions, and/or present-day threats and stressors that are best interpreted at park, watershed, or landscape scales (though NRCAs do not report on condition status for land areas and natural resources beyond park boundaries). Intensive cause-and-effect analyses of threats and stressors, and development of detailed treatment options, are outside the scope of NRCAs.

Due to their modest funding, relatively quick timeframe for completion, and reliance on existing data and information, NRCAs are not intended to be exhaustive. Their methodology typically involves an informal synthesis of scientific data and information from multiple and diverse sources. Level of rigor and statistical repeatability will vary by resource or indicator, reflecting differences in existing data and knowledge bases across the varied study components.

The credibility of NRCA results is derived from the data, methods, and reference values used in the project work, which are designed to be appropriate for the stated purpose of the project, as well as adequately documented. For each study indicator for which current condition or trend is reported, we will identify critical data gaps and describe the level of confidence in at least qualitative terms. Involvement of park staff and National Park Service (NPS) subject-matter experts at critical points during the project timeline is also important. These staff will be asked to assist with the selection of study indicators; recommend data sets, methods, and reference conditions and values; and help provide a multi-disciplinary review of draft study findings and products.

NRCAs can yield new insights about current park resource conditions, but, in many cases, their greatest value may be the development of useful documentation regarding known or suspected resource conditions within parks. Reporting products can help park managers as they think about near-term workload priorities, frame data and study needs for important park resources, and communicate messages about current park resource conditions to various audiences. A successful NRCA delivers science-based information that is both credible and has practical uses for a variety of park decision making, planning, and partnership activities.

Important NRCA Success Factors

- *Obtaining good input from park staff and other NPS subject-matter experts at critical points in the project timeline*
- *Using study frameworks that accommodate meaningful condition reporting at multiple levels (measures ⇨ indicators ⇨ broader resource topics and park areas)*
- *Building credibility by clearly documenting the data and methods used, critical data gaps, and level of confidence for indicator-level condition findings*

However, it is important to note that NRCAs do not establish management targets for study indicators. That process must occur through park planning and management activities. What an NRCA can do is deliver science-based information that will assist park managers in their ongoing, long-term efforts to describe and quantify a park's desired resource conditions and management

targets. In the near term, NRCA findings assist strategic park resource planning[6] and help parks to report on government accountability measures.[7] In addition, although in-depth analysis of the effects of climate change on park natural resources is outside the scope of NRCAs, the condition analyses and data sets developed for NRCAs will be useful for park-level climate-change studies and planning efforts.

NRCAs also provide a useful complement to rigorous NPS science support programs, such as the NPS Natural Resources Inventory & Monitoring (I&M) Program.[8] For example, NRCAs can provide current condition estimates and help establish reference conditions, or baseline values, for some of a park's vital signs monitoring indicators. They can also draw upon non-NPS data to help evaluate current conditions for those same vital signs. In some cases, I&M data sets are incorporated into NRCA analyses and reporting products.

NRCA Reporting Products…

Provide a credible, snapshot-in-time evaluation for a subset of important park natural resources and indicators, to help park managers:

- *Direct limited staff and funding resources to park areas and natural resources that represent high need and/or high opportunity situations* ***(near-term operational planning and management)***
- *Improve understanding and quantification for desired conditions for the park's "fundamental" and "other important" natural resources and values* ***(longer-term strategic planning)***
- *Communicate succinct messages regarding current resource conditions to government program managers, to Congress, and to the general public* ***("resource condition status" reporting)***

Over the next several years, the NPS plans to fund an NRCA project for each of the approximately 270 parks served by the NPS I&M Program. For more information visit the NRCA Program website.

[6] An NRCA can be useful during the development of a park's Resource Stewardship Strategy (RSS) and can also be tailored to act as a post-RSS project.

[7] While accountability reporting measures are subject to change, the spatial and reference-based condition data provided by NRCAs will be useful for most forms of "resource condition status" reporting as may be required by the NPS, the Department of the Interior, or the Office of Management and Budget.

[8] The I&M program consists of 32 networks nationwide that are implementing "vital signs" monitoring in order to assess the condition of park ecosystems and develop a stronger scientific basis for stewardship and management of natural resources across the National Park System. "Vital signs" are a subset of physical, chemical, and biological elements and processes of park ecosystems that are selected to represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values.

Chapter 2 Introduction and Resource Setting

Introduction

Enabling Legislation

The creation of Cape Hatteras National Seashore (CAHA), the country's first national seashore, was authorized by Congress in 1937, but was not officially established until January 1953 (McManamay et al. 2018). The authorization act required the acquisition of the land by the U.S. government prior to park establishment:

> *When title to all the lands except those within the limits of established villages, within boundaries to be designated by the Secretary of the Interior within the area of approximately one hundred square miles on the islands of Chicamacomico, Ocracoke, Bodie, Roanoke, and Collington, and the waters and the lands beneath the waters adjacent thereto shall have been vested in the United States, said area shall be, and is hereby, established, dedicated, and set apart as a national seashore for the benefit and enjoyment of the people and shall be known as the Cape Hatteras National Seashore: Provided, that the United States shall not purchase by appropriation of public moneys any lands within the aforesaid area, but such lands shall be secured by the United States only by public or private donation*. (16 U.S.C. sec. 459.)

This authorization act also stated:

> *Except for certain portions of the area, deemed to be especially adaptable for recreational uses, particularly swimming, boating, sailing, fishing, and other recreational activities of similar nature, which shall be developed for such uses as needed, the said area shall be permanently reserved as a primitive wilderness and no development of the project of plan for the convenience of visitors shall be undertaken which would be incompatible with the preservation of the unique flora and fauna or the physiographic conditions now prevailing in this area.* (16 U.S.C. sec. 459a-2.)



Aerial view of Bodie Island Light Station at CAHA (NPS photo by Sara Strickland).

Geographic Setting

Situated just off the northeast coast of North Carolina, CAHA includes two of the barrier islands and connected banks known as the "Outer Banks": Ocracoke Island, Hatteras Island, and the southern portion of Bodie Island (which is not an island) (Figure 1). Bodie Island is connected to the mainland by two highways and Hatteras Island is accessible from Bodie Island via North Carolina Highway 12, but Ocracoke Island is accessible only by ferry. The park boundary includes 12,282 ha (30,350 ac), the majority of which (~81%) is owned by the NPS (NPS 2015d). Pea Island National Wildlife Refuge (PINWR) is on the northern end of Hatteras Island, from Oregon Inlet to just north of Rodanthe, and is also part of CAHA; it is jointly managed by the NPS and U.S. Fish and Wildlife Service (USFWS) (USFWS 2006). As of 2011, CAHA included 444 km (276 mi) of shoreline (Curdts 2011), although this shifts over time due to natural shoreline erosion and accretion.

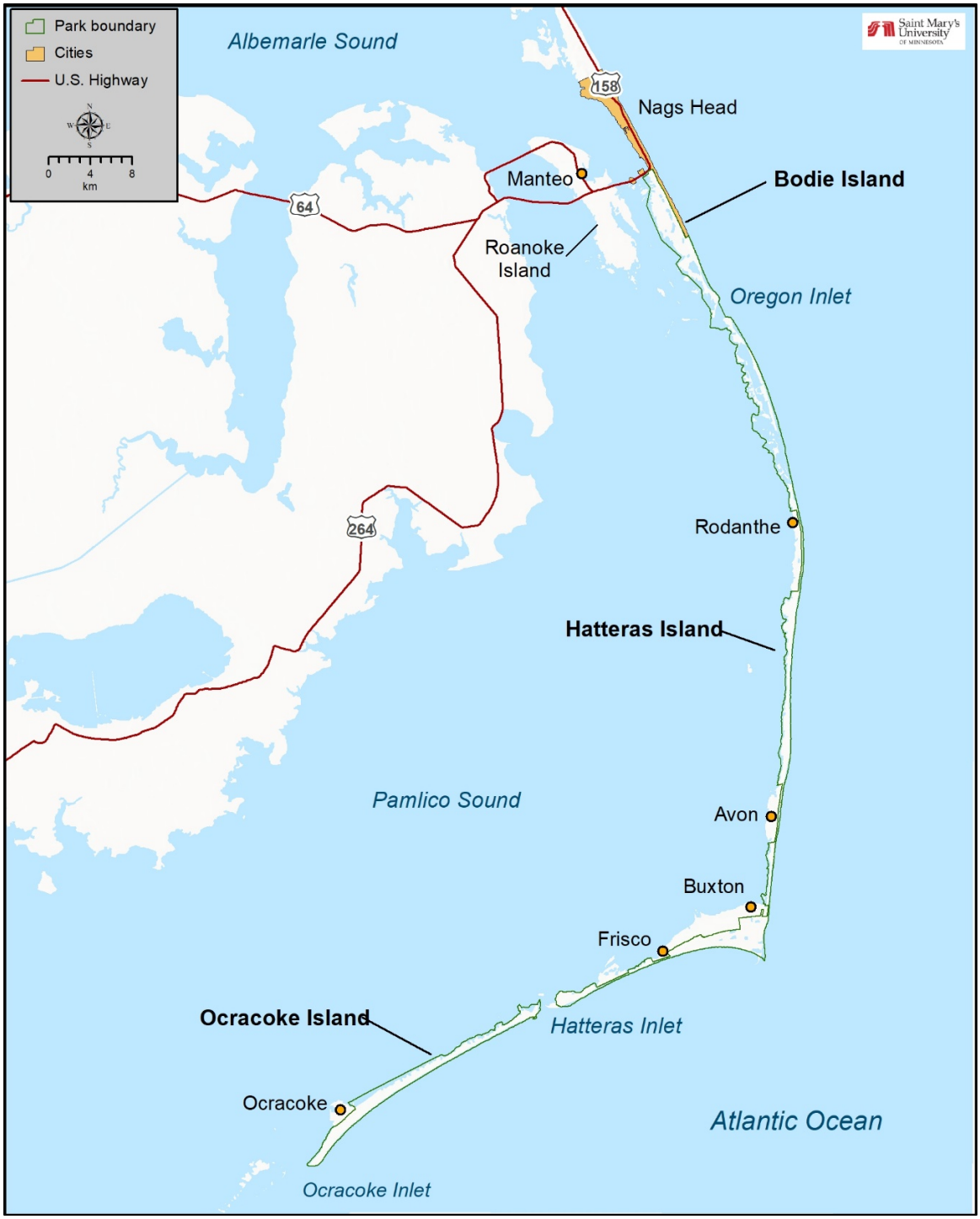


Figure 1. The three islands of CAHA and their surroundings.

The lands of CAHA have a humid, warm-temperate climate with hot summers, somewhat moderated by ocean breezes (Davey et al. 2007, McManamay et al. 2018). High temperatures in July average just below 30°C (85°F), and winter lows are typically above freezing (0°C [32°F]). Precipitation is primarily in the form of rain, including occasional tropical storms and hurricanes in the summer and

fall months (Davey et al. 2007). Temperature and precipitation normals from the Cape Hatteras weather station near Frisco, NC are shown in Table 1.

Table 1. 30-year climate normals (1981–2010) from the Cape Hatteras Billy Mitchell Field station (USW00093729), near Frisco on Hatteras Island (NCEI 2018).

Month	Temperature in °C (°F)		Average precipitation in cm (in)
	Average daily min	Average daily max	
January	3.7 (38.7)	11.2 (52.2)	13.3 (5.24)
February	4.4 (40.0)	11.9 (53.5)	10.2 (4.02)
March	7.0 (44.6)	14.8 (58.6)	12.1 (4.77)
April	11.4 (52.6)	19.1 (66.3)	9.2 (3.64)
May	15.8 (60.5)	23.2 (73.7)	9.1 (3.57)
June	20.7 (69.3)	27.2 (81.0)	10.2 (4.03)
July	23.1 (73.6)	29.2 (84.6)	12.7 (4.99)
August	22.7 (72.9)	28.9 (84.1)	17.6 (6.93)
September	20.6 (69.0)	26.6 (79.9)	15.9 (6.25)
October	15.4 (59.7)	22.2 (72.0)	13.7 (5.38)
November	10.7 (51.2)	17.8 (64.0)	12.6 (4.95)
December	5.9 (42.7)	13.3 (55.9)	10.8 (4.27)
Annual	13.4 (56.2)	20.4 (68.8)	147.4 (58.04)

Visitation Statistics

In almost every year across three decades, CAHA has received over 2 million annual visitors (NPS 2018a). Over the past ten years (2008–2017), annual visitation has ranged from 1.96 million visitors (2011) to 2.43 million (2017), with a mean of 2.24 million visitors. Visitation is highest from June to August and drops to its lowest point from December to February (NPS 2018a). Popular activities include beach walking, fishing, swimming, wildlife viewing, and climbing two of the park's lighthouses (NPS 2018b). The Cape Hatteras and Bodie Island Lighthouses are typically open to visitors from late April through mid-October (Figure 2). Off road vehicle use and horseback riding are allowed on the ocean and sound-facing beaches, and waterfowl hunting is permitted, in accordance with state regulations, only on the sound side of Bodie Island and in other soundfront shoreline along Hatteras and Ocracoke Islands (NPS 2018b). The NPS manages four campgrounds within the park: Oregon Inlet (Bodie Island), Cape Point and Frisco (Hatteras Island), and Ocracoke (Ocracoke Island). Park rangers also staff three visitor centers, one each on Bodie Island, Hatteras Island, and Ocracoke Island, and offer numerous educational programs.



Figure 2. The view from the top of Cape Hatteras Lighthouse (NPS photo).

Natural Resources

Ecological Units and Watersheds

CAHA lies within the Environmental Protection Agency's (EPA) Middle Atlantic Coastal Plain Level III Ecoregion. The Middle Atlantic Coastal Plain consists of flat, low-elevation plains with numerous marshes, swamps, and estuaries, stretching from Delaware to the southern border of South Carolina (EPA 2013). The EPA divides Level III Ecoregions into smaller Level IV Ecoregions. The park falls in the Carolinian Barrier Islands and Coastal Marshes Level IV Ecoregion, which extends from Bodie Island to just across the South Carolina border (Griffith et al. 2002). The ecoregion contains beaches, dunes, marshes, and barrier islands, but is slightly warmer and wetter than the Virginian Barrier Island ecoregion to the north. The region also includes a transitional area where northern and southern maritime forests overlap, contributing to high vegetative diversity (Griffith et al. 2002).

As an island, CAHA is not part of a larger "watershed," in the traditional sense; no water flows into the park from "upstream", and there are no terrestrial areas "downstream" of the park. Precipitation that falls on the island remains as surface water or flows into the surrounding ocean and sound directly or via natural and artificial drainage systems. A number of drainage ditches have been constructed on Bodie Island, draining into Roanoke Sound, and on central Hatteras Island, draining into Pamlico Sound (Stroh 1982, Mallin et al. 2006); there are numerous drainage ditches constructed on Ocracoke Island as well (David Hallac, pers. comm., July 2020). Tidal creeks also naturally drain Ocracoke Island and southern Hatteras Island (Mallin et al. 2006).

Resource Descriptions

Barrier islands like those that comprise CAHA are low-lying, narrow strips of land that are constantly shifting and changing in response to wave and wind action, ocean currents, storms, and

sea level changes (Godfrey and Godfrey 1976, McManamay et al. 2018). These natural processes contribute to shoreline erosion/accretion, overwash events, and inlet formation/migration. As a result, the island's vegetation communities and some of the wildlife that depend on them are also frequently shifting (McManamay et al. 2018). The vegetation communities of CAHA range from maritime forests and freshwater wetlands to salt marshes and dune grasslands (Figure 3).



Figure 3. Vegetation communities of CAHA include salt marshes (foreground), shrublands, and forest (background) (NPS photo from McManamay et al. 2018).

The park supports just over 1,150 confirmed vascular plant taxa, including subspecies and varieties (NPS 2018e). Eight of these species are considered threatened or endangered by the State of North Carolina, and one species is also federally listed as threatened: seabeach amaranth (*Amaranthus pumilus*) (Table 2; Robinson and Finnegan 2017). Northeastern North Carolina is seen as a "transition zone," with overlap of species more characteristic of southern biomes and northern biomes reaching the edge of their ranges in this area (Bellis 1995). This may contribute to higher plant species diversity on northern North Carolina islands than on more southerly barrier islands.

Table 2. CAHA plant species designated as threatened or endangered by the state of North Carolina (Robinson and Finnegan 2017, NPS 2018e).

Scientific name	Common name	State status*	Habitat
Ipomoea imperati	beach morning-glory	threatened (S1)	seabeaches and foredunes
Corydalis micrantha	smallflower fumewort	threatened (S1)	rock outcrops or cliffs
Eleocharis cellulosa	Gulf Coast spikerush	endangered (S2)	interdune ponds, brackish marshes & tidal freshwater marshes
Ludwigia lanceolata	lanceleaf primrose-willow	endangered (S1)	interdune ponds, open wet areas
Lechea maritima var. *virginica*	Virginia pinweed	endangered (S1)	barren dunefields
Aeschynomene virginica	Virginia jointvetch	threatened (S1)	freshwater to slightly brackish tidal marshes and wet ditches
Polygonum glaucum	seaside knotweed	endangered (S1)	ocean and sound beaches
Amaranthus pumilus	seabeach amaranth	threatened (S1S2)	ocean beaches and island-end flats

* S1 = critically imperiled due to extreme rarity or some factor(s) making it especially vulnerable to extirpation from the state, S2 = Imperiled due to rarity or some factor(s) making it very vulnerable to extirpation from the state. A rank involving two numbers indicates that uncertainty due to limited data does not allow a single determination to be made.

Twenty-five mammal species have been confirmed within the park, and an additional eight species (all marine mammals) are considered probably present (NPS 2018e). Common mammals include white-tailed deer (*Odocoileus virginianus*), eastern cottontails (*Sylvilagus floridanus*), muskrats (*Ondatra zibethicus*), and gray squirrels (*Sciurus carolinensis*). During the winter months, seals sometimes haul out on CAHA beaches to rest; these are usually harbor seals (*Phoca vitulina*, Figure 4), but harp seals (*Pagophilus groenlandicus*) and gray seals (*Halichoerus grypus*) are occasionally observed (NPS 2012a, 2016b, 2017a).



Figure 4. A white-tailed deer near the Salvo day use area (left) and a harbor seal hauled out on Ocracoke island (right) (NPS photos).

More than 360 species of birds have been confirmed at CAHA, many of which are migratory species (NPS 2018e). Nearly 30 of these species are considered of conservation concern by the State of North Carolina and four species are federally endangered or threatened (see Chapter 4.4). The shorelines of CAHA provide important shorebird habitat for species such as the Piping Plover (*Charadrius melodus*), American Oystercatcher (*Haematopus palliates*), and Least Tern (*Sternula antillarum*) (Figure 5) (NPS 2016c). Raptors and waterfowl (e.g., ducks and geese) are also abundant at the park.



Figure 5. Least Tern chicks (left) and an American Oystercatcher (right) (NPS photos).

CAHA is an important nesting area for sea turtle species (Figure 6), particularly the federally threatened loggerhead (*Caretta caretta*) (Mays and Shaver 1998, NMFS and USFWS 2008). Over the past decade, approximately 100–300 loggerhead nests have been documented on park beaches annually (Seaturtle.org 2019). Other turtle species that regularly nest on park beaches in smaller

numbers include the green (*Chelonia mydas*) and Kemp's ridley (*Lepidochelys kempii*) (see Chapter 4.6). In addition to five sea turtle species, the park supports at least 32 other reptile species (snakes, lizards, freshwater turtles) and 12 amphibian species (frogs, toads, salamanders) (NPS 2018e).



Figure 6. An adult sea turtle (left) and a timber (or canebrake) rattlesnake (*Crotalus horridus*, right), a species of special concern in North Carolina, at CAHA (NPS photos).

The waters in and around CAHA support 60 confirmed fish species (Appendix A), with over 230 additional species considered "probably present" (NPS 2018e). These range from small fish (minnows, anchovies, killifish) and eels to flounder, red drum (*Sciaenops ocellatus*), and spotted seatrout (*Cynoscion nebulosus*).The park's shorelines, salt marshes, and estuarine waters also support a wide variety of macroinvertebrates, including shellfish (Class Bivalivia), snails (Class Gastropoda), crustaceans (Subphylum Crustacea), and various echinoderms (e.g., sea stars and brittle stars, Class Echinoidea) (DeVivo and Gregory 2012). These organisms have not been closely surveyed or studied, despite their value to the food web as prey species. Macroinvertebrate taxa that have been documented at CAHA are listed in Appendix B.

Resource Issues Overview

Human Development

In recent decades, the amenities of coastal areas such as the Outer Banks of North Carolina have attracted an influx of full-time and seasonal residents, as well as increased tourism (Cole and Bratton 1994, Rowe 2015). The coastal zone of North Carolina has experienced some of the highest population growth rates in the state, accompanied by urban expansion, largely driven by the tourism industry (Riggs et al. 2008). Development has been particularly extensive just north of CAHA in the Nags Head and Kitty Hawk areas and on central Hatteras Island (e.g., Avon, Buxton), increasing water use and wastewater production on the islands (Cole and Bratton 1994, Parman et al. 2012). Some have claimed that the Outer Banks have been engulfed by "overdevelopment" (Frankenberg 2012), which is described as "the development of structures (mainly houses and resorts) as well as an increasing population, which both work in conjunction to inhibit natural coastal processes, such as overwash and longshore drift, which in essence, sustain the coastal system itself" (Rowe 2015). Human efforts to convert these barrier islands into stable, engineered systems are in direct conflict with the dynamic nature of the ecosystem (Riggs et al. 2008). Development impacts to date include

forest clearing, wetland filling and channelization, shallow water dredging, and drainage alteration due to increased surface pavement, all of which have contributed to varying degrees of degraded water quality (Riggs et al. 2008).

Dune Construction/Landscape Alteration

The largest project to stabilize the islands of CAHA was a dune building program initiated in 1934, known as the North Carolina Beach Erosion Control Project (Stroh 1982, Firth 1987). The program was federally funded and utilized workers from the Civilian Conservation Corps (CCC), the Works Progress Administration (WPA), and the National Youth Administration (NYA). Construction started in the vicinity of Nags Head and eventually extended south all the way to Ocracoke Inlet (Firth 1987). Approximately 250 km (155 mi) of artificial dunes were built with brush and slat fences, followed by the planting of native grasses, trees, and shrubs (Figure 7). The NPS took over the project in May 1936, and work on Bodie Island was nearly complete by November 1938. From Nags Head to Oregon Inlet, the dune line had been raised to a height of about 4 m (13 ft) and 20,000 tree seedlings were planted behind those dunes (Firth 1987). Work was suspended in 1941 when the U.S. entered World War II and the project remained inactive for 13 years. Some of the height and continuity of the dune line was lost during this time.



Figure 7. Workers constructing a sand fence during 1930s dune construction efforts (left, NPS photo) and planting stabilizing beach grasses on dunes in 1956 (NPS photo by Verde Watson).

Maintenance and repair of the dune system was re-initiated in 1954, after the official establishment of CAHA (Firth 1987). The aim was to restore a continuous dune line at an average height of 2.5–3.0 m (8.2–9.8 ft) for the entire length of the National Seashore. Bulldozers were used to quickly build dune mass and height in critical locations and native grasses were again planted to stabilize and build up the dunes (Nash 1962, Firth 1987). Periodic fertilization was used to promote the growth of the grasses. Additional tree planting occurred, with 21,000 pine seedlings planted between 1956 and 1961 (Nash 1962). Also, in 1961, the park received 100,000 loblolly (*Pinus taeda*) and slash pine (*P. elliottii*) seedlings and some eastern redcedar (*Juniperus virginiana*) trees (Firth 1987). During the 1970s, researchers and NPS managers recognized that continuing dune maintenance was expensive and not feasible, and may have been contributing to beach erosion (Stroh 1982, Firth 1987). In 1982, the NPS officially ended dune maintenance on park-owned property on Bodie Island. However,

active maintenance of dunes on northern Hatteras Island has continued in order to protect Highway 12 and access to and from the island (Mallinson et al. 2009, see Chapter 4.1). Dune management has ultimately occurred throughout CAHA, as areas all along Hatteras Island, in and between the various villages, and many erosion hot spots (especially around north Ocracoke Island) have all seen active maintenance efforts (D. Hallac, pers. comm., July 2020).

In addition to dune construction, ditching/dredging for highway roadwork and mosquito control efforts have modified the park landscape (Stroh 1982). Extensive marsh dredging took place in the CAHA area in order to build up the roadbed elevation on Highway 12. Mosquito control efforts on Bodie Island involved the digging of deep channels that drain west into Roanoke Sound (Stroh 1982).

Invasive Species

Non-native invasive species pose one of the greatest threats to biodiversity and ecosystem integrity worldwide, with the potential to impact ecological community composition, structure, and function (Mooney et al. 2005, Beard and App 2013). These species can compete with native plants and animals and disrupt ecosystem processes such as nutrient cycling and disturbance regimes (e.g., fire, flooding). According to NPS (2018e), 234 non-native plant species have been documented within CAHA. Some of these are ornamental species that were intentionally brought to the islands by inhabitants and are likely not a threat to invade natural ecosystems. Forty-one of the non-native plant species confirmed at CAHA are considered invasive by the North Carolina Native Plant Society (NCNPS 2017); 10 of these species are considered a severe threat, 15 species a significant threat, and 16 species are a lesser threat to natural ecosystems in North Carolina (Appendix C). An additional 16 non-native plant species present at CAHA are on a “watch list”, as they are not currently known to be invasive in the state but could become a problem in the future (NCNPS 2017).



Common reed (*Phragmites australis*), an invasive species that has spread in CAHA wetlands, and is ranked as a severe threat in North Carolina (NPS photo from McManamay et al. 2018).

Air Quality

Concerns have been raised over CAHA's air quality, due to its potential impact on natural resources, as well as visitor experience and human health (NPS 2018c). The NPS Air Resources Division (ARD) uses four key parameters to assess air quality in national parks: nitrogen deposition, sulfur deposition, ozone, and visibility. As of 2015, the ARD ranked CAHA's nitrogen deposition of significant concern and the three remaining parameters of moderate concern (NPS 2016a). These conditions are based on 5-year average estimates (i.e., 2015 ratings are based on 2011–2015 measurements) using interpolation from data outside the park, as no monitors are present within CAHA boundaries. In the 3 years prior to 2015, three of the five air quality parameters were ranked of significant concern, with only the ozone metrics of moderate concern (Table 3) (NPS 2016a). The recent shift in two metrics from significant to moderate concern suggests that overall air quality conditions at CAHA may be improving.

Table 3. Air quality conditions at CAHA, 2012–2015 (NPS 2016a). The degree of confidence in these condition assessments is medium for all metrics except visibility because estimates are based on interpolated data from more distant monitors. ppm = parts per million; dv = deciview, the unit for the haze index, calculated from light extinction measurements.

Parameter	2012	2013	2014	2015
Ozone, human health	Moderate Concern **72.0 ppb**	Moderate Concern **68.8 ppb**	Moderate Concern **68.2 ppb**	Moderate Concern **65.8 ppb**
Ozone, plant health (W126 metric)	Moderate Concern **9.7 ppm-hrs**	Moderate Concern **7.8 ppm-hrs**	Moderate Concern **8.5 ppm-hrs**	Moderate Concern **7.3 ppm-hrs**
Visibility (haze index)	Significant Concern **8.7 dv**	Significant Concern **8.4 dv**	Significant Concern **8.1 dv**	Moderate Concern **7.8 dv**
Nitrogen deposition	Significant Concern **4.5 kg/ha/yr**	Significant Concern **4.3 kg/ha/yr**	Significant Concern **4.2 kg/ha/yr**	Significant Concern **4.3 kg/ha/yr**
Sulfur deposition	Significant Concern **3.9 kg/ha/yr**	Significant Concern **3.4 kg/ha/yr**	Significant Concern **3.1 kg/ha/yr**	Moderate Concern **2.8 kg/ha/yr**

Climate Change

Climate is a key driving factor in the ecological and physical processes influencing park ecosystems throughout the Southeast Coast Network (SECN) (Davey et al. 2007). As a result of global climate change, temperatures are projected to increase across the southeastern United States over the next century (Carter et al. 2014). Warmer air temperatures will increase evaporation rates and plant transpiration (i.e., plant water use), meaning that even if annual precipitation remains constant or slightly increases, overall conditions could still become drier in the future (Carter et al. 2014). Higher air temperatures will lead to higher water body temperatures, which will impact sensitive aquatic ecosystems (Hoegh-Guldberg and Bruno 2010). In the marine and estuarine environments, for example, many species are adapted to a particular temperature range and are negatively impacted if temperatures fluctuate too far or too frequently outside that range. Some organisms rely on temperature cues to initiate behaviors such as migration or reproduction; climate changes may disrupt the timing of these vital processes (Hawkes et al. 2009, Hoegh-Guldberg and Bruno 2010). Warmer waters also hold less dissolved oxygen, which is necessary for most aquatic organisms, than cooler waters (USGS 2016d). In addition, warmer ocean waters can intensify storm impacts, including hurricanes (Hoegh-Guldberg and Bruno 2010, IPCC 2013).

Warming temperatures has triggered sea level rise (SLR), due to both the thermal expansion of water and the melting of continental ice (IPCC 2013). Between 1993 and 2010, global SLR averaged 3.2 mm/year (0.13 in/year) (IPCC 2013). At the Oregon Inlet Marina, sea level rise averaged 4.36 mm/year (0.17 in/yr) from 1977–2017, which is equivalent to a rise of approximately 42.7 cm (1.4 ft) over 100 years (Figure 8) (NOAA 2017). Rises at the Oregon Inlet Marina have likely increased additionally since 2017, although at the time of publication no more recent data were available. The SLR rate is expected to increase over the remainder of this century, so that total SLR by 2100 will be

between 0.28–0.98 m (0.9–3.2 ft) (IPCC 2013). Under the highest greenhouse gas emissions scenario, modeling suggests that SLR at Oregon Inlet Marina could be as high as 25.1 cm (9.9 in) by 2045 (NC CRC Science Panel 2015).

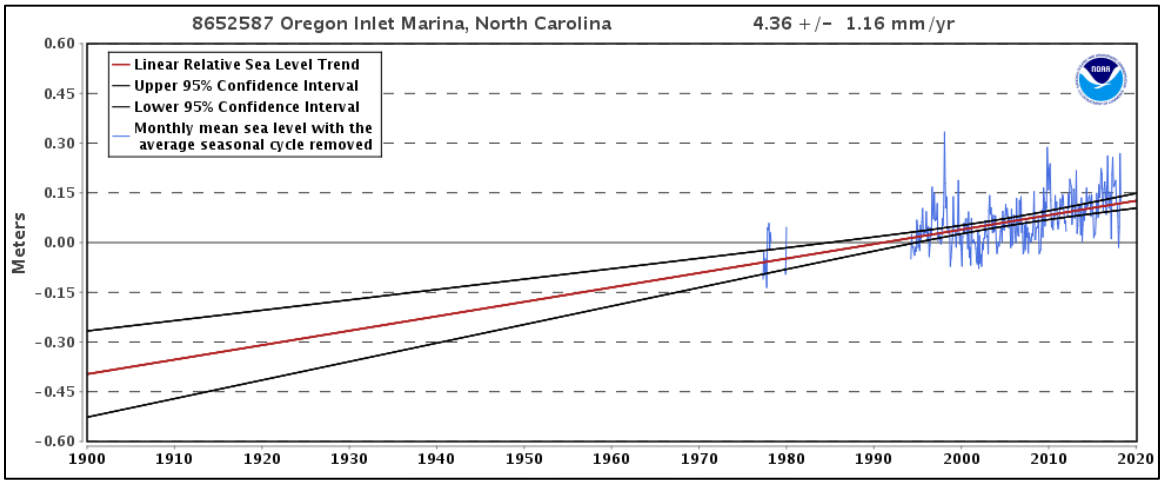


Figure 8. Mean sea level trend for Oregon Inlet Marina, NC (NOAA 2017).

Sea level rise results in the loss of coastal lands, as rising waters inundate additional areas along the shore. In some cases, accretion (sediment accumulation) may keep up with the rate of SLR, but models project that higher rates of SLR (~1 m [3.3 ft] by 2100) may result in the conversion of tidal wetlands to open water (Schupp 2015). Rising water levels are also likely to alter coastal dynamics (e.g., sediment supply and transport), potentially exposing additional shoreline to accelerated erosion, (Schupp 2015).

The increase in carbon dioxide (CO_2) levels that is contributing to climate change is also causing ocean acidification. Acidification refers to the decrease in ocean pH when CO_2 reacts with seawater to produce carbonic acid (NOAA 2016). The pH of ocean water is currently around 8.1, but is projected to decline 0.4 pH units by the end of this century (Feely et al. 2009). A decline in pH will impact many marine organisms, but particularly aquatic invertebrates that build shells or exoskeletons from calcium carbonate (e.g., shellfish, corals, some plankton) (Feely et al. 2009). Acidification reduces the amount of calcium carbonate dissolved in sea water and available for shell-building. If calcium carbonate saturation levels drop too low, the shells and exoskeletons of these organisms will begin dissolving and thinning (Feely et al. 2009).

Resource Stewardship

Management Directives and Planning Guidance

The purpose of CAHA is

> *…to permanently preserve the wild and primitive character of the ever-changing barrier islands, protect the diverse plant and animal communities sustained by the coastal island processes, and provide for recreational use and enjoyment that is*

compatible with preserving the distinctive natural and cultural resources of the nation's first national seashore. (NPS 2016f, p. iii)

According to the park's resource management plan (Turner 1984), a 1978 "Statement for Management" identified three resource management goals:

- To manage Cape Hatteras National Seashore in ways that will enhance the natural processes of barrier island dynamics and succession of native vegetation and wildlife and will mitigate the impacts of human interference with these processes;
- To integrate planning and management for Cape Hatteras National Seashore into regional planning and economic considerations; and
- To adopt an off-road vehicle management plan which would preserve the values of the National Seashore.

This resource management plan also states that the goal of vegetation management will be "to restore, to the extent feasible, natural processes, as well as a semblance of the natural mosaic of plants, on the Seashore" (Turner 1984).

Status of Supporting Science

The SECN identifies key resources network-wide and for each of its parks that can be used to determine the overall health of the parks. These key resources are called Vital Signs. In 2008, the SECN completed and released a Vital Signs Monitoring Plan (DeVivo et al. 2008); Table 4 shows the SECN Vital Signs selected for monitoring in CAHA.

Table 4. SECN Vital Signs selected for monitoring in CAHA (DeVivo et al. 2008).

Category	SECN Vital Sign	Category 1[a]	Category 2[b]	Category 3[c]
Air and Climate	Ozone	–	X	–
	Wet and Dry Deposition	–	X	–
	Visibility and Particulate Matter	–	X	–
	Air Contaminants	–	X	–
	Weather and Climate	–	X	–
Geology and Soils	Coastal Shoreline Change	X	–	–
	Salt Marsh Elevation	X	–	–
Water	Groundwater Dynamics	–	X	–
	Water Chemistry	X	–	–

[a] **Category 1** represents Vital Signs for which the network will develop protocols and implement monitoring.

[b] **Category 2** represents Vital Signs that are monitored by the park, another NPS program, or by another federal or state agency using other funding.

[c] **Category 3** represents priority Vital Signs for which monitoring has been deferred.

Table 4 (continued). SECN Vital Signs selected for monitoring in CAHA (DeVivo et al. 2008).

Category	SECN Vital Sign	Category 1[a]	Category 2[b]	Category 3[c]
Biological Integrity	Invasive/Exotic Plants	X	–	–
	Marine Invertebrates	–	–	X
	Fish Communities	–	–	X
	Amphibians	X	–	–
	Breeding Forest Birds	X	–	–
	Small Mammals	–	–	X
	Plant Communities	X	–	–
	Shorebirds (T&E species)	–	–	X
	T&E Species	–	X	–
Human Use	Fisheries Take	–	X	–
	Visitor Use	–	X	–
Landscapes (Ecosystem Patterns and Processes)	Fire and Fuel Dynamics	X	–	–
	Land Cover and Use	X	–	–

[a] **Category 1** represents Vital Signs for which the network will develop protocols and implement monitoring.

[b] **Category 2** represents Vital Signs that are monitored by the park, another NPS program, or by another federal or state agency using other funding.

[c] **Category 3** represents priority Vital Signs for which monitoring has been deferred.

The park has active monitoring programs and publishes annual reports for shorebird nesting, sea turtle nesting, and marine mammal strandings (NPS 2017b). Research has been conducted within CAHA by cooperators including the USFWS, U.S. Geological Survey (USGS), the North Carolina Wildlife Resources Commission, Virginia Tech, and East Carolina University (NPS 2016d).

Chapter 3 Study Scoping and Design

This NRCA is a collaborative project between the NPS and SMUMN GSS. Project stakeholders include the CAHA resource management team, and SECN Inventory and Monitoring Program staff. Before embarking on the project, it was necessary to identify the specific roles of the NPS and SMUMN GSS. Preliminary scoping meetings were held, and a task agreement and a scope of work document were created cooperatively between the NPS and SMUMN GSS.

Preliminary Scoping

A preliminary scoping meeting was held on 16–17 January 2018. At this meeting, SMUMN GSS and NPS, SECN, and park staff confirmed that the purpose of the CAHA NRCA was to evaluate and report on current conditions, critical data and knowledge gaps, and selected existing and emerging resource condition influences of concern to CAHA managers. Certain constraints were placed on this NRCA, including the following:

- Condition assessments are conducted using existing data and information that were available at the time Stage 1 of the project concluded (early 2018);
- Identification of data needs and gaps is driven by the project framework categories;
- The analysis of natural resource conditions includes a strong geospatial component;
- Resource focus and priorities are primarily driven by CAHA resource management.

This condition assessment provides a "snapshot-in-time" evaluation of the condition of a select set of park natural resources that were identified and agreed upon by the project team. Project findings will aid CAHA resource managers in the following objectives:

- Develop near-term management priorities (how to allocate limited staff and funding resources);
- Engage in watershed or landscape scale partnership and education efforts;
- Consider new park planning goals and take steps to further these;
- Report program performance (e.g., Department of Interior Strategic Plan "land health" goals, Government Performance and Results Act [GPRA]).

Specific project expectations and outcomes included the following:

- For key natural resource components, consolidate available data, reports, and spatial information from appropriate sources including CAHA resource staff, the NPS Integrated Resource Management Application (IRMA) website, Inventory and Monitoring Vital Signs, and available third-party sources. The NRCA report will provide a resource assessment and summary of pertinent data evaluated through this project;

- When appropriate, define a reference condition so that statements of current condition may be developed. The statements will describe the current state of a particular resource with respect to an agreed upon reference point;

- Clearly identify "management critical" data (i.e., those data relevant to the key resources). This will drive the data mining and gap definition process;

- Where applicable, develop GIS products that provide spatial representation of resource data, ecological processes, resource stressors, trends, or other valuable information that can be better interpreted visually;

- Utilize "gray literature" and reports from third party research to the extent practicable.

Study Design

Indicator Framework, Focal Study Resources and Indicators

Selection of Resources and Measures

As defined by SMUMN GSS in the NRCA process, a "framework" is developed for a park or preserve. This framework is a way of organizing, in a hierarchical fashion, bio-geophysical resource topics considered important in park management efforts. The primary features in the framework are key resource components, measures, stressors, and reference conditions.

"Components" in this process are defined as natural resources (e.g., birds), ecological processes or patterns (e.g., natural fire regime), or specific natural features or values (e.g., geological formations) that are considered important to current park management. Each key resource component has one or more "measures" that best define the current condition of a component being assessed in the NRCA. Measures are defined as those values or characterizations that evaluate and quantify the state of ecological health or integrity of a component. In addition to measures, current condition of components may be influenced by certain "stressors," which are also considered during assessment. A "stressor" is defined as any physical, biological, or chemical agent that induces adverse changes within a component (EPA 2016a). These typically refer to anthropogenic factors that adversely affect natural ecosystems, but may also include natural processes or disturbances such as floods, fires, or predation.

During the CAHA NRCA scoping process, key resource components were identified by NPS staff and are represented as "components" in the NRCA framework. While this list of components is not a comprehensive list of all the resources in the park, it includes resources and processes that are unique to the park in some way, or are of greatest concern or highest management priority in CAHA. Several measures for each component, as well as known or potential stressors, were also identified in collaboration with NPS resource staff.

Selection of Reference Conditions

A "reference condition" is a benchmark to which current values of a given component's measures can be compared to determine the condition of that component. A reference condition may be a historical condition (e.g., flood frequency prior to dam construction on a river), an established

ecological threshold (e.g., EPA standards for air quality), or a targeted management goal/objective (e.g., a bison herd of at least 200 individuals) (Stoddard et al. 2006).

Reference conditions in this project were identified during the scoping process using input from NPS resource staff. In some cases, reference conditions represent a historical reference before human activity and disturbance was a major driver of ecological populations and processes, such as "pre-fire suppression." In other cases, peer-reviewed literature and ecological thresholds helped to define appropriate reference conditions.

Finalizing the Framework

An initial framework was adapted from the organizational framework outlined by the H. John Heinz III Center for Science's "State of Our Nation's Ecosystems 2008" (Heinz Center 2008). Key resources for the park were adapted from the CAHA State of the Park Report (NPS 2016f). This initial framework was presented to park resource staff to stimulate meaningful dialogue about key resources that should be assessed. Significant collaboration between SMUMN GSS analysts and NPS staff was needed to focus the scope of the NRCA project and finalize the framework of key resources to be assessed.

The NRCA framework was finalized by the end of February 2018 following review and acceptance from NPS resource staff. The framework contains a total of nine components (Table 5) and was used to drive analysis in this NRCA. This framework outlines the components (resources), most appropriate measures, known or perceived stressors and threats to the resources, and the reference conditions for each component for comparison to current conditions

Table 5. Cape Hatteras National Seashore natural resource condition assessment framework.

Category	Component	Measures (Significance Level)	Stressors	Reference Condition
Biotic Composition/ Ecological Communities	Backshore and Dune Communities	Plant species richness (3), percent vegetative cover (3), acreage of communities (1)	Erosion (wind and water), dune developments and future developments, overwash events, ORV use	Ocracoke south of 72 and Ramp 55 on Hatteras Island represent areas relatively untouched by man and representative of barrier islands. CALO conditions may provide some reference.
	Maritime Forests	Acreage of maritime forests (3), plant species richness (3), wildlife species richness (3), stand structure (2), recruitment (in the understory) (2)	Groundwater salinity, controlled burns/wildfire, deer browse, pests and pathogens	Possibly stands at Nags Head Woods, Fort Raleigh, and CALO
	Wetlands and Marshes (fresh and saltwater)	Acreage of palustrine wetlands (3), acreage of estuarine wetlands (2), plant species richness of palustrine wetlands (3), plant species richness of estuarine wetlands (2), sediment elevation table of saltwater marshes (3), linear distance of drainage features (3), water quality (3)	Shrub encroachment, invasive species, sedimentation, climate change (sea level rise, changes in storm frequency/intensity), development (e.g., ditching and groundwater withdrawals)	Possibly wetlands at CALO or in Kitty Hawk Woods
Biotic Composition/ Wildlife	Birds	Shorebird species richness (3), shorebird relative abundance (3), landbird species richness (2), landbird relative abundance (2), annual waterfowl harvest (1)	Habitat changes, predation, recreational use, wind turbines, light and noise pollution, non-native vegetation, climate change, sea level rise, storm overwash/inundation, vehicle collision, fishing gear entanglement	Undefined
	Mammals	Mesocarnivore species richness (3), small mammal species richness (3), white-tailed deer density (3)	Habitat fragmentation (e.g., from development and roads), hunting that occurs outside park boundaries, human feeding/habituation, feral cat predation, disease	Undefined; nearby barrier islands may provide some insight

Table 5 (continued). Cape Hatteras National Seashore natural resource condition assessment framework.

Category	Component	Measures (Significance Level)	Stressors	Reference Condition
Biotic Composition/ Wildlife (continued)	Sea Turtles	Number of sea turtle nests (3), sea turtle emergence success (3)	Fisheries entanglements, marine debris, housing development and construction projects (including artificial lighting), dredging, human recreation, beach erosion, storms, habitat change, climate change, predation	Desired future conditions are outlined in the park's ORV management plan
Environmental Quality	Water Quality	Nutrients (3), fecal coliform bacteria (3), dissolved oxygen (3), SpC (3) (freshwater only), pH (3), water clarity/turbidity (3), chlorophyll *a* (3)	Human development (particularly septic systems), stormwater runoff, oil/fuel spills, harmful algal blooms, sea level rise (saltwater intrusion)	North Carolina state standards and criteria used by the SECN water quality monitoring program
	Dark Night Skies	NPS NSNSD suite of metrics	Artificial lighting in park, surrounding communities, air pollution, communication towers and lighthouses, construction lighting, beach nourishment lighting	Absence of anthropogenic light
Physical Characteristics	Barrier Island Geomorphology	Mean rates of change in island width at specific locations of interest (3), mean rates of change in length of the islands (3), change in total island area (3), change in beachfront area (3)	Natural erosional processes (wind, waves, currents, storms), human manipulation (inlet modification/maintenance, including dredging, shoreline stabilization), sea level rise, climate change, and visitor impacts (beach driving, pedestrians)	CALO's Core Banks; historic rates of change at CAHA may provide some insight

General Approach and Methods

This study involved gathering and reviewing existing literature and data relevant to each of the key resource components included in the framework. No new data were collected for this study; however, where appropriate, existing data were further analyzed to provide summaries of resource condition or to create new spatial representations. After all data and literature relevant to the measures of each component were reviewed and considered, a qualitative statement of overall current condition was created and compared to the reference condition when possible.

Data Mining

The data mining process (acquiring as much relevant data about key resources as possible) began at the initial scoping meeting, at which time CAHA staff provided data and literature in multiple forms, including: NPS reports and monitoring plans, reports from various state and federal agencies, published and unpublished research documents, databases, tabular data, and charts. GIS data were provided by NPS staff or downloaded from IRMA. Additional data and literature were also acquired through online bibliographic literature searches and inquiries on various state and federal government websites. Data and literature acquired throughout the data mining process were inventoried and analyzed for thoroughness, relevancy, and quality regarding the resource components identified at the scoping meeting.

Data Development and Analysis

Data development and analysis was highly specific to each component in the framework and depended largely on the amount of information and data available for the component and recommendations from NPS reviewers and sources of expertise including NPS staff from CAHA and the SECN. Specific approaches to data development and analysis can be found within the respective component assessment sections located in Chapter 4 of this report.

Scoring Methods and Assigning Condition

Significance Level

A set of measures are useful in describing the condition of a particular component, but all measures may not be equally important. A "Significance Level" represents a numeric categorization (integer scale from 1–3) of the importance of each measure in assessing the component's condition; each Significance Level is defined in Table 6. This categorization allows measures that are more important for determining condition of a component (higher significance level) to be more heavily weighted in calculating an overall condition. If a measure is given a Significance Level of 1, it is thought to be of low importance when determining the overall condition of the component. For this reason, measures with a Significance Level of 1 are not discussed in detail in the Current Condition and Trends section of a component's chapter. Significance Levels were determined for each component measure in this assessment through discussions with park staff and/or outside resource experts.

Table 6. Scale for a measure's Significance Level in determining a components overall condition.

Significance Level (SL)	Description
1	Measure is of low importance in defining the condition of this component.
2	Measure is of moderate importance in defining the condition of this component.
3	Measure is of high importance in defining the condition of this component.

Condition Level

After each component assessment is completed (including any possible data analysis), SMUMN GSS analysts assign a Condition Level for each measure on a 0–3 integer scale (Table 7). This is based on all the available literature and data reviewed for the component, as well as communications with park and outside experts.

Table 7. Scale for Condition Level of individual measures.

Condition Level (CL)	Description
0	**GOOD CONDITION**. No net loss, degradation, negative change, or alteration.
1	Of **LOW** concern. Signs of limited and isolated degradation of the component.
2	Of **MODERATE** concern. Pronounced signs of widespread and uncontrolled degradation.
3	Of **SIGNIFICANT** concern. Nearing catastrophic, complete, and irreparable degradation of the component.

Weighted Condition Score

After the Significance Levels (SL) and Condition Levels (CL) are assigned, a Weighted Condition Score (WCS) is calculated via the following equation:

$$WCS = \frac{\sum_{i=1}^{\#\ of\ measures} SL_i * CL_i}{3 * \sum_{i=1}^{\#\ of\ measures} SL_i}$$

The resulting WCS value is placed into one of three possible categories: resource is in good condition (WCS = 0.0–0.33); condition warrants moderate concern (WCS = 0.34–0.66); and condition warrants significant concern (WCS = 0.67 to 1.00). Tables 8 and 9 display and describe the symbology used to represent a component's condition in this assessment. The colored circles represent the categorized WCS; red circles signify a significant concern, yellow circles a moderate concern, and green circles are in good condition. White circles are used to represent situations in which SMUMN GSS analysts and park staff felt there was currently insufficient data to make a statement about the condition of a component. The border of the circles represent SMUMN GSS's confidence in the assessment of current condition; bold borders indicate high confidence, normal borders indicate medium confidence, and a dashed-border indicates low confidence. The arrows

inside the circles indicate the trend of the condition of a resource component, based on data and literature from the past 5–10 years, as well as expert opinion. An upward pointing arrow indicates the condition of the component has been improving in recent times. An arrow that points to the left and right indicates a stable condition or trend and an arrow pointing down indicates a decline in the condition of a component in recent times. These are only used when it is appropriate to comment on the trend of condition of a component. An empty circle with no arrow is reserved for situations in which the trend of the component's condition is currently unknown.

Table 8. Description of symbology used for individual component assessments.

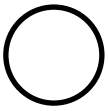
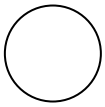
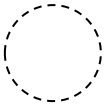
Condition Status		Trend in Condition		Confidence in Assessment	
Condition Icon	**Condition Icon Definition**	**Trend Icon**	**Trend Icon Definition**	**Confidence Icon**	**Confidence Icon Definition**
	Resource is in Good Condition		Condition is Improving		High
	Resource warrants Moderate Concern		Condition is Unchanging		Medium
	Resource warrants Significant Concern		Condition is Deteriorating		Low

Table 9. Example indicator symbols and descriptions of how to interpret them in WCS tables.

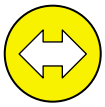
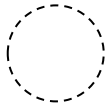
Symbol Example	Verbal Description
	Resource is in good condition; its condition is improving; high confidence in the assessment.
	Condition of resource warrants moderate concern; condition is unchanging; medium confidence in the assessment.
	Condition of resource warrants significant concern; trend in condition is unknown or not applicable; low confidence in the assessment.

Table 9 (continued). Example indicator symbols and descriptions of how to interpret them in WCS tables.

Symbol Example	Verbal Description
	Current condition is unknown or indeterminate due to inadequate data, lack of reference value(s) for comparative purposes, and/or insufficient expert knowledge to reach a more specific condition determination; trend in condition is unknown or not applicable; low confidence in the assessment.

Preparation and Review of Component Draft Assessments

The preparation of draft assessments for each component was a highly cooperative process among SMUMN GSS analysts, and CAHA and SECN staff. Though SMUMN GSS analysts rely heavily on peer-reviewed literature and existing data in conducting the assessment, the expertise of NPS resource staff also plays a significant and invaluable role in providing insights into the appropriate direction for analysis and assessment of each component. This step is especially important when data or literature are limited for a resource component.

The process of developing draft documents for each component began with a detailed phone or conference call with an individual or multiple individuals considered local experts on the resource components under examination. These conversations were a way for analysts to verify the most relevant data and literature sources that should be used and also to formulate ideas about current condition with respect to the NPS staff opinions. Upon completion, draft assessments were forwarded to component experts for initial review and comments.

Development and Review of Final Component Assessments

Following review of the component draft assessments, analysts used the review feedback from resource experts to compile the final component assessments. As a result of this process, and based on the recommendations and insights provided by CAHA resource staff and other experts, the final component assessments represent the most relevant and current data available for each component and the sentiments of park resource staff and resource experts.

Format of Component Assessment Documents

All resource component assessments are presented in a standard format. The format and structure of these assessments is described below.

Description

This section describes the relevance of the resource component to the park and the context within which it occurs in the park setting. For example, a component may represent a unique feature of the park, it may be a key process or resource in park ecology, or it may be a resource that is of high management priority in the park. Also emphasized are interrelationships that occur among the featured component and other resource components included in the NRCA.

Measures

Resource component measures were defined in the scoping process and refined through dialogue with resource experts. Those measures deemed most appropriate for assessing the current condition of a component are listed in this section, typically as bulleted items.

Reference Conditions/Values

This section explains the reference condition determined for each resource component as it is defined in the framework. Explanation is provided as to why specific reference conditions are appropriate or logical to use. Also included in this section is a discussion of any available data and literature that explain and elaborate on the designated reference conditions. If these conditions or values originated with the NPS experts or SMUMN GSS analysts, an explanation of how they were developed is provided.

Data and Methods

This section includes a discussion of the data sets used to evaluate the component and if or how these data sets were adjusted or processed as a lead-up to analysis. If adjustment or processing of data involved an extensive or highly technical process, these descriptions are included in an appendix for the reader or a GIS metadata file. Also discussed is how the data were evaluated and analyzed to determine current condition (and trend when appropriate).

Current Condition and Trend

This section presents and discusses in-depth key findings regarding the current condition of the resource component and trends (when available). The information is presented primarily with text but is often accompanied by detailed maps or plates that display different analyses, as well as graphs, charts, and/or tables that summarize relevant data or show interesting relationships. All relevant data and information for a component is presented and interpreted in this section.

Threats and Stressor Factors

This section provides a summary of the threats and stressors that may impact the resource and influence to varying degrees the current condition of a resource component. Relevant stressors were described in the scoping process and are outlined in the NRCA framework. However, these are elaborated on in this section to create a summary of threats and stressors based on a combination of available data and literature, and discussions with resource experts and NPS natural resources staff.

Data Needs/Gaps

This section outlines critical data needs or gaps for the resource component. Specifically, what is discussed is how these data needs/gaps, if addressed, would provide further insight in determining the current condition or trend of a given component in future assessments. In some cases, the data needs/gaps are significant enough to make it inappropriate or impossible to determine condition of the resource component. In these cases, stating the data needs/gaps is useful to natural resources staff seeking to prioritize monitoring or data gathering efforts.

Overall Condition

This section provides a qualitative summary statement of the current condition that was determined for the resource component using the WCS method. Condition is determined after thoughtful review

of available literature, data, and any insights from NPS staff and experts, which are presented in the Current Condition and Trend section. The Overall Condition section summarizes the key findings and highlights the key elements used in determining and justifying the level of concern, if any, that analysts attribute to the condition of the resource component. Also included in this section are the graphics used to represent the component condition.

Sources of Expertise

This is a listing of the individuals (including their title and affiliation with offices or programs) who had a primary role in providing expertise, insight, and interpretation to determine current condition (and trend when appropriate) for each resource component. Sources are listed alphabetically by last name.

Chapter 4 Natural Resource Conditions

This chapter presents the background, analysis, and condition summaries for the nine key resource components in the project framework. The following sections discuss the key resources and their measures, stressors, and reference conditions. The summary for each component is arranged around the following sections:

1. Description
2. Measures
3. Reference Condition
4. Data and Methods
5. Current Condition and Trend (including threats and stressor factors, data needs/gaps, and overall condition)
6. Sources of Expertise
7. Literature Cited

The order of components follows the project framework (Table 5):

4.1 Backshore and Dune Communities

4.2 Maritime Forests

4.3 Wetlands and Marshes

4.4 Birds

4.5 Mammals

4.6 Sea Turtles

4.7 Water Quality

4.8 Dark Night Skies

4.9 Barrier Island Geomorphology

Backshore and Dune Communities

Description

The harsh natural conditions on barrier islands have forced some vegetation communities to adapt to a "near constant state of change" (McManamay et al. 2018, p. 5). This is particularly apparent in the backshore (from mean high tide line to the dune base) and foredune communities, which are most exposed to salt spray, shifting sands, and storm impacts (Van der Valk 1975, McManamay et al. 2018). Backshore and dune sands are also low in nutrients, particularly nitrogen and phosphorus, which limits plant growth (Van der Valk 1975). Vegetative cover in these areas is highly variable and consists primarily of species adapted to harsh, variable conditions (McManamay et al. 2018). The sparse backshore vegetation includes disturbance-tolerant succulents such as American searocket (*Cakile edentula*) (USFWS 2006, McManamay et al. 2018). The dune community is dominated by grasses such as seaoats (*Uniola paniculata*, Figure 9), American beachgrass (*Ammophila breviligulata*), and bitter panicgrass (*Panicum amarum*) (Stalter and Lamont 1997, McManamay et al. 2018). The vegetation communities and some common plant species found in the backshore and dune areas of CAHA are shown in Table 10.



Figure 9. Seaoats on a low dune at CAHA (NPS photo).

Table 10. Vegetation mapping units found on CAHA's backshore and dunes, along with their common plant species, as described by McManamay et al. (2018).

Vegetation mapping unit	Common plant species
Centipede Grass Planted Herbaceous Vegetation	centipede grass* (*Eremochloa ophiuroides*), saltmeadow cordgrass (*Spartina patens*)
Sea-oats Temperate Herbaceous Alliance	seaoats, bitter panicgrass, seacoast marsh elder (*Iva imbricata*), seabeach evening primrose (*Oenothera humifusa*)
Overwash Dune Grassland	saltmeadow cordgrass, largeleaf pennywort (*Hydrocotyle bonariensis*), seabeach evening primrose
Southern Hairgrass – Saltmeadow Cordgrass – Dune Fingergrass Herbaceous Vegetation	pinewoods fingergrass (*Eustachys petraea*), purple lovegrass (*Eragrostis spectabilis*), saltmeadow cordgrass, largeleaf pennywort, seaside goldenrod (*Solidago sempervirens*)

* non-native species

The backshore and lower foredunes of Atlantic barrier islands provide habitat for several rare plant species, including the federally threatened seabeach amaranth (*Amaranthus pumilus*) (Marion 2009, McManamay et al. 2018). Seabeach amaranth (Figure 10) particularly favors the base of lower foredunes and overwash flats at the accreting ends of islands (Marion 2009, NPS 2016c). It is tolerant of marginal environmental conditions but is a poor competitor with other plants, and often seems to move around the landscape as suitable habitat opens up (NPS 2016c). As an annual species, seabeach amaranth must regrow from seed each year, and dormant seed can remain viable in the soil for many years. As a result, populations may vary greatly in an area between years (NPS 2016c). Historically, CAHA supported large amounts of seabeach amaranth, with as many as 3,000–15,000 individuals during the late 1980s. However, the species has declined at the park and across its range since the mid-1990s. It was last documented at CAHA in 2005 (just four plants) and may be locally extirpated, but park staff still conduct annual surveys for the species due to the highly variable nature of populations (NPS 2016c).



Figure 10. Seabeach amaranth (USGS photo by Stephen M. Young).

Measures

- Plant species richness
- Percent vegetative cover
- Acreage of communities

Reference Condition/Values

It is challenging to select a reference condition for vegetation communities such as the backshore and dunes that are naturally so dynamic and variable, and given the extreme manipulation of vegetation communities in these areas that occurred during major planting and fertilization efforts (D. Hallac, pers. comm., July 2020). At CAHA, it is even more difficult due to the fact that many of the dunes are man-made and maintained. According to park managers (pers. comm., January 2018), the two backshore/dune areas at CAHA that are most representative of natural barrier island conditions and least influenced by human impacts are on Ocracoke Island south of ramp 72 (Figure 11, Figure 12) and on Hatteras Island south of ramp 55. However, no published descriptions/information specific to these areas are available. Backshore and dune communities at nearby Cape Lookout National Seashore (CALO) may also offer some comparison, although environmental conditions and land use history are somewhat different than for CAHA (e.g., human development and stabilized dunes/beaches at CAHA vs. less disturbed, natural systems on CALO).



Figure 11. The backshore and foredunes south of Ramp 72 on Ocracoke Island (NPS photo by Amy Thompson).



Figure 12. The back side of the dunes pictured above, south of Ramp 72 on Ocracoke Island (NPS photo by Amy Thompson).

Data and Methods

The earliest known botanical survey in the area that is now CAHA was a 5-day field visit to Ocracoke Island by Kearney (1900) in October 1898. The resulting report described the island's vegetation communities, common plant species within each community, and included a list of all plant species observed. Not long after the establishment of the National Seashore, Burk (1962) conducted a floristic study of the North Carolina Outer Banks, which included at least one collection site within CAHA.

Van der Valk (1974, 1975) studied the vegetation and mineral cycling in the foredune communities of CAHA. The study of mineral cycling took place on two constructed foredunes, one on Bodie Island and one on Ocracoke Island (Van der Valk 1974). In addition to documenting mineral deposition and content in plant tissues, the author reported vegetation composition and cover for each study site. Van der Valk (1975) explored similarities and differences in the vegetation composition on the front (beach side), top, and back of foredunes across CAHA. Twenty-two sites were sampled during August 1971.

Otte (1981) prepared a description of the vegetation communities of Ocracoke Island for a book on ecological diversity classification (Radford et al. 1981). The description was based on data collected during an October 1977 field visit and includes a list of plant species commonly found in dune and

marsh communities (Otte 1981). Davison et al. (1987) compiled a plant species checklist for Bodie Island based on published and unpublished literature, park herbarium records, and additional collections during 1984–1985.

Stalter and Lamont (1997) conducted a multi-year floristic study of the Outer Banks from Ocracoke Island to Virginia, which included all of the islands within CAHA. Visits were made to the study area approximately monthly during the growing seasons from June 1989 to October 1995. The final result of this study was an annotated plant species list for the area, including the vegetation community where each species was found (Stalter and Lamont 1997).

VegBank (Peet et al. 2013) is a vegetation plot database maintained by the Ecological Society of America's Panel on Vegetation Classification. Sixty-nine sampling plots within CAHA boundaries from the Carolina Vegetation Survey (CVS) have been entered into the VegBank database. Ten of these sampling plots were within backshore and dune communities (*Uniola paniculata – Hydrocotyle bonariensis* Herbaceous Vegetation and *Ammophila breviligulata – Panicum amarum* var. *amarum* Herbaceous Vegetation): seven on Hatteras Island, two on Bodie Island, and one on Ocracoke Island. Plots were visited in June 2003, with the exception of the plot on Ocracoke Island, which was sampled in September 2009 (Peet et al. 2013).

In 2010, the SECN initiated a vegetation monitoring project at CAHA as part of the Vital Signs monitoring program (Byrne et al. 2012a). Data were collected at 24 sampling locations across the island during August and September that year. Four of these locations fell within backshore and dune vegetation communities (CAHA02, CAHA12, CAHA22, CAHA28). Sampling methods are described in detail in Byrne et al. (2012a). Monitoring was repeated in 2015, but these data are not available for public review (Paula Capece, SECN Ecologist/Data Manager, email communication, 24 July 2018).

The SECN completed an updated vegetation classification and mapping project for CAHA in 2014 (McManamay et al. 2018). Plant communities were classified into vegetation associations using the U.S. National Vegetation Classification (NVC) (FGDC 2008). NatureServe was consulted to provide a preliminary list of vegetation communities likely to occur at CAHA. The mapping and classification involved a combination of field surveys and aerial imagery interpretation. A total of 40 field plots of various sizes were surveyed for classification purposes from 2005–2006, and aerial imagery was obtained in May 2009. Upon completion of a draft vegetation map in 2012, field reconnaissance was conducted to finalize the image analysis phase. Field accuracy assessments were completed at 450 locations across the park during April 2012 to ensure the Federal Geographic Data Committee (FGDC) mandated map accuracy of 80% (McManamay et al. 2018).

Current Condition and Trend

Plant Species Richness

Due to the harsh environmental conditions to which backshores and dunes are exposed, they tend to exhibit lower plant species richness. Richness can also vary within these vegetation communities due to microclimatic differences; for example, Van der Valk (1975) found that the back sides of foredunes supported more plant species on average than the front and top of foredunes (19.0 vs. 10.2

and 11.4, respectively). Multiple studies over time, dating back to Kearney's (1900) observations over a century ago, have collectively documented 98 taxa in backshore and dune communities (Appendix D). Seven of these species (7%) are known to be non-native. Due to differences in methodology and survey locations (e.g., one island vs. park-wide), the various studies over time cannot be accurately compared to determine if there are any trends in species richness within these communities. However, the number of plant species observed during SECN monitoring in CAHA's backshore and dune communities and in comparable communities at CALO was similar (47 vs. 53), and more sampling plots fell within backshore/dune community types at CALO (4 at CAHA vs. 12 at CALO) (Byrne et al. 2012a, b).

Percent Vegetative Cover

Vegetative cover influences the stability of beach and dune communities, with higher cover contributing to higher stability (Ames and Riggs 2006). As mentioned previously, vegetative cover in backshore and dune areas is highly variable, depending on environmental conditions and disturbance history. Areas that are more exposed to wind, salt spray, and high tides are likely to have lower vegetative cover than more protected areas. Storm events can also drastically and suddenly reduce vegetative cover through overwash, wind erosion, or burial under blowing sands (McManamay et al. 2018). In broad descriptions of CAHA vegetation communities, McManamay et al. (2018) stated that backshore vegetation is sparse (~20%) while vegetative cover on dune slopes ranged from 30–80%.

Limited data are available regarding vegetative cover within CAHA's backshore and dune communities. During August 1971 sampling, Van der Valk (1975) reported 3–6% cover on the front side of CAHA foredunes, 3–8% cover on the top, and 15–25% cover on the back of foredunes. In 10 backshore and dune sampling plots from the CVS, vegetative cover ranged from 1% (Ocracoke, 2009) to 70.2% (Hatteras, 2003) (Table 11). Cover in the seven Sea-oats Temperate Herbaceous Alliance was more variable than in the three Beachgrass-Panicgrass Dune Grasslands (18.0–37.5%) (Peet et al. 2013).

Table 11. Relative vegetative cover percentages from CVS backshore and dune plots, June 2003 for Hatteras and Bodie plots and September 2009 for Ocracoke Island (Peet et al. 2013).

Veg community	Plot #	Island	% Vegetative cover
Uniola paniculata – Hydrocotyle bonariensis Herbaceous Vegetation	057-01-0831	Hatteras	31.5
	057-04-0832	Bodie	31.8
	057-06-0825	Hatteras	70.2
	057-06-0826	Hatteras	44.0
	057-06-0827	Hatteras	7.0
	057-09-0832	Hatteras	65.1
	117-09-0086	Ocracoke	1.0
Ammophila breviligulata – Panicum amarum var. amarum Herbaceous Vegetation	057-01-0839	Hatteras	18.0
	057-06-0828	Hatteras	21.5
	057-07-0825	Bodie	37.5

During 2010 SECN monitoring, vegetative cover across dune community plots ranged from 37–47%, with bare ground accounting for 20–54% (Table 12). In comparison, the average percent of bare ground across all 24 sampling plots at CAHA was 9.5% (Byrne et al. 2012a). Similar vegetation communities at CALO showed vegetative cover ranging from 34–48%, with bare ground covering 17–46% (Byrne et al. 2012b).

Table 12. Relative cover percentages of groundcover vegetation, bare ground, and leaf litter/duff at Byrne et al. (2012a) sampling locations within CAHA dune communities.

Cover type	CAHA02	CAHA12	CAHA22	CAHA28
Vegetative cover	37.8	47.1	40.9	39.3
Bare ground	53.7	20.6	39.4	33.3
Leaf litter/duff	8.5	32.3	19.7	27.4

Acreage of Communities

According to the CAHA vegetation mapping report (McManamay et al. 2018), backshore and dune vegetation communities cover 1,335 ha (3,299 ac) within the park (Table 13). This accounts for 13% of total park area and 19% of the park's naturally vegetated area. The majority is made up of the Centipede Grass Planted Herbaceous Vegetation / Sea-oats Temperate Herbaceous Alliance / Overwash Dune Grassland mapping unit (Figure 13). This vegetation is primarily found in a narrow strip along the ocean side of the barrier islands (Figure 14-Figure 17). At CALO, for comparison, similar communities comprise just over 12% of park area (McManamay 2017).

Table 13. Extent of backshore and dune community vegetation types at CAHA based on 2009 aerial imagery, as reported in McManamay et al. (2018).

Vegetation community	Area (ha/ac)
Centipede Grass Planted Herbaceous Vegetation / Sea-oats Temperate Herbaceous Alliance / Overwash Dune Grassland	1,322.9 (3,269.0)
Southern Hairgrass – Saltmeadow Cordgrass – Dune Fingergrass Herbaceous Vegetation	12.2 (30.1)
Total	**1,335.1 (3,299.1)**



Figure 13. Sea-oats Temperate Herbaceous Alliance (left) and Southern Hairgrass – Saltmeadow Cordgrass – Dune Fingergrass Herbaceous Vegetation (right) (NPS photos).



Figure 14. Location of vegetation mapping units found in backshore and dune communities in the northernmost portion of CAHA, including PINWR (McManamay et al. 2018).



Figure 15. Location of vegetation mapping units found in backshore and dune communities on central Hatteras Island within CAHA, from PINWR south to Avon (McManamay et al. 2018).

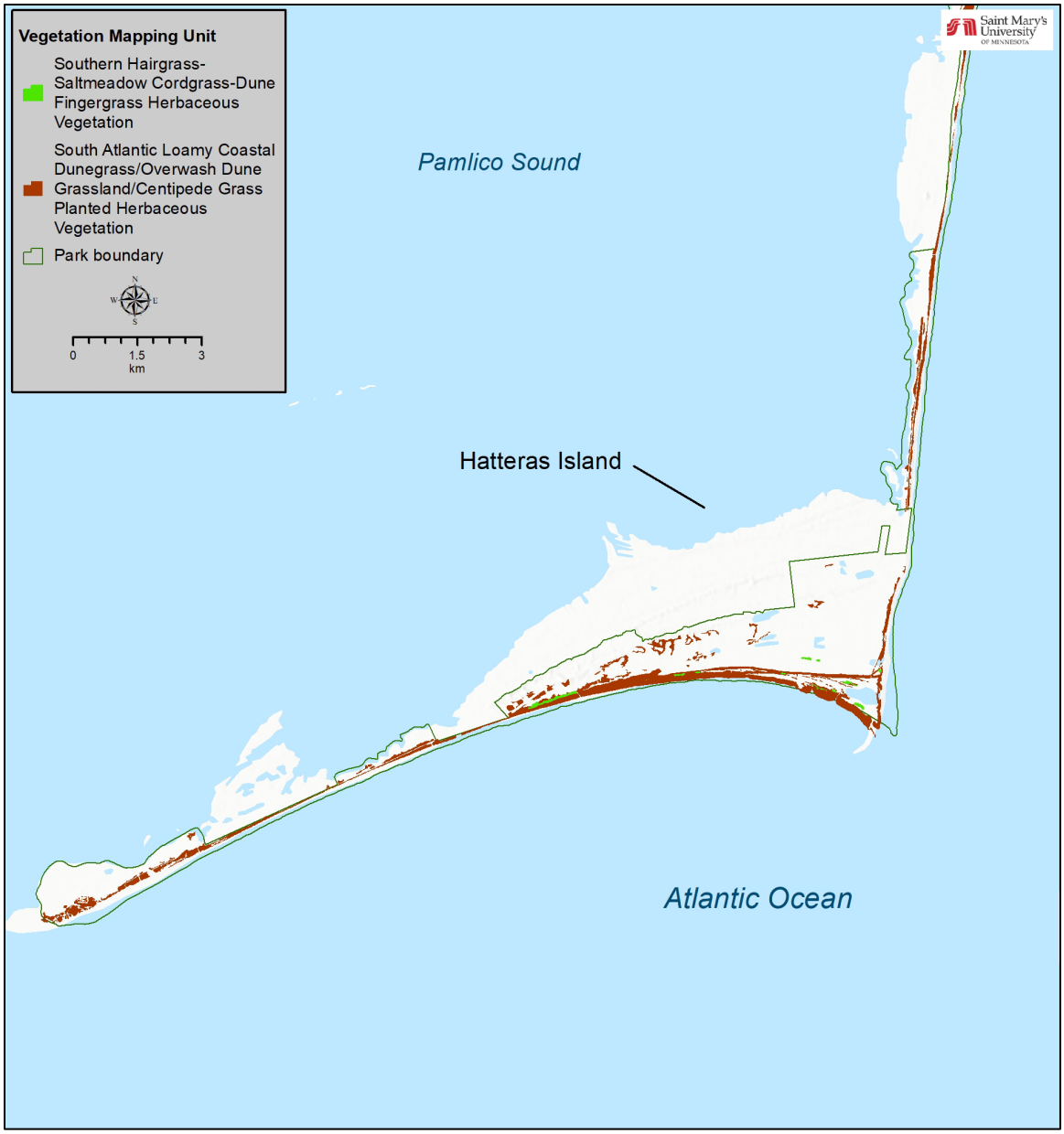


Figure 16. Location of vegetation mapping units found in backshore and dune communities on southern Hatteras Island within CAHA (McManamay et al. 2018).



Figure 17. Location of vegetation mapping units found in backshore and dune communities on Ocracoke Island at the southern end of CAHA (McManamay et al. 2018).

Threats and Stressor Factors

Threats and stressors to CAHA's backshore and dune vegetation communities include development and maintenance (e.g., keeping Highway 12 clear), overwash events, and excessive wind and water erosion, which may be exacerbated by climate change. Human development (residential, infrastructure, etc.) on the park's islands has negatively impacted dune communities, particularly through vegetation removal that exposes dune and backshore areas to accelerated erosion (Firth 1987). Beach and dune stabilization efforts to protect human developments have disrupted natural barrier island processes (Riggs et al. 2008, McManamay et al. 2018; see Chapter 4.9 for further

discussion), and reduced the area available for dune and backshore communities (Marion 2009). The most visible example of these efforts is the maintenance of North Carolina Highway 12 on the north end of Hatteras Island. This road is critical to the coastal tourism industry and provides the only vehicular evacuation route in case of hurricanes (Mallinson et al. 2009). Artificial barrier dunes were historically constructed to protect the roadway, but the dunes are largely unvegetated and highly unstable due to the harsh barrier island conditions. Sand from the dunes frequently covers the road during high winds, and storm events often cause dune breaches, overwash, and flooding of the road (Riggs and Ames 2011, Sciaudone et al. 2016). The North Carolina Department of Transportation (NCDOT) regularly uses bulldozers and sand fencing to rebuild the dunes and keep the road clear (Mallinson et al. 2009, Sciaudone et al. 2016). In 2018, NCDOT began building a bridge over Pamlico Sound to bypass one of the areas most vulnerable to breaches and overwash (the "s-curves, north of Rodanthe) (NCDOT 2019). The bridge is scheduled for completion in the fall of 2021.

Wind and water erosion are natural stressors to backshore and dune communities that may be exacerbated due to human influence (e.g., dune and shore modification, infrastructure development, climate change). Hurricanes, nor'easters, and extreme high tides can trigger overwash events, which may breach dunes and even cause new inlets to form (Sciaudone et al. 2016, McManamay et al. 2018). These forces may destroy backshore/dune vegetation and physically erode barrier dunes. In August 2011, for example, Hurricane Irene wiped out the dune field in two areas on Hatteras Island: in northern Rodanthe and near Mile 6 within the Pea Island National Wildlife Refuge (PINWR) (Sciaudone et al. 2016). Dune erosion is typically more severe in areas with narrower beach widths, where ocean waves are already in closer proximity to the dunes (DeKimpe et al. 1991). If vegetation is not directly destroyed during these storms, the after-effects from increased salt spray and sandblasting may cause plants to die back (Van der Valk 1975). The intensity of hurricanes is projected to increase over the next century due to global climate change (Knutson et al. 2010), which may in turn increase storm impacts upon backshore and dune communities.

Habitat loss due to erosion has been cited as a primary threat to seabeach amaranth (Marion 2009, NPS 2016c). Around Hatteras Inlet, large portions of historic seabeach amaranth habitat have simply eroded away (NPS 2016c). The loss of suitable habitat to erosion is likely to accelerate if sea levels continue to rise as a result of global climate change (Marion 2009).

Data Needs/Gaps

While some information is available for each of the measures selected, additional surveys and monitoring are needed to better understand the condition of backshore and dune communities at CAHA. Only a few of the initial SECN monitoring plots were located in backshore and dune communities; however, this monitoring was re-designed in 2018 to include more plots. Continuation of this re-designed SECN vegetation monitoring will provide additional data for the backshore and dunes communities, and help to detect any changes in plant species richness and vegetative cover. It may also be possible to study vegetative cover in these communities using aerial photography interpretation and GIS. This would allow park managers to better understand the variability in vegetative cover within these communities and to track changes over time. Additionally, the park has a goal to develop a "Target Vegetation Community Plan" (Tracy Ziegler, CAHA Chief of Resource

Management and Science, written communication, February 2020). This plan could help establish reference or target conditions for CAHA's backshore and dune communities.

CAHA also offers a potential site to study the reintroduction/restoration of seabeach amaranth. The USFWS is investigating the species' rapid decline and considering reintroduction efforts in suitable areas (NPS 2016c). The possible development of a restoration/reintroduction plan for CAHA was discussed in the park's original Off-Road Vehicle Management Plan (NPS 2010). Potential suitable sites include Southern Ocracoke Island Spit, Hatteras Island Spit, North Ocracoke Spit, Cape Point, and Bodie Island Spit (NPS 2010).

Overall Condition

Plant Species Richness

The project team assigned this measure a *Significance Level* of 3. Plant species richness is often low in communities under harsh environmental conditions, such as in backshore and dune areas. Over time, 98 total plant taxa have been documented in the park's backshore and dune communities, only seven of which are non-native (Appendix C). SECN vegetation monitoring recorded a similar number of plant species in CAHA and CALO backshore/dune community sampling plots (Byrne et al. 2012a, b). As a result, this measure is assigned a *Condition Level* of 1, indicating low concern.

Percent Vegetative Cover

The vegetative cover measure was also assigned a *Significance Level* of 3. Information regarding vegetative cover in CAHA's backshore and dune communities is limited to one study from the 1970s (Van der Valk 1975), 10 CVS plots sampled over a decade ago (Peet et al. 2013), and one SECN monitoring visit, where only four sampling locations fell within backshore/dune communities (Byrne et al. 2012a). While these data do not indicate any cause for concern, they are not sufficient to assign a *Condition Level* at this time.

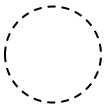
Acreage of Communities

A *Significance Level* of 1 was assigned for this final measure. Backshore and dune vegetation communities cover 1,335 ha (3,299 ac) or approximately 13% of total park area (McManamay et al. 2018). There is no apparent cause for concern regarding the total area covered by these communities within CAHA, but there is not currently enough information to assign a *Condition Level* for this measure.

Weighted Condition Score

A Weighted Condition Score could not be calculated for CAHA's backshore and dune communities due to limited data and information, including the difficulty in defining a clear reference condition (Table 14). While there is no indication of immediate cause for concern regarding the state of these communities park-wide, the current condition and trend are considered unknown.

Table 14. Current condition and trend for the Backshore and Dune Communities of CAHA.

Measures	Significance Level	Condition Level	WCS = N/A
Plant Species Richness	3	1	–
Percent Vegetative Cover	3	n/a	–
Acreage of Communities	1	n/a	–
Overall	–	–	

Sources of Expertise

Forbes Boyle, SECN Botanist

Tracy Ziegler, CAHA Chief of Resource Management and Science

Maritime Forests

Description

Maritime forests are woody communities that occur on coastal barrier islands, typically on stabilized dune systems with some protection from harsh weather (Lopazanski et al. 1988, Bellis 1995). Plant species within maritime forests still must be able to survive the inhospitable conditions on barrier islands, including salt spray, high winds, and nutrient-poor soils (Lopazanski et al. 1988). Maritime forest species composition varies depending on environmental conditions and land use history. North Carolina's maritime forests are typically characterized by four tree species: live oak (*Quercus virginiana*), Darlington or sand laurel oak (*Q. hemisphaerica*), loblolly pine (*Pinus taeda*), and eastern redcedar (*Juniperus virginiana*) (Godfrey and Godfrey 1976, Lopazanski et al. 1988, McManamay et al. 2018). Plant species commonly found in Outer Banks maritime forests are presented in Table 15. While these forests are dominated by upland woods, they are often interspersed with small herbaceous and wooded wetlands, which contributes to their overall diversity. As a result, maritime forests also protect and recharge freshwater aquifers on barrier islands (Lopazanski et al. 1988).

Table 15. Common plant species in Outer Banks maritime forests (Lopazanski et al. 1988, Stalter and Lamont 1997, McManamay et al. 2018).

Plant type	Species
Canopy trees	live oak, loblolly pine, eastern redcedar, Darlington or sand laurel oak
Understory trees	black cherry (*Prunus serotina*), redbay (*Persea borbonia*), American hornbeam (*Carpinus caroliniana*)
Shrubs and vines	flowering dogwood (*Cornus florida*), American holly (*Ilex opaca*), yaupon (*I. vomitoria*), wax myrtle (*Morella cerifera*), grape vines (*Vitis* spp.), Virginia creeper (*Parthenocissus quinquefolia*), poison ivy (*Toxicodendron radicans*)
Herbaceous	slender woodoats (*Chasmanthium laxum*), elephantsfoot (*Elephantopus* spp.), coastal bedstraw (*Galium bermudense*), partridgeberry (*Mitchella repens*), narrowleaf silkgrass (*Pityopsis graminifolia*)

At approximately 1,215 ha (3,000 acres), Buxton Woods on Hatteras Island (Figure 18) is the largest remaining maritime forest on North Carolina's Outer Banks (Lopazanski et al. 1988, Mallinson et al. 2009). It supports the full range of typical maritime forest habitats, from mature forested ridges and successional forest patches to swamp forests and interdunal ponds, some of which occur nowhere else in the state (Lopazanski et al. 1988). Buxton Woods provides habitat for rare plant species and a variety of wildlife, as well as serving as the primary recharge area for the aquifer providing fresh water to the region's villages (Lopazanski et al. 1988). Nearly one-third of Buxton Woods falls under NPS management. Additional maritime forests within CAHA are found near Ocracoke Village on Ocracoke Island and near Salvo on Hatteras Island (Godfrey and Godfrey 1976, McManamay et al. 2018).



Figure 18. Buxton Woods, on Hatteras Island within CAHA.



A maritime forest at CAHA (NPS photo by Paul Doshkov).

Measures

- Acreage of maritime forests
- Plant species richness
- Wildlife species diversity
- Stand structure
- Recruitment

Reference Condition/Values

The ideal reference condition for this component would be the condition of maritime forests on the islands prior to European settlement. However, little is known about maritime forests during this time. Some researchers believed, based on historic accounts, that forest cover was historically more extensive and had been reduced by human disturbance (e.g., logging and grazing) (summarized in Bratton and Davison 1985, Firth 1987). Other researchers suggest that it is unlikely maritime forest would be extensive on the Outer Banks because large portions of the islands are so narrow and offer little protection from dynamic environmental conditions (e.g., storms, overwash, salt spray, sea level rise) (Godfrey and Godfrey 1976, Firth 1987). Potential nearby maritime forests that could offer some comparison for this NRCA include Nags Head Woods (north of CAHA on Bodie Island), the woods at Fort Raleigh National Historic Site (on Roanoke Island, west of CAHA), and stands at

CALO. While published scientific information is limited for the vegetation of the first two sites, some monitoring has been conducted at CALO by the SECN over the past decade (Byrne et al. 2012b). However, Nags Head Woods, Fort Raleigh, and the sites sampled at CALO are further from the ocean and likely more sheltered than sites sampled at CAHA.



A 1940 photo of the Hammock Oaks on Ocracoke Island (from Engels 1942).

Data and Methods

Several of the sources that were previously utilized for the backshore and dune community component were also used for this component. These include Kearney (1900), Burk (1962), Stalter and Lamont (1997), Byrne et al. (2012a), and McManamay et al. (2018). Burk's (1962) collection sites included CAHA's Buxton Woods and three of Byrne et al.'s (2012a) sampling locations (CAHA03, CAHA10, CAHA13) fell within the maritime forest of Buxton Woods (Figure 19). Several maritime forest plots visited in 1988 by Peet et al. (2013) for the CVS were also located in Buxton Woods; this data is available at VegBank.org.

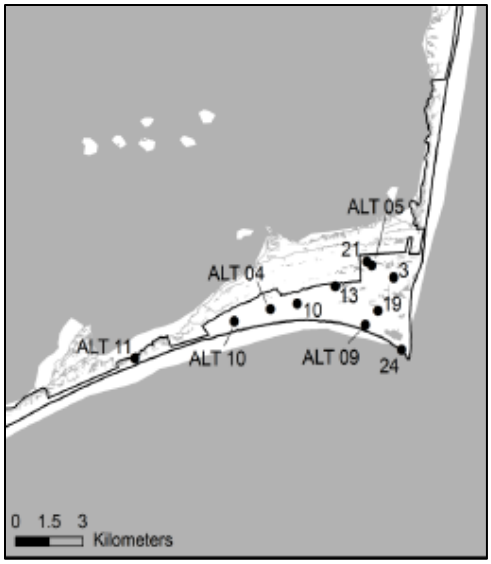


Figure 19. The locations of SECN monitoring plots (3, 10, and 13) within the maritime forests of Buxton Woods (Byrne et al. 2012a).

Settel (1937) conducted a timber survey of Buxton Woods, reporting various stand structure and recruitment metrics for the forested vegetation community types. Bratton and Davison (1985) searched historic records, interviewed local residents, and conducted sampling to study the disturbance history of Buxton Woods. Vegetation sampling was conducted within 20x40 m (66x131 ft) plots at 25 sites. Woody species were tallied by species and diameters at breast height (DBHs) measured; ground cover of woody species was also estimated (Bratton and Davison 1985).

Current Condition and Trend

Acreage of Maritime Forests

The CAHA vegetation mapping report (McManamay et al. 2018) identified 587 ha (~1,451 ac) of maritime forest (Live Oak – [Cabbage Palmetto] Forest Alliance/Live Oak/Yaupon Shrubland), which accounts for 6% of total park area and 8% of the park's naturally vegetated area. The majority of this area lies in Buxton Woods, with smaller amounts on Ocracoke and Bodie Islands (Figure 20-Figure 22). In comparison, comparable maritime forest communities at nearby CALO cover just 1.5% of the park's naturally vegetated area (McManamay 2017).



Figure 20. Location of maritime forest vegetation in the northern portion of CAHA (McManamay et al. 2018).



Figure 21. Location of maritime forest vegetation in the central portion of CAHA (McManamay et al. 2018).



Figure 22. Location of maritime forest vegetation on Ocracoke Island within CAHA (McManamay et al. 2018).

Plant Species Richness

Various studies over time have documented 124 different taxa in CAHA's maritime forests (Appendix E). However, as with backshore and dune communities, these studies cannot be compared to determine if there are any trends in plant diversity within these communities due to differences in methodology and survey locations (e.g., opportunistic observations on Ocracoke [Kearney 1900] vs. scientific sampling in Buxton Woods [Byrne et al. 2012a]). To offer some comparison or reference, a 1950s survey of 17 maritime forest stands along the North Carolina coast identified a total of 107 flowering plant species (Bourdeau and Oosting 1959). During recent SECN vegetation sampling, a

similar number of plant species were found in the three CAHA maritime forest plots (70 species) and in the two CALO plots (78 species) (Byrne et al. 2012b). Several species noted as common in a description of Nags Head Woods upland forests have not been documented in CAHA's maritime forests: southern red oak (*Quercus falcata*), mockernut hickory (*Carya tomentosa*), and eastern hophornbeam (*Ostrya virginiana*) (Lopazanski et al. 1988).

Wildlife Species Diversity

Maritime forests on barrier islands often serve as refuges for wildlife (Bellis 1995), and the diversity of habitats in Buxton Woods in particular are thought to support a higher diversity of mammalian fauna than on other forested North Carolina barrier islands (Lopazanski et al. 1988). Studies related specifically to wildlife diversity in the Buxton Woods area and the maritime forests of the park have been very limited. Bellis (1995) compiled a list of vertebrate species found in the maritime forests of CAHA which included 91 total species: seven amphibians, 16 reptiles, 48 birds, and 20 mammals (Appendix I). More recent SECN herpetofauna monitoring (Byrne et al. 2011b) found two additional reptile species in the forests of Buxton Woods: eastern box turtle (*Terrapene carolina*) and green anole (*Anolis carolinensis*). According to Webster (2010), the gray fox (*Urocyon cinereoargenteus*), red fox (*Vulpes vulpes*), and southern short-tailed shrew (*Blarina carolinensis*) are also associated with the maritime forests of CAHA. In addition, Webster (2010) notes that the white-footed mouse found at CAHA is a unique endemic subspecies not described until 2005 (Shipp-Pennock et al. 2005)—the Buxton Woods white-footed mouse (*Peromyscus leucopus buxtoni*). Further discussion of wildlife diversity across the park as a whole can be found in Chapters 4.4 (Birds) and 4.5 (Mammals).

Stand Structure

Stand structure is often studied using size class distributions and can be helpful in inferring the history and current successional status of a forest stand (DeYoung 2016). Tree size can indicate the age of a stand (i.e., larger trees occur in older stands) while size class distributions can provide information regarding disturbance history. Even-aged stands, with trees that are all of similar size, often develop after large-scale disturbances (e.g., logging, wildfire, strong storms) (DeYoung 2016). Canopy cover may also provide some insight into stand structure, including stand density, forest productivity, and disturbance history (Smith et al. 2008b).

Settel (1937) recorded stand structure measures including species densities and DBH during a 1937 "timber cruise" of Buxton Woods. The vegetation community identified by Settel (1937) that seems closest to maritime forest was called the "mixed hardwood sapling type." The most common trees in this type were yaupon (*Ilex vomitoria*; 62 trees/ha), loblolly pine (40 trees/ha), and common persimmon (*Diospyros virginiana*; 16 trees/ha). Live oak density was 8 trees/ha. Settel (1937) also reported the size distribution for these stands (Figure 23). The average DBH of all trees was 8.5 cm (3.3 in), with the majority of trees <7.6 cm (3.0 in) in diameter. Trees greater than 30.5 cm (12 in) in DBH were rare (Settel 1937).

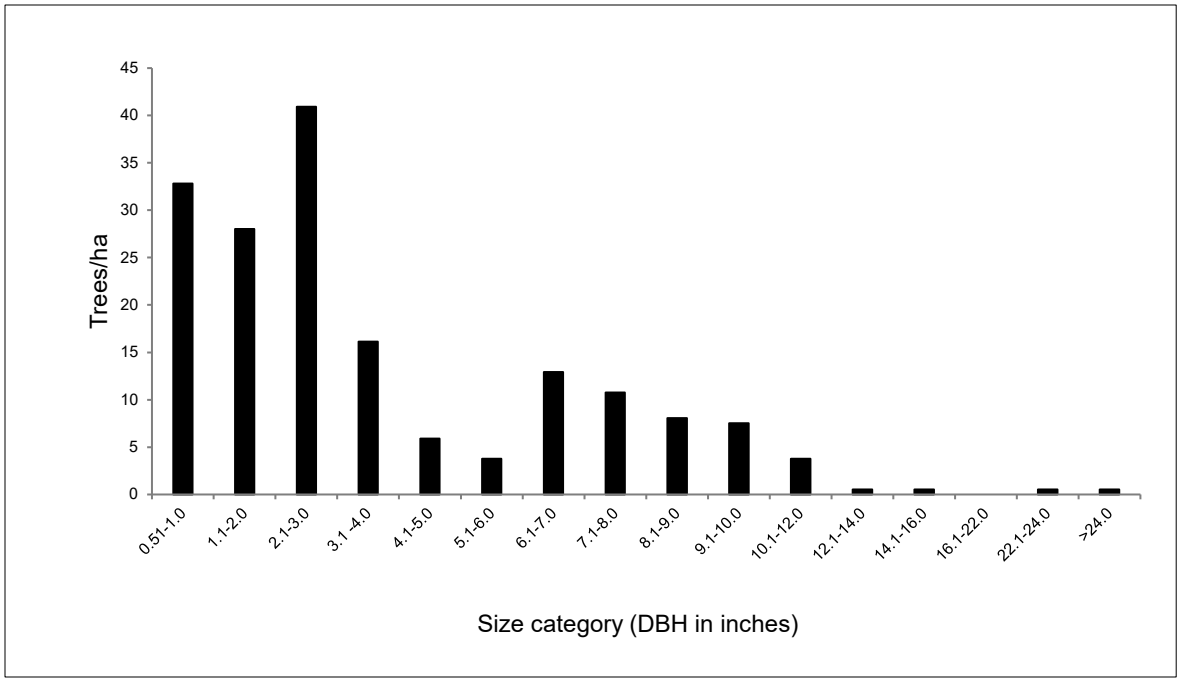


Figure 23. Tree size distribution in Buxton Woods mixed hardwood stands in 1937 (Settel 1937).

Bratton and Davison (1985) reported on stand structure at locations in Buxton Woods during the mid-1980s. The authors found a "typical" hardwood stand had an average tree DBH of 7.6 cm (3.0 in), but a "better developed" stand nearby had an average DBH of 13.6 cm (5.4 in), including one laurel oak (*Quercus laurifolia*) with a DBH of 65.5 cm (25.8 in) (Bratton and Davison 1985, p. 26). Mature live oaks were reportedly uncommon in the forest at this time.

Peet et al. (2013) documented tree sizes during 1988 sampling of maritime forest plots in Buxton Woods. Loblolly pines ranged in size from 7.5–51.5 cm DBH (3–20 in) while live oaks ranged from 1.75–108.5 cm DBH (0.7–43 in) (Table 16). Sand laurel oak were more common than live oak but generally smaller, ranging from 0.5–45.5 cm DBH (0.2–18 in) (Peet et al. 2013).

Table 16. Size range (DBH in cm) of primary maritime forest tree species in maritime forest plots within Buxton Woods, May 1988 (Peet et al. 2013). Numbers in parentheses are the total number of trees of each species within the plot. The final column lists other tree species in each plot with individual stems larger than 10 cm in DBH.

Plot	Loblolly pine range (# stems)	Live oak range (# stems)	Sand laurel oak range (# stems)	Other species >10 cm DBH
78937	17.5–49.5 (17)	–	–	American hornbeam (1), flowering dogwood (3)
78938	7.5–51.5 (13)	–	3.75–22.5 (34)	flowering dogwood (3), redbay (3)
78940	–	–	7.5–17.5 (3)	flowering dogwood (5), redbay (3)
78942	17.5 (1)	65.5–71.5 (2)	0.5–22.5 (183)	American hornbeam (1), flowering dogwood (4), American holly (2), redbay (2)
78957	17.5–48.5 (13)	32.5–37.5 (2)	3.75–45.5 (57)	flowering dogwood (2)
78960	12.5–37.5 (6)	1.75–22.5 (72)	0.5–27.5 (36)	–
78977	–	89.5–108.5 (2)	17.5–22.5 (6)	American hornbeam (4), flowering dogwood (16), redbay (8)

Byrne et al. (2012a) documented the average canopy cover and average canopy tree size by measuring each tree's DBH; the number of trees of each species per plot was also reported. Of the three maritime forest locations sampled (Figure 19), plot CAHA13 showed the greatest average canopy cover at 84.5% (Byrne et al. 2012a). The remaining two plots averaged 71.4% and 71.2% canopy cover. For comparison, the average canopy cover in the two maritime forest plots at CALO were 84.7% and 78.7% (Byrne et al. 2012b). In two of the three maritime forest plots, loblolly pine was the most abundant species, and also one of the largest species, averaging nearly 30 cm (11.8 in) DBH in one plot (Table 17) (Byrne et al. 2012a). Live oak was also among the largest species in two plots, with average DBHs of 26.7 cm (10.5 in) and 20.1 cm (7.9 in) in the two plots. In the third plot where loblolly pine and live oak were absent, eastern redcedar was the largest species on average (DBH of 14.8 cm [5.8 in]) and wax myrtle (*Morella cerifera*) was most abundant. Based on tree size and diversity, these findings suggest that the maritime forest at CAHA13 is the most mature (i.e., has gone the longest without substantial disturbance) of the three sites. In CALO maritime forest plots, the most abundant tree species included laurel oak, loblolly pine, eastern redcedar, and live oak (Byrne et al. 2012b). The largest trees at CALO were live oaks and eastern redcedars, with average DBHs of 28.0 cm (11.0 in) and 24.4 cm (9.6 in), respectively.

Table 17. Average canopy species size at vegetation monitoring sampling locations within maritime forest plots at CAHA, measured as DBH in cm (Byrne et al. 2012a). Numbers in parentheses indicate the number of individual trees measured within each plot.

	Average canopy tree size (DBH in cm)		
Location	**CAHA3**	**CAHA10**	**CAHA13**
Carpinus caroliniana	–	–	6.5 (6)
Ilex opaca	–	8.7 (1)	5.3 (1)
Ilex vomitoria	4.2 (2)	5.6 (4)	5.0 (4)
Juniperus virginiana	12.5 (2)	14.8 (3)	8.5 (1)
Morella cerifera	4.0 (1)	6.2 (28)	5.0 (2)
Persea borbonia	–	14.3 (12)	5.7 (2)
Pinus taeda	16.9 (17)	–	29.6 (14)
Quercus laurifolia	–	–	14.3 (9)
Quercus virginiana	20.1 (6)	–	26.7 (3)
Dead *I. vomitoria*	–	–	5.1 (1)
Dead *M. cerifera*	–	9.9 (8)	–
Dead *P. borbonia*	–	9.6 (7)	–
Dead *Q. virginiana*	18.0 (1)	–	–

Recruitment

Studies of tree recruitment, such as the composition and density of the seedling and sapling layers, can provide insight into the future character of the forest (McWilliams et al. 2015). Shifts in the composition of seedlings/saplings may indicate an eventual change in the composition of the forest as a whole, which can impact forest dynamics and wildlife habitat (McWilliams et al. 2015). For maritime forests, oak species recruitment is of particular interest.

The earliest known comment on forest recruitment within what is now CAHA comes from Kearney (1900, p. 271). The author noted that in Ocracoke Island's oak groves, "all the specimens of live oak seen were apparently of considerable age. Seedlings were few or none, and no acorns were observed." Around 1960, Burk (1962) reported that the seedling layer under the pines of Buxton Woods consisted primarily of oaks.

Settel (1937) reported tree seedling densities for Buxton Woods mixed hardwood stands in 1937; yaupon showed the highest seedling density (51 seedlings/ha), followed by loblolly pine (30 seedlings/ha), and common persimmon (4 seedlings/ha). Settel (1937) also reported ground cover percentages for these stands, which provides some insight into recruitment. Woody species in the ground cover layer included wax myrtle (12.7%), yaupon (12.7%), loblolly pine (11.7%), redbay (*Persea borbonia*, 8.0%), common persimmon (6.7%), live oak (6.7%), American holly (*Ilex opaca*, 2.3%), and American hornbeam (*Carpinus caroliniana*, 1.0%).

In a mid-1980s study similar to Settel (1937), Bratton and Davison (1985) found notable changes in the composition of woody species in the understory of Buxton Woods hardwood stands. While the

cover percentages are not directly comparable, relative proportions offer some insight into changes. Yaupon cover increased (28.4%) while wax myrtle (0.03%), loblolly pine (0.12%), and oak species (3.8%) decreased, and common persimmon was not found at all. The density of oak seedlings in hardwood stands was 2.5 seedlings/m^2 and pines were 0.03 seedlings/m^2 (Bratton and Davison 1985).

During SECN monitoring (Byrne et al. 2012a), surveyors recorded the frequency of tree/shrub seedlings per plot. In 2010, a total of 74 oaks (including 10 live oak and 35 laurel oak) were found in the seedling layers at five of the 24 plots sampled (Byrne et al. 2012a). Of the three plots specifically within maritime oak forest, live oak seedlings were present at relative low frequencies in two plots and laurel oak seedlings were found in one plot (Table 18). All three plots contained seedlings of other species characteristic of maritime forests, such as eastern redcedar, loblolly pine, redbay, and yaupon (Byrne et al. 2012a). Overall, plot CAHA10 showed the highest total seedling frequency at 8.32 seedlings/m^2. The highest seedling frequency for a single species among the three maritime forest plots was for laurel oak (2.92 seedlings/m^2) in CAHA13. In the two remaining plots, yaupon showed the highest seedling frequency (Table 15). In comparison, CALO maritime forest plots showed higher overall seedling frequencies (11.76 and 8.08 seedlings/m^2) and higher live oak seedling frequencies (2.5 and 4.8 seedlings/m^2) but low loblolly pine recruitment (0.08 seedlings/m^2 in one plot) and no laurel oak recruitment (Byrne et al. 2012b).

Table 18. Seedling frequency (seedlings/m^2) of maritime tree species in the seedling layer at vegetation monitoring sampling locations within maritime forest plots at CAHA, 2010 (Byrne et al. 2012a).

	Seedling frequency (seedlings/m^2)		
Location	**CAHA3**	**CAHA10**	**CAHA13**
Carpinus caroliniana	–	–	0.17
Diospyros virginiana	0.25	0.08	–
Ilex opaca	0.08	–	–
Ilex vomitoria	1.5	2.5	1.67
Juniperus virginiana	0.25	1.83	0.08
Morella cerifera	1.0	1.58	–
Persea borbonia	0.58	0.25	1.0
Pinus taeda	0.25	1.75	0.08
Quercus laurifolia	–	–	2.92
Quercus virginiana	0.5	0.33	–
Total	**4.41**	**8.32**	**5.92**

Threats and Stressor Factors

Threats to CAHA's maritime forests identified by the NRCA project team include increasing groundwater salinity, wildfires/controlled burns, deer browse, climate change, and pests and pathogens.

Depth to groundwater and groundwater salinity are key factors in determining the establishment, distribution, and succession of vegetation communities on barrier islands, including maritime forests (Masterson et al. 2014). Sea level rise elevates groundwater table levels (i.e., decreases depth to groundwater) and reduces the thickness of the freshwater lens within the groundwater table (Figure 24). Masterson et al. (2014) found that SLR of just 20 cm contributes to substantial change in water table depth, as well as the depth and extent of saltwater intrusion. Such changes could limit freshwater availability for vegetation, negatively impacting maritime forest areas. While maritime forest trees are more tolerant of salt spray than many other plants, they generally do not tolerate lengthy saltwater inundation, whether above or below the ground surface. Over the past 30 years, sea level has risen approximately 14 cm (5.5 in) in the CAHA area (NOAA 2017). Park managers have noted live oaks dying off near Salvo cemetery, with the cause likely being severe erosion and inundation of roots in saltwater (Tracy Ziegler, D. Hallac, written communication, February and July 2020). The rate of SLR is expected to accelerate over the remainder of this century, so that total SLR by 2100 is likely to be 28–98 cm (11–38 in) (IPCC 2013).

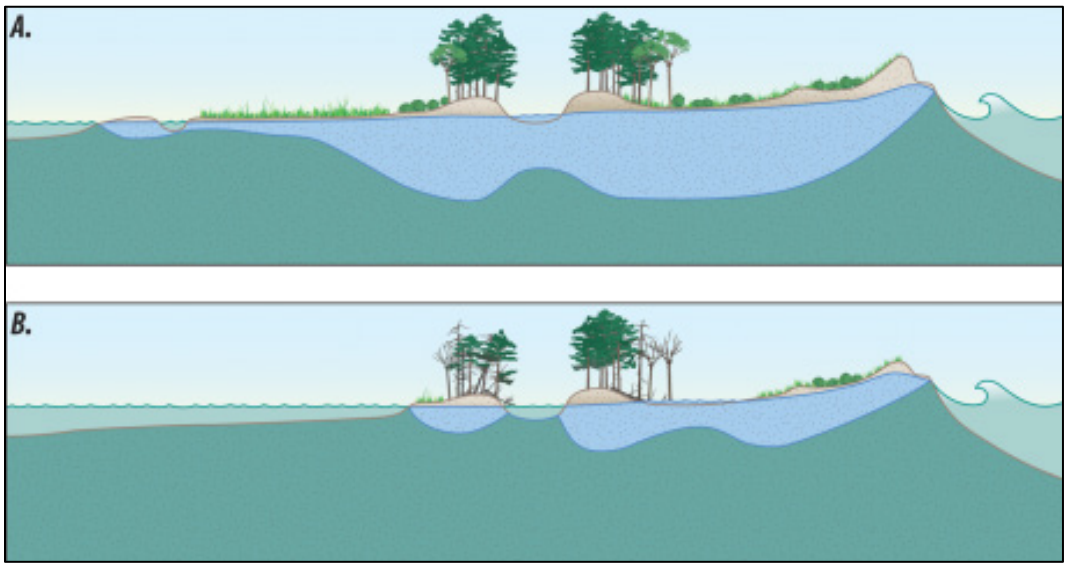


Figure 24. A diagram showing how SLR can influence the depth to groundwater (light brown) and freshwater lens thickness (light blue), which influences island vegetation. The top graphic (A) shows a barrier island at a baseline sea level and the bottom (B) shows the same island after SLR (Masterson et al. 2014).

Wildlife browsing, particularly by white-tailed deer, is known to impact plant regeneration in eastern U.S. forests (Lorimer 1993, Russell et al. 2001). On Cumberland Island, a south Georgia barrier island, researchers found that deer browsing was a major source of suppression of regrowth in the park's maritime forests (Bratton and Kramer 1989). On North Carolina's barrier islands, maritime forests have been cleared and fragmented by development (Lopazanski et al. 1988), which may force deer populations into the smaller and more isolated remaining forest patches, potentially increasing the browsing pressure in these areas. Bellis (1995) noted that herbivore foraging on the young plants

of maritime forest species such as eastern redcedar and yaupon can slow the expansion of the forest into new or previously occupied areas.

The historical significance of fire to the Outer Banks maritime forests is unclear. Summer thunderstorms with lightning that could naturally ignite wildfires are much less common in the CAHA area as they are on more southern barrier islands (Bellis 1995), suggesting that natural fires may not have been frequent occurrences. While the canopy trees of maritime forests (oaks and pines) seem well-adapted to fire, fire behavior characteristics often differ between stands dominated by pines vs. oaks, which impacts forest understory layers (Bellis 1995). Oak-dominated maritime forests have a denser canopy with a sparse understory, which tends to favor slow, smoldering fires. Pine-dominated forests, in contrast, tend to be drier with more ground fuels, which allows for faster, hotter fires. These hotter fires can kill off young oaks and other hardwoods and create conditions favorable for pine regeneration (Bratton and Davison 1985, Bellis 1995). At CAHA, several large fires reportedly occurred during the 1940s due to understory regrowth and increased fuel loading after the cessation of grazing in the 1930s (Bratton and Davison 1985). This, along with other historic land uses (e.g., logging), may have contributed to the current higher abundance of loblolly pine and shrubby species over oaks. Any controlled burns or wildfires in CAHA's maritime forests at this time could further favor pines and fire-tolerant shrubs over oak species.

Pests and pathogens that may impact CAHA's maritime forest include the gypsy moth (*Lymantria dispar*), laurel wilt disease, and pine beetles (*Dendroctonus frontalis* and *Ips* sp.). Native pine beetles are not generally a problem on coastal barrier islands like CAHA, but outbreaks may occur and cause mortality in trees that are damaged or stressed by storms or drought (Settel 1937, Gardner et al. 1992, Mallinson et al. 2009). This occurred in the Buxton area after Hurricane Emily in 1994 (Mallinson et al. 2009).

The non-native gypsy moth (Figure 25) has been present in North Carolina for at least a decade, if not longer (STS 2004). Gypsy moth infestation does not cause direct mortality, but extensive defoliation by the caterpillars increases a tree's vulnerability to other stressors (e.g., disease, other pests) (Hoover 2001). Oaks are the primary host for this moth, but it will also feed on other hardwoods, redcedars, and pines (Hoover 2001). An infestation near the northeast corner of Buxton Woods (outside park boundaries) has been the subject of suppression treatments since 2016 (NCDACS 2018). In 2015, the gypsy moth trapping program detected as many as 800 male moths per trap in this area. By 2017, after two rounds of aerial treatments, the highest number of moths per trap was 64. Ground treatments in a smaller area were scheduled for 2018 (NCDACS 2018).



Figure 25. A gypsy moth caterpillar (left, USFWS photo); and male (brown) and female (white) adults (right, USFS photo by John Ghent).

Laurel wilt disease (LWD) is a lethal fungus (*Raffaelea lauricola*) spread by a non-native ambrosia beetle (*Xyleborus glabratus*) (Shearman and Wang 2016). It was first detected along the southeastern Atlantic Coast in 2003. LWD affects members of the laurel family, including redbay and sassafras (*Sassafras albidum*) (NCFS 2017). The first sign of LWD is often wilting of branch tips or entire branches; this wilting then spreads throughout the entire crown and trees typically die soon after (Fraedrich et al. 2008). While LWD has not yet been detected at CAHA, it is present in southeastern North Carolina and poses a serious threat to CAHA's redbay trees (NCFS 2017).

Climate is a key driving factor in the ecological and physical processes influencing vegetation in parks throughout the SECN (Davey et al. 2007). Climate also affects the spread of invasive plant species and pests, which also threaten CAHA's forests (Davey et al. 2007). As a result of global climate change, temperatures are projected to increase across the southeast over the next century (Carter et al. 2014). Warming temperatures will likely allow invasive plants and forest pests to expand their ranges and potentially their impact, as well as altering the habitat suitability of certain areas for some tree species (Fisichelli et al. 2014). Temperature changes may also alter weather patterns, resulting in more storms with forest-damaging high winds (Carter et al. 2014). As the impacts of climate change and related stressors compound over time, forests will experience more widespread changes in tree species composition, with cascading effects on other plants and wildlife (Fisichelli et al. 2014). In an effort to estimate the magnitude of potential change that forests on eastern national park lands may experience, Fisichelli et al. (2014) assessed the percentage of tree species expected to show large decreases or large increases in habitat suitability under climate change scenarios. Across 121 national park properties in the eastern U.S., estimated potential forest change ranged from 22–77%. The estimated forest change for CAHA (i.e., percent of tree species expected to experience large increases or decreases in habitat suitability) was 55% (Fisichelli et al. 2014). This includes all forested areas at CAHA, not just maritime forest. Habitat suitability

projections for several of CAHA's maritime forest tree species are shown in Table 19. Projected climate changes may actually favor live oak, a key species in maritime forests.

Table 19. Potential change in habitat suitability by 2100 for select CAHA tree species based on two future climate scenarios (the "least change" scenario represents strong cuts in greenhouse gas emissions and modest climatic changes, the "major change" scenario represents continued increasing emissions and rapid warming). Reproduced from Fisichelli (2015).

Scientific name	Common name	Least change scenario	Major change scenario
Ilex opaca	American holly	large decrease	large decrease
Magnolia virginiana	sweetbay	small decrease	small decrease
Persea borbonia	redbay	no change	no change
Pinus taeda	loblolly pine	no change	no change
Quercus laurifolia	laurel oak	small increase	small increase
Quercus phellos	willow oak	small increase	small increase
Quercus virginiana	live oak	new potential habitat	new potential habitat

Data Needs/Gaps

While some data are available for each of the selected measures, it is largely limited to a few sampling locations or a small period of time. To better understand the current condition of this vegetation community, a comprehensive plant survey of Buxton Woods and additional sampling of stand structure/recruitment would be useful. Studies of Outer Banks maritime forests outside CAHA (e.g., Nags Head Woods, Fort Raleigh, other barrier islands) for comparison would also provide further insight. Additional surveys of wildlife species specifically within CAHA's maritime forests and other Outer Banks forests would also be needed to assess the diversity of the wildlife community.

On a deeper level, little is known about the ecological processes that shape the development of maritime forests on coastal dunes (Lopazanski et al. 1988). According to Lopazanski et al. (1988, p. 2), "The dispersal and colonization events that shape the progress of plant succession are poorly understood for barrier islands and are in need of study." A better understanding of these processes could help park staff better manage and maintain these communities moving forward. Management efforts could also benefit from the development of a target vegetation plan for CAHA as a whole (Ziegler, written communication, February 2020).

Overall Condition

Acreage of Maritime Forests

A *Significance Level* of 3 was assigned for the acreage measure. According to the McManamay et al. (2018) vegetation mapping effort, maritime forest covers 587 ha (~1,451 ac) within CAHA. While this is a small percentage of the park (6%), it is more forest cover than on many Outer Banks barrier islands (e.g., CALO) (McManamay 2017, McManamay et al. 2018). The loss and fragmentation of maritime forests due to human development has been a concern in the CAHA area for several

decades (Bourdeau and Oosting 1959, Lopazanski et al. 1988). However, since quantitative information regarding the extent of maritime forest within CAHA is limited, a *Condition Level* has not been assigned.

Plant Species Richness

This measure was assigned a *Significance Level* of 3. A total of 124 plant species have been documented in CAHA's maritime forests over time. For comparison, a 1950s survey of 17 North Carolina maritime forest stands identified 107 flowering plant species (Bourdeau and Oosting 1959). Also, a similar number of species were found in CAHA and CALO maritime forest plots during recent SECN monitoring (Byrne et al. 2012a, b). As a result, this measure is currently of low concern (*Condition Level* = 1).

Wildlife Species Diversity

A *Significance Level* of 3 was assigned for this measure as well. Nearly 100 wildlife species have been documented in CAHA's maritime forests (Bellis 1995, Webster 2010, Byrne et al. 2011b). However, much of the information regarding the park's forest wildlife is decades old. Due to a lack of more recent data, a *Condition Level* could not be assigned for this measure.

Stand Structure

The stand structure measure was assigned a *Significance Level* of 2. While some data are available regarding CAHA's maritime forest stand structure from historical sources (Settel 1937, Bratton and Davison 1985) and SECN monitoring (Byrne et al. 2012a), this is not enough information to assess condition, and a *Condition Level* has not been assigned.

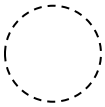
Recruitment

This measure was also assigned a *Significance Level* of 2. As with stand structure, the data regarding recruitment in CAHA's maritime forests from historical sources (Settel 1937, Bratton and Davison 1985) and SECN monitoring (Byrne et al. 2012a) is limited. Therefore, a *Condition Level* has not been assigned for this measure.

Weighted Condition Score

A Weighted Condition Score was not calculated for CAHA's maritime forests due to a lack of data for a majority of the selected measures and some uncertainty regarding reference conditions (Table 20). The current condition and trend for the park's maritime forests is considered unknown.

Table 20. Current condition and trend for the Maritime Forests of CAHA.

Measures	Significance Level	Condition Level	WCS = N/A
Acreage of Maritime Forests	3	n/a	–
Plant Species Richness	3	1	–
Wildlife Species Diversity	3	n/a	–
Stand Structure	2	n/a	–
Recruitment	2	n/a	–
Overall	–	–	

Sources of Expertise

Forbes Boyle, SECN Botanist

Tracy Ziegler, CAHA Chief of Resource Management and Science

Wetlands and Marshes

Description

Wetlands on and around barrier islands provide critical habitat and resources for plants and wildlife, as well as performing vital ecosystem functions (Zedler and Kercher 2005, NPS 2017d). Salt marshes, in particular, are highly productive ecosystems that provide food and shelter for fish, birds, and invertebrates, and play a key role in energy cycling (e.g., decomposition, primary productivity) (Cooper and Waits 1973, NPS 2017d). Freshwater wetlands, such as those in the Buxton Woods area, are critical areas for groundwater recharge of the aquifer that supplies fresh water for towns on Hatteras Island (Lopazanski et al. 1988). This assessment will include both palustrine (non-flowing freshwater) and estuarine (saltwater) wetland communities. Estuarine waters are coastal, semi-enclosed areas that have a connection to the ocean but also receive freshwater inputs (Gregory and Smith 2011). This mixing of salt and fresh water often contributes to high biological productivity (Parman et al. 2012).

The wetlands of CAHA are diverse and include freshwater wetland swales, open ponds, tidal salt marsh, and high salt marsh. Vegetation composition and structure varies with tidal influence, salinity, exposure to the elements, and disturbance history (Burk 1962, Otte 1981, McManamay et al. 2018). Some park wetlands have been modified by road construction (e.g., borrow pit excavation), ditching or flooding for mosquito control, and historic wildlife habitat improvements (e.g., impoundments/dikes) (Firth 1987). The major wetland vegetation types found at CAHA and the common plant species in each type are presented in Table 21.

Table 21. Wetland vegetation community types found at CAHA and their common plant species, as described by McManamay et al. (2018).

Wetland system	Vegetation mapping unit	Common plant species
Palustrine	Maritime Red Bay Shrub Swamp	swamp bay (*Persea palustris*), live oak, yaupon, wax myrtle (*Morella cerifera*), southern redcedar (*Juniperus virginiana* var. *silicicola*), greenbriers (*Smilax* sp.)
	Atlantic Coast Stiff Dogwood Dune Swale	stiff dogwood (*Cornus foemina*), swamp bay, climbing hempvine (*Mikania scandens*), smallspike false nettle (*Boehmeria cylindrica*)
	Coastal Loblolly Pine Wetland Forest	loblolly pine, swamp bay, wax myrtle, yaupon
	Atlantic Coast Interdune Swale	wax myrtle, saltmeadow cordgrass (*Spartina patens*), turkey tangle fogfruit (*Phyla nodiflora*)
	Chestnut Fimbry [a] – Common Threesquare Seasonally Flooded Herbaceous Vegetation	fimbry (*Fimbristylis* sp.), sturdy bulrush (*Bolboschoenus robustus*), saltgrass (*Distichlis spicata*), saltmeadow cordgrass

[a] Chestnut fimbry is a formerly accepted name for marsh fimbry (*Fimbristylis spadicea*).

[b] Non-native species.

Table 21 (continued). Wetland vegetation community types found at CAHA and their common plant species, as described by McManamay et al. (2018).

Wetland system	Vegetation mapping unit	Common plant species
Palustrine (continued)	Southern Cattail – Giant Foxtail Herbaceous Vegetation	southern cattail (*Typha domingensis*), marsh bristlegrass (*Setaria parviflora*), saltmeadow cordgrass
Estuarine	Groundsel-tree – Maritime Marsh-elder Tidal Shrubland Alliance	Jesuit's bark (*Iva frutescens*), eastern baccharis (*Baccharis halimifolia*), wax myrtle
	Seaside Oxeye Tidal Shrub Flat	bushy seaside tansy (*Borrichia frutescens*), saltwater false willow (*Baccharis angustifolia*), Jesuit's bark, needlegrass rush (*Juncus roemerianus*)
	Sawgrass Tidal Herbaceous Vegetation	Jamaica swamp sawgrass (*Cladium jamaicense*), saltmeadow cordgrass, largeleaf pennywort (*Hydrocotyle bonariensis*)
	Needlerush High Marsh	needlegrass rush, climbing hempvine
	Reed Tidal Marsh	common reed (*Phragmites australis*) [b], needlegrass rush, climbing hempvine
	Southern Atlantic Coast Salt Marsh	smooth cordgrass (*Spartina alterniflora*), needlegrass rush
	Mid-Atlantic High Salt Marsh	saltgrass, smooth cordgrass, needlegrass rush

[a] Chestnut fimbry is a formerly accepted name for marsh fimbry (*Fimbristylis spadicea*).

[b] Non-native species.

Notable wetlands at CAHA include the wetland swales and swamp forests of Buxton Woods (Bratton and Turner 1986, Mallin et al. 2006). According to Lopazanski et al. (1988), the wetlands of Buxton Woods are unique community variants that occur nowhere else in North Carolina. The swale wetlands, known locally as “sedges”, vary from 2–50 m (6.6–164 ft) in width and 5–1,000 m (16.4–3,281 ft) in length, with seasonal water depths up to 1 m (3.3 ft) (Cole and Bratton 1994). At about 240 ha (593 ac), Jennette Sedge is the largest of the sedges, stretching approximately 3.5 km (2.2 mi) through the middle of Buxton Woods (Figure 26) (Rheinhardt and Faser 2001, Mallin et al. 2006).

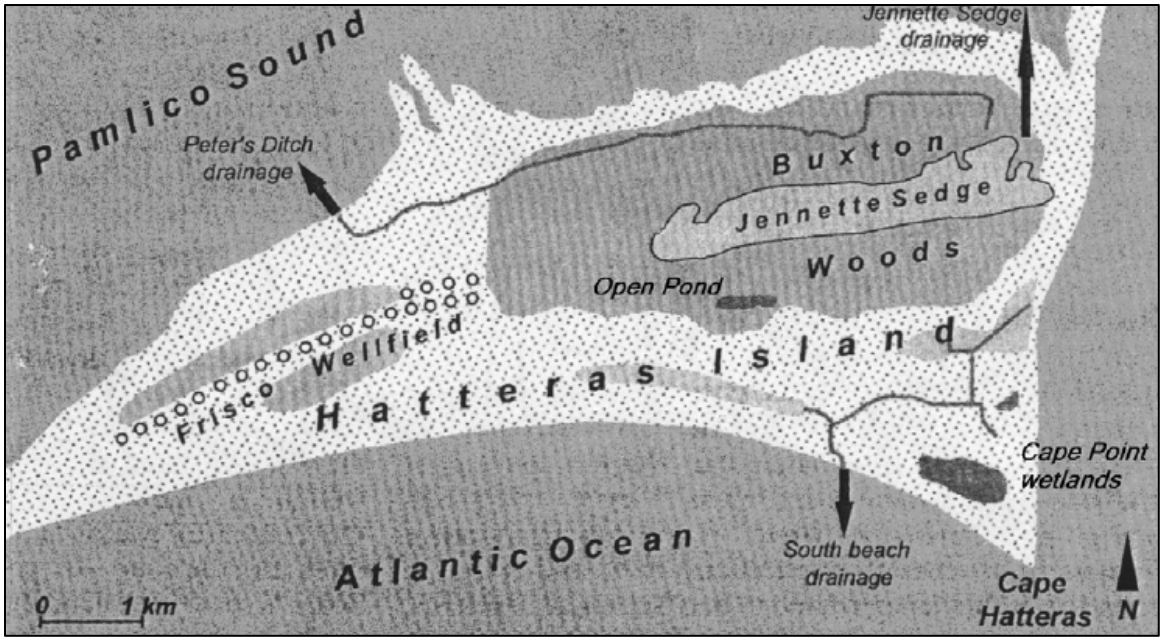


Figure 26. Map of Hatteras Island showing the location of the Cape Point wetlands and Jennette Sedge (Anderson 1999).



Maritime wetland on south Ocracoke Island (Mallin et al. 2006).

Measures

- Acreage of palustrine wetlands
- Acreage of estuarine wetlands
- Plant species richness of palustrine wetlands
- Plant species richness of estuarine wetlands
- Sediment elevation table of saltwater marshes

- Linear distance of drainage features
- Water quality

Reference Condition/Values

As with the maritime forests component, the ideal reference condition for the wetlands and marshes component would be their condition on the islands prior to European settlement. However, since little is known about the vegetation communities at this time and substantial human modification has occurred over time, this is not a practical reference point. A comparison to wetlands and marshes at nearby CALO can offer some insight, although environmental conditions and land use history are somewhat different than at CAHA (e.g., human development and stabilized dunes/beaches at CAHA vs. less disturbed, natural systems on CALO). The wetlands of Kitty Hawk Woods on Bodie Island north of the park are potentially comparable to the Buxton Woods wetlands, but little published scientific information is available regarding the vegetation of Kitty Hawk Woods. The data presented in this NRCA may serve as a reference condition for future assessments.

Data and Methods

Several of the data sources utilized for previous vegetation components were also used for this component, including Kearney (1900), Otte (1981), Davison et al. (1987), Stalter and Lamont (1997), Byrne et al. (2012a), CVS (Peet et al. 2013), and McManamay et al. (2018). These reports provide information on wetland community extent and vegetation composition. Nine of Byrne et al.'s (2012a) sampling locations fell within wetlands; six were palustrine (CAHA01, 15, 17, 20, 26, 27, and Alt3) and three were estuarine (CAHA16, 29, and 30) (Note: GSS analysts used the presence of the halophytic plants smooth cordgrass [*Spartina alterniflora*] and chickenclaws [*Sarcocornia perennis*] to determine which SECN sampling locations were estuarine). Nine CVS plots were within CAHA palustrine wetlands and 10 plots were within estuarine wetlands (Peet et al. 2013). Plots were distributed across all three islands and were visited in May 1988 (three sites), June 2003 (12 sites), or August 2009 (four sites).

Cooper and Waits (1973) studied the vegetation in a salt marsh on southern Bodie Island, just north of the lighthouse. Vegetation and environmental data were collected from a random sampling of 0.1 m^2 plots. Sampling was conducted in September 1963 (130 plots) and February 1964 (562 plots) (Cooper 1964).

Data on the location and extent of wetlands within CAHA was also obtained from the National Wetland Inventory (NWI), a database maintained by the U.S. Fish and Wildlife Service (USFWS). The data for CAHA are based on 2009–2010 aerial imagery and can be downloaded through USFWS "Wetlands Mapper" website at http://www.fws.gov/wetlands/. Since this component focuses especially on palustrine and estuarine wetlands, any marine, lacustrine, and riverine wetlands within park boundaries are not included. It should be noted that NWI mapping is largely based on digital imagery interpretation at a broad scale and on-the-ground field verification is often limited. As a result, NWI data may not be as accurate or "fine-tuned" as more focused, on-the-ground mapping efforts.

Because the acreage measures for this component are split into estuarine and palustrine wetlands, some manipulation of the McManamay et al. (2018) vegetation mapping data was required to obtain a more accurate estimate of wetland extent. The authors grouped some vegetation communities together for the mapping effort to improve classification accuracy. In most cases, those grouped wetland communities were either all palustrine or all estuarine, but there was one exception. In the Mid-Atlantic High Salt Marsh/ Chestnut Fimbry – Common Threesquare Seasonally Flooded Herbaceous Vegetation/ Southern Cattail – Giant Foxtail Herbaceous Vegetation map class, the first community is estuarine and the last two are palustrine. Based on vegetation community descriptions in McManamay et al. (2018, Appendix B), the Mid-Atlantic High Salt Marsh is more common at CAHA than the two palustrine community types. To estimate how much of this mixed map class consisted of palustrine communities, a GSS analyst used the Esri "intersect" tool to identify the overlap between the vegetation map class in question and the NWI wetlands classified as palustrine, non-wooded. This acreage was included in the palustrine wetlands measure of the NRCA while the remaining acreage from the mixed map class was included in the estuarine wetlands measure.

No published data could be found on the current linear distance of drainage features within park boundaries. In an effort to obtain a rough estimate of the extent of drainage features, an SMUMN GSS analyst used aerial imagery in ArcGIS to digitize visual linear drainage features within park boundaries. Imagery was scanned at a scale of 1:6,000; artificial drainage features could be recognized by their unnatural straightness and the presence of shrub-covered spoil piles nearby (Figure 27). Published reports describing the locations of drainage features (e.g., Mallin et al. 2006) assisted in locating some ditches. These results should be considered a rough minimum estimate, as some artificial drainage features may not be visible in aerial imagery.

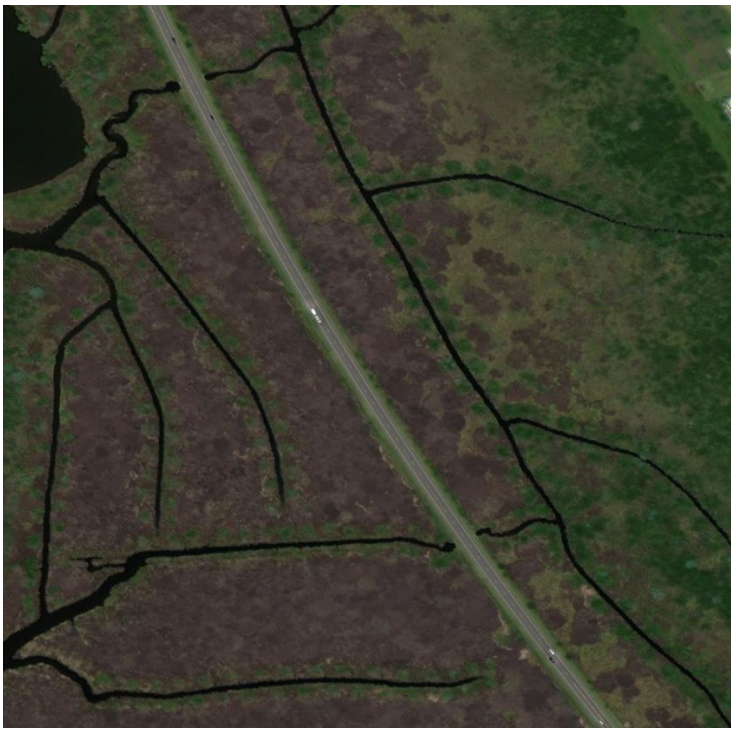


Figure 27. The straightness of the drainages (black lines) bordered with shrub-covered spoil piles (greener dots) are indications of artificial drainage features on south Bodie Island (ESRI world imagery basemap).

Current Condition and Trend

Acreage of Palustrine Wetlands

According to the CAHA vegetation mapping report (McManamay et al. 2018), palustrine wetland vegetation covers 2,312 ha (~5,712 ac) of the park, which accounts for 32.6% of the park's vegetated area (Table 22). The majority of this (86%) was classified as Atlantic Coast Interdune Swale. The smallest palustrine wetland vegetation community was Coastal Loblolly Pine Wetland Forest at just 1.7 ha (4.2 ac) (McManamay et al. 2018). The extent of palustrine wetland vegetation communities at CAHA is shown in Figure 28-Figure 30. At CALO, for comparison, a smaller percentage of park vegetated area (<20%) is comprised of palustrine wetlands (McManamay 2017).

Table 22. Extent of palustrine wetland vegetation types at CAHA based on 2009 aerial imagery, as reported in McManamay et al. (2018).

Vegetation community	Area in ha (ac)
Maritime Red Bay Shrub Swamp / Atlantic Coast Stiff Dogwood Dune Swale	133.6 (330.1)
Coastal Loblolly Pine Wetland Forest	1.7 (4.2)
Atlantic Coast Interdune Swale	1,991.7 (4,921.6)
Chestnut Fimbry – Common Threesquare Seasonally Flooded Herbaceous Vegetation/ Southern Cattail – Giant Foxtail Herbaceous Vegetation (GIS estimate)	184.7 (456.3)
Total	**2,311.7 (5,712.3)**

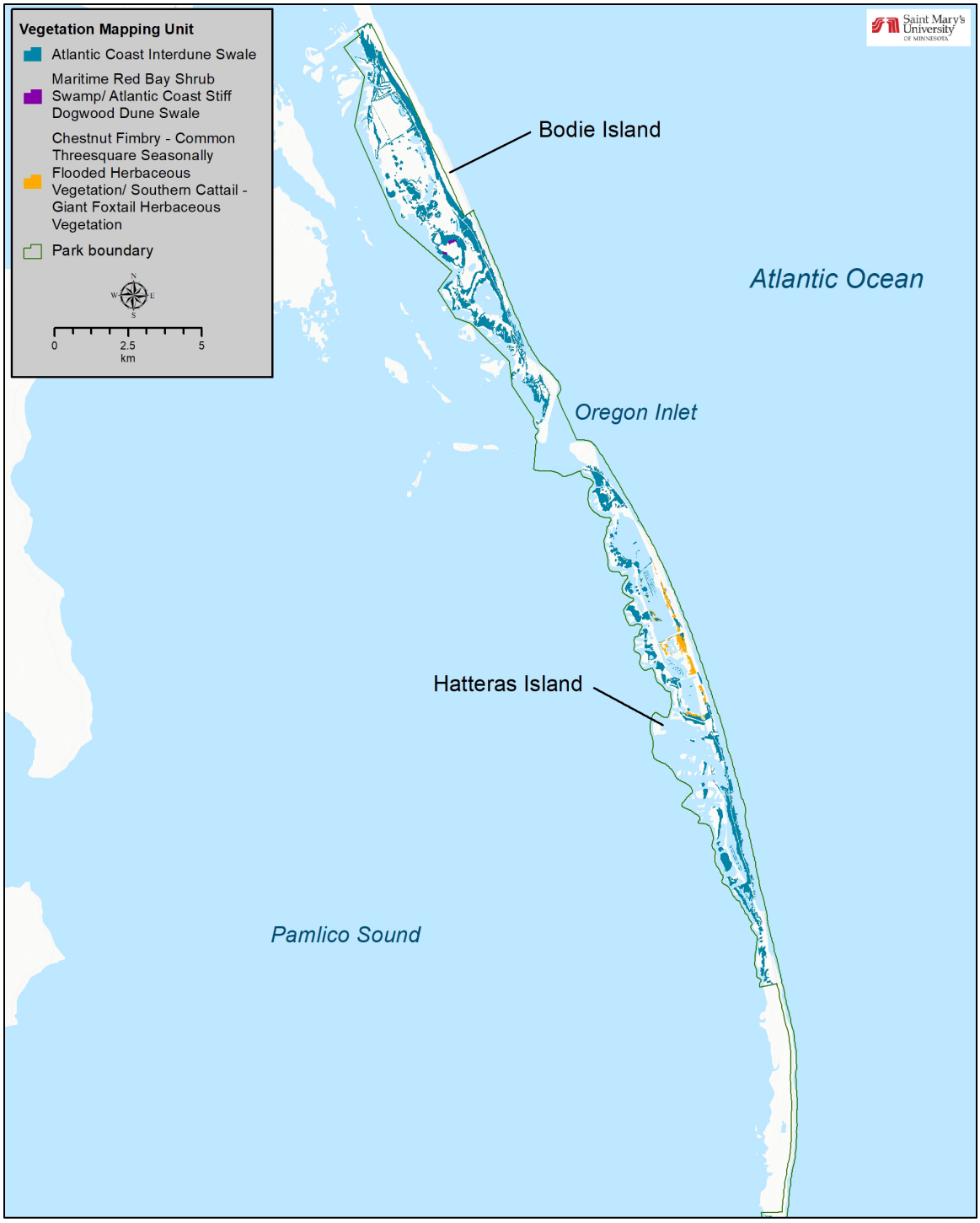


Figure 28. The extent of palustrine wetland vegetation in the northern portion of CAHA as mapped by McManamay et al. (2018).

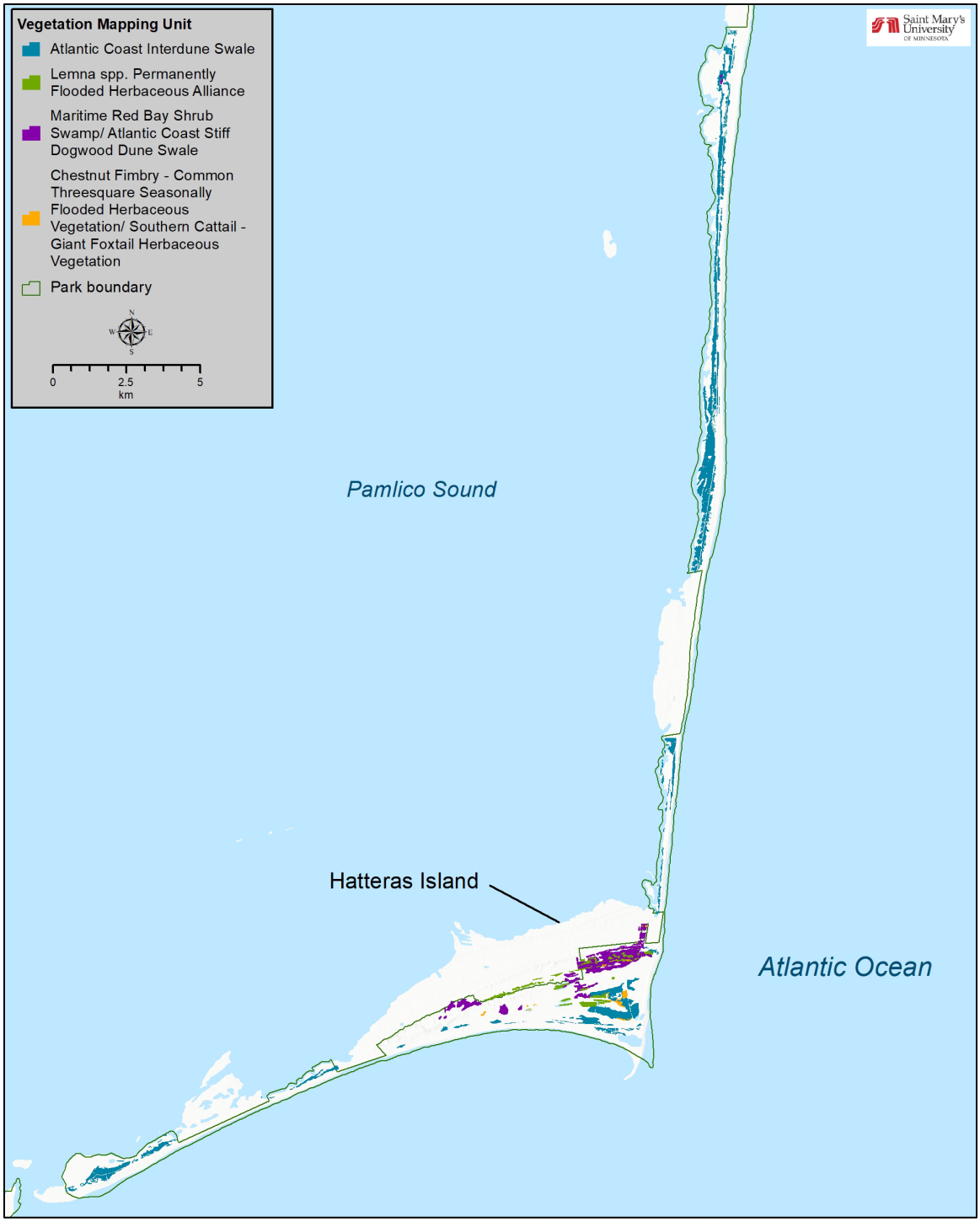


Figure 29. The extent of palustrine wetland vegetation in the central portion of CAHA, as mapped by McManamay et al. (2018).

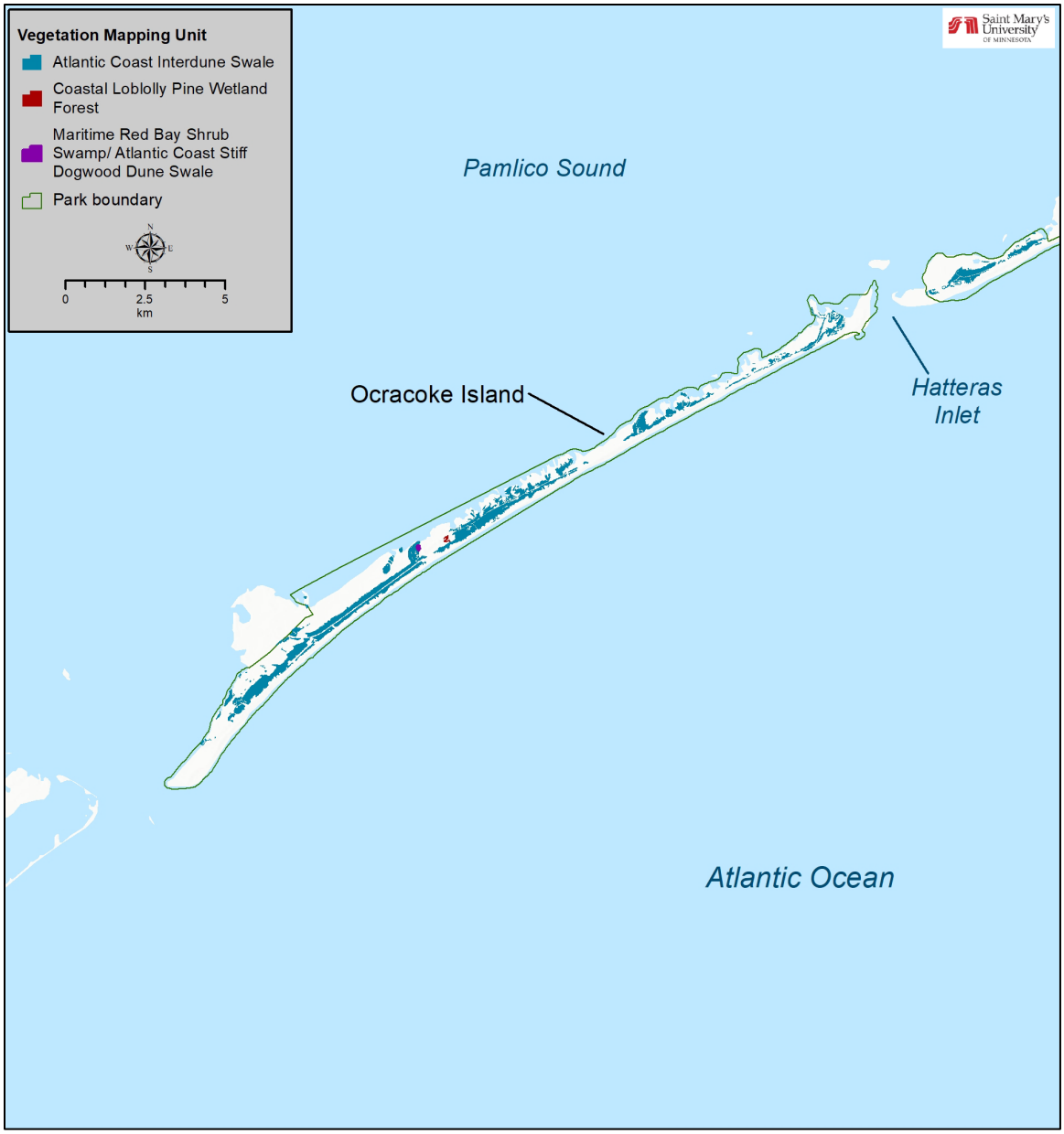


Figure 30. The extent of palustrine wetland vegetation on Ocracoke Island in the southernmost portion of CAHA, as mapped by McManamay et al. (2018).

NWI mapping identified nearly 786 ha (1,941 ac) of palustrine wetlands at CAHA (Figure 31-Figure 32). The NWI classifies wetlands by vegetation type (e.g., emergent, scrub-shrub, forested) and by water regime (e.g., permanently flooded, seasonally flooded, saturated). According to NWI wetland mapping (USFWS 2018), the most extensive palustrine wetlands at CAHA are scrub-shrub (PSS) (Table 23). These scrub-shrub wetlands covered 267 ha (~659 ac) or 34% of the palustrine wetlands mapped. A mix of scrub-shrub and emergent (herbaceous) vegetation accounted for an additional 119 ha (293 ac). Forested wetlands totaled approximately 160 ha (~397 ac) and emergent wetlands covered 156 ha (385 ac) (USFWS 2018).

Table 23. Extent of palustrine wetlands at CAHA by vegetation type, as mapped by the NWI (USFWS 2018). P = palustrine, EM = emergent (herbaceous) vegetation, SS = scrub-shrub, FO = forest, SB = streambed, US = unconsolidated (bare) shore, UB = unconsolidated bottom (open water).

Wetland community type	# of wetlands	Total area in ha (ac)	% of palustrine area
PEM	82	155.8 (385.0)	19.8
PEM/SS	23	118.5 (292.7)	15.1
PSS	116	266.8 (659.4)	34.0
PSS/EM	20	63.1 (155.9)	8.0
PFO/SS	3	10.6 (26.3)	1.4
PFO	66	160.5 (396.7)	20.4
PUS	9	2.9 (7.2)	0.4
PUB	15	7.4 (18.2)	0.9
Total	**334**	**785.7 (1941.4)**	**–**

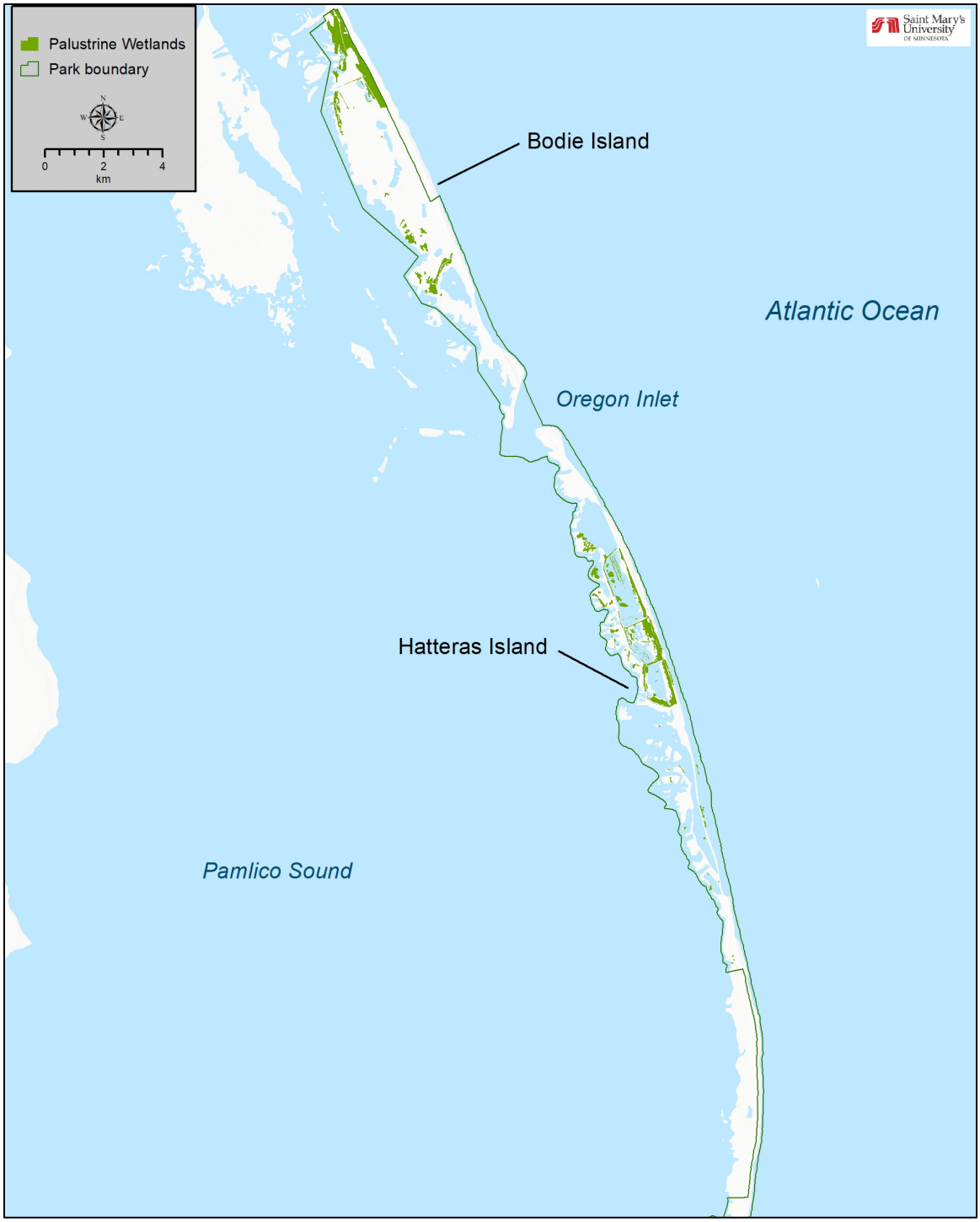


Figure 31. The extent of palustrine wetlands in northern CAHA, as mapped by the NWI (USFWS 2018).



Figure 32. The extent of palustrine wetlands in central CAHA, as mapped by the NWI (USFWS 2018). No palustrine wetlands were mapped on Ocracoke Island, in the southernmost portion of CAHA; therefore, a map is not included.

When analyzed by water regime, seasonally flooded (C) wetlands are most extensive, with 372 ha (919 ac) (Table 24). In seasonally flooded wetlands, "surface water is present for extended periods especially early in the growing season, but is absent by the end of the season in most years," (Cowardin et al. 1979, p. 39). Seasonally flooded – tidal (R) and semi permanently flooded (F) wetlands were also common, covering 255 ha (629 ac) and 107 ha (265 ac), respectively. In seasonally flooded – tidal wetlands (R), the presence of surface water is similar to C wetlands, but the water is considered tidal (i.e., largely influenced by oceanic tides). A table with full NWI codes (including modifiers) and acreages for all wetlands at CAHA can be found in Appendix F.

Table 24. Extent of palustrine wetlands by water regime, as mapped by the NWI (USFWS 2018). A = temporary flooded, C = seasonally flooded, F = semi permanently flooded, H = permanently flooded, R = seasonally flooded – tidal, S = temporary flooded – tidal, V = permanently flooded – tidal.

Water regime	# of wetlands	Total area in ha (ac)	% of wetland area
A	49	24.7 (61.1)	3.1
C	142	371.9 (918.9)	47.3
F	36	107.0 (264.5)	13.6
H	13	7.3 (18.0)	0.9
R	109	254.5 (628.8)	32.4
S	7	20.2 (49.8)	2.6
V	2	0.1 (0.2)	<0.1



A CAHA palustrine wetland with cattail (*Typha* sp.) (NPS photo from McManamay et al. 2018).

Acreage of Estuarine Wetlands

Estuarine wetlands cover an estimated 2,545 ha (~6,288 ac) or 35.8% of park vegetated area, according to McManamay et al. (2018) (Table 25). This is slightly more area than the extent covered by palustrine wetland communities. The most common estuarine vegetation communities were Needlerush High Marsh (49%) and Mid-Atlantic High Salt Marsh (36%). The extent of estuarine wetland vegetation communities at CAHA is shown in Figure 33-Figure 35.

Table 25. Extent of estuarine wetland vegetation types at CAHA based on 2009 aerial imagery, as reported in McManamay et al. (2018).

Vegetation community	Area in ha (ac)
Groundsel-tree – Maritime Marsh-elder Tidal Shrubland Alliance / Seaside Oxeye Tidal Shrub Flat	94.2 (232.8)
Sawgrass Tidal Herbaceous Vegetation	12.8 (31.6)
Needlerush High Marsh	1,237.1 (3,056.9)
Reed Tidal Marsh	41.0 (101.3)
Southern Atlantic Coast Saltmarsh	238.2 (588.6)
Mid-Atlantic High Salt Marsh	921.3 (2,276.6)
Total	**2,544.6 (6,287.8)**



Figure 33. The extent of estuarine wetland vegetation in the northern portion of CAHA as mapped by McManamay et al. (2018).



Figure 34. The extent of estuarine wetland vegetation in the central portion of CAHA as mapped by McManamay et al. (2018).

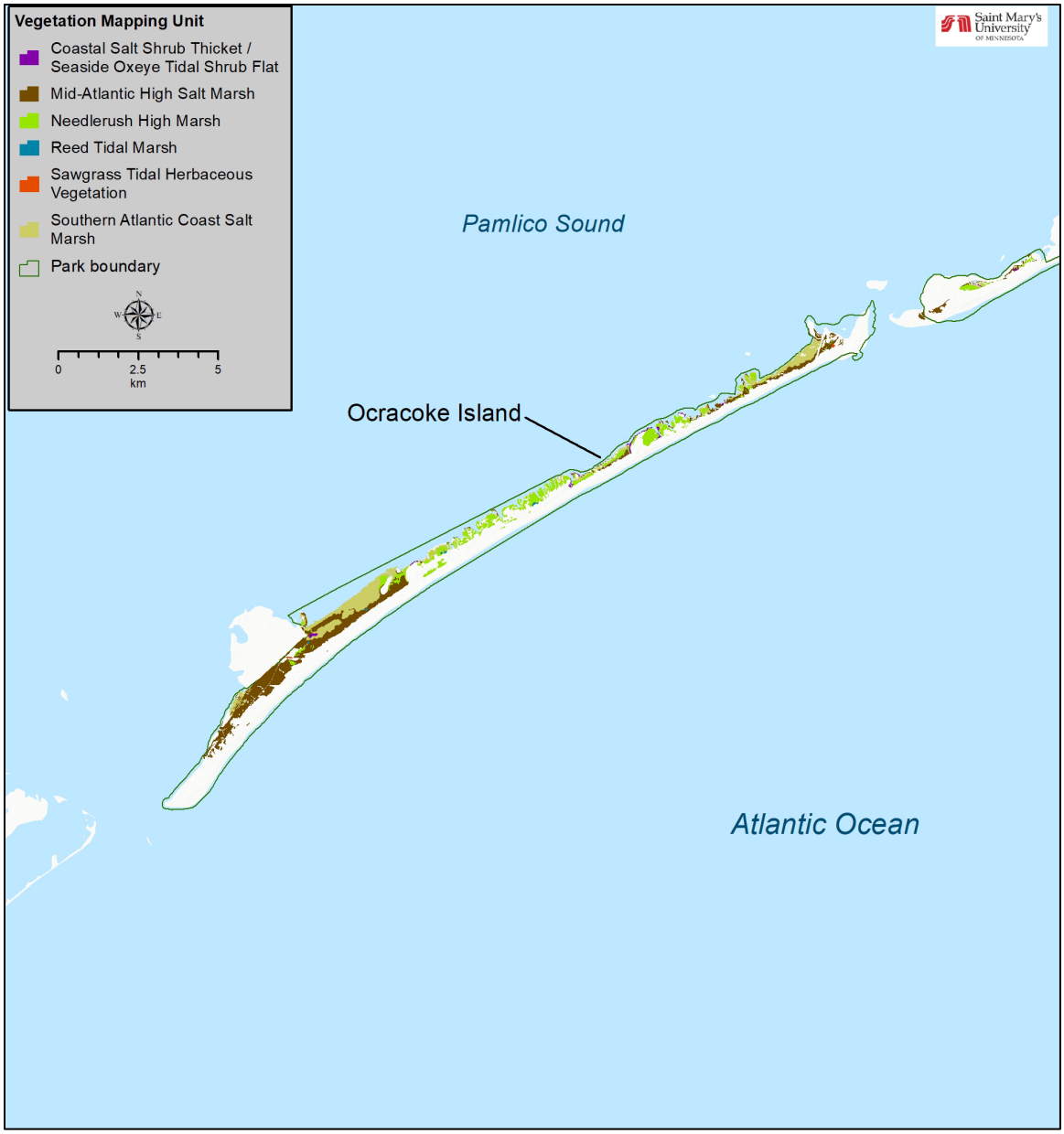


Figure 35. The extent of estuarine wetland vegetation on Ocracoke Island in the southernmost portion of CAHA, as mapped by McManamay et al. (2018).

NWI mapping identified 628,242 ha (~1.5 million ac) of estuarine wetlands within CAHA boundaries (Figure 36). This is nearly 10 times the acreage of palustrine wetlands mapped by the NWI. According to NWI data (USFWS 2018), 99% of estuarine wetlands at CAHA are subtidal (E1, continuously submerged) and only 1% are intertidal (E2, alternately flooded and exposed). Nearly all of the subtidal wetlands are unvegetated (unconsolidated/UB) (Table 26). The most extensive intertidal estuarine wetlands at CAHA consist of emergent vegetation (EM), with 2,744 ha (6,781 ac). A smaller amount of scrub-shrub (SS) and aquatic bed (AB, plants that grow principally on or below the water's surface) estuarine wetlands were documented.

Table 26. Extent of estuarine wetlands at CAHA by vegetation type, as mapped by the NWI (USFWS 2018). E1 = subtidal estuarine, E2 = intertidal estuarine, EM = emergent (herbaceous) vegetation, SS = scrub-shrub, AB = aquatic bed (plants that grow on or below the water's surface), US = unconsolidated (bare) shore, UB = unconsolidated bottom (open water).

Wetland community type	# of wetlands	Total area in ha (ac)	% of wetland area
E2EM	578	2,744.1 (6,780.9)	0.4
E2EM/SS	101	286.9 (709.0)	<0.1
E2EM/US	4	18.2 (44.9)	<0.1
E2SS/EM	68	332.4 (821.3)	<0.1
E2SS	363	895.5 (2,212.8)	0.1
E2SS/US	18	22.8 (56.4)	<0.1
E2FO	5	41.1 (101.6)	<0.1
E2US	189	1,006.3 (2,486.6)	0.1
E1AB	8	244.1 (603.1)	<0.1
E2AB	15	229.9 (568.2)	<0.1
E1UB	226	622,420.4 (1,538,034.2)	99
Total	**1,575**	**628,241.7** (**1,552,419.0**)	**–**

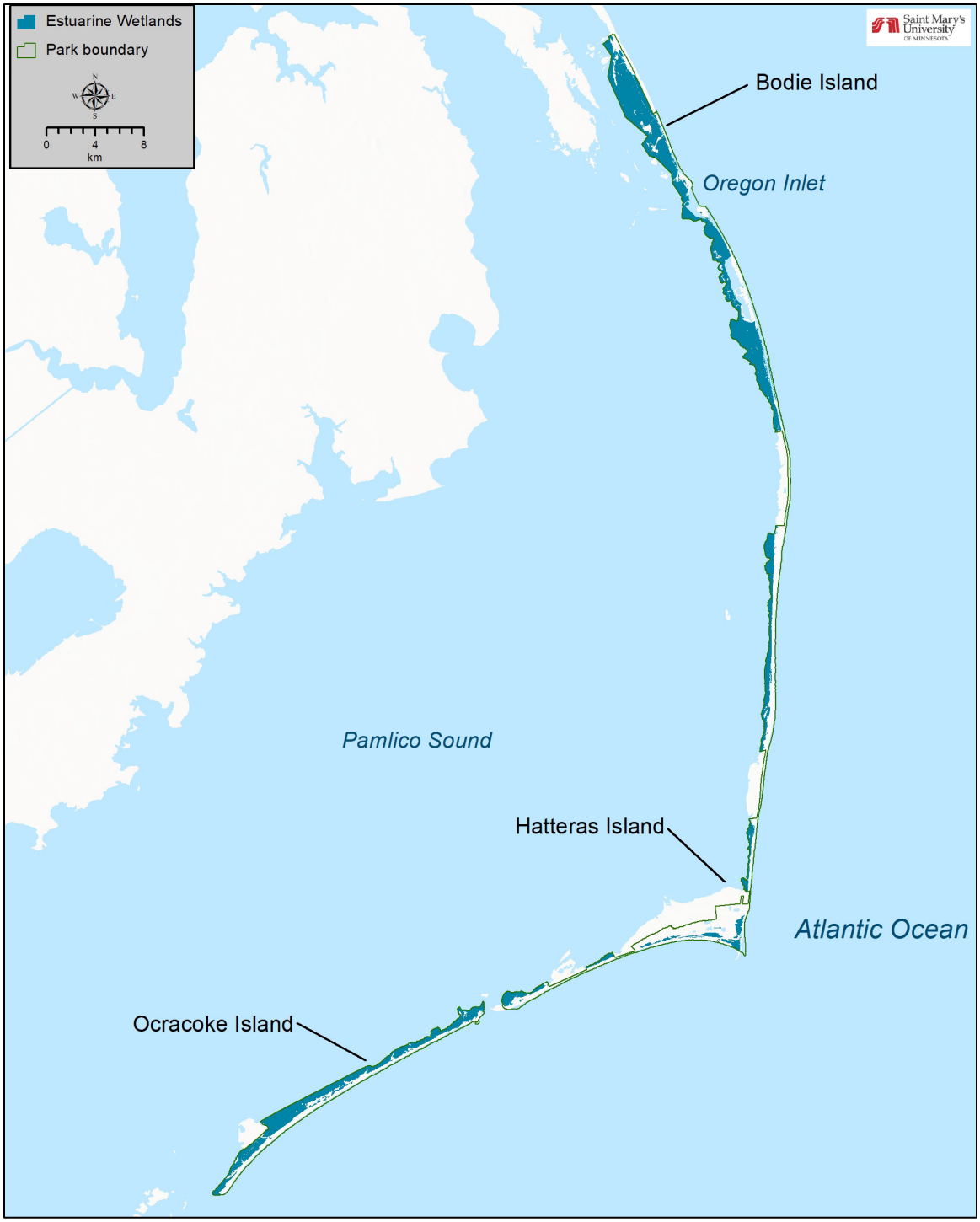
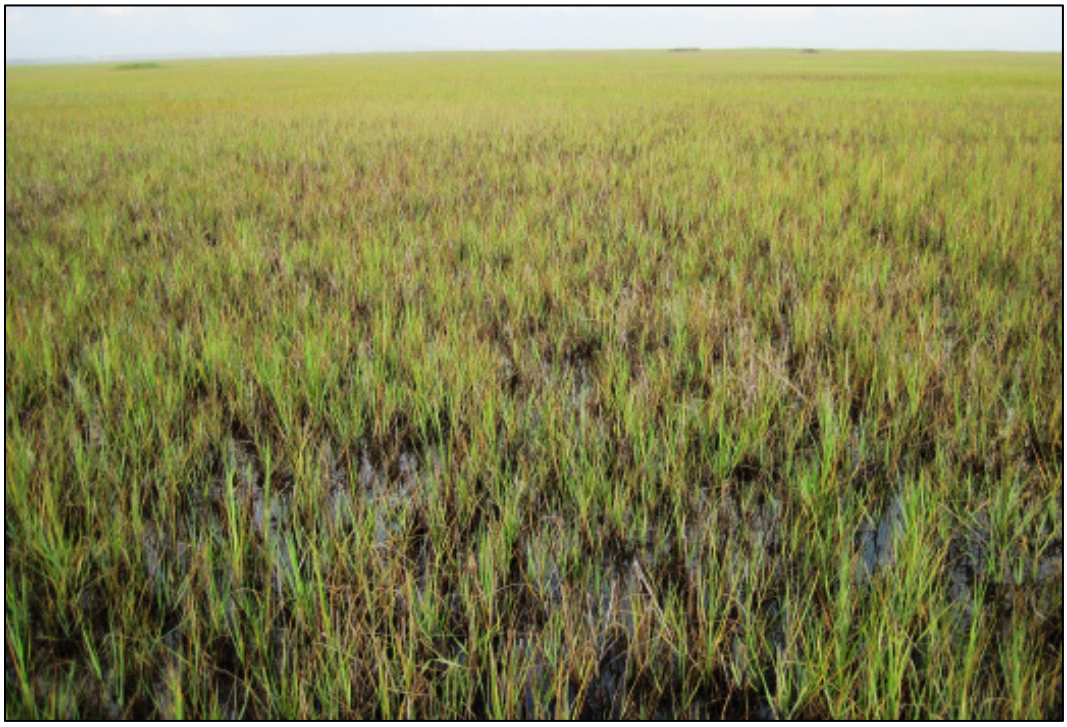


Figure 36. The extent of estuarine wetlands in CAHA, as mapped by the NWI (USFWS 2018).

When analyzed by water regime, over 99% of estuarine wetlands were in the subtidal (L) water regime (Table 27). Other water regimes present included irregularly exposed (M), regularly flooded (N), and irregularly flooded (P) (USFWS 2018).

Table 27. Extent of estuarine wetlands by water regime, as mapped by the NWI (USFWS 2018). L = subtidal, M = irregularly exposed, N = regularly flooded, P = irregularly flooded.

Water regime	# of wetlands	Total area (ha/ac)	% of wetland area
L	234	622,664.4 (1,538,637.3)	99.1
M	88	742.0 (1,833.5)	0.1
N	281	1,262.6 (3,119.9)	0.2
P	972	3,572.6 (8,828.1)	0.6



A southern Atlantic coast salt marsh at CAHA dominated by smooth cordgrass (NPS photo from McManamay et al. 2018).

Plant Species Richness of Palustrine Wetlands

Over time, various surveys of CAHA have documented 173 different plant species across the park's palustrine wetlands (Appendix G). Eight of these species (4.6%) are non-native. Due to differences in methodology (e.g., opportunistic observations vs. scientific sampling) and survey locations (e.g., one island vs. park-wide), in most cases the various studies over time cannot be accurately compared to determine if there are any trends in species richness.

Previous vegetation components have compared species richness results from SECN monitoring of CAHA and CALO (Chapter 4.1, 4.2). It is difficult to make such a comparison for wetlands, because only three CALO sampling locations were located in wetlands (McManamay 2017) and it is unclear whether they were within communities comparable to those sampled at CAHA. However, 34 of the

49 plant species documented at CALO wetland sampling locations were also present in CAHA wetland sampling locations (McManamay 2017, McManamay et al. 2018).

Plant Species Richness of Estuarine Wetlands

Surveys of CAHA's estuarine wetlands over time have documented 120 different plant species, only four of which (3.3%) are considered non-native (Appendix H). Fifty of the species documented in estuarine wetlands were also found in palustrine wetlands. Despite covering much more park area than palustrine wetlands (as mapped by McManamay et al. 2018), the estuarine wetlands supported fewer plant species. However, this is not surprising given the harsher conditions of an estuarine setting (e.g., salinity, tidal fluctuations). Comparisons could not be made between SECN monitoring results for CAHA and CALO because none of the wetland locations sampled at CALO appear to be estuarine (McManamay 2017). However, Burk (1962) included a list of 35 plant species "which occur with high fidelity" in Outer Banks tidal marshes that offers a reference for comparison. Of these 35 species, 29 have been found in CAHA estuarine wetlands; four of the six species not found at CAHA are not considered wetland plants and three are naturalized weeds (NRCS 2018).

Sediment Elevation Table of Saltwater Marshes

Sediment elevation is a key factor in determining the presence and composition of vegetation in estuarine environments (Cooper and Waits 1973). Sea level rise and subsidence reduce saltmarsh elevation while sediment accretion increases elevation (NPS 2017e). If accretion rates do not match or exceed sea level rise, a marsh becomes submerged and may eventually transition from a vegetated wetland to a mud flat or shallow open water (Otte 1981, NPS 2017e). Cooper and Waits (1973) found that sediment elevation influenced vegetation composition, with a needlegrass rush-dominated community at lower elevations and saltmeadow cordgrass dominating at slightly higher elevations.

The SECN has initiated a saltwater marsh elevation monitoring program that includes one sampling location with three replicate data-collection stations on south Bodie Island in CAHA (DeVivo et al. 2015). The program utilizes a rod-surface elevation table (RSET) technique (Cahoon et al. 2002), which offers a non-destructive process to precisely measure sediment elevation over a long period of time relative to a fixed subsurface (Figure 37) (Asper and Curtis 2013). With repeated measurements over time, a rate of change can be calculated to detect any shifts or trends of concern. The sampling location at CAHA was installed in 2014 and sampling occurred in 2015, 2016, and 2018 (Lisa Cowart Baron, SECN Coastal Ecologist, email communication, 6 December 2018). However, these data have not yet been fully reviewed and analyzed and are therefore not ready for publication.



Figure 37. An NPS ecologist using a rod-surface elevation table to measure saltmarsh elevation at CAHA (NPS-SECN photo).

Linear Distance of Drainage Features

Drainage ditches can substantially alter wetland ecosystems (see discussion in "Threats and Stressor Factors" below). Ditching has occurred in many areas of CAHA, but particularly on southern Bodie Island and on Hatteras Island in the Buxton Woods/Cape Point vicinity (Rheinhardt and Faser 2001, Mallin et al. 2006). As mentioned previously, no published data could be found on the current linear distance of drainage features within park boundaries.

Aerial photography mapping/digitization by an SMUMN GSS analysts in ArcGIS yielded a rough estimate of 46.3 km (28.8 mi) of linear drainage features within CAHA boundaries (Figure 38). The majority of these features (29.7 km [18.5 mi]) are on Bodie Island near Nag's Head (Table 28). There may be additional features on the islands but outside CAHA boundaries that are close enough to influence the hydrology of park wetlands.

Table 28. Estimated linear distance of drainage features within CAHA boundaries by island.

Metric	Bodie Island	Hatteras Island	Ocracoke Island	CAHA total
Linear Distance	29.7 (18.5)	10.2 (6.3)	6.4 (4.0)	46.3 (28.8)

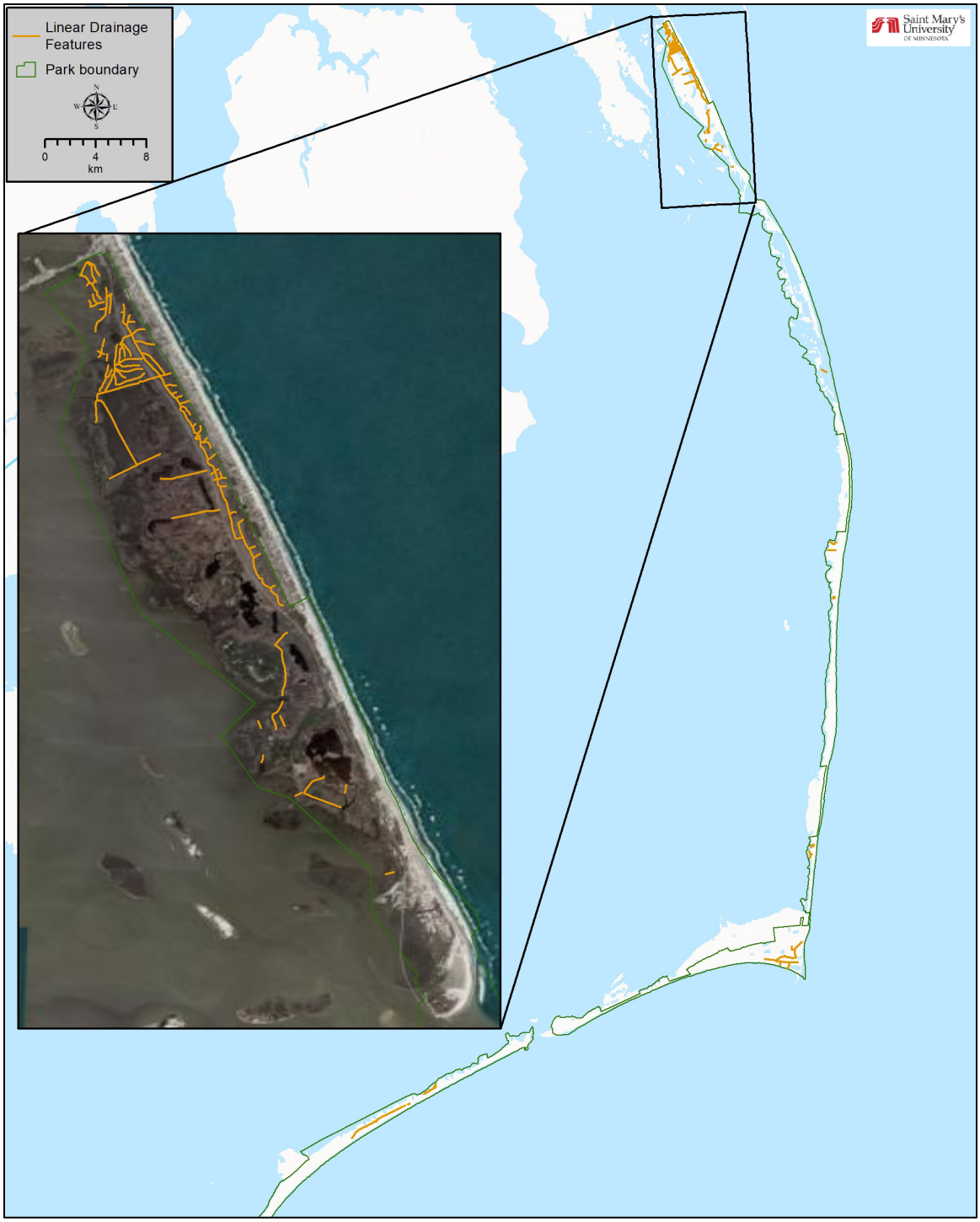


Figure 38. Linear drainage features within CAHA boundaries that are visible on aerial imagery, as mapped in ArcGIS by an SMUMN GSS analyst. These results should be considered a rough minimum estimate of linear distance.

Water Quality

Water quality influences the vegetation and aquatic organisms present within a wetland (UNEP 2008). Degraded water quality could reduce the biodiversity and productivity of wetlands, which can impact their ability to perform ecosystem services. Important parameters include temperature, pH, nutrients, salinity, clarity, and contaminants. Available information on the water quality of CAHA's wetlands is discussed in detail in Chapter 4.7 of this assessment.

Threats and Stressor Factors

Threats and stressors to CAHA's wetlands and marshes include shrub encroachment, invasive species, sedimentation, climate change (e.g., sea level rise, changes in storm frequency/intensity), and development (including ditching and groundwater withdrawals). Little published information could be found on sedimentation in CAHA wetlands and its impacts. The USFWS (2006) listed excessive sedimentation due to hydrologic alterations and deforestation as a factor contributing to aquatic system degradation. When excess sediment enters water bodies and wetlands, the depth and surface area of inundation is reduced, often triggering changes in vegetation (USFWS 2006).

For the past 50–60 years, park managers and researchers have noted shrub encroachment into herbaceous and open water marshes (Stroh 1982, Rheinhardt and Faser 2001). In a study of historic aerial photos of southern Bodie Island, Stroh (1982) found that shrub vegetative cover increased substantially in sound-side marshes between 1932 and 1982. Similar changes have been observed in the Jennette Sedge area of Buxton Woods, with 45% of emergent marsh and open water being replaced by shrub swamp between 1955 and 1990 (Rheinhardt and Faser 2001). This encroachment has reduced waterfowl habitat and obscured views into and across the wetlands (NPS 1984, Firth 1987). The increase in shrub cover is believed to be a result of human modification of the natural landscape and hydrological processes, such as drainage/ditching, groundwater withdrawals, and a reduction in overwash/flooding events due to dune construction (Turner 1984, Rheinhardt and Faser 2001).

Drainage ditches have been constructed on the islands to control flooding and mosquito populations (Anderson 1999, Mallin et al. 2006). Many ditches in the Buxton Woods area were constructed during the 1930s, prior to park establishment (Rheinhardt and Faser 2001). Peters Ditch runs from northern Buxton Woods west into Pamlico Sound at Frisco, and additional ditches run north from Jennette Sedge to Pamlico Sound (see Figure 26) (Mallin et al. 2006). A study by the USGS found that the Jennette Sedge ditch drained an estimated 0.01–0.1 cubic meters per second (cms) (0.4–4.5 cubic feet per second) of water from September to April in 1994 and 1995 (Rheinhardt and Faser 2001). Simulations based on this rate of drainage predicted that the water table in Jennette Sedge was about 30 cm (11.8 in) lower during wet periods than if there was no drainage (Anderson 1999, Rheinhardt and Faser 2001). The reduction in duration of flooding and/or soil saturation due to drainage here and on south Bodie Island has promoted the invasion of shrubs into more open wetland areas (Rheinhardt and Faser 2001).

Prior to dune construction and other stabilization efforts, it is likely that storm surge periodically flooded fresh and saltwater marshes, killing off wetland shrubs (Rheinhardt and Faser 2001). Herbaceous wetland vegetation may have been impacted as well but typically recovers quickly. Dune

construction, as well as road and ditch construction, have impeded storm surge and reduced the frequency and magnitude of marsh flooding. This hydrological alteration appears to have contributed to the invasion of shrubs into open marshes (Turner 1984, Rheinhardt and Faser 2001). Other historic development projects that have altered park wetlands include the filling of a small salt marsh adjacent to the Oregon Inlet Marina in 1962 and the excavation of "borrow pits" in the Whalebone Junction area for Highway 12 construction in 1958–59 (Firth 1987). The borrow pits are now a line of ponds that are over 1m (3.3 ft) deep in some places (Figure 39).



Figure 39. Aerial photo of southern Bodie Island, just south of the Whalebone Junction area, showing some of the borrow pit ponds (note the unnatural shapes) west of Highway 12 (ESRI world imagery basemap).

Groundwater withdrawals for human use may lower the water table, which can reduce the supply of water to marshes and wetland vegetation (Mallin et al. 2006, Schupp 2015). Impacts to the ecosystem from these withdrawals may include reduced plant species diversity in wetland swales, shifts in vegetation community distribution, and impaired wetland function. At CAHA, groundwater withdrawal amounts vary during the year, increasing with the summer influx of seasonal residents and tourists. According to estimates based on records from the Cape Hatteras Water Association, water consumption on lower Hatteras Island in the mid-1990s rose from a winter minimum of 400,000 gallons per day (gpd) to a summer maximum of 1.4 million gpd (Mallin et al. 2006). This results in an estimated 0.6–0.9 m (2–3 ft) change in water table elevation from winter to summer.

Some intermittently-flooded wetlands within the park have been invaded by the aggressive non-native grass, common reed (*Phragmites australis*) (McManamay et al. 2018). Common reed is a

perennial plant that can reach 3 m (10 ft) tall and can spread up to 2 m (6.6 ft) annually through the vigorous vegetative growth of rhizomes (NPS 2016f). Also, a prolific seed producer, common reed can sustain densities of up to 300 stems per square meter (Hara et al. 1993, NPS 2016f). These characteristics allow the species to completely dominate a wetland and exclude native plants (Chambers et al. 1999, McManamay et al. 2018). In 2012, approximately (800 ac) of brackish marsh within CAHA was severely impacted by common reed (NPS 2016f). Since that time, park managers have been cooperating with the Southeastern Invasive Plant Management Team (IPMT) to chemically treat isolated patches of the species in an effort to stop the spread of this invasive plant into even more natural communities. Staff use backpack sprayers to apply herbicide during the summer and early fall when common reed is actively growing, but multiple treatments are usually required to eliminate these patches (Figure 40) (NPS 2013b, 2016f). In the summer of 2013, for example, the IPMT crew treated 1.5 ha (3.8 ac) of common reed in the Cape Point area between Ramps 44 and 45 (NPS 2013b).



Figure 40. IPMT crew members treating common reed in a Cape Point marsh (NPS photo).

As discussed in Chapter 2, temperatures are projected to increase across the southeastern United States over the next century as a result of global climate change (Carter et al. 2014). Warmer temperatures will increase evapotranspiration rates, meaning that even if annual precipitation remains constant or slightly increases, overall conditions could become drier in the future (Carter et al. 2014). The frequency and intensity of droughts is projected to increase with higher temperatures (Karl et al. 2009, DeVivo et al. 2011), which will likely have a negative impact on wetland vegetation. In contrast, warming ocean temperatures due to climate change are projected to increase the intensity of Atlantic hurricanes, with more precipitation and higher wind speeds (Karl et al. 2009). For every 1°C (1.8°F) increase in ocean surface temperatures, hurricane rainfall amounts are likely to increase by 8–16%, along with wind speed increases of 1–8% (Gutowski et al. 2008).

Sea level rise (SLR) driven by climate change can increase the likelihood of saltwater intrusion into freshwater wetlands, particularly wetlands close to the shoreline. Saltwater intrusion can occur over land during flooding or by encroaching into the shallow surficial water table (Ataie-Ashtiani 2013). A sudden increase in salinity from saltwater intrusion can diminish or kill off aquatic vegetation not adapted to saline or brackish conditions, altering plant community composition (McKee and Mendelssohn 1989, Riggs and Ames 2003). If sea levels rise over the next century as predicted (IPCC 2013), saltwater intrusion is likely to become an increased threat to CAHA's freshwater wetlands (Karl et al. 2009, Ataie-Ashtiani 2013). In addition to increasing salinity, storm surge and overwash events can physically alter wetlands by redistributing sand and uprooting or otherwise damaging vegetation (Figure 41) (USGS 2016c, McManamay et al. 2018). If SLR accelerates, tidal saltmarshes may become permanently inundated, killing off the wetland vegetation (Feldman et al. 2009, Schupp 2015).



Figure 41. Aerial photos from May 2008 (left) and August 2011 show a marsh area on Ocracoke Island that was covered by sand from overwash during Hurricane Irene (USGS photos).

Data Needs/Gaps

Mallin et al. (2006, p. 63) noted "a lack of good quality, up-to-date maps that show the key aquatic features including fresh and brackish wetlands, tidal creeks, ponds and major ditches on all of the Park's islands." The authors suggested that the creation of such maps should be a high priority, which may require additional on-site wetlands/hydrological delineations. This could be part of a larger, park-wide wetlands inventory. Also, a more in-depth understanding of the islands' hydrologic dynamics would assist managers in maintaining the park's valuable wetlands, particularly the unique interior wetland complex in the Buxton Woods area (Bratton and Turner 1986).

The continuation and possibly an expansion of SECN sediment elevation table monitoring would provide insight into the future persistence of CAHA's saltmarshes, given predicted accelerated SLR. A plant survey of park palustrine wetlands specifically would help to document the diversity within and between these communities, and allow for future detection of any shifts in vegetation that may indicate larger environmental changes of concern. This could be addressed by a comprehensive

baseline vegetation inventory, which would also benefit other park vegetation communities (Ziegler, written communication, April 2020).

Overall Condition

Acreage of Palustrine Wetlands

The project team assigned this measure a *Significance Level* of 3. McManamay et al. (2018) mapped 2,312 ha (~5,712 ac) of palustrine wetland vegetation within park boundaries. In comparison, NWI mapping identified nearly 786 ha (1,941 ac) of palustrine wetlands at CAHA (USFWS 2018), based on interpretation of aerial imagery from a similar time frame as that utilized by McManamay et al. (2018) (Table 29). The discrepancy in area between the two studies is likely due to differences in methodology and the categorization of palustrine vs. estuarine. The NWI is a national program where mapping is often completed by large regions, possibly an entire state at a time, with some field verification. In contrast, McManamay et al. (2018) focused specifically on CAHA and completed two rounds of more extensive field reconnaissance. As a result, McManamay et al. (2018) classifications were likely more informed by on-the-ground conditions and may be deemed more accurate than NWI data (e.g., palustrine vs. estuarine distinction). However, McManamay et al. (2018) focused on vegetation communities and could potentially have "lumped" some estuarine areas mixed with or adjacent to communities classified as palustrine if the vegetation signature looked similar in aerial imagery. Because there is some uncertainty due to the discrepancy between these two sources and no adequate reference for comparison to the current status, a *Condition Level* could not be assigned for this measure.

Table 29. Comparison of palustrine, estuarine, and total wetland area at CAHA by mapping effort.

Wetland system	McManamay et al. (2018)	NWI
Palustrine wetlands	2,312 ha	786 ha
Estuarine wetlands (vegetated)	2,545 ha	4,500 ha
Total wetlands	**4,857 ha**	**5,286 ha**

Acreage of Estuarine Wetlands

This measure was assigned a *Significance Level* of 2. According to McManamay et al. (2018), estuarine wetland communities cover 2,545 ha (~6,288 ac) of the park. The NWI identified 628,242 ha (~1.5 million ac) of estuarine wetlands, approximately 4,500 ha (11,120 ac) of which is vegetated (Table 29) (USFWS 2018). As explained above, the discrepancy between the two studies is likely due to differences in methodology and palustrine vs. estuarine categorization. For example, because McManamay et al. (2018) focused on mapping vegetation communities, they likely did not map unvegetated wetlands included in the NWI. Also, for the same reasons given in the previous measure, a *Condition Level* has not been assigned for the acreage of estuarine wetlands.

Plant Species Richness of Palustrine Wetlands

A *Significance Level* of 3 was assigned for this measure. While 173 plant species have been documented in CAHA's palustrine wetlands over time, the lack of a clear reference for comparison,

either historical or in a nearby comparable environment (e.g., CALO), makes it difficult to assess this measure. As a result, a *Condition Level* has not been assigned at this time.

Plant Species Richness of Estuarine Wetlands

This species richness measure was assigned a *Significance Level* of 2. Despite the harsher conditions of the estuarine environment relative to palustrine wetlands, 120 plant species have been documented in CAHA's estuarine wetlands. Of 35 plant species considered to "occur with high fidelity" in Outer Banks tidal marshes (Burk 1962), 29 species have been found in CAHA estuarine wetlands, and three of the species that have not been found are considered naturalized weeds. Based on best professional judgement, this measure is assigned a *Condition Level* of 1.

Sediment Elevation Table of Saltwater Marshes

A *Significance Level* of 3 was assigned for this measure. While sediment elevation is a key factor in determining the presence and composition of vegetation in salt marshes, no data are currently available for this parameter at CAHA. Results from the SECN monitoring program should be available soon, but at this time a *Condition Level* cannot be assigned.

Linear Distance of Drainage Features

This measure was assigned a *Significance Level* of 3. Evidence suggests that ditching and drainage has contributed to significant changes in wetland vegetation at CAHA. Rough analysis by an SMUMN GSS analyst identified a minimum estimate of 45.7 km (28.4 mi) of linear drainage features within park boundaries, primarily on Bodie Island (Figure 39). At this time, this measure is assigned a *Condition Level* of 2, indicating moderate concern.

Water Quality

The water quality measure was assigned a *Significance Level* of 3. An in-depth discussion of park water quality can be found in Chapter 4.7 of this report. At this time, water quality is considered of moderate concern at CAHA (*Condition Level* = 2) with no clear overall trend in condition.

Weighted Condition Score

A Weighted Condition Score was not calculated for CAHA's wetlands and marshes, as *Condition Levels* could not be assigned for four of the seven selected measures (Table 30). Condition was particularly difficult to assess for measures without a clear point of reference, either historical or in a comparable environment outside the park. However, given the conditions of measures which could be assessed, and the threats faced by wetlands today, it seems likely that this resource is of moderate concern.

Table 30. Current condition and trend for the Wetlands and Marshes of CAHA.

Measures	Significance Level	Condition Level	WCS = N/A
Acreage of Palustrine Wetlands	3	n/a	–
Acreage of Estuarine Wetlands	2	n/a	–
Plant Species Richness of Pal. Wetlands	3	n/a	–
Plant Species Richness of Est. Wetlands	2	1	–
Sediment Elevation Table	3	n/a	–
Linear Distance of Drainage Features	3	2	–
Water Quality	3	2	–
Overall	–	–	

Sources of Expertise

Forbes Boyle, SECN Botanist

Lisa Cowart Baron, SECN Coastal Ecologist

Tracy Ziegler, CAHA Chief of Resource Management and Science

Birds

Description

Bird populations often serve as excellent indicators of an ecosystem's health (Morrison 1986, Hutto 1998, NABCI 2009). Birds are typically highly visible components of ecosystems, and bird communities often reflect the abundance and distribution of other organisms with which they co-exist (Blakesley et al. 2010). Resident birds provide insight into the current status of the habitats they frequent, while migratory birds serve as excellent ecological indictors because a disturbance adversely affecting any of the habitats used by these species (e.g., stopover, wintering, or breeding habitats) can cause declines in populations and a decrease in species' reproductive success (Hilty and Merenlender 2000, Zöckler 2005).

The unique ecosystems and physical formations of the Atlantic and Pamlico Sound Coasts, combined with the intertidal dune formations and the maritime forests and freshwater marshes of Buxton Woods, provide bird species with ideal habitats. Although heavily impacted by human activity, the shorelines of CAHA represent a vital stop for many bird species during the migratory, breeding, and overwintering periods. In fact, several avian North Carolina state species of conservation concern, such as the American oystercatcher (Figure 42) and Wilson's Plover (*Charadrius wilsonia*), utilize a variety of habitats in CAHA at various stages throughout the year. Another species that is highly dependent on the park's coastlines year-round is the piping plover. The Piping Plover is a federally threatened species along the Atlantic Coast, and observations of banded individuals have shown that some of the birds that overwinter in the CAHA area are from the Great Lakes population of plovers where the species is considered endangered (Cohen 2005). Recent research has shown that South Point on Ocracoke Island likely serves as an important stopover site for the Piping Plover (Weithman et al. 2018), with approximately 10% of the global population and 15% of the Atlantic Coast population stopping over at the site during the fall migration. The Atlantic Coast of the U.S. typically provides refuge for plovers as they escape cold winter conditions in the Midwest and Great Plains. However, cold snaps in the Southeast can have devastating effects on the wintering birds (Gibson et al. 2016). Accordingly, the National Audubon Society has designated CAHA as a Globally Important Bird Area (Audubon 2017), and the USFWS has designated over 800 ha (2,000 ac) of land along the Outer Banks as important piping plover habitat (USFWS 2008).



Figure 42. American Oystercatcher near Cape Point (NPS Photo).

CAHA has confirmed the presence of more than 360 species of birds, many of which are migratory species (NPS 2018e). Additionally, CAHA has confirmed the presence of 30 bird species that are either federally listed as threatened or endangered, or are state listed as threatened, endangered, or of special concern (Table 31). The shorelines of CAHA represent important shorebird habitat; the U.S. Shorebird Conservation Plan Partnership has identified 15 shorebird species in the park as "Species of Greatest Conservation Concern" or "Species of High Conservation Concern" (USSCPP 2016) (Table 31).

Table 31. State and federal bird species of conservation concern that have been documented in CAHA.

Common name	North Carolina status [b]	Federal status [b]	USSCPP (2016) [c]
American Golden-Plover [a]	–	–	High Concern
American Oystercatcher [a]	SC	–	Greatest Concern (breeding ssp. *palliatus*)
Bachman's Sparrow	E, SC	–	–
Bald Eagle	T	–	–
Bar-tailed Godwit [a]	–	–	Greatest Concern (ssp. *baueri*)
Bewick's Wren	E	–	–
Black Rail	SC	–	–
Black Skimmer [a]	SC	–	–
Brown Creeper	SC (ssp. *nigrescens*)	–	–
Buff-breasted Sandpiper [a]	–	–	High Concern
Cerulean Warbler	SC	–	–
Common Tern [a]	SC	–	–
Glossy Ibis	SC	–	–
Golden-winged Warbler	SC	–	–
Gull-billed Tern (ssp. *aranea*) [a]	T	–	–
Hudsonian Godwit [a]	–	–	High Concern
Least Bittern	SC	–	–
Least Tern [a]	SC	–	–
Lesser Yellowlegs	–	–	High Concern
Little Blue Heron	SC	–	–
Loggerhead Shrike	SC	–	–
Long-billed Curlew [a]	–	–	High Concern
Marbled Godwit [a]	–	–	High Concern
Northern Saw-whet Owl	T	–	–
Olive-sided Flycatcher	SC	–	–
Painted Bunting	SC	–	–
Pectoral Sandpiper	–	–	High Concern
Peregrine Falcon (ssp. *anatum*)	E	–	–
Piping Plover [a]	E(ssp. *circumcinctus*)	T(ssp. *anatum*)	–

[a] = Shorebird Species

[b] E = Endangered; T = Threatened; SC = Species of Concern; ESA = Endangered Species Act Listed

[c] = U.S. Shorebird Conservation Plan Partnership Shorebirds of Concern.

Table 31 (continued). State and federal bird species of conservation concern that have been documented in CAHA.

Common name	North Carolina status [b]	Federal status [b]	USSCPP (2016) [c]
Red Crossbill	SC	–	–
Red Knot (ssp. *rufa*)	–	T	ESA (ssp. *rufa*); Greatest Concern (ssp. *roselaari*)
Roseate Tern [a]	E	E	–
Semipalmated Sandpiper	–	–	High Concern
Short-billed Dowitcher [a]	–	–	High Concern
Snowy Egret	SC	–	–
Snowy Plover [a]	–	–	Greatest Concern
Tricolored Heron	SC	–	–
Vesper Sparrow	SC	–	–
Willet [a]	–	–	High Concern
Wilson's Plover [a]	SC	–	Greatest Concern (breeding ssp. *wilsonia*)
Wood Stork	E	T	–
Yellow-bellied Sapsucker	SC (ssp. *appalachiensis*)	–	–

[a] = Shorebird Species

[b] E = Endangered; T = Threatened; SC = Species of Concern; ESA = Endangered Species Act Listed

[c] = U.S. Shorebird Conservation Plan Partnership Shorebirds of Concern.

As evidenced by Table 26, CAHA represents an important area of shorebird habitat, and is home to several species of conservation concern. As mandated by the park's ORV management plan (NPS 2010), CAHA has identified several shorebird species for annual monitoring in the park, these species are referred to as focal shorebird species in this report and include: Piping Plovers, Red Knots, American Oystercatchers, and Wilson's Plovers. All other shorebird species are defined as species that belong the order Charadriiformes. Under this definition, shorebirds includes typical waders (e.g., stilts, avocets, oystercatchers, and sandpipers), larids (Charadriiformes: *Laridae*; e.g., gulls, terns, and allies), as well as alcids (Charadriiformes: *Alcidae*; e.g., Razorbill [*Alca torda*]). Species in *Laridae* and *Alcidae* were included in the shorebirds group at the request of CAHA staff, despite the fact that this family is often omitted from the broad definition of "shorebird." The vast majority of the park's bird monitoring is focused on shorebird species, primarily the focal shorebird species.

CAHA is located at approximately the midpoint of the Atlantic Flyway, which is one of the major migration flyways in North America (Figure 43). The park is used as a feeding and resting ground for many species, such as the Red Knot (*Calidris canutus*) which passes through the park on its way

from wintering grounds in the south to breeding grounds in the north. CAHA also acts as an important over-wintering area for several migratory species, such as the Long-billed Curlew (*Numenius americanus*) and the Black-bellied Plover (*Pluvialis squatarola*), as these species spend the winter months along CAHA's coastlines before returning to their breeding grounds in the spring.

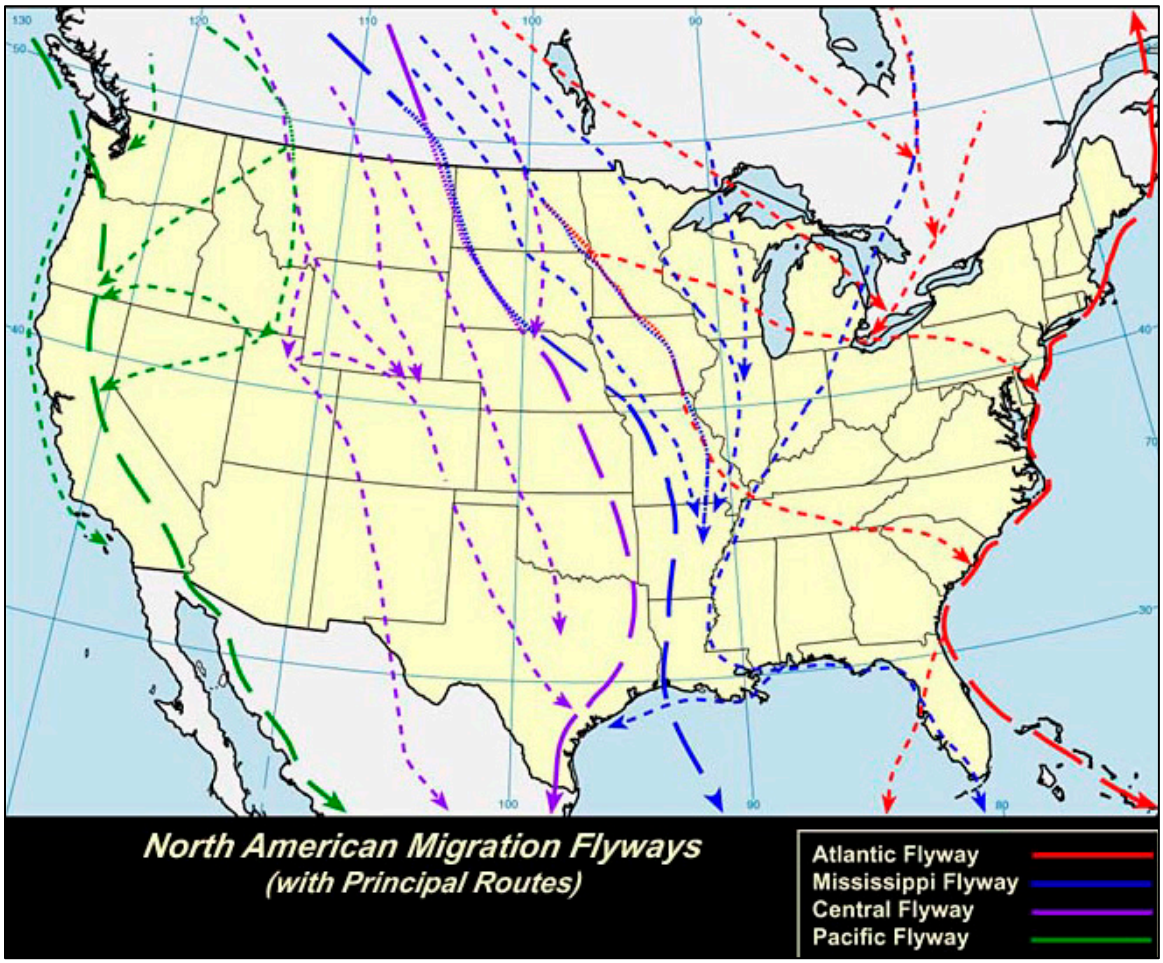


Figure 43. Major North American migratory flyways. CAHA is located along the Atlantic Flyway (NPS 2016e).Bolded, longer dashed lines indicate principal migratory routes, while shorter dashes indicate secondary and alternate migration routes.

Long-distance migratory species are highly informative indicator species, as their overall health depends on several different ecosystems. Global Christmas Bird Count (CBC) and Breeding Bird Survey data indicate declines in migratory bird numbers in recent years (Peterjohn and Sauer 1999, Vickery and Herkert 2001, Niven et al. 2009). The Red Knot is one of the park's longest-distance migrants, migrating south from breeding grounds in the High Arctic tundra to wintering grounds in the park. Monitoring of long-distance migratory species populations (such as the Red Knot) as they pass through or overwinter in CAHA may help managers to develop a better understanding of the overall health of not only the CAHA ecosystem, but also the other ecosystems that these bird species rely on.

Measures

- Shorebird species richness
- Shorebird relative abundance
- Landbird species richness
- Landbird relative abundance
- Annual waterfowl harvest

Reference Condition/Values

A reference condition was not assigned to the birds component during project scoping. The observations of Bishop (1901) took place in the Pea Island area and represent the earliest published list of observed bird species for the CAHA area; this source of data can be used as a coarse snapshot of the park's winter bird population near the beginning of the 20th Century. However, this species list: 1) was not the result of a rigorous bird survey and did not have a specified methodology, 2) occurred only during February in the Pea Island area, and 3) is useful only for the species richness measure of this component. Condition assessments for most measures in this assessment will rely on the best professional judgement of identified subject matter experts and NPS staff. Future assessments of condition may be able to utilize the summary in this NRCA as a baseline for comparison.

Data and Methods

The NPS Certified Bird Species List (NPS 2018e) for CAHA was used for this assessment, as this list represents all of the confirmed bird species present in the park. The list was populated by the various bird inventories and surveys that occurred in the park's area, and in the case of parks with limited bird work, will likely resemble the overall species list of the primary bird inventory effort for the park. SMUMN GSS made the following modifications and clarifications to the NPS (2018) list when creating Appendix J:

- Species that were listed on NPS (2018), but identified as "not in park" (e.g., California Quail [*Lophortyx californica californica*]) were excluded;
- Records that failed to identify an individual to the species level (e.g., "jaeger sp.") were excluded;
- The Atitlan Grebe (*Podilymbus gigas*) was excluded. This species was listed in NPS (2018) as "unconfirmed", however, this species was endemic to a single lake in Guatemala and was declared extinct in 1994 (BLI 2016).

Pea Island National Wildlife Refuge completed a comprehensive conservation plan in 2006 (USFWS 2006). Part of this effort was documenting the different biota that have been observed in the refuge and including those species as an appendix to the plan. The avian species documented by USFWS (2006) are included in Appendix J of this report.

In February 1901, Dr. Louis B. Bishop visited Pea Island by boat in order to document the birds of the marshes and flats of the island. Weather remained mostly clear and warm for the duration of the observations (7 February–18 February), with only a few days having storms. While Bishop (1901) represents one of the earliest published bird lists for the Cape Hatteras/Pea Island area, it does not represent an expected species list, rather only the winter species encountered during the author's visit. It is highly likely that other migratory species were encountered and not counted or missed altogether.

Golder (1986) represents an informal survey/day-list of species on CAHA lands before a prescribed burn in the Bodie Island Marsh Unit. The author walked the unit on 15 March 1986 and documented all bird species encountered. In addition to the species, the number of individuals and the approximate habitat of the observation were documented. General recommendations on burn strategy in the unit were provided in Golder (1986) based on the results of the survey, with the author suggesting that burns to the area should only improve habitat for nesting avian species. This data source is not the result of a rigorous survey, but rather a historic day-list for the park unit. It provides information regarding a snapshot of avian life on a random day in 1986, but likely serves little utility in condition assessment. It is included here to provide a complete summary of the park's available historic avian occurrences.

Cooper (1986) documented all birds that were found in the Buxton Woods of CAHA during May and June of 1986. Surveys were completed by walking a 2.55 km (1.6 mi) transect, which was marked every 50 m (164 ft), and all bird species seen or heard were documented. The transect followed portions of Open Pond Road and Doctor's Road, while also including off-road portions between the two roads and also along the NPS boundary (Figure 44). Surveys began 30 minutes before sunrise, and the transect was traversed in alternating directions during eleven visits. In order to determine the distribution of bird species across the transect, birds were assigned to one of seven different habitat "communities" based on where their observation occurred on the transect: 1) pond and edge, 2) mixed hardwoods, 3) mature pine, 4) young pine, 5) wet thicket, 6) open dry thicket, and 7) overhead (no specific habitat, species observed overhead flying) (Cooper 1986). These habitat types were described based on field verification of overhead aerial imagery.

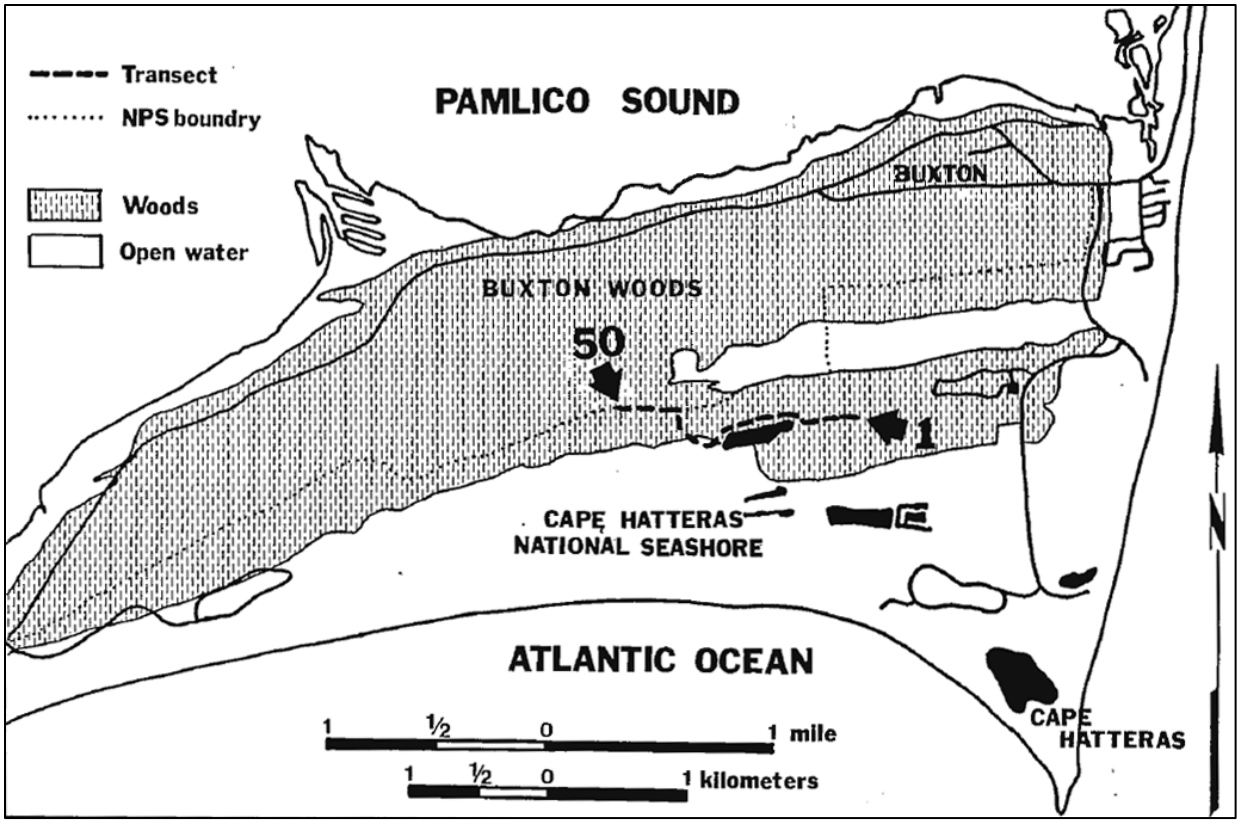


Figure 44. Cooper (1986) transect locations in Buxton Woods. Figure reproduced from Cooper (1986).

Dinsmore et al. (1998) documented shorebird seasonal abundance, distribution, and habitat importance along the Outer Banks of North Carolina from March 1992–December 1993. Five sites were selected for surveys:

- Bodie Island – Extended 9 km (5.6 mi) from the southern edge of Nags Head to Oregon Inlet;
- North Beach – 28 km (17 mi) stretch running from Rodanthe Pier south to a point 1 km (0.6 mi) north of Buxton town limit;
- South Beach – Began just south of the Cape Hatteras Lighthouse and ran south to Cape Hatteras Point and west to Hatteras Inlet, totaled 24 km (15 mi) in length;
- Ocracoke Island – included the entire Ocracoke Island (28 km [17 mi]);
- North Core Banks – the only site located entirely outside of CAHA boundaries. A 34 km (21.1 mi) stretch running from Ocracoke Inlet south to New Drum Inlet.

An additional site in PINWR 19 km (11.8 mi) in length was surveyed by Dinsmore et al. (1998) during the fall of 1993. All these sites were selected based on habitats that were represented and how accessible they were to observers. Surveys were conducted primarily from vehicles and occurred twice a month; nearly all surveys began 1.5 hours before low tide. Observers recorded all bird

species that were present on the outer beach, ignoring flying birds that were not flying as a result of observer disturbance. Abundance estimates were created by taking the mean of the two monthly censuses for a site.

During 2006 and 2007 the SECN assisted CAHA with the development of shorebird monitoring methods (Byrne et al. 2009b) and assisted the park with monitoring efforts for focal shorebird populations (Piping Plovers, Red Knots, American Oystercatchers, and Wilson's Plovers) during the migratory (August–October) and winter (February–April) seasons (Byrne et al. 2009b). This protocol focused on habitat types near beach and dune communities of coastal parks, and utilized line transects to survey shorebirds. These transects were surveyed for 30 minutes and were approximately 1.6 km (1 mi) in length. Observers documented focal shorebird species, habitat, activity, distance from observer, and in instances where there were observations of deceased shorebirds, observers recorded possible cause of death (Byrne et al. 2009b).

The specific objectives of the network-wide shorebird monitoring protocol were to:

1. Determine the status and trends in migratory and wintering shorebirds in SECN parks using normalized observations.

2. Determine the trends in migratory and wintering shorebirds in areas open and closed to vehicles in SECN parks using normalized observations.

3. Determine the habitat types used by migratory and wintering shorebirds in SECN parks and whether these patterns change over time (Byrne et al. 2009a).

Sampling sites were established and divided into units that corresponded with park miles (approximately 62 park miles of beaches exist in CAHA). These units (park miles) were divided into subunits based on geography, and had approximately the same number of sampling units within each; the subunits were: Bodie Island, South Hatteras Island, Middle Hatteras Island, and Ocracoke Island (Figure 45). The sampling units were classified as either high-intensity sites (i.e., sites that had previously or reported observed focal-shorebird use) or low-intensity sites (i.e., all other ocean/beachside units). Five high-intensity monitoring sites were chosen, all of which coincided with accreted areas of the park: Bodie Island Spit, Hatteras Island Cape Point, Hatteras Island Spit, Northeast Ocracoke Island, and Ocracoke Island Spit (Byrne et al. 2009b). For a complete breakdown of sampling methodologies used for the high- and low-intensity sites see Byrne et al. (2009a).

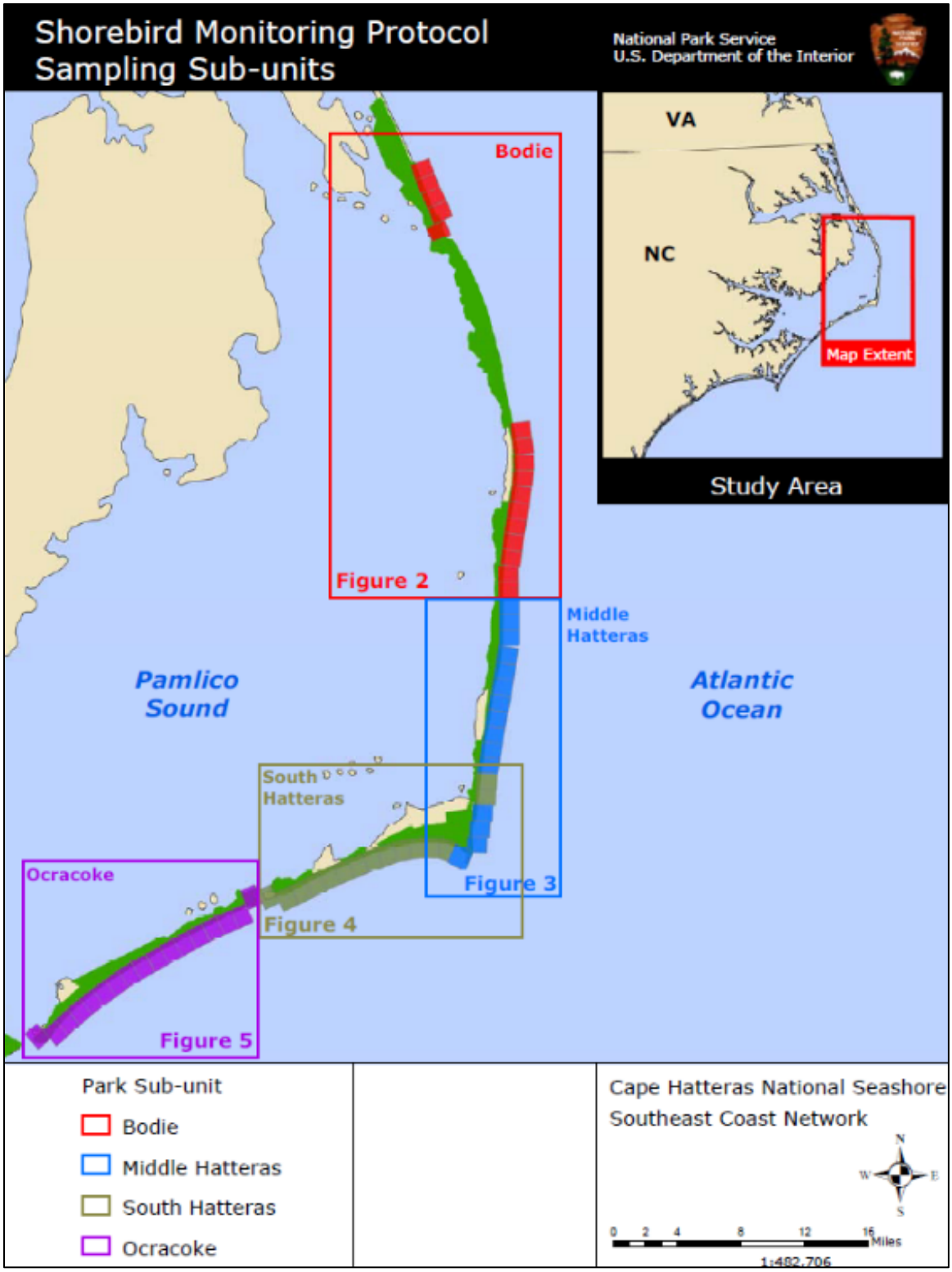


Figure 45. Shorebird monitoring and sampling subunits utilized by Byrne et al (2009b). References to Figures 2–5 correlate to Byrne et al. (2009b) and not this report (Figure reproduced from Byrne et al. 2009b). It should be noted that this methodology was abandoned following the 2009 publication, and CAHA now utilized a modified methodology.

From 2014–2018, the results of priority shorebird and colonial waterbird monitoring conducted by the CAHA staff in CAHA were summarized in annual monitoring reports (available from https://www.nps.gov/caha/learn/nature/annualreports.htm). Monitoring methods for each priority species had variations, with some following the more rigorous protocol of Byrne et al. (2009a), and others using unique, modified procedures. The sampling units and subunits highlighted in Figure 45 were largely abandoned in subsequent (post 2007) monitoring efforts. These reports focus exclusively on focal species, and their utility for this assessment is limited, as no discussions of broad shorebird abundance or species richness are provided. When appropriate, they are used in discussions below.

Landbirds (i.e., species that have a principally terrestrial life cycle; does not include the parks focal group for shore birds) were identified as a high-ranking Vital Sign by the SECN during the Vital Sign selection process (DeVivo et al. 2008). Consequently, the SECN began a landbird monitoring program in all network parks, including CAHA, with the specific objective of determining trends in landbird species occupancy, distribution, diversity, and community composition in network parks (Byrne et al. 2011a). Monitoring began at CAHA in 2010, and followed a separate sampling protocol later published by Byrne et al. (2014). Thirty sites were chosen using a random, spatially balanced algorithm, and each site was surveyed using a variation of the variable-circular plot (VCP) technique from April to June. Using this technique, observers were stationed at the center point of a 0.5 ha (1.2 ac) macroplot and recorded all species observed and heard during a 12-minute window. Birds that flew over the macroplot during sampling were recorded as flyover species. When possible, observers documented the time frame that the bird was recorded (e.g., 0–3 minutes after start, 3–6 minutes, etc.), and the distance of the observation from the observer. Distance was recorded in one of four intervals: 0–25 m (0–82 ft), 25–50 m (82–164 ft), 50–100 m (164–328 ft), and >100 m (328 ft). Subsequent surveys conducted depended solely on the use of audio recordings collected at the same permanent plots (Byrne et al. 2011a).

Three annual CBCs are hosted in CAHA, one on each of the main islands (Bodie, Hatteras, Ocracoke), and have been completed annually since 1981. The Cape Hatteras CBCs are part of the International CBC, which started in 1900 and is coordinated by the Audubon Society. Multiple volunteers surveyed a 24 km (15 mi) diameter area on one day, typically between 14 December and 5 January, by foot, boat, or car. Unlike surveys that occur during the breeding season (such as a breeding bird survey or nesting shorebird surveys), the CBC surveys overwintering and resident birds that are not territorial and singing. The total number of species and individuals were recorded each year. The unique landscape of CAHA limits these count circles a bit, and observers typically focus on priority and high use areas of each island. For example, the Hatteras Island CBC focuses efforts in the Cape Point and Hatteras Inlet areas. The center points and buffer distances of the 24 km (15 mi) diameter count circles are displayed in Figure 46, Figure 47, and Figure 48.

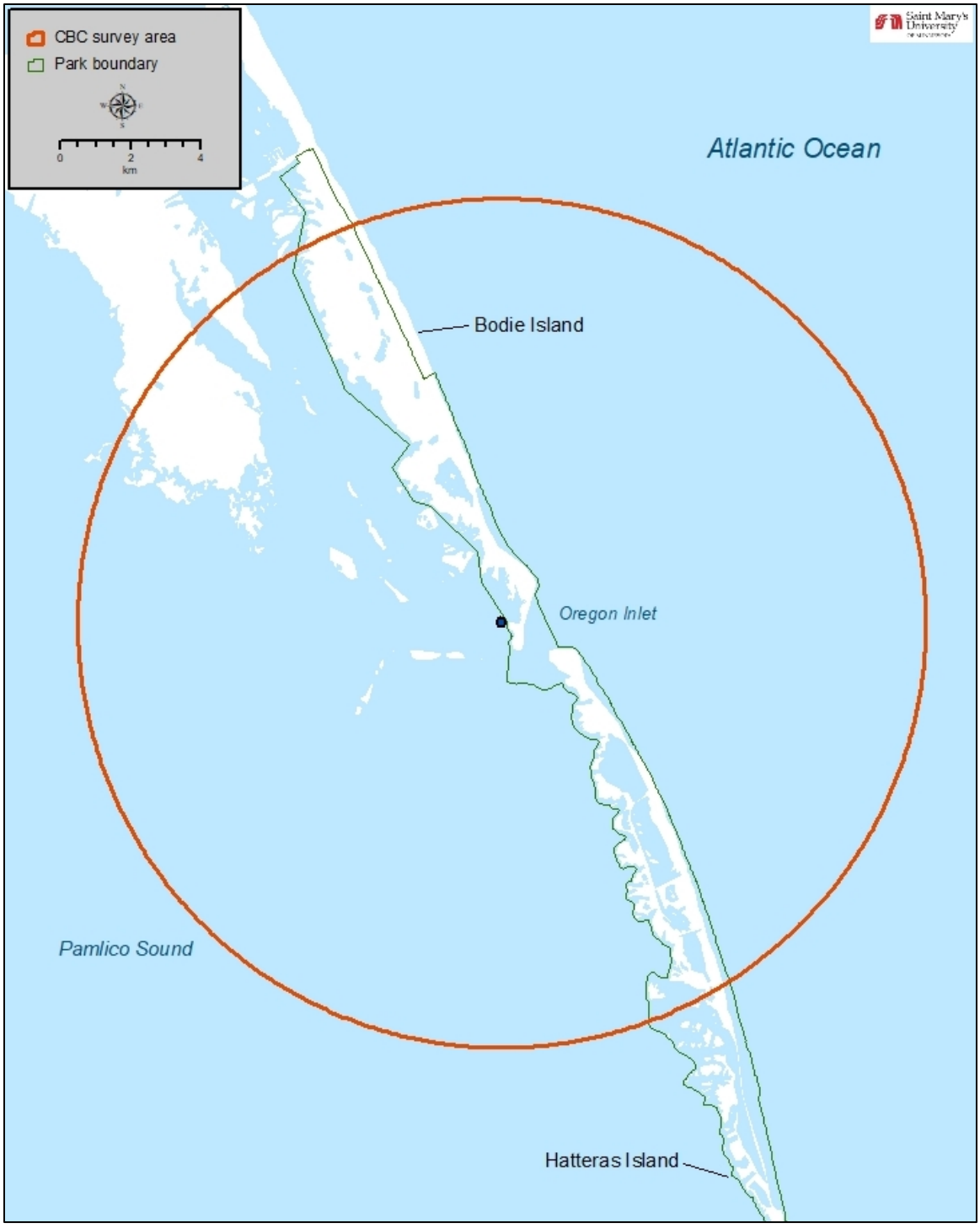


Figure 46. Christmas bird count survey area for the Bodie Island CBC. The Bodie Island CBC has been conducted annually since 1981.



Figure 47. Christmas bird count survey area for the Hatteras Island CBC. The Hatteras Island CBC has been conducted annually since 1981.



Figure 48. Christmas bird count survey area for the Ocracoke Island CBC. The Ocracoke Island CBC has been conducted annually since 1981.

Data from the CAHA CBCs were obtained from: http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx and the following adjustments were made to the datasets:

- All incomplete species identifications were omitted (e.g, *Buteo* spp., *Vireo* spp., American Black Duck/Mottled Duck).
- Aggregated observations of species separated by color morphs (e.g., white and blue form of *Ardea herodias*) were not treated as unique species observations.
- Observations of American Green-winged Teal and Green-winged Teal were treated as one category as both refer to *Anas crecca*; similarly, observations of American Barn Owl and Barn Owl were treated as one species as both refer to *Tyto alba*.
- Observations of either the Pacific Wren or Winter Wren were treated as observations of *Troglodytes troglodytes*.
- Ridgways's Rail, Mangrove Rail, and Clapper Rails were treated as the same species until 2014; all observations of these species were treated as observations of Clapper Rails (*Rallus longirostris*), the species which occurs in the Atlantic region and is in accordance with current taxonomy.
- Records of American Golden-Plover, Pacific Golden-Plover, and Lesser Golden-Plover were treated as observations of one species: *Pluvialis dominica*.

Limited waterfowl hunting is allowed on Bodie Island in CAHA during species-specific seasons throughout the year, as well as in various areas along the sound on Hatteras and Ocracoke Islands as well (Table 32). Unfortunately, annual harvest data were unavailable to the authors at the time of publication; the NPS has indicated that harvest data exist for Bodie Island and are collected annually from hunters, these data should be summarized in future assessments of condition. Hunters register for a drawing to hunt at one of twenty designated hunt stations on the island (Figure 49). Each hunter is allowed to hunt within a 15 m (50 ft) radius from the designated hunting post. Only non-toxic shot (no lead allowed) may be used, and hunters may only shoot from one half hour before sunrise until sunset. Hunter bag limits and possession limits are outlined in Table 32.

Table 32. Waterfowl hunting seasons and regulations in CAHA for the 2019–2020 hunting season (NPS 2019).

Season	Dates	Bag limit	Possession limit
Ducks [a], Coots, and Mergansers	Oct 2–5, 2019	See table notes [b]	3 X daily bag
	Nov 16–Dec 2, 2019	See table notes [b]	3 X daily bag
	Dec 14, 2019–Jan 31, 2020	See table notes [b]	3 X daily bag
Sea Ducks [c]	Nov 23, 2019–Jan 31, 2020	See table notes [b, d]	3 X daily bag
Dark Geese (Canada and White-fronted Geese)	**Northeast Hunt Zone (by permit only)** Jan 16–31, 2020	1	3
Light Geese (Snow, Blue, and Ross' geese)	**Regular Season** Oct 8, 2019–Feb 8, 2020	25	No limit
	Conservation Order Season [e] Feb 10–Mar 31, 2020	No limit	No limit
Brant	Dec 28, 2019–Jan 31, 2020	1	3
Tundra Swan (by permit only)	Nov 9, 2019–Jan 31, 2020	1	1
Youth Waterfowl Days [f, g]	Feb 1, 2020–Feb 8, 2020	see above	see above

[a] Black and Mottled Duck season closed until November 23, 2019

[b] Conventional bag limit is 6 ducks, with no more than 4 scoters, 4 eiders, 4 Long-tailed Ducks, 4 Mallards with no more than 2 hens, 3 Wood Ducks, 2 scaup, 2 Redheads, 1 pintail, 2 Canvasback, 2 Black Ducks, 1 Mottled Duck, or 1 Fulvous Whistling Duck. Bag limit for coots is 15 and mergansers is 5 (2 hooded mergansers).

[c] In special sea duck areas only

[d] In special sea duck areas bag limit is 5 sea ducks (includes scoters, eiders, and Long-tailed Ducks) with no more than 4 scoters, 4 eiders, or 4 Long-tailed Ducks

[e] By permit only, electronic calls and unplugged guns are allowed, shooting hours are .5 hours past sunset

[f] Includes ducks, geese, brant, mergansers, coots, and Tundra Swans; youth must have a valid permit to hunt tundra swans and geese in NE hunt zone only

[g] Must be 15 years or younger and accompanied by licensed adult (who cannot participate in duck hunt).

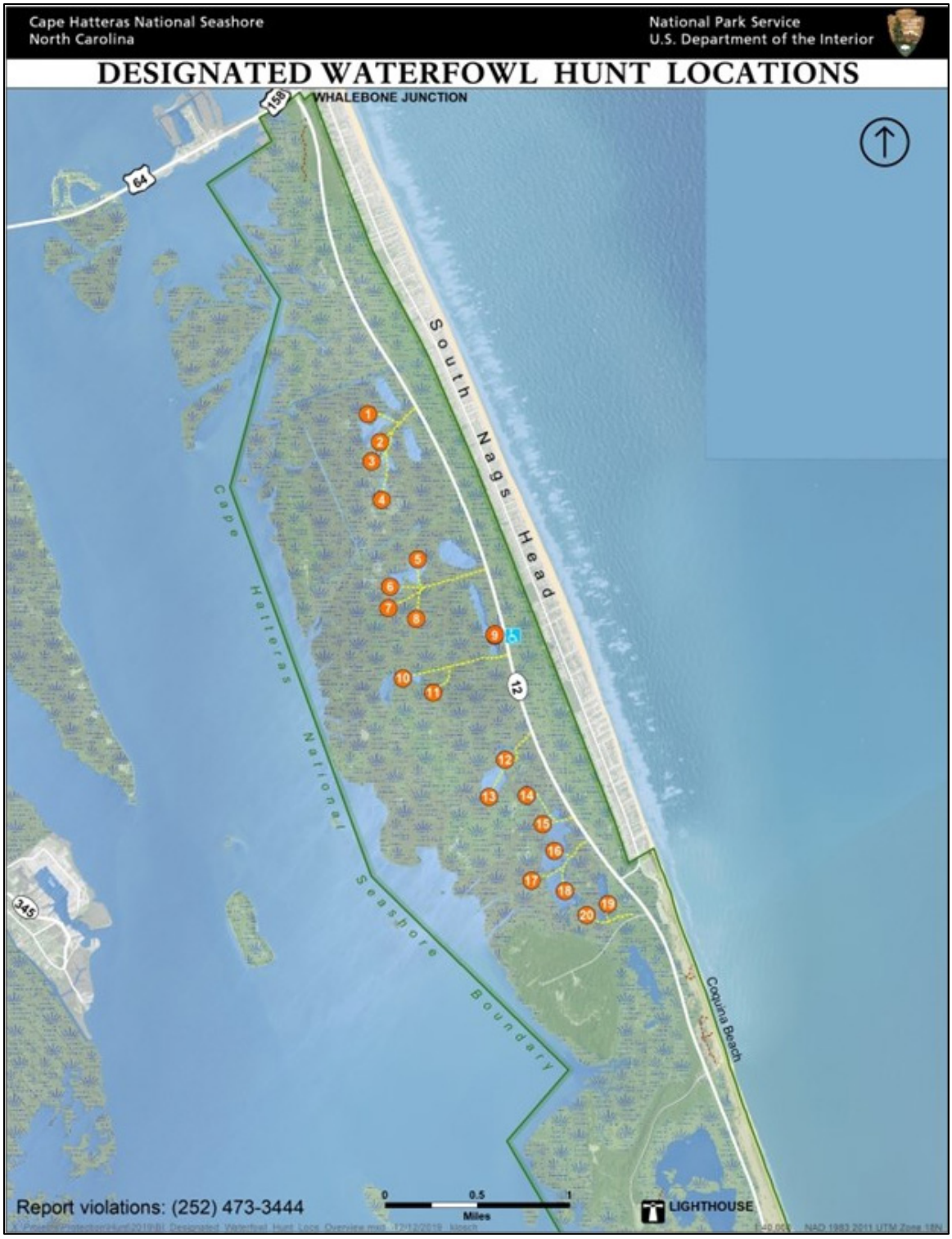


Figure 49. Hunting areas on Bodie Island within CAHA boundaries. Image courtesy of the NPS and reproduced from (NPS 2019).

Current Condition and Trend

Note, for the purpose of this assessment, the definition of shorebird will be any species that belongs to the order *Charadriiformes*. Under this definition, "shorebird" includes typical waders (e.g., stilts, avocets, oystercatchers, and sandpipers), larids (*Charadriiformes*: *Laridae*; e.g., gulls, terns, and allies), as well as alcids (*Charadriiformes*: *Alcidae*; e.g., Razorbill [*Alca torda*]). Species in *Laridae* and *Alcidae* were included in the shorebirds group at the request of CAHA staff, despite the fact that this family is often omitted from the broad definition of "shorebird."

During project scoping, CAHA staff identified shorebird species as a central component of the park's avifauna. The overall health of focal shorebird species (i.e., Wilson's Plover, Piping Plover, American Oystercatcher, and Red Knot) is well summarized in annual reports from 2014–2017 published by the NPS (available from https://www.nps.gov/caha/learn/nature/annualreports.htm). At the direction of park staff, the measures below will not summarize or discuss reproductive metrics for shorebirds, as these data are thoroughly summarized/synthesized annually, and are available to the general public. Instead, the shorebird measures of this component will focus only on the number of species observed (species richness), and the approximate number of individuals observed (relative abundance).

The definition of a landbird for this assessment will follow that of Rich et al. (2004), which defines the group as "a bird species that has a principally terrestrial life cycle." This definition includes approximately 448 species native to North America from 45 families. These families are identified in Box 2 of the Partners in Flight North American Landbird Conservation Plan (Rich et al. 2004).

Shorebird Species Richness

The species richness measure refers to the total number of species present in a given study, survey, or other monitoring effort. This definition is in line with the traditional definition in published literature. It is important to note that a higher species richness estimate does not always correlate to a healthier population. This is particularly true in developed landscapes, as the fragmentation of these areas may encourage generalist bird species or guilds to move in, which would increase the species richness estimate, but would lower the overall condition of the measure. In instances where trends or ecosystem function was unclear, the best professional judgement of NPS managers was used for this measure. The definition of species richness will be the same for both shorebirds and landbirds in this document.

Each of the many bird surveys that have occurred in CAHA have focused on a unique guild of birds (e.g., shorebirds, colonial waterbirds, landbirds). Because of this, it is difficult to compare the results of the studies to each other. The differing methodologies, focal species, and timing make the trends and patterns observed in each study difficult to compare, and the results are best analyzed individually. This assessment presents the results of each study, but does not compare the species richness values between any studies.

NPS Certified Species List (NPS 2018)

Unlike annual bird surveys, NPS (2018e) has generally not been well suited for an analysis of annual species richness, as no data are collected yearly to specifically update the NPS (2018) list. The NPS

Certified Species List documents the presence (or historic presence) of the identified species and serves as a useful point of comparison to determine which species have been documented in the park.

The NPS Certified Bird Species List for CAHA contains 366 species that are confirmed in the park, 86 (23.5%) of which are classified as shorebirds (Appendix K). This list also identifies two shorebird species that may be present in the area but have not been confirmed within the park's boundaries. These species were identified as "Probably Present" by NPS (2018), and included the Great Skua (*Stercorarius skua*) and the South Polar Skua (*Stercorarius maccormicki*). Other designations included in NPS (2018) are "Unconfirmed", which is indicative of a species that has been attributed to the park, but little or no evidence to support its presence exists, and "Not In Park", which indicates species not known to occur in the park, but may be included as the result of misidentification during past research. There were three shorebird species identified as "Unconfirmed" by NPS (2018): Black-winged Stilt (*Himantopus himantopus*), California Gull (*Larus californicus*), and Common Murre (*Uria aalge*). Species identified as "Not in Park" were omitted from this assessment.

Pea Island National Wildlife Refuge Avian Checklist (USFWS 2006)

Similar to NPS (2018), USFWS (2006) represents the avian species that have been documented in PINWR, or are suspected to occur in the refuge throughout various portions of the year. In total, USFWS (2006) documents 274 species as occurring in the refuge, 60 (22%) of which were shorebird species (Appendix K). PINWR is situated within CAHA's administrative boundaries, but is managed by the USFWS. Because of this proximity, the refuge has a very similar avian community structure as CAHA.

Bishop (1901)

Bishop (1901) represents the earliest published avian species list for the CAHA area, and documents all of the species observed during a winter visit to Pea Island. A single observer in Bishop (1901) documented 40 species, most of which were species that relied upon aquatic habitats; ten species of shorebirds (25%) were documented (Appendix K).

Golder (1986)

During an informal survey of an area on Bodie Island that was scheduled to be included in a prescribed burn, Golder (1986) documented 29 bird species; only three (10%) were shorebird species (Black-bellied Plover, Common Snipe [*Gallinago gallinago*], Lesser Yellowlegs [*Tringa flavipes*]) (Appendix K). This survey appears to have been conducted by a single observer that did not follow any sort of rigorous methodology; the observer likely scanned the area for avian species and documented all species observed. A limited description of the habitat sampled is provided, but because it was a survey of a pre-burn marsh/pond area, it is likely that this survey looked at habitat more suited for landbird and waterfowl species than shorebird species.

Cooper (1986)

A 1986 survey of Buxton Woods documented 53 bird species, with three (6%) of those species (Laughing Gull [*Leucophaeus atricilla*], Black Skimmer [*Rynchops niger*], Forster's Tern [*Sterna forsteri*]) being classified as shorebirds (Appendix K). Similar to Golder (1986), Cooper (1986) surveyed an inland area of the park that contained habitat more suitable for landbird and waterfowl

species as opposed to shorebird species. This is likely why the species richness estimates and percent of shorebirds relative to all bird species for these two surveys were relatively low.

Byrne et al. (2011)

While Byrne et al. (2011a) focused on the landbird population of CAHA, the survey efforts did not exclude shorebird species, and 88 total species were documented during the 2010 surveys. Sixteen of the observed species (18%) represented shorebird species (Appendix K).

Additional SECN-led shorebird monitoring efforts have been completed in CAHA, with annual reports existing from 2014–2017 (available from https://www.nps.gov/caha/learn/nature/annualreports.htm, also see Doshkov et al. 2018b). These monitoring efforts are directed at focal shorebird/colonial waterbird species (i.e., Piping Plovers, Red Knots, American Oystercatchers, and Wilson's Plovers) and do not include many of the other shorebird species that frequent the park. Because these annual reports do not identify shorebird species outside of the priority species, a summary and discussion of species richness for those sources is not provided in this section.

Christmas Bird Counts (Bodie, Hatteras, Ocracoke; 1981–2017)

Counts such as the CBC (or other index counts, e.g., breeding bird surveys) are neither censuses nor density estimates (Link and Sauer 1998). The overall usefulness of index count data is often limited by possible biases of count locations and the number of observers, and it is often not advisable to estimate overall population sizes from these data alone (Link and Sauer 1998). These biases may influence how many individuals or species are observed in a given year, and may potentially explain the annual variation observed in species each year. Results of the three CAHA CBCs should be interpreted with a degree of caution. However, these winter counts also provide managers with an opportunity to observe migratory species not otherwise detected during traditional breeding counts, as illustrated by the vagrant Snowy Owl (*Bubo scandiacus*) shown in Figure 50.



Figure 50. Snowy Owl photographed at CAHA during the winter (Photo by Joyce Edwards, NPS).

Cumulatively, 52 shorebird species (19.25% of all observation) were observed during CBCs in CAHA between 1981 and 2017 (Appendix K). Data from the 2018 and 2019 count years exist, although they have yet to be summarized and published on the Audubon Society's online web portal. The results of each annual CBC are discussed individually below.

Bodie Island CBC

CBC efforts on Bodie Island between 1981 and 2017 resulted in the identification of 44 shorebird species (18.72% of all observations). The maximum number of shorebird species observed was 30 species in 2007 (17 observers), while the minimum number of shorebird species observed was 13 in 2017 (26 observers) (Figure 51). The average number of shorebird species observed in a CBC on Bodie Island was 25.16 species, and the average number of observers per year was 26.76.

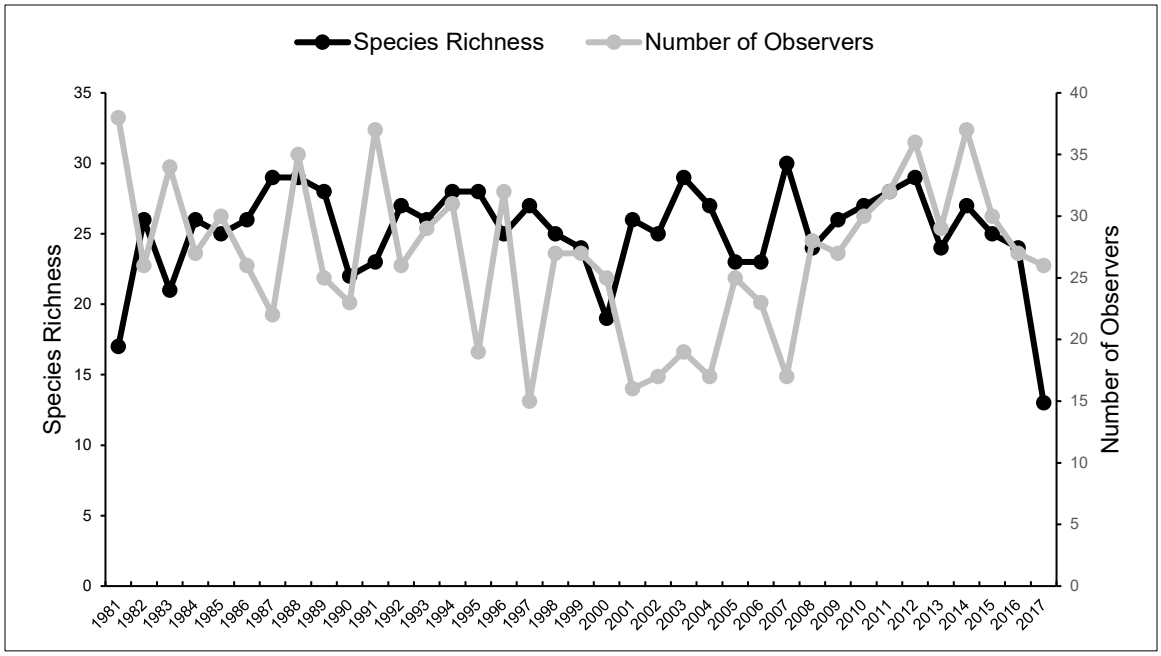


Figure 51. Number of shorebird species and observers during the Bodie Island CBC between 1981 and 2017. Data retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Hatteras Island CBC

CBC efforts on Hatteras Island between 1981 and 2016 resulted in the identification of 48 shorebird species (19.51% of all observations). The maximum number of shorebird species observed was 30 species in 2007 (25 observers), while the minimum number of shorebird species observed was 16 in 2013 (27 observers) (Figure 52). The average number of shorebird species observed in a CBC on Hatteras Island was 22.5 species, and the average number of observers per year was 26.72.

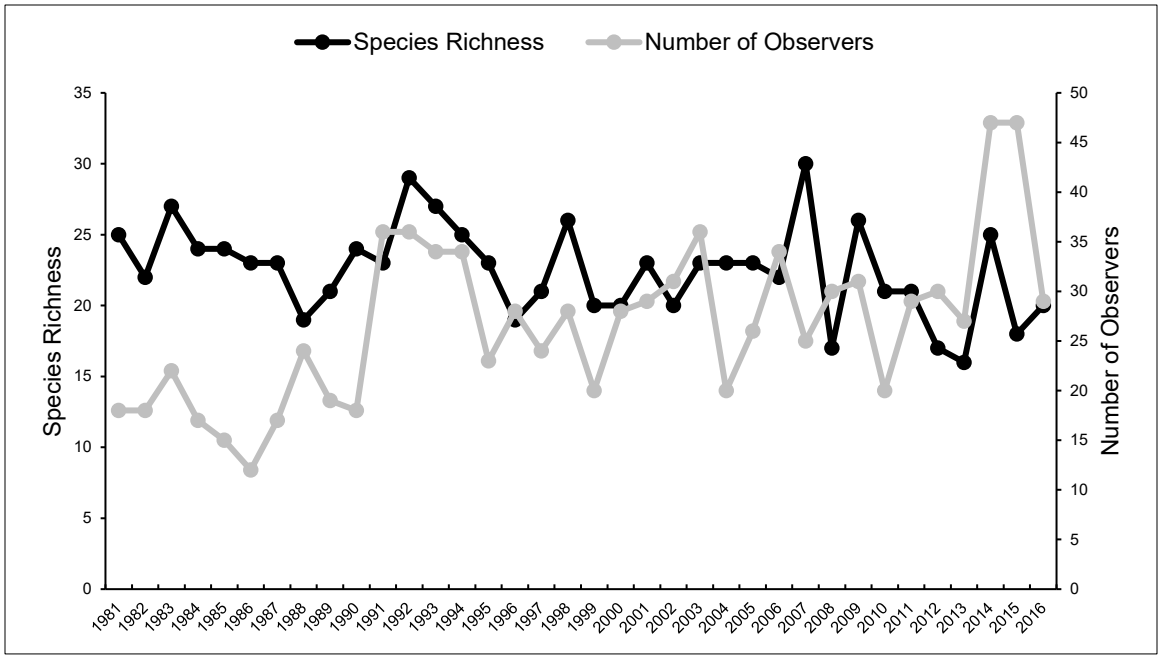


Figure 52. Number of shorebird species and observers during the Hatteras Island CBC between 1981 and 2016. Data retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Ocracoke Island CBC

CBC efforts on Ocracoke Island between 1981 and 2017 resulted in the identification of 36 shorebird species (19.15% of all observations); note that no count occurred in 1983. The maximum number of shorebird species observed was 23 species in 1987 and 2007 (six and 18 observers, respectively), while the minimum number of shorebird species observed was five in 2017 (15 observers) (Figure 53). The average number of shorebird species observed in a CBC on Ocracoke Island was 15.67 species, and the average number of observers per year was 11.55 (no observer data reported from 2013–2015).

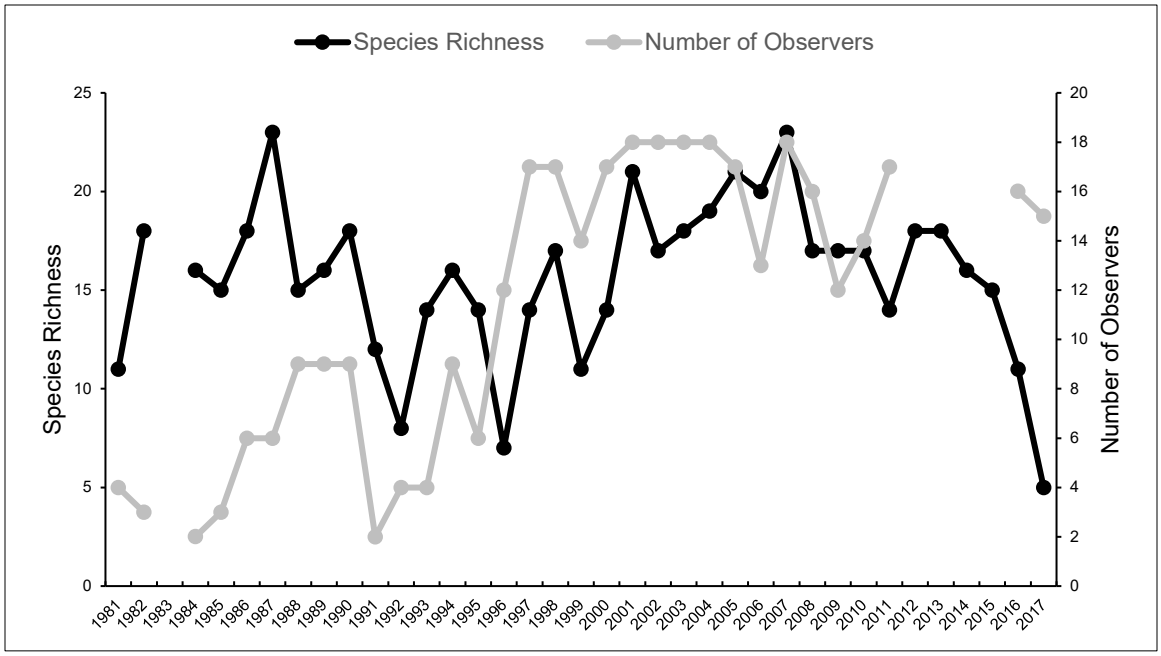


Figure 53. Number of shorebird species and observers during the Ocracoke Island CBC between 1981 and 2017. Note that no count occurred in 1983, and that observer data from 2013–2015 are not reported on annual data summaries. Data retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Shorebird Relative Abundance

Species abundance refers to how many individuals are documented in a given survey/monitoring period. Often, the surveys that have taken place in CAHA have summarized abundance by the total number of observations made for each species, although some have further discussed the total proportion of all observations a species represents (relative abundance). Some studies (Cooper 1986) instead averaged abundance estimates across multiple surveys and censuses. It needs to be noted, however, that all species have different detection probabilities, and measures of abundance reported here should be considered "naïve" estimates, as they do not account for these variable detection probabilities.

Golder (1986)

As mentioned previously, Golder (1986) documented only three shorebird species during an informal survey of an area on Bodie Island scheduled to be included in a prescribed burn. The Lesser Yellowlegs had the most detections during the survey (nine), followed by the Black-bellied Plover (seven) and the Common Snipe (one).

Cooper (1986)

For this data source, abundance estimates were averaged for all 11 censuses across all habitat types. Eleven censuses across seven habitat types in Buxton Woods in 1986 documented three shorebird species. Shorebirds were only detected in two of the seven habitat types: pond and edge habitat, and overhead. The Forster's Tern was detected most frequently (2.91 detections per census in pond and

edge, 0.73 detections per census overhead). The Laughing Gull and Black Skimmer were infrequently detected during census efforts (Table 33).

Table 33. Average number of shorebird individuals detected in each habitat per census during Golder (1986). Eleven censuses across seven habitats were conducted during the spring of 1986.

Common name	Pond and Edge	Overhead
Forster's Tern	2.91	0.73
Laughing Gull	0.18	0.09
Black Skimmer	0.09	Not detected

Byrne et al. (2011)

Byrne et al. (2011a) focused on the landbird population of CAHA, so shorebird detections were largely accidental or were due to sampling occurring in areas closer to shore-related habitats. The laughing gull was detected most frequently among shorebird species, with nearly 120 detections; laughing gull detections comprised 10% of all species detections (including both shore and landbirds) during the study. Other abundant shorebird species included, in order of detection frequency, Semipalmated Sandipers (*Calidris pusilla*; with nearly 100 detections), Great Black-backed Gulls (*Larus marinus*), Herring Gulls (*Larus argentatus*), and Sanderlings (*Calidris alba*) (Bryne et al. 2011).

Christmas Bird Counts (Bodie, Hatteras, Ocracoke; 1981–2017)

The CBC takes place over the winter months when some migratory and breeding shorebird species are no longer present in the area; the abundance estimates and species observed may look very different when compared to breeding or migratory season surveys. As was done with the species richness measure, shorebird relative abundance estimates are discussed below for each of the three CBCs that occur in CAHA.

Bodie Island CBC

When looking at the average number of shorebird individuals of a particular species per year from 1981–2017, the Ring-billed Gull (*Larus delawarensis*) had the highest annual average abundance with 4,690.05 detected/year (Table 34). Other abundant shorebird species during the Bodie Island CBC included the Herring Gull, Dunlin (*Calidris alpina*), Great Black-backed Gull, and the Bonaparte’s Gull (*Chroicocephalus philadelphia*) (Table 34).

Table 34. Average annual abundance for the 10 most frequently observed species during the Bodie Island CBC from 1981–2017. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	Average number of individuals/Year
Ring-billed Gull	4,690
Herring Gull	2,187
Dunlin	756
Great Black-backed Gull	624
Bonaparte's Gull	537
Sanderling	503
Forster's Tern	150
Black-bellied Plover	79
Willet	65
Laughing Gull	52

Hatteras Island CBC

The Hatteras Island CBC occurred from 1981–2017 (although a count did not occur in 1983), with the Ring-billed Gull being detected most frequently during that time (21,870.81 detections/year) (Table 35). Other shorebird species detected annually in high numbers included the Herring Gull (7,403.86 detections/year), Great Black-backed Gull (1,998.69 detections/year), Dunlin (555.81 detections/year), and the Laughing Gull (381.86 detections/year) (Table 35).

Table 35. Average annual abundance for the 10 most frequently observed species during the Hatteras Island CBC from 1981–2017. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	Average number of individuals/Year
Ring-billed Gull	21,871
Herring Hull	7,404
Great Black-backed Gull	1,999
Dunlin	556
Laughing Gull	382
Sanderling	340
Bonaparte's Gull	226
Forster's Tern	173
Willet	118
Red Knot	112

Ocracoke Island CBC

Average annual abundance values during Ocracoke Island's CBC efforts was highlighted by the Ring-billed Gull, which was detected most frequently from 1981–2017 (1,983.75 detections/year).

The Herring Gull was also detected in comparatively high numbers (1,425.81 detections/year). Other species detected frequently included the Great Black-backed Gull (533.36 detections/year), Dunlin (290.31 detections/year), and the Sanderling (198.42 detections/year) (Table 36).

Table 36. Average annual abundance for the 10 most frequently observed species during the Ocracoke Island CBC from 1981–2017. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	Average number of individuals/Year
Ring-billed Gull	1,984
Herring Gull	1,426
Great Black-backed Gull	533
Dunlin	290
Sanderling	198
Red Knot	141
Willet	55
Marbled Godwit	55
Black-bellied Plover	44
Laughing Gull	44

Landbird Species Richness

As previously mentioned, landbirds in this assessment are those species of birds that have a principally terrestrial life cycle (Rich et al. 2004). Similar to the shorebird species richness measure, it is difficult to compare the results of the many avian studies in CAHA to each other due to the differing methodologies, focal species, and timing. This assessment presents the results of each study, but does not compare the species richness values between any studies.

NPS Certified Species List (NPS 2018)

NPS (2018e) is not well suited for an analysis of annual species richness, as no data are collected yearly. The NPS Certified Species List documents the presence (or historic presence) of the identified species and serves as a useful point of comparison to determine which species have been documented in the park.

The NPS Certified Bird Species List contains 366 species that are confirmed in the park, 189 (51.6%) of which are classified as landbirds by Rich et al. (2004) (Appendix L). The list also identifies three landbird species that may be present in the area, but are currently unconfirmed within CAHA boundaries. These species were the Nelson's Sparrow (*Ammospiza nelsoni*), Northern Goshawk (*Accipiter gentilis*), and the Rufous Hummingbird (*Selasphorus rufus*).

Pea Island National Wildlife Refuge Avian Checklist (USFWS 2006)

Much like NPS (2018), USFWS (2006) presents the avian species that have been documented in PINWR, or are suspected to occur in the refuge throughout various portions of the year. In total, USFWS (2006) documented 274 species as occurring in the refuge, 145 (52.9%) of which are

landbird species (Appendix L). Because of PINWR's close proximity to CAHA, the refuge likely has a very similar avian community structure as CAHA.

Bishop (1901)

The earliest published avian species list in the CAHA area, Bishop (1901) documented all species observed during a winter visit to Pea Island in 1901. Of the 40 species documented in the region, 15 (35%) were landbird species (Appendix L). The sampling/observation process of the single individual were poorly described, but aquatic habitats were sampled in high number, perhaps skewing the species groups that were documented.

Golder (1986)

Golder (1986) represents an informal bird survey, as researchers simply intended to document species use of an area on Bodie Island that was scheduled to be involved in a prescribed burn. This survey also appears to be the work of a single individual that did not follow any sort of rigorous or repeatable methodology. During this effort, 29 bird species were documented, and 15 (51.7%) of those were landbird species (Appendix L).

Cooper (1986)

Cooper's (1986) survey of Buxton Woods in 1986 documented 53 bird species, with the majority of those species (38 [72%]) being landbirds (Appendix L). Similar to the efforts of Golder (1986), Cooper (1986) looked only at an inland area of the park that contained ample habitat for landbird species, which likely explains the high proportion of landbird species observed compared to waterfowl or shorebird species.

Byrne et al. (2011)

Byrne et al. (2011a) is the only avian study to occur in the park that has focused exclusively on the landbird community of CAHA. While efforts focused on landbirds, Byrne et al. (2011) did not exclude shorebird species when one was observed. The total number of species observed in CAHA was 88 species, with 47 (53.4%) of those species being landbirds (Appendix L). Byrne et al. (2011) also documented two landbird species that had been previously unconfirmed in the park: the Nelson's sparrow, and the northern goshawk.

Christmas Bird Counts (Bodie, Hatteras, Ocracoke; 1981–2017)

Cumulatively, 135 landbird species (50% of all observation) were observed in CAHA between 1981 and 2017 (Appendix L). Data from the 2018 and 2019 count years exist, although they have yet to be summarized and published on the Audubon Society's online web portal. The results of each annual CBC are discussed individually below.

Bodie Island CBC

CBC efforts on Bodie Island between 1981 and 2017 resulted in the identification of 117 landbird species (43.3% of all observations). The maximum number of landbird species observed in a count was 80 species in 2003 (19 observers), while the fewest number of shorebird species observed was 58 in 2017 (26 observers) (Figure 54). The average number of shorebird species observed in a CBC on Bodie Island was 70.3 species, and the average number of observers per count was 26.8.

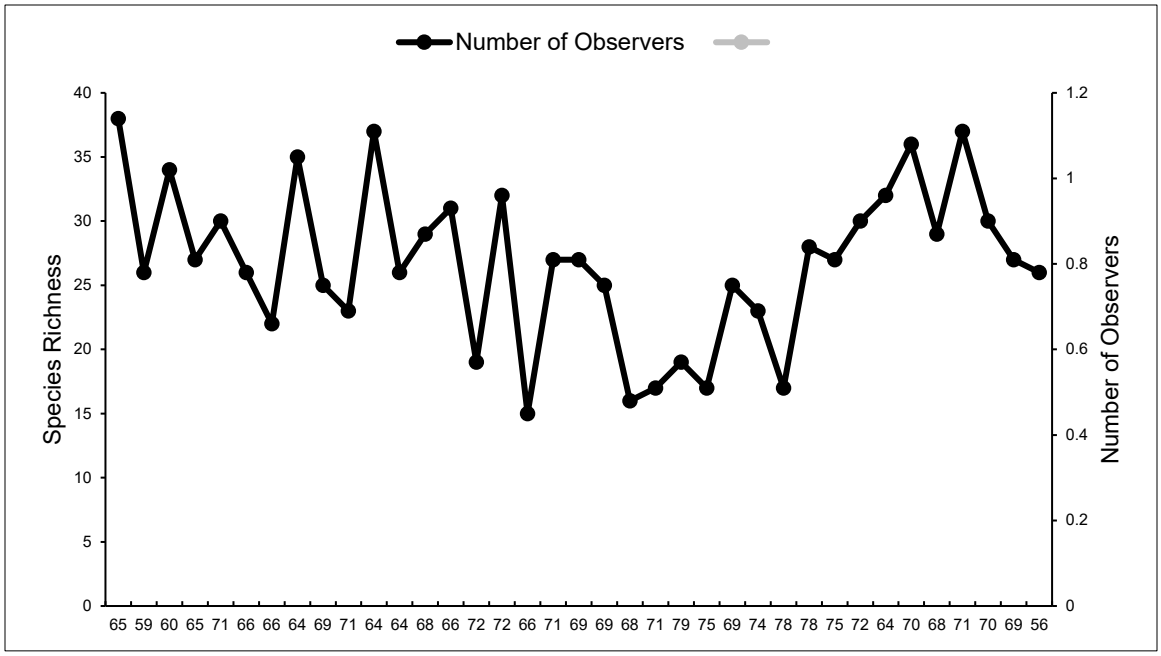


Figure 54. Number of landbird species and observers during the Bodie Island CBC between 1981 and 2017. Data retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Hatteras Island CBC

CBC efforts on Hatteras Island between 1981 and 2016 resulted in the identification of 125 landbird species (46.3% of all observations). The maximum number of landbird species observed in a count was 78 species in 1992 (36 observers), while the lowest number of landbird species observed was 54 in 1986 (12 observers) (Figure 55). The average number of landbird species observed in a CBC on Hatteras Island was 66.4 species, and the average number of observers per count was 26.7.

Ocracoke Island CBC

CBC efforts on Ocracoke Island between 1981 and 2017 resulted in the identification of 94 landbird species (34.8% of all observations); note that no count occurred in 1983. The maximum number of landbird species observed during a count was 52 species in 1989 (nine observers), while the minimum number of landbird species observed in a count was 25 in 2014 (number of observers not reported) (Figure 56). The average number of landbird species observed in a CBC on Ocracoke Island was 38.1 species, and the average number of observers per year was 11.5 (no observer data reported from 2013–2015).

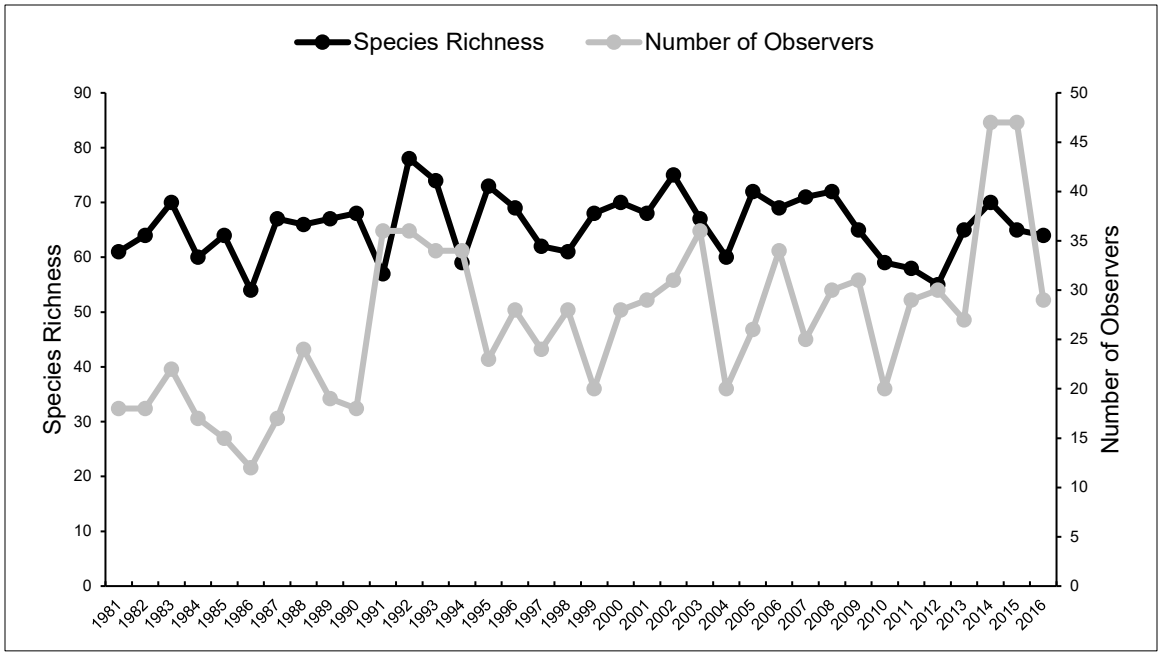


Figure 55. Number of landbird species and observers during the Hatteras Island CBC between 1981 and 2016. Data retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

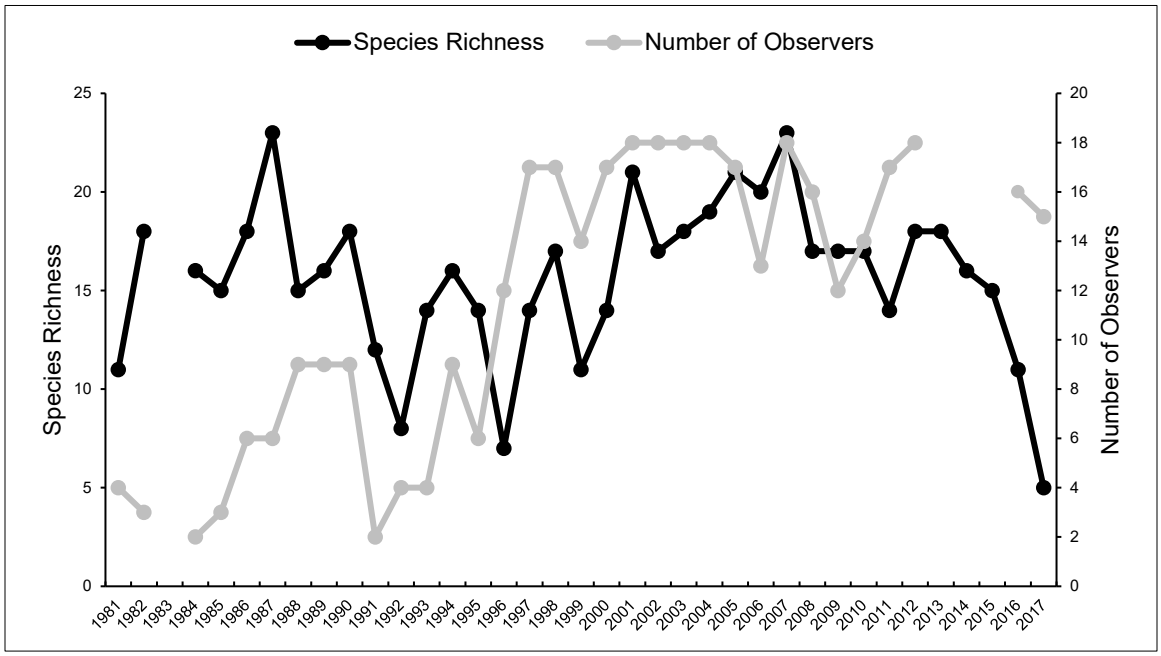


Figure 56. Number of landbird species and observers during the Ocracoke Island CBC between 1981 and 2017. Note that no count occurred in 1983, and that observer data from 2013–2015 are not reported on annual data summaries. Data retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Landbird Relative Abundance

Similar to the shorebird relative abundance measure, landbird species abundance refers to how many individuals are documented in a given survey/monitoring period. Often, the surveys that have taken place in CAHA have summarized abundance by the total number of observations made for each species, although some have further discussed the total proportion of all observations a species represents (relative abundance). Some studies (Cooper 1986) instead averaged abundance estimates across multiple surveys and censuses. It needs to be noted, however, that all species have different detection probabilities, and measures of abundance reported here should be considered "naïve" estimates, as they do not account for these variable detection probabilities.

Golder (1986)

Golder (1986) documented fifteen landbird species during an informal survey of an area on Bodie Island scheduled to be included in a prescribed burn. The Yellow-rumped Warbler (*Setophaga coronata*) was the most frequently detected species, with over 100 detections during the survey. Other landbird species were detected in much lower numbers, as the Fish Crow (*Corvus ossifragus*, eight detections) and the Red-winged Blackbird (*Agelaius phoeniceus*, six detections) were the next most frequently detected species (Table 37). A discussion of relative abundance is not possible, as the precise number of Yellow-rumped Warblers was not provided, which prevents an accurate creation of observation proportions.

Table 37. Number of detections for the 10 most frequently detected landbird species during the informal Golder (1986) survey of Bodie Island. Note that a precise number of yellow-rumped warblers was not provided due to their perceived abundance.

Common name	Number of detections
Yellow-rumped Warbler	100+
Fish Crow	8
Red-winged Blackbird	6
Boat-tailed Grackle	5
Eastern Towhee	4
Carolina Wren	3
Swamp Sparrow	2
Mourning Dove	2
Eastern Meadowlark	1
Northern Harrier	1
Belted Kingfisher	1
House Wren	1
Barn Owl	1
Gray Catbird	1
Sharp-shinned Hawk	1

Cooper (1986)

For this data source, abundance estimates were created by averaging the results of all 11 censuses that occurred at each of the seven habitat types. Results varied by habitat type (Appendix M), but the Northern Cardinal (*Cardinalis cardinalis*) was the most frequently detected species across nearly every habitat type (Table 38). The cardinal had the highest overall abundance estimates in the Wet Thicket habitat, averaging 12.82 detections/census. While 38 landbird species were documented by Cooper (1986), Table 38 displays the five most abundant species (highest average number of detections/census) in each of the seven habitat types sampled.

Table 38. The most frequently detected landbird species (based on average number of landbird individuals detected in each habitat per census) across all habitats (denoted by letters A–G) during Golder (1986). Eleven censuses across seven habitats were conducted during the spring of 1986.

	Avg. # of detections [a]						
Common name	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Northern Cardinal	–	**3.55** [b]	**5.45** [b]	**6** [b]	**12.82** [b]	**1.64** [b]	–
Pine Warbler	–	0.45	**3.73** [b]	1.09	–	–	–
Carolina Wren	–	**3** [b]	**3.64** [b]	**5.55** [b]	**11** [b]	**1.45** [b]	–
Blue Jay	–	**0.91** [b]	**1.91** [b]	**2.45** [b]	0.64	**0.45** [b]	–
American Crow	–	**1.09** [b]	**1.82** [b]	**2.18** [b]	1.09	0.09	**1.82** [b]
Red-winged Blackbird	**1.82** [b]	0.18	0.09	0.27	0.18	–	–
Wood Thrush	**0.09** [b]	–	0.09	–	–	–	–
Fish Crow	–	**1.09** [b]	0.36	0.82	0.82	**0.45** [b]	0.82
Prothonotary Warbler	–	0.45	–	**2.45** [b]	**3** [b]	–	–
Prairie Warbler	–	0.45	0.55	1.73	**5.27** [b]	**2.64** [b]	–
Common Grackle	–	0.64	1.09	0.45	**1.45** [b]	**0.82** [b]	**4.91** [b]
Brown-headed Cowbird	–	0.18	0.36	0.36	–	**0.45** [b]	**3**
Common Yellowthroat	–	–	–	–	**1.45** [b]	0.27	–
Purple Martin	–	–	–	–	–	–	**2.73** [b]
Barn Swallow	–	–	–	–	–	–	**1.82** [b]

[a] Habitat Zones: A = Pond and Edge; B = Mixed Hardwood; C = Mature Pine; D = Young Pine; E = Wet Thicket; F = Open Dry Thicket; G = Overhead

[b] Indicates the five most abundant species for each habitat zone (also in bold).

Byrne et al. (2011)

Byrne et al. (2011a) focused on the landbird population of CAHA, and while the report did not specify relative abundance metrics the way previous sources in this chapter did, it did document the proportion of the 30 sampling sites where a species was observed (Appendix N), and general evenness/dominance metrics.

During surveys of 30 sites in CAHA in 2010, no species was detected at all of the sampling sites. However, the Boat-tailed Grackle (*Quiscalus major*), Carolina Wren (*Thryothorus ludovicianus*),

Red-winged Blackbird, and Eastern Towhee (*Pipilo erythrophthalmus*) were detected at between 70–80% of all sites (Appendix N). Evenness and dominance indices calculated by Byrne et al. (2011a) (e.g., Smith and Wilson [E_{var}, $E_{1/D}$], Berger-Parker [D_{BP}]) indicated that the relative abundance of the bird species in CAHA were highly variable, with low evenness, and were not dominated by a single species (Table 39). It must be noted, however, that the evenness and dominance indices calculated by Byrne et al. (2011a) included all species, and were not limited to just landbirds. While the majority of species observed were landbirds, the results still must be viewed with caution as shorebirds, waterfowl, and wading birds are also included in the estimates.

Table 39. Evenness and dominance indices calculated by Byrne et al (2011). CI= Confidence Interval.

Index	Symbol	CAHA value	Lower 95% CI	Upper 95% CI	Interpretation
Smith and Wilson [a]	E_{var}	0.32	0.31	0.38	Species occur in several relative abundances, low evenness
Smith and Wilson 1/D [b]	$E_{1/D}$	0.27	0.26	0.33	Species occur in several relative abundances, low evenness
Gini [c]	E_G	0.34	0.23	0.45	Species occur in several relative abundances, low evenness
Berger-Parker [d]	D_{BP}	0.11	0.09	0.13	Sample is not dominated by a single species, diverse assemblage of species

[a] Values range from 0 (no evenness) to 1 (perfectly even and all species exists in relatively equal abundance); weighs common species more heavily than rare species (desirable in certain cases).

[b] Values range from 0 (no evenness) to 1 (perfectly even and all species exists in relatively equal abundance); weighs rare and abundant species equally (desirable in certain cases).

[c] Values range from 0 (no evenness) to 1 (perfectly even and all species exists in relatively equal abundance); Good discriminant ability and low sensitivity to sample size

[d] Values range from 0 (no single-species dominance) to 1 (sample is strongly dominated by a single species); describes the proportional dominance of the single most abundant species; low sensitivity to sample size but poor discriminant ability—not used for across year or site comparisons

Christmas Bird Counts (Bodie, Hatteras, Ocracoke; 1981–2017)

As discussed previously, the CBC takes place over the winter months when some migratory and breeding landbird species are no longer present in the area; the abundance estimates and species observed during these counts may look very different when compared to breeding or migratory season surveys. As was done with the species richness measure, landbird relative abundance estimates are discussed below for each of the three CBCs that occur in CAHA.

Bodie Island CBC

When looking at the average number of landbird individuals of a particular species per year from 1981–2017, the Yellow-rumped Warbler had the highest annual average abundance with 22,951

detections/count, and was seven times as numerous as the next most abundant species (American Robin [*Turdus migratorius*] – 3,073.22 detections/count) (Table 40). Other frequently detected species during the Bodie Island CBC included the Red-winged Blackbird, Fish Crow, and Boat-tailed Grackle (Table 40).

Table 40. Average annual abundance for the 10 most frequently observed landbird species during the Bodie Island CBC from 1981–2017. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	Average number of individuals/Year
Yellow-rumped Warbler	22,951
American Robin	3,073
Red-winged Blackbird	1,565
Fish Crow	660
Boat-tailed Grackle	386
Tree Swallow	363
Song Sparrow	269
Swamp Sparrow	140
Savannah Sparrow	120
Mourning Dove	109

Abundance estimates obtained by CBC efforts at Bodie Island in the past 5 years have generally been below average for the species identified in Table 35; the 5-year average (2013–2017) for these species was below the 37-year average for all but three species. Of the species identified in Table 35, no single species has experienced a decline in abundance as drastic as the fish crow. The 37-year average for this species was 660 species, but in the last 5 years, the highest estimate of Fish Crows observed during the Bodie Island CBC was six (Table 41). Yellow-rumped Warbler abundance has also been greatly reduced, as the highest number of individuals observed in the past 5 years was 2,585 individuals in 2014, below the 37-year average of 3,073 individuals (Table 41). The 2017 Bodie Island CBC appears to have been a low count year, as low species abundances were documented for nearly all species encountered.

Perceived trends from CBC effort could be due to observer effort, untrained observers, or other variabilities that could be attributed to the lack of a rigorous, repeatable sampling methodology.

Table 41. Average annual abundance estimates from 2013–2017 CBC efforts for the 10 species historically detected most frequently at Bodie Island. Negative values are also shown in red text. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx. Note: departure from average has not been tested for statistical significance, and represents only the difference between the 5-year average and the 37-year average.

Common name	2013	2014	2015	2016	2017	5-Year Avg.	Departure from 37-year average
Yellow-rumped Warbler	2,585	1370	935	730	903	1,304.6	−1,762
American Robin	8	7220	219	1,093	121	1,732.2	167.47
Red-winged Blackbird	807	1,700	410	560	124	720.2	60.17
Fish Crow	2	0	0	6	0	1.6	−384.13
Boat-tailed Grackle	369	376	229	188	25	237.4	−125.17
Tree Swallow	621	0	1410	33	62	425.2	155.85
Song Sparrow	103	108	43	74	64	78.4	−61.57
Swamp Sparrow	194	102	37	52	48	86.6	−32.91
Savannah Sparrow	133	121	48	72	55	85.8	−23.34
Mourning Dove	142	170	39	72	58	96.2	−9.12

Hatteras Island CBC

The Yellow-rumped Warbler had the highest average number of individuals detected per year during the Hatteras Island CBC, with 3,437.64 detections per year (Table 42). Only one other species approached the numbers of the yellow-rumped warbler, as the American Robin was detected an average of 1,258.14 times per/count (Table 42). While less abundant, other frequently detected species at Hatteras Island included the Red-winged Blackbird, Boat-tailed Grackle, Cedar Waxwing (*Bombycilla cedrorum*), and Fish Crow (Table 42).

Table 42. Average annual abundance for the 10 most frequently observed landbird species during the Hatteras Island CBC from 1981–2016. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	Average number of individuals/Year
Yellow-rumped Warbler	3,438
American Robin	1,258
Red-winged Blackbird	267
Boat-tailed Grackle	224
Cedar Waxwing	168
Fish Crow	158

Table 42 (continued). Average annual abundance for the 10 most frequently observed landbird species during the Hatteras Island CBC from 1981–2016. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	Average number of individuals/Year
Mourning Dove	156
Common Grackle	146
Northern Cardinal	126
Carolina Wren	106

The most recent 5-year (2012–2016) average abundance estimates were below the 37-year average for all ten species (Table 43). Abundance estimates were particularly low in 2016, with every species falling well below their historic average. Yellow-rumped Warbler estimates declined below 1,000 detections twice in the last 5 years (2013, 2016), which represent departures of over 50% from their 37-year average. The Fish Crow has drastically declined in abundance in recent years, with a peak abundance estimate of just three individuals in 2015, and zero detections in 2012 and 2013. This is a noteworthy departure from the 37-year average of 97 detections per year.

Table 43. Average annual abundance estimates from 2012–2016 CBC efforts for the 10 landbird species historically detected most frequently at Hatteras Island. Negative values are also shown in red text. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	2012	2013	2014	2015	2016	5-Year Avg	Departure from 37-year average
Yellow-rumped Warbler	615	2,629	2,832	4,318	912	2,261.20	−1,176.44
American Robin	38	482	1833	103	1702	831.60	−426.54
Red-winged Blackbird	53	336	484	286	82	248.20	−18.63
Boat-tailed Grackle	1	300	128	125	48	120.40	−103.13
Cedar Waxwing	26	87	15	484	48	132	−35.61
Fish Crow	0	0	1	3	2	1.20	−156.52
Mourning Dove	89	136	140	124	79	113.60	−42.71
Common Grackle	169	0	13	56	6	48.80	−97.31
Northern Cardinal	48	74	135	92	56	81	−45.39
Carolina Wren	28	50	101	123	56	71.60	−33.90

Ocracoke Island CBC

The Yellow-rumped Warbler had the highest average number of individuals detected per year (1,561.83 detections) during the Ocracoke Island CBC, and had an average of over five times as

many detections/year as the next most abundant species (American Robin) (Table 44). While less abundant, other frequently detected species at Ocracoke Island included the Fish Crow, Mourning Dove (*Zenaida macroura*), Red-winged Blackbird, and Gray Catbird (*Dumetella carolinensis*) (Table 44).

Table 44. Average annual abundance for the 10 most frequently observed landbird species during the Ocracoke Island CBC from 1981–2017. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	Average number of individuals/Year
Yellow-rumped Warbler	1,562
American Robin	303
Fish Crow	177
Mourning Dove	63
Red-winged Blackbird	61
Tree Swallow	36
House Finch	34
Cedar Waxwing	33
Common Grackle	32
Gray Catbird	22

Recent 5-year (2013–2017) average abundance estimates were below the 37-year average for eight of 10 species (Table 45). Abundance estimates were particularly low in 2014, with six of the 10 historically most abundant species being absent from count results. It should briefly be noted that observer effort statistics were not available for 2014, and these results could be the result of low observer turnout. Despite being detected in high numbers for the first 15–20 years of the CBC, the fish crow has drastically declined in abundance in recent years, and has not been detected on the Ocracoke CBC since 2009.

Table 45. Average annual abundance estimates from 2013–2017 CBC efforts for the 10 landbird species historically detected most frequently at Ocracoke Island. Negative values are also shown in red text. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	2013	2014	2015	2016	2017	5-Year Avg	Departure from 37-year average
Yellow-rumped Warbler	1,940	166	768	1,571	1,227	1,134.40	−427.43
American Robin	35	41	0	665	478	243.80	−59.06
Fish Crow	0	0	0	0	0	0	−177.44
Mourning Dove	44	30	266	36	46	84.40	21.68
Red-winged Blackbird	8	0	17	1	97	24.60	−36.79
Tree Swallow	75	0	15	0	4	18.80	−16.89

Table 45 (continued). Average annual abundance estimates from 2013–2017 CBC efforts for the 10 landbird species historically detected most frequently at Ocracoke Island. Negative values are also shown in red text. Data were retrieved from http://netapp.audubon.org/CBCObservation/Historical/ResultsByCount.aspx.

Common name	2013	2014	2015	2016	2017	5-Year Avg	Departure from 37-year average
House Finch	12	0	25	17	15	13.80	−20.53
Cedar Waxwing	110	0	18	0	0	25.60	−7.12
Common Grackle	400	0	390	0	0	158	126.11
Gray Catbird	30	2	8	15	22	16	−6.06

Threats and Stressor Factors

Bird species face deteriorating habitat conditions along their migratory routes, breeding grounds, and on wintering grounds. Most of the birds that breed in the U.S. winter in the Neotropics (MacArthur 1959); deforestation in these wintering grounds has occurred at an annual rate up to 3.5% (Lanly 1982). While forest and habitat degradation does occur in the U.S., it does not approach the level of degradation seen in the tropics (WRI 1989). Furthermore, Robbins et al. (1989) supported the suggestion that deforestation in the tropics has a more direct impact on Neotropical migrant populations than deforestation and habitat loss in the U.S. In an evaluation of 529 bird species from the continental U.S., Rosenberg et al. (2019)estimated that nearly 3 billion birds have been lost, a reduction of 29% of 1970 global abundance estimates across all North American Biomes, indicative of a continuing and ongoing avifaunal crisis. Species overwintering in South American have experienced a net reduction in abundance of 40% (Rosenberg et al. 2019).

Wetlands represent a habitat type that has been declining across much of the continental U.S., with Dahl (1990) estimating that 53% of the wetlands in the continental U.S. were lost between 1780 and 1980. The wetlands of CAHA are diverse and include freshwater wetland swales, open ponds, tidal salt marsh, and high salt marsh. Wetlands in CAHA have been heavily impacted by historic human use, with ditching and drainage features across the landscape that have likely resulted in significant changes in wetland plant species composition (see discussion in Chapter 4.3 of this document). Wetlands represent a critical habitat for many avian species of concern, particularly in CAHA, and these changes in community structure likely dramatically impacted avian species in regards to abundance, richness, and density. Any additional changes to these communities should be monitored to prevent additional declines in avian abundance.

Some intermittently-flooded wetlands within the park have been invaded by the aggressive non-native grass, common reed (McManamay et al. 2018). Common reed is a perennial plant that can reach 3 m (10 ft) tall and can spread up to 2 m (6.6 ft) annually through the vigorous vegetative growth of rhizomes (NPS 2016f). Also, a prolific seed producer, common reed can sustain densities of up to 300 stems per square meter (Hara et al. 1993, NPS 2016f). These characteristics allow the species to completely dominate a wetland and exclude native plants (Chambers et al. 1999, McManamay et al. 2018). In 2012, approximately (800 ac) of brackish marsh within CAHA was

severely impacted by common reed (NPS 2016f). Since that time, park managers have been cooperating with the Southeastern Exotic Plant Management Team (now the Southeastern IPMT) to chemically treat isolated patches of the species in an effort to stop the spread of this invasive plant into even more natural communities. Staff use backpack sprayers to apply herbicide during the summer and early fall when common reed is actively growing, but multiple treatments are usually required to eliminate these patches (NPS 2013b, 2016f). In the summer of 2013, for example, the IPMT crew treated 1.5 ha (3.8 ac) of common reed in the Cape Point area between Ramps 44 and 45 (NPS 2013b).

While the threat of predation is a natural occurrence for avian species, there are several instances of predation from non-native animals that represent a more substantial threat. Annual shorebird monitoring in the park has identified that predation of eggs and chicks are one of the most common stressors affecting shorebird in the park. Predation from non-native species (such as feral dogs [*Canis lupus familiaris*] or cats [*Felis catus*]) has a significant impact on nesting shorebird and priority avian species. Domestic and feral cats are one of the largest causes of bird mortality in the United States, including National Park lands. (Loss et al. 2013, Dayer et al. 2019). According to Loss et al. (2013), annual global bird mortality caused by outdoor cats is estimated to be between 1.4 and 3.7 billion individuals. The median number of birds killed by cats annually was estimated at 2.4 billion individuals, and almost 69% of bird mortality due to cat predation was caused by un-owned cats (i.e., strays, barn cats, and completely feral cats) (Loss et al. 2013). Feral cats are present on all three CAHA islands, and from 2010–2015, a total of 188 cats were captured and removed from the park (NPS 2015b). Beginning in 2018, the U.S. Department of Agriculture (USDA), in conjunction with the NPS, has led trapping efforts on the islands of CAHA in an effort to remove predators of shorebirds. The predators of greatest concern on the islands include the coyote (*Canis latrans*; Bodie Island), red fox (*Vulpes vulpes*; Cape Point), raccoon (*Procyon lotor*; Cape Point, Ocracoke Island), feral cat (Ocracoke Island), and mink (*Neovison vison*, Ocracoke Island). Traps are set on the islands during shorebird nesting season, and are placed around suspected nesting areas for up to 15 days (Doshkov et al. 2018b).

Temperatures are projected to rise across the southeastern United States over the next century as a result of global climate change (Carter et al. 2014). This increase in temperatures will likely increase evapotranspiration rates, meaning that even if annual precipitation remains constant or slightly increases, overall conditions could become drier in the future (Carter et al. 2014). An additional effect of temperature increases is that the frequency and intensity of droughts will also increase (Karl et al. 2009, DeVivo et al. 2011), which will likely have a negative impact on important wetland bird habitats. Drought represents a major threat to most of the natural resources in CAHA. Not only do periods of drought remove potential sources of standing water in CAHA (particularly the freshwater wetland areas), but these periods also affect availability of food for birds. Drought may reduce forage items such as insects and plant species (Smith 1982), and could lead to starvation for many birds in the park. Another impact of drought is that it may alter the nesting success of species, as some colonial nesting species have been observed relocating entire rookeries in response to drought conditions (Gaines et al. 2000). Drought could also interrupt or alter the migratory patterns of species (Zeng 2003, Dai et al. 2004, Gordo 2007).

Climate change-driven SLR can increase the likelihood of saltwater intrusion into freshwater wetlands, particularly wetlands close to the shoreline. These areas affected by SLR are often vitally important nesting, staging, and foraging areas for shoreline species, as well as migrants passing through along the coast. Saltwater intrusion can occur over land during flooding or by encroaching into the shallow surficial water table (Ataie-Ashtiani 2013). A sudden increase in salinity from saltwater intrusion can diminish or kill off aquatic vegetation and macroinvertebrates not adapted to saline or brackish conditions, altering plant community composition and altering critical avian food sources and habitat (McKee and Mendelssohn 1989, Riggs and Ames 2003). In addition to increasing salinity, storm surge and overwash events can physically alter avian habitats by redistributing sand and uprooting or otherwise damaging vegetation (USGS 2016c, McManamay et al. 2018). Washovers due to storms and high tides have been identified as a major factor in shorebird nest failure (D. Hallac, pers. comm., July 2020). If SLR continues or accelerates, tidal saltmarshes may become permanently inundated, killing off the wetland vegetation and displacing nesting or foraging avian species (Feldman et al. 2009, Schupp 2015).

Being located along a major migration route, CAHA is frequently home to migratory "fallout" events. Fallouts occur when migrating birds descend to the ground in large numbers in response to a disturbance of some kind. While exhaustion is one of the most common causes of fallout, many factors can influence a species' migration pattern and cause fallout events. Examples of these factors include food availability (Niles et al. 1996), the presence of a large desert (Berthold 1993) or open body of water (Alerstam 1990), topographic features (Berthold 1993, Strickland 2015), or adverse weather events (Alerstam 1990, Niles et al. 1996). In CAHA, weather-related fallout events are common, as hurricanes and strong thunderstorms may occur along the coast during migratory periods. Spring fallout events in North Carolina may occur after strong, fast-moving cold fronts move across the coast. The heavy rain and wind that accompany these cold fronts force migratory birds to the ground to avoid exhaustion. Migratory species that reach CAHA via a transoceanic flight (across the Caribbean Sea or Gulf of Mexico) typically avoid periods of unfavorable weather, and large-scale movements often coincide with favorable wind conditions (Richardson 1976, Williams et al. 1977, Williams 1985, Moore et al. 1995, Butler 2000). Birds migrating over landmasses tend to ground when wind and weather conditions deteriorate (Butler 2000).

Recreational use of the island's beaches represents a threat to the avian community of CAHA, particularly the shorebird nesting species. The habitat of many avian species of concern is in areas vulnerable to human disturbance, usually caused by pedestrian or off-road vehicle (ORV) use. CAHA establishes seasonal ORV closures, and vehicle-free areas along the beach. While these vehicle free areas are primarily for providing a non-motorized experience, they also provide areas that protect breeding bird habitat from ORV use. Additional wildlife enclosures are also established to protect identified shorebird nesting areas, these areas are generally established to protect nests from pedestrian and off-leash dog traffic, as these stressors present a greater threat to birds than ORV use (D. Hallac, pers. comm., July 2020). In 2018, resource management staff at the park documented 429 pedestrian, 21 ORV, and 52 dog/boat/horse intrusions in these wildlife protection areas (areas that include all prenesting areas and wildlife buffers around important habitats) (Doshkov et al. 2018b). The exact number of intrusions or disturbances in the park is difficult to estimate, as direct

observations often are not reported, and evidence of the intrusions is either washed away by tide or blown away (tracks in the sand). It is important to note, however, that these intrusions do not necessarily have any direct relationship to disturbance of wildlife in those areas. Pedestrians that disturb avian species often have to make a concerted effort to get around park-installed barriers (string fence) and signage. Unleashed dogs in the park also represent a major concern to nesting shorebird species, and the number of these types of disturbances in the park are currently unknown.

According to the USFWS, avian collisions with vehicles are believed to be one of the most common causes of avian mortality in the U.S. Loss et al. (2014) estimates that between 89 and 340 million birds die annually from vehicle strikes on U.S. roads. With Highway 12 bisecting much of CAHA, the risk of vehicle strikes is elevated across many habitats. Ground nesting birds and juvenile waterfowl are at particular risk as they travel at heights near a vehicle's strike zone. Another group of species at particular risk of vehicle strikes are water birds and gulls, especially on bridges perpendicular to wind direction, as winds travelling across bridges can direct or propel these birds into oncoming traffic (Jacobson 2005). Predatory avian species such as raptors, and scavengers such as vultures, are often struck while foraging on roadkill or while chasing prey species along traffic corridors.

Data Needs/Gaps

Continuation of shorebird monitoring in the park (Doshkov et al. 2018b) is needed to analyze and observe trends in priority and at-risk shorebird species. While there have been several shorebird studies focusing on a subset of priority species in the park (e.g., American Oystercatcher, Piping Plover), a broad summary and characterization of the shorebird community is needed. While the metrics reported on here included species richness and species abundance, nesting success parameters for the broad shorebird community would provide a clearer picture into the fledging rates and overall community health for all shorebird species. According to CAHA staff, the priority data needs and gaps in understanding the productivity and use habitats by shorebirds is related to:

1. Understanding the biotic and abiotic factors affecting their productivity;
2. Understanding the impacts of predator management;
3. Understanding how forage availability and habitat quality affects productivity;
4. Understanding the role of CAHA habitats as sink versus source and primary habitat within the species' range; and
5. The effects of the loss of habitat due to erosion, which has been severe (miles lost of the last decade), and SLR's effect on habitat availability and quality (D. Hallac, pers. comm., July 2020).

The SECN landbird monitoring effort of Byrne et al. (2011a) have continued and these data will be used to better characterize the landbird species richness and relative abundance of the park, and to analyze any potential trends in species presence or abundance over a longer period. Currently, data from only a single field season have been reported (2010), and those data were considered outdated

and unable to be used to assess current condition of this resource. Parkwide surveys have been conducted again in 2015 and in 2020, however, these data sets were not available to assess more recent and/or current conditions. The resident landbird population in CAHA serves as an excellent indicator of the entire park's health, and a routine monitoring program could provide managers with a better understanding of the health of both the resident bird population and the many CAHA ecosystems.

Citizen science-based initiatives such as eBird could be summarized and may provide park managers with an enhanced species list for the park. Many of the observations reported via eBird include photographic documentation, as well as spatial coordinates of the observations, and park managers could verify observations as confirmed without the use of a formal avian survey in the park. These citizen science efforts, including surveys and counts like the annual CBCs, and International Migratory Bird Day, are beneficial to document species that occur in the park and can help to continually update the park's confirmed species list (NPS 2018e).

Nesting shorebirds have received a good deal of attention from CAHA, as nesting enclosures and opportunistic documentation of nest disturbances are noted during annual shorebird monitoring. Expansion of these efforts to see how landbirds or non-priority shorebird species are affected may provide managers with a broader picture of how the avian community in the park is impacted by these disturbances.

This assessment was conducted without having access to annual waterfowl harvest data for Bodie Island. Authors were not made aware of the existence of this data until late in development, and the summarization and synthesis of these data were not possible. Future assessments of avian condition should summarize these data so that the annual waterfowl harvest metric may be accurately assessed. The publication of these data as a standalone summary or resource brief may also be beneficial to researchers and the general public.

Overall Condition

While there can be little doubt that CAHA provides important bird habitat for a variety of species, data as they relate to the specific measures of this assessment are lacking or are now out of date and do not provide an accurate snapshot-in-time picture of the park's current health. The most recent avian survey that focused on non-priority species (i.e., species not identified as focal shorebirds) was completed nearly 10 years ago (Byrne et al. 2011a). While CBC data are available from relative recent counts, count data can be unreliable (see previous discussion in this section), and only captures the avian community of the park on 1 day during the winter; a large portion of the park's avian community (e.g., breeding birds) are underrepresented in these counts. While current condition is not assigned to this component, it is important to recognize that this is not a statement of poor health or condition, but rather represents a need for expanded research and data collection for this very diverse community in the park. CAHA draws visitors from across the world to view its unique avifauna, and an expansion of knowledge as it relates to current conditions and community structure would be very beneficial.

Shorebird Species Richness

The NRCA project team assigned this measure a *Significance Level* of 3 during project scoping. CAHA is home to many different shorebird species (an estimated 81 species). However, the collective shorebird community of the park has been understudied. CAHA monitors and summarizes the annual reproductive success of priority shorebird species (Piping Plovers, Red Knots, American Oystercatchers, and Wilson's Plovers) yearly (Doshkov et al. 2018b). Yet the park is in need of broad shorebird surveys across all islands in order to accurately document the species composition of the islands. Species richness estimates for priority species are well documented, however the species richness of the community as a whole represents a data gap. A *Condition Level* for shorebird species richness was not assigned due to a lack of contemporary data related to the community as a whole.

Shorebird Relative Abundance

A *Significance Level* of 3 was assigned to the shorebird relative abundance measure. Similar to the shorebird species richness measure, the relative abundance of the shorebird community as a whole represents a data gap. Priority shorebird species continue to be monitored for reproductive success (Doshkov et al. 2018b), but even these species have data gaps related to relative abundance across all islands of the park. Until more expansive and contemporary data are available for the shorebird community as a whole, a *Condition Level* cannot be assigned to this measure.

Landbird Species Richness

The NRCA project team assigned this measure a *Significance Level* of 2 during project scoping. CAHA is home to a large number of landbird species (estimated at nearly 200 species), including rare vagrant species as they pass through the park during migration. Monitoring of the park's landbird community has been sporadic, with the most recent data coming from annual CBC efforts. Byrne et al. (2011a) established a baseline for the landbird community of the park, but has not been repeated and is now almost 10 years old. Continuation and summarization of network monitoring and data analysis will allow for a more accurate depiction of the park's landbird species richness. While it is unlikely that the species richness of the park's landbird community is in poor condition, until more recent data become available, a *Condition Level* for this measure cannot be accurately assigned.

Landbird Relative Abundance

A *Significance* of 2 was assigned to the landbird relative abundance measure. As discussed previously with the shorebird relative abundance measure, the only data that exist for this measure are either not suitable for a snapshot-in-time condition assessment (Byrne et al. 2011a), or are only representative of a single day's survey that captures the migratory and overwintering community and underrepresents the breeding community (CBC efforts). A *Condition Level* was not assigned to this measure.

Annual Waterfowl Harvest

This measure was assigned a *Significance Level* of 1. Measures with a *Significance Level* of 1 are not discussed in depth in the current condition section of this assessment, but available information is summarized here in the overall condition section. Like other measures in this assessment, this metric represents a data gap at the time of publication. CAHA is one of the rare NPS units that allows waterfowl harvest annually. Complete regulations and guidelines for hunters utilizing CAHA lands

for hunting are available at https://www.nps.gov/caha/planyourvisit/waterfowlhunting.htm. CAHA also provides a limited number of maintained, semi-permanent blinds, and in 2019 constructed a handicap accessible blind and wildlife viewing platform about 3.2 km (2 mi) north of the Bodie Island Lighthouse (Figure 57). Data related specifically to annual waterfowl harvest were not available at the time of publication. Without these data, a *Condition Level* was not assigned to this measure. Future assessments of condition should summarize the available harvest data from Bodie Island and fill in this data gap for managers.

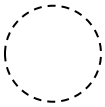


Figure 57. A handicap accessible hunting and wildlife viewing blind in Bodie Island Marsh (NPS Photo).

Weighted Condition Score

The *Weighted Condition Score* for the birds component in CAHA is currently undefined (Table 46). While it is known that the park has a broad assemblage of birds, additional annual monitoring of the many groups of birds, specifically shorebirds and landbirds, is needed. There are several species of high conservation concern that utilize the park at various stages of the year, and annual monitoring would also help to identify potential trends in these species.

Table 46. Current condition and trend for the Birds of CAHA.

Measures	Significance Level	Condition Level	WCS = N/A
Shorebird Species Richness	3	n/a	–
Shorebird Relative Abundance	3	n/a	–
Landbird Species Richness	2	n/a	–
Landbird Relative Abundance	2	n/a	–
Annual Waterfowl Harvest	1	n/a	–
Overall	–	–	

Sources of Expertise

Tracy Ziegler, CAHA Chief of Resource Management and Science

Michael Parrish, SECN Wildlife Biologist

Mammals

Description

Mammals are important components of healthy ecosystems; small mammals provide food for predatory birds, reptiles, and other mammals, while carnivores control herbivore and granivore species that can harm vegetation if populations become too high (Cook et al. 2006, Roemer et al. 2009). Mammals can also influence habitat successional dynamics by feeding on plants and insects at varying intensities (Cook et al. 2006). According to the NPS certified species list for CAHA (NPS 2018e), 26 terrestrial mammal species have been confirmed at the park, eight marine mammals are considered probably present, and one terrestrial mammal is classified as unconfirmed (hispid cotton rat [*Sigmodon hispidus*]) (Appendix O). Six of the terrestrial mammals are non-native, and one of these (domestic dog [*Canis familaris*]) is not considered a permanent resident of the park (Webster 2010, NPS 2018e). The majority of CAHA's terrestrial mammals have broad habitat tolerances and are widely distributed throughout the southeastern U.S. (Webster 2010).

Islands and coastal areas often exhibit low native mammal diversity, partly because they are vulnerable to catastrophic, habitat-altering weather events (e.g., hurricanes, nor'easters) (Webster 2010). The size and accessibility of islands strongly influence mammal species richness (Engels 1942, Webster and Reese 1992). Larger islands often contain more habitat types in larger patches that may be more sheltered from the elements, and can therefore support more mammal species. Islands that are farther from the mainland and lack artificial connections (e.g., bridges, road causeways) may have lower mammal species richness because they are more challenging to colonize, particularly for small mammals. Based on these patterns, Ocracoke would be expected to have the fewest mammal species of CAHA's islands based on its size, distance from the mainland, and lack of physical connection to any other land (Webster and Reese 1992). Bodie Island would be expected to have higher mammal species richness because it is currently connected to the mainland at its northern end and by several bridges further south; additionally, its size allows for a diversity of habitat types (Engels 1942).



The eastern cottontail (*Sylvilagus floridanus*, left) and muskrat (*Ondatra zibethicus*, right) are two mammals common at CAHA (USFWS photos).

Measures

- Mesocarnivore species richness[1]
- Small mammal species richness
- White-tailed deer density

Reference Condition/Values

Identifying a reference condition for CAHA's mammal populations is challenging, given the shifting conditions on Outer Banks barrier islands. Species may be extirpated by extreme events or habitat change and recolonize decades later, contributing to the difficulty in classifying species as native or non-native. The undeveloped islands of CALO may offer some insight as a baseline, as there are no bridges to those islands and no paved roads on the islands (NPS 2017c). At this time, the reference condition for species richness measures at CAHA is undefined, although the information provided in this assessment may serve as a baseline for future assessments.

Very few studies of white-tailed deer density have been conducted on Atlantic Coast barrier islands and no target or goal levels have been published for the northern Outer Banks region. In a 2008–2009 study of deer populations on Bald Head Island, off the coast of southern North Carolina, Sherrill et al. (2010) documented deer densities of 15–17 per square km (38–44 per square mi). The authors recommended that the population be managed at that level to "prevent degradation of important maritime forest habitat" until further research could be conducted (Sherrill et al. 2010, p. 38). This number could serve as an informal reference point until a target more specific to the CAHA island environment is identified.

Data and Methods

Several studies over time have recorded the occurrence of mammal species on CAHA's islands. Engels (1942) spent 38 days on Ocracoke Island between the summer of 1940 and spring of 1942 documenting the island's vertebrate fauna. Engels (1942) reported species that were present and those that were "probably absent;" a species was considered probably absent "only when rigorous inspection of all observable or obtainable facts indicates that a species can be excluded, without reasonable doubt" (Engels 1942, p. 293). Decades later, Lee et al. (1982) published a state-wide distributional survey of North Carolina's mammals, which included the Outer Banks.

Boone (1988) compiled a list of mammal species for the Bodie and Hatteras Island portion of CAHA, based on trapping and observations by the author, as well as reports from other reliable observers. The list also includes relative abundance estimates for each species, based largely on "the ease of observation/capture of the animal or its sign" (Boone 1988).

[1] A mesocarnivore is any species in the order Carnivora that is small or mid-sized (i.e., <15 kg [33 lbs]) (Roemer et al. 2009).

Webster and Reese (1992) explored patterns in mammal diversity on North Carolina barrier islands based on differences in island size and distance to mainland (i.e., accessibility). The study included all three CAHA islands, Roanoke Island to the west, and six additional islands south of the park.

Webster (2010) attempted to document mammalian species that were present in all 19 SECN parks. The study had two major objectives:

1. To visit major North American museums in order to inspect/document mammal specimens that were either collected within or adjacent to park boundaries, and;

2. To visit each of the 19 SECN parks and conduct extensive field sampling in order to confirm/refute a species' presence and to document the overall mammalian faunal community in the park.

For the CAHA portion of the inventory, Webster (2010) utilized historic mammalian inventories (e.g., Parnell et al. 1992), checklists, and museum specimens to estimate what species were likely to inhabit the island. Nineteen museum collections were found to have mammal specimens from Dare and Hyde Counties, where CAHA is located. Site visits occurred between January and July of 2005 (Webster 2010). In total, five major habitats were selected for monitoring: dunes and overwash terraces, maritime shrub thickets and forests, swales and ponds, estuarine marshes, and out-buildings and piles of debris. No trapping was conducted, but each site was surveyed for evidence of mammals (e.g., scat, shed, tracks). Sites visited included locations sampled by Parnell et al. (1992). Bat surveys were conducted in Buxton Woods on four nights using SONOBAT (Webster 2010).

Park staff provided 2010–2015 and 2019 data from a trapping program that targeted mammalian predators of protected shorebird species and sea turtle hatchlings (NPS 2012c, 2015b, USDA Wildlife Services 2019). The objective of the program was to reduce the loss of federal and state-protected species at any life stage to predation by mammals, which poses a direct threat to species recovery efforts. It was not intended to completely eliminate mammalian predation or to eradicate any mammal species, whether native or non-native (NPS 2012c). Traps were set within 1.6 km (1 mi) of recent shorebird breeding areas; targeted species included feral cats (*Felis catus*), raccoon (*Procyon lotor*), mink (*Mustela vison*), Virginia opossum (*Didelphis virginiana*), gray fox, red fox, coyote (*Canis latrans*), and bobcat (*Lynx rufus*). Although not a predator, the non-native nutria (*Myocastor coypus*) was also targeted to reduce the damage these animals can cause in critical wetland habitats (Jojola et al. 2005, NPS 2012c).

Lastly, deer harvest data for Buxton Woods (2010-present) and Dare County (2003-present) were obtained from the North Carolina Wildlife Resources Commission (NCWRC) website (NCWRC 2018b). Deer hunting is not allowed within CAHA boundaries, but there are 403 ha (995 ac) of "public game lands" in Buxton Woods outside and adjacent to park boundaries where deer hunting is allowed (Figure 58).

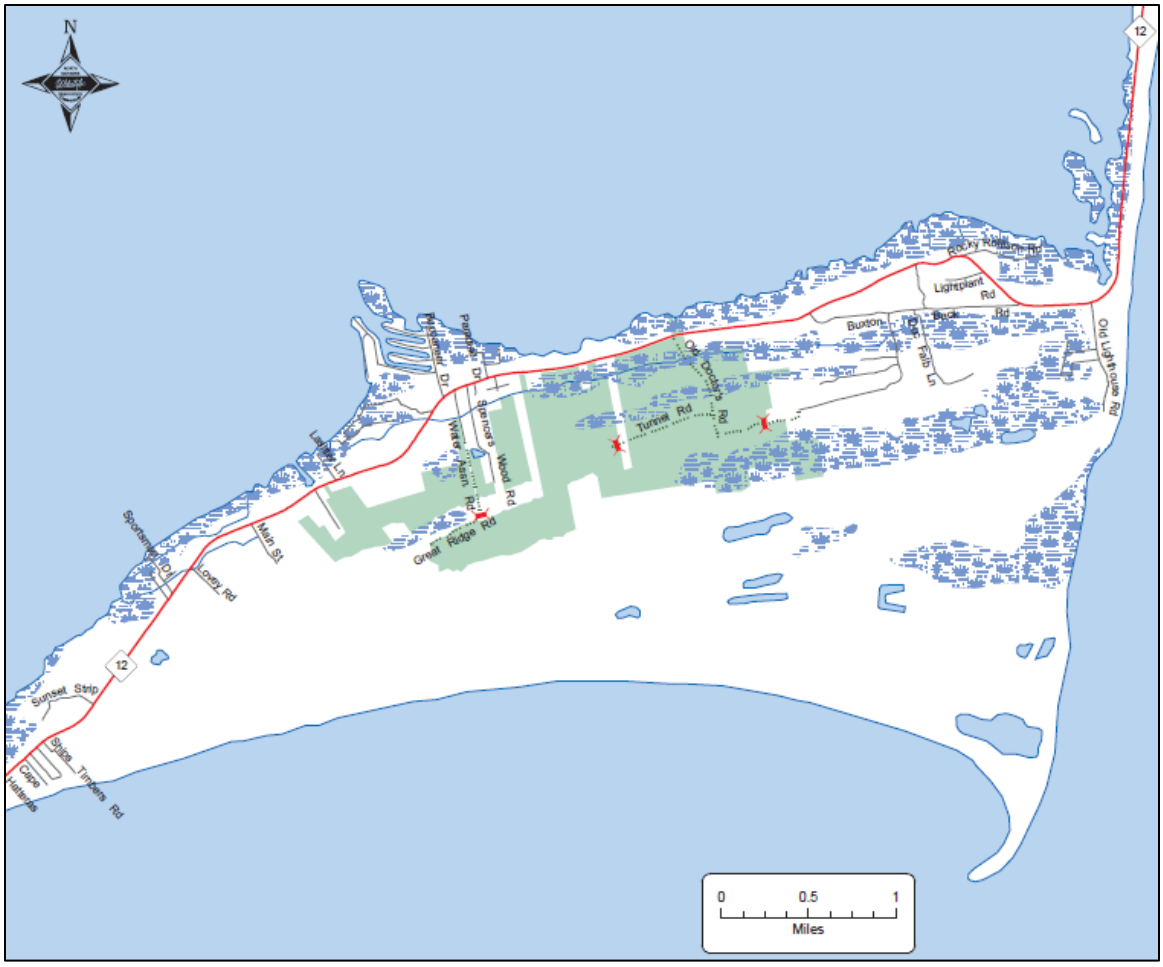


Figure 58. Public game lands (in green) within Buxton Woods on Hatteras Island (reproduced from NCWRC 2004).

Current Condition and Trend

Mesocarnivore Species Richness

Mesocarnivores typically have higher annual species richness numbers and more diverse behaviors and ecology than the larger carnivore species. Because of the relatively small size of mesocarnivores, and the fact that they can survive and thrive in a variety of habitat types, mesocarnivores are sometimes more abundant in a given habitat type compared to other mammals (Roemer et al. 2009). The size of the coyotes at the park is not well documented, as the species is thought to have arrived at CAHA (Bodie Island only) in the early 2000s. While coyotes sometimes have a body mass that exceeds the mesocarnivore range (Bekoff and Gese 2003), the project team elected to include coyotes in this measure (Tracy Ziegler, email communication, February 2019).

According to NPS (2018e), six mesocarnivore species occur at CAHA (Table 47). Only the feral cat is identified as non-native, but the red fox is considered a newer arrival, as it was not detected within the park prior to the late 1990s. Former NPS staff believe the red fox moved in along Bodie Island and reached the Cape Point/Cape Hatteras Lighthouse area in 2000–2001 (Webster 2010). All six of

these mesocarnivores were observed on Bodie and Hatteras Islands and four of the species (excluding the foxes) were observed on Ocracoke Island by Webster (2010). For comparison, only four mesocarnivore species were documented at CALO by Webster (2010) (Table 47).

Table 47. Mesocarnivore species documented on the NPS Certified Species List with relative abundance (NPS 2018e) and island distributions (Bod = Bodie, Hat = Hatteras, Ocr = Ocracoke) according to Webster (2010). x = present at that location.

Scientific name	Common name	Abundance	Distribution (Webster 2010)			
			Bod	Hat	Ocr	CALO
Vulpes vulpes	red fox	Uncommon [a]	x	x	–	–
Urocyon cinereoargenteus	gray fox	Common	x	x	–	–
Procyon lotor	raccoon	Common	x	x	x	x
Felis catus [b]	feral cat	Uncommon [a]	x	x	x	x
Mustela vison	mink	Common [c]	x	x	x	x
Lontra canadensis	river otter	Uncommon	x	x	x	x

[a] While NPS (2018e) identifies these species as uncommon, NPS staff has noted that these species are considered common in the park.

[b] Non-native species.

[c] While NPS (2018e) identifies this species as common, NPS staff believes that they are only common on Ocracoke Island and rare in the rest of CAHA (D. Hallac, pers. comm., July 2020).



The gray fox (left) and mink (right) are two common mesocarnivores at CAHA (USFWS photos).

Parnell et al. (1992) reported five mesocarnivores at CAHA, all of those listed in Table 47 except the red fox. Around this same time, Webster and Reese (1992), which focused exclusively on mammals they identified as native, documented two mesocarnivores on Ocracoke Island (mink and river otter), four on Hatteras Island (no red fox), and five native mesocarnivores on Currituck-Bodie Island. Webster and Reese (1992) reported red fox on Currituck-Bodie Island, likely because they included areas of the island north of the park boundary. For comparison, three mesocarnivore species were documented on Shackleford Banks (raccoon, mink, river otter), an island within CALO (Webster and Reese 1992).

According to distribution maps in Lee et al. (1982), four mesocarnivores had been documented in CAHA by the early 1980s: gray fox, raccoon, river otter, and mink. In the early 1940s, Engels (1942) found just one mesocarnivore on Ocracoke Island, the mink.

During 2010–2015 predator trapping efforts, eight mesocarnivore species were captured. Park staff trapped all of the species identified in Table 47, as well as bobcat and coyote on Bodie Island (NPS 2015b, 2018e). A bobcat and coyotes were also observed on a wildlife trail camera on Bodie Island in 2014 (NPS 2014a). Only four species were captured on Ocracoke Island: raccoon, feral cat, mink, and river otter. In 2019, targeted trapping efforts captured raccoons and feral cats on all three islands (USDA Wildlife Services 2019). Coyotes were also captured on Bodie Island, and coyote and fox tracks were observed on Hatteras Island (USDA Wildlife Services 2019).

Small Mammal Species Richness

Small mammal species richness estimates presented here include all species, and are not just limited to native species. Because of this, a higher estimate of species richness may not correlate to an improved or better condition, as non-native species could make up a sizable percentage of the total richness estimates. Results presented below should be interpreted accordingly.

Determining what species are considered "small mammals" can be somewhat challenging. Merritt (2010) defined "small" as mammals weighing less than 5 kg (11 lbs). This definition will be used for this assessment. According to NPS (2018e), 20 small mammal species occur at CAHA, four of which are identified as non-native (Table 48). Nineteen of these species were observed at CAHA by Webster (2010); only the evening bat (*Nycticeius humeralis*) was not documented. Eight species were observed on Ocracoke Island, 17 on Hatteras Island, and 16 on Bodie Island (Table 48). For comparison, 11 of the species found at CAHA were also present at CALO, and one species (Seminole bat [*Lasiurus seminolus*]) was observed at CALO that was not detected at CAHA (Webster 2010). The white-footed mice in the Buxton Woods vicinity are considered an endemic subspecies, the Buxton white-footed mouse, which was first described in 2005 (Shipp-Pennock et al. 2005). The subspecies, which is larger and more brightly colored than typical white-footed mice, is isolated to the southern portion of Hatteras Island and is considered a species of special concern by the State of North Carolina (Shipp-Pennock et al. 2005, LeGrand et al. 2012).

Table 48. Small mammal species on the NPS Certified Species List (NPS 2018e) and documented by Webster (2010) by island. x = present at that location.

Scientific name	Common name	Abundance	Distribution (Webster 2010)			
			Bod	Hat	Ocr	CALO
Blarina carolinensis	southern short-tailed shrew	Uncommon	x	–	–	–
Cryptotis parva	least shrew	Common	x	x	–	x
Didelphis virginiana	Virginia opossum	Uncommon	x	x	–	–
*Felis catus**	feral cat	Uncommon	x	x	x	x
Lasionycteris noctivagans	silver-haired bat	Rare	–	x	x	–
Lasiurus borealis	eastern red bat	Unknown	x	x	–	x

* Non-native species.

Table 48 (continued). Small mammal species on the NPS Certified Species List (NPS 2018e) and documented by Webster (2010) by island. x = present at that location.

Scientific name	Common name	Abundance	Distribution (Webster 2010)			
			Bod	Hat	Ocr	CALO
Microtus pennsylvanicus	meadow vole	Uncommon	x	x	–	–
*Mus musculus**	house mouse	Common	x	x	–	x
Mustela vison	mink	Common	x	x	x	x
Nycticeius humeralis	evening bat	Unknown	–	–	–	–
Ondatra zibethicus	muskrat	Common	x	x	x	x
Oryzomys palustris	marsh rice rat	Common	x	x	x	x
Peromyscus leucopus	white-footed mouse	Abundant	x	x	–	–
*Rattus norvegicus**	Norway rat	Unknown	x	x	–	x
*Rattus rattus**	black rat	Unknown	–	–	x	–
Scalopus aquaticus	eastern mole	Common	x	x	–	x
Sciurus carolinensis	eastern gray squirrel	Common	–	x	–	–
Sylvilagus floridanus	eastern cottontail	Common	x	x	x	x
Sylvilagus palustris	marsh rabbit	Unknown	x	x	x	x
Urocyon cinereoargenteus	common gray fox	Common	x	x	–	–

* Non-native species.

Parnell et al. (1992) documented the same 19 small mammals as Webster (2010), plus the hispid cotton rat. Focusing exclusively on native mammals, Webster and Reese (1992) reported three small mammal species on Ocracoke Island, 10 species on Hatteras Island, and 13 on Bodie Island, including the hispid cotton rat. Webster (2010) hypothesized that the hispid cotton rat colonized the Outer Banks from Virginia, eventually reaching Cape Hatteras, but were unable to survive within CAHA. For comparison, six small mammal species were documented on Shackleford Banks, an island within CALO. All the small mammal species found on Shackleford Banks also occur at CAHA (Webster and Reese 1992).

Boone (1988) documented 15 small mammal species on Bodie and Hatteras Islands combined, including the first record of southern short-tailed shrew for the Outer Banks and a record of Virginia opossum on Hatteras Island after it had been reported as extinct on Hatteras in the 1950s. Distribution maps from the early 1980s (Lee et al. 1982) suggest that 15 small mammal species were documented within CAHA at that time. Engels (1942) observed five small mammal species on Ocracoke Island alone. Species documented on Ocracoke by Webster (2010) that were not found by Engels (1942) were the silver-haired bat (*Lasionycteris noctivagans*), muskrat, marsh rice rat (*Oryzomys palustris*), and feral cat. In contrast, the house mouse (*Mus musculus*) was reported on Ocracoke by Engels (1942) but not by Webster (2010). Webster (2010) also noted that an attempt to introduce gray squirrels to Ocracoke Village was unsuccessful.

During the 2010–2015 predator trapping program, four small mammal species were captured on Bodie Island and five species were captured on both Hatteras and Ocracoke Islands (Table 49). This included the first available record of a Virginia opossum on Ocracoke Island, when one was trapped

in 2012 (NPS 2018e). However, these observations are incidental rather than a result of scientific sampling; therefore, they can confirm the presence of a species but a lack of observations of any particular species does not confirm its absence.

Table 49. Small mammal species captured during the 2010–2015 CAHA predator trapping program (NPS 2018e). x = present at that location.

Species	Bodie Island	Hatteras Island	Ocracoke Island
Virginia opossum	x	x	x
feral cat*	x	x	x
mink	–	x	x
muskrat	–	x	–
eastern cottontail	x	x	x
common gray fox	x	–	–
black rat*	–	–	x

* Non-native species.

White-tailed Deer Density

White-tailed deer are sometimes considered "ecosystem engineers" because of the impact on forest structure and functioning through their browsing activity (Côté et al. 2004). An over-abundance of deer in an area can affect the growth and survival of many plant species, from understory herbs to tree seedlings and saplings. This can modify plant cover and diversity, nutrient cycling, and vegetation succession (Côté et al. 2004). Such changes can then impact other wildlife, including insects, birds, and other mammals. As mentioned previously, Sherrill et al. (2010) recommended maintaining deer densities of no more than 15–17 per square km (38–44 per square mi) in a 2008–2009 study of deer populations on Bald Head Island. As an additional reference point, the USFS found that forests in the northeastern U.S. can regenerate when white-tailed deer densities are below 7.7 per square km (20 per square mile) (Nisley 2012). However, lower densities of white-tailed deer (<10 per square mile) in temperate forests may allow some plant species to become overabundant, outcompeting other species and reducing plant diversity, due to a lack of foraging pressure (Nisley 2012).

USFWS (2006) reported that white-tailed deer numbers had been increasing in the PINWR vicinity on Hatteras Island in recent years. No studies or surveys of CAHA's white-tailed deer population are available to provide insight with regard to deer density. An undated draft of the park Natural Resources Management Plan (NPS N.D.) mentions a deer census of Buxton Woods occurring sometime in the mid-1980s, but the results of this census could not be found. However, the NCWRC has tracked deer harvest in Buxton Woods since 2010 and across Dare County since 2003. In the absence of population size monitoring, harvest numbers and trends may provide some insight into the condition of wildlife populations, although these numbers can vary with hunter effort (e.g., number of hunters, days spent hunting). From 2010–2018, annual deer harvest at Buxton Woods ranged from 1–18 individuals, with the majority of deer harvested being antlered bucks (Figure 59) (NCWRC

2018b). Numbers were highest from 2010–2012 and lowest from 2014–2017, but it is unclear if this represents a change in deer population or simply variation in hunter effort.

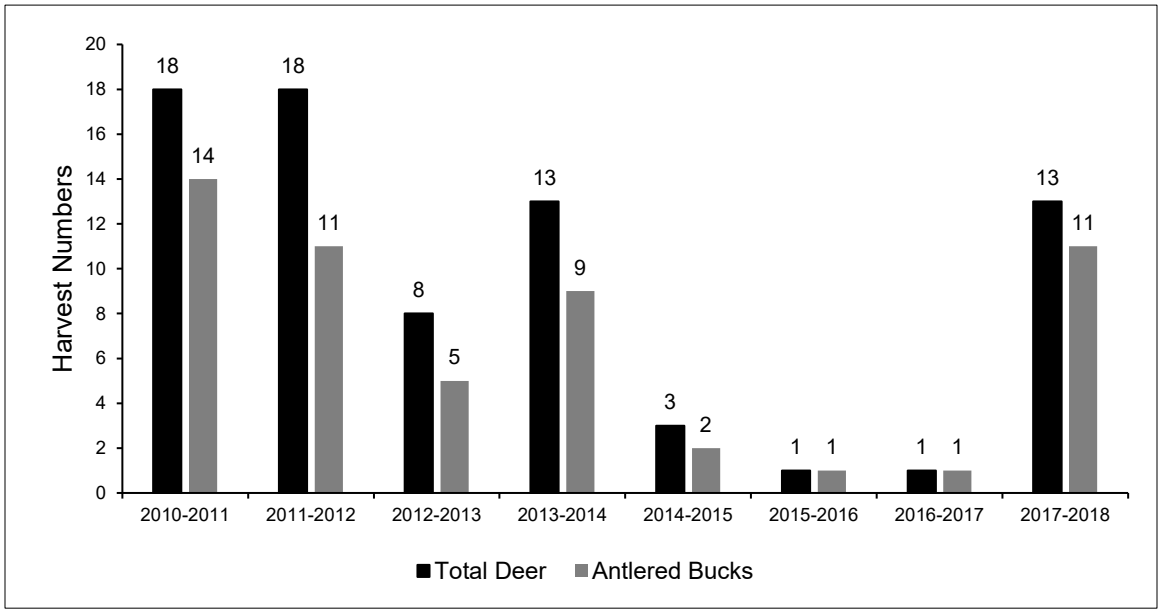


Figure 59. Deer harvest statistics for Buxton Woods public game lands (outside CAHA boundaries), 2010–2018 (NCWRC 2018b).



A white-tailed deer yearling in Buxton Woods (NPS photo).

Across Dare County, of which CAHA is just a small part, harvest numbers were also highest from 2010–2012 (Table 50, Figure 60). Annual harvest numbers have remained between 110–190 individuals since 2012 (NCWRC 2018b). The NCWRC calculated antlered buck density for Dare County, which ranged from 0.17 (2016–2017) to 0.62 bucks per square mile (2009–2010). As with Buxton Woods numbers, it is unclear if changes in harvest over time represent changes in deer population or variation in hunter effort.

Table 50. Deer harvest statistics for Dare County, 2003–2018 (NCWRC 2018b).

Hunting season	Total deer harvested	# of antlered bucks	Antlered bucks/mi^2
2003–2004	103	68	0.32
2004–2005	172	125	0.60
2005–2006	124	99	0.47
2006–2007	150	120	0.57
2007–2008	159	110	0.53
2008–2009	201	124	0.59
2009–2010	181	129	0.62
2010–2011	239	137	0.43
2011–2012	243	126	0.40
2012–2013	158	89	0.28
2013–2014	185	105	0.33
2014–2015	149	83	0.26
2015–2016	167	78	0.20
2016–2017	114	67	0.17
2017–2018	133	78	0.20

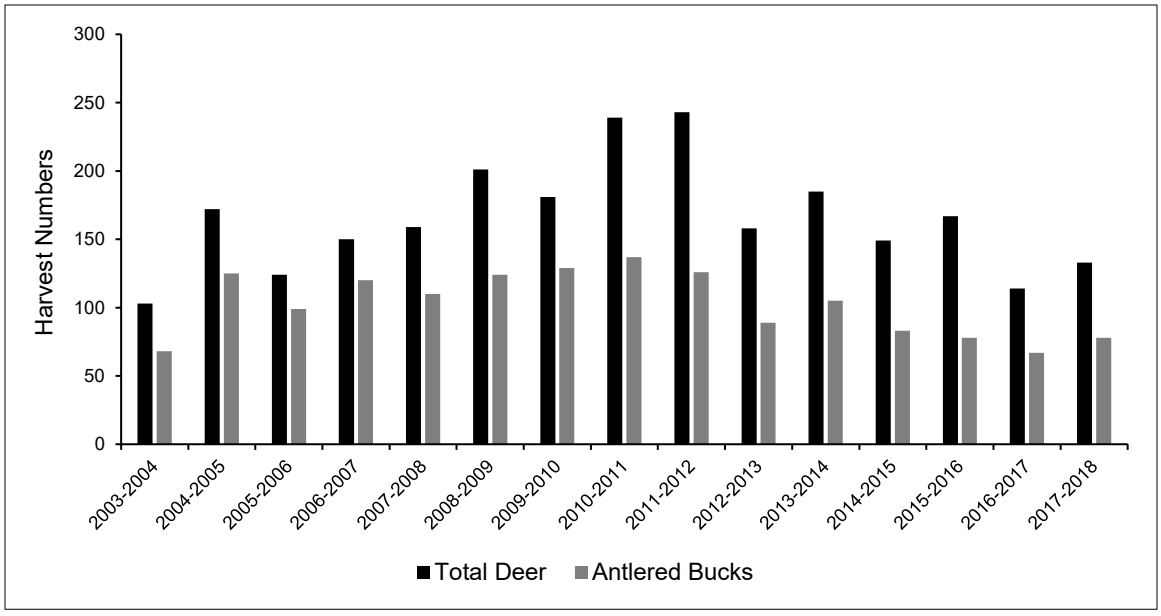


Figure 60. Deer harvest numbers for Dare County, 2003–2018 (NCWRC 2018b).

Threats and Stressor Factors

Threats to CAHA's mammal species include habitat fragmentation (e.g., from development and roads), hunting that occurs outside park boundaries, human feeding/habituation, feral cat predation, and disease. Additional threats to marine mammals, which are not discussed in detail here, include fisheries interactions (e.g., entanglements), marine debris, dredging, and military training exercises involving sonar (NPS 2012a, 2016b).

Roads pose a potential threat to the mammals of CAHA in several ways: they contribute to habitat loss and fragmentation, isolate animal populations, and can increase mortality due to traffic collisions (Jaeger et al. 2005, Ament et al. 2008). Some small mammals actually favor the unique habitat in road rights-of-way (Adams and Geis 1983), which may increase their risk of being struck by vehicles. Other small mammals, including the white-footed mouse, are known to avoid road surfaces (Jaeger et al. 2005). Since 2010, approximately 30–50 animal collisions have been reported on Dare County roads each year (Oliver 2018). These are collisions that cause vehicle damage, and the number of smaller mammals killed that go unreported is likely much higher. Expanding residential and commercial development on the Outer Banks have also contributed to wildlife habitat loss (Bellis 1995).

The coastal zone of North Carolina has experienced some of the highest population growth rates in the state, accompanied by urban expansion, largely driven by the tourism industry (Riggs et al. 2008). Increased development and tourism has increased the exposure of wildlife to humans, which may contribute to habituation that could negatively impact mammal species (Geffroy et al. 2015). Habituation is any change in an animal's behavior (e.g., decreased responsiveness to stimuli) due to repeated exposure (George and Crooks 2006). Habituated animals may become less likely to avoid human contact, which could increase their vulnerability to hunters, traffic collisions, or other

negative human interactions (George and Crooks 2006, Geffroy et al. 2015). Some opportunistic mammal species, such as raccoons, opossums, deer, and rabbits, exploit human-related food sources including trash and cultivated plants (McKinney 2002, Storm et al. 2007). When such food sources are abundant, these opportunistic mammals may increase in number, altering the natural structure and possibly even functions within wildlife communities (McKinney 2002, Geffroy et al. 2015, NPS 2016f). Aggregation around human food sources may also lead to increased aggression within and between species, causing injuries (Geffroy et al. 2015).

Hunting and trapping of game species such as deer, coyote, and smaller mammals is allowed on private land within the park boundary and at the state game lands at Buxton Woods. Deer hunting seasons in eastern North Carolina extend from mid-September through the end of January (NCWRC 2018a). Small game seasons (e.g., raccoon, opossum, rabbit, squirrel, fox) run from late fall through January (fox) or February (all others), while coyote and nutria can be hunted and trapped year-round (NCWRC 2018a).

Feral cats are considered a threat to small mammals and birds and, in some scenarios, have been implicated in wildlife extinctions (Webster 2010, Loss et al. 2013). The estimate of mammal mortalities caused by free-ranging cats annually in the contiguous United States is between 6.3 and 22.3 billion (~162–355 mortalities per cat per year) (Loss et al. 2013). The findings indicate that 75–100% of the prey taken by feral cats in suburban and rural areas consist of native species, such as rabbits and native rodents (Loss et al. 2013). Feral cats are present on all three CAHA islands; from 2010–2015, a total of 188 cats were captured and removed from the park (Table 51). Other potential predators of small mammals that have been removed from the park include red foxes and coyotes (NPS 2015b).

Table 51. Predators trapped on CAHA islands, 2010–2015 and 2019 (NPS 2015b, USDA Wildlife Services 2019). Note that these numbers do not include any estimate of survey effort, and only represent presence and not density.

Species	Island	2010	2011	2012	2013	2014	2015	2019
Feral cat	Bodie	7	10	9	8	7	9	1
	Hatteras	30	16	16	23	8	2	1
	Ocracoke	21	15	3	3	1	0	2
Red fox	Bodie	8	0	2	1	3	0	0
	Hatteras	0	1	0	0	0	0	tracks
Coyote	Bodie	2	8	4	6	4	4	5

Although not currently on the park's NPSpecies list, coyotes have been documented on Bodie Island since 2010 (NPS 2015b). Coyote tracks were also observed on Hatteras Island in 2019 (USDA Wildlife Services 2019), and have been documented on the island numerous times since, with several roadkills being documented (D. Hallac, pers. comm., July 2020). The species likely migrated to the park from the north, where the Outer Banks connect to southern Virginia (Webster 2010). While this is a natural range expansion, it exposes other park mammals to a novel predator or competitor that

has not been experienced previously. The arrival of coyotes in the park brings the threat of disease, as the species is known to be affected by canine parvovirus, canine infectious hepatitis virus, and the plague bacterium (*Yersinia pestis*) (Bekoff and Gese 2003). Coyotes may also carry rabies and a variety of ecto- (e.g., fleas, ticks, lice) and endo-parasites (e.g., flukes, tapeworms, heartworms) (Bekoff and Gese 2003). These diseases and parasites can infect other mammals, including foxes and raccoons. Non-native rodents, such as black and Norway rats (*Rattus rattus* and *R. norvegicus*) can also spread diseases such as hantavirus, tularemia, and typhus (Webster 2010).

Data Needs/Gaps

A thorough inventory of mammal species at CAHA and other parks in the SECN (Webster 2010) provides a relatively current snapshot of mammal species richness in the park and in similar environments (i.e., CALO). However, regular monitoring would be useful to detect any changes or trends in park mammal populations (richness, abundance, distribution, etc.). The NPS (2012b) recommended the establishment of a monitoring program for mammalian predators to estimate predator species abundance and distribution. Monitoring efforts could include spotlight, road-kill, camera and track surveys, with cameras being used to determine which predator species are most impacting protected species. Wildlife cameras will likely provide information on the presence of other non-predatory mammals as well. In addition, a bat monitoring project would also be of interest (Michael Parrish, SECN Wildlife Biologist, written communication, March 2020).

Regular monitoring (every 2–3years) for feral hogs (*Sus scrofa*) on Bodie Island has also been recommended, after a single feral hog was captured and removed from western Bodie Island in 2014 (NPS 2015a). Monitoring could consist of simply scouting for feral hog sign (e.g., tracks, scat, rooting) or setting up bait stations and wildlife cameras.

A regular census of the CAHA's white-tailed deer population is needed to estimate deer density and to monitor any changes or trends over time. Additional study of deer impacts on park ecosystems, particularly vegetation, may help park managers identify threshold densities at which significant ecological impacts occur in order to maintain ecosystem integrity (Côté et al. 2004). It may also be useful to study deer distribution and movements to understand how deer utilize suitable habitats within and outside park boundaries. Another data gap related to deer is a greater understanding of the abundance of deer in the park and the impact CAHA's predator management program has had on deer density, disease, condition, and the overall conditions of the forest understory.

Overall Condition

Mesocarnivore Species Richness

The project team assigned this measure a *Significance Level* of 3. Six mesocarnivore species were documented at CAHA by Webster (2010), only one of which was non-native (feral cat). Predator trapping efforts from 2010–2015 suggest that bobcats may sometimes occur on Bodie Island. For comparison, only four mesocarnivore species were found at nearby CALO (Table 47). Mesocarnivore species richness on other North Carolina barrier islands and comparable NPS properties is similar or slightly lower (Webster and Reese 1992, Webster 2010). As a result, this measure is currently considered of low concern (*Condition Level* = 1).

Small Mammal Species Richness

This measure was also assigned a *Significance Level* of 3. The NPSpecies list for CAHA includes 20 small mammal species, 19 of which were documented by Webster (2010). Four of these species are non-native (Table 48). For comparison, 12 small mammal species were found at CALO, 11 of which also occur at CAHA (Webster 2010). As with mesocarnivores, CAHA's small mammal species richness is similar to or slightly higher than other North Carolina barrier islands and comparable NPS properties (Webster and Reese 1992, Webster 2010). Therefore, this measure is also considered of low concern (*Condition Level* = 1).

White-tailed Deer Density

A *Significance Level* of 3 was assigned for this final measure. No park-specific deer density data are available. The only existing information is deer harvest statistics for Buxton Woods game lands (since 2010) and Dare County as a whole (since 2003) (NCWRC 2018b). At this time, a *Condition Level* cannot be assigned for this measure.

Weighted Condition Score

The Weighted Condition Score for CAHA's mammals is 0.33, which is at the edge of the good condition range (Table 52). Given the somewhat limited information and some uncertainty regarding reference condition, a trend has not been assigned and a medium confidence border was assigned.

Table 52. Current condition and trend for the Mammals of CAHA.

Measures	Significance Level	Condition Level	WCS = 0.33
Mesocarnivore Species Richness	3	1	–
Small Mammal Species Richness	3	1	–
White-tailed Deer Density	3	n/a	–
Overall	–	–	

Sources of Expertise

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Sea Turtles

Description

CAHA occurs at the northern edge of the sea turtle nesting range on the East Coast of North America. Five sea turtle species occur in the waters around CAHA, all of which are federally listed as threatened or endangered (Table 53) (NPS 2016c, 2018e). Nests of all five species have been documented on park beaches, although some are less common than others. Females nest along the ocean coast from May through early September, typically laying multiple clutches during this time (NPS 2018a). As mentioned in Chapter 2, CAHA serves as an important nesting area for the loggerhead sea turtle (Figure 61). The loggerheads nesting at CAHA are part of the Northern Nesting Subpopulation (Mays and Shaver 1998). Although relatively small, this subpopulation is an important source of male hatchlings. Sex determination in sea turtles is temperature-dependent; lower incubation temperatures produce male hatchlings and higher temperatures produce females (NMFS and USFWS 2008). As a result, the majority of loggerhead hatchlings from warmer Florida nesting beaches are female (Mays and Shaver 1998). Desired future conditions for sea turtle nesting are described in Table 54.

Table 53. Sea turtle species documented and nesting within CAHA and their conservation status (NPS 2018e, Seaturtle.org 2019).

Scientific name	Common name	Fed status*
Caretta caretta	loggerhead	T
Chelonia mydas	green sea turtle	T
Dermochelys coriacea	leatherback turtle	E
Eretmochelys imbricata	hawksbill	E
Lepidochelys kempii	Kemp's ridley	E

* Fed status: T = threatened, E = endangered.

Table 54. Desired future conditions for sea turtle nesting at CAHA, as outlined in the ORV management plan (NPS 2010).

Metric	Short-term target	Long-term target
Number of loggerhead nests	94 nests with an average annual increase of 2%*	115 nests with an average annual increase of 2%
Percent of North Carolina total loggerhead nests	5-year average of 10% of North Carolina total	same as short-term
Number of nests relocated	5-year average of <30%	same as short-term

* Rate of annual increase based on the 2004–2008 average of 77.2 nests; a 2% increase is identified as a goal for the Northern Recovery Unit in the Species Recovery Plan (NMFS and USFWS 2008).



Figure 61. Female loggerhead turtle (NPS photo).

Data and Methods

Sea turtle monitoring has occurred at CAHA since 1987, following guidelines defined by the NCWRC in the Handbook for Sea Turtle Volunteers in North Carolina and by the USFWS (NPS 2018a). Daily beach patrols begin each year on 30 April and typically continue until late September or early October. Each discovered nest is documented and surrounded by a 10m x 10m (33 ft x 33 ft) signed area to protect from human disturbance. Nests may be relocated if they are at or below the high tide line, or in an area susceptible to erosion (NPS 2016c). Throughout the patrol season, staff monitor nests for egg/hatchling loss due to depredation, storm and tide impacts, and human disturbance. Several days after a hatching event, staff excavate the nest to count unhatched eggs, remaining eggshells, and live or dead hatchlings to determine hatch and emergence success (Figure 62) (NPS 2018a). Monitoring data from 2009 through the present are available to the public through http://www.seaturtle.org. Data for CAHA from 2001–2008 were provided to SMUMN GSS by the NCWRC. Mays and Shaver (1998) included CAHA monitoring results from the 1990s in a report that covers additional islands and/or National Seashores.



Figure 62. CAHA staff conduct a nest excavation for visitors, as part of the park's interpretive program (NPS photo).

Current Condition and Trend

Number of Sea Turtle Nests

Loggerhead turtles are the dominant nesting species at CAHA; green, leatherback (*Dermochelys coriacea*) and Kemp's ridley nests are less common (NPS 2016b). Because female loggerheads typically nest every 2–3 years rather than every year (Cohen 2009), the number of nests on any beach can vary widely between years. Since 2001, loggerhead nest numbers have ranged from 40 (2004) to 440 (2019), with an average of 158 nests annually (Table 55). Green turtle nests have also been observed at CAHA every year, with nest numbers ranging from one (2001, 2012) to 32 (2019). Kemp's ridley nests were found in 2011 (one nest), 2016 (one nest), 2018 (six nests), and 2019 (one nest) (Seaturtle.org 2019). Single leatherback nests were reported in 5 separate years (2002, 2004, 2007, 2009, and 2012). Hawksbill (*Eretmochelys imbricata*) nests have only been identified once (2015) since monitoring began. Although numbers have been variable between years, an overall increasing trend is apparent over the past decade (Table 55, Figure 63). Since 2009, CAHA has supported at least 15% of total sea turtle nests in the state of North Carolina (Seaturtle.org 2019).

Table 55. Annual sea turtle nest numbers by species since 2001 (Seaturtle.org 2019).

Year	Loggerhead	Green	Kemp's ridley	Hawksbill	Leatherback	Unknown sp.
2001	74	1	–	–	–	–
2002	95	3	–	–	1	–
2003	83	4	–	–	–	–
2004	40	3	–	–	1	–
2005	63	9	–	–	–	–
2006	80	4	–	–	–	–
2007	73	8	–	–	1	–
2008	109	3	–	–	–	–
2009	101	2	–	–	1	–
2010	148	5	–	–	–	–
2011	138	8	1	–	–	–
2012	220	1	–	–	1	–
2013	231	23	–	–	–	–
2014	122	2	–	–	–	–
2015	277	10	–	2	–	–
2016	314	10	1	–	–	–
2017	238	12	–	–	–	2
2018	155	5	6	–	–	–
2019	440	32	1	–	–	–

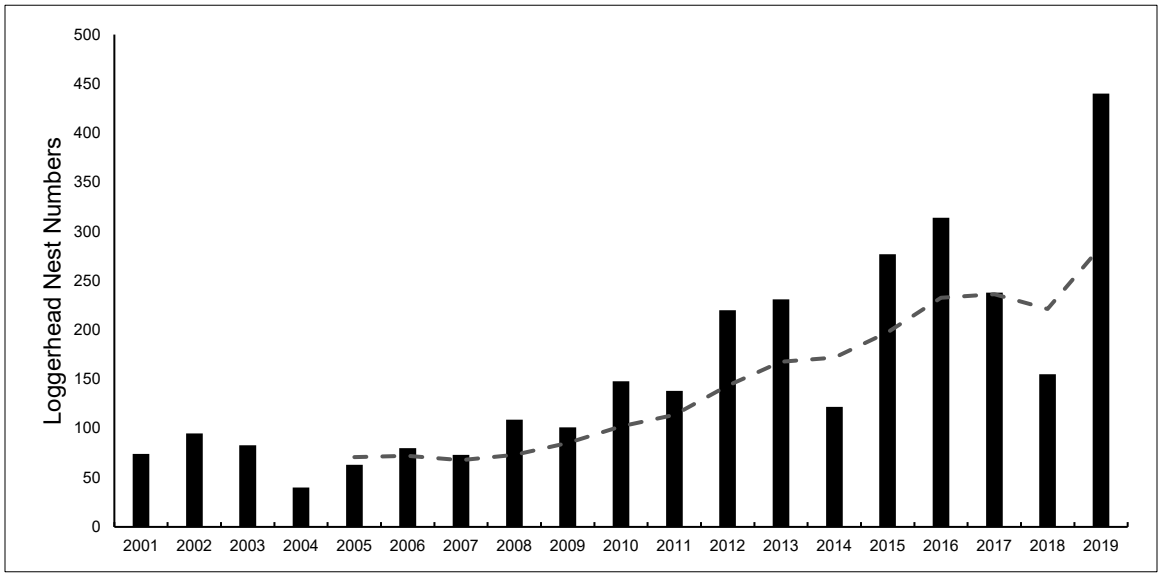


Figure 63. Number of loggerhead turtle nests on CAHA beaches, with a 5-year moving average (gray dashed line) showing an increasing trend (Seaturtle.org 2019).



Female green turtle nesting (NPS Photo).

Sea Turtle Emergence Success

Sea turtle reproductive success can be measured in several ways. Hatch success simply measures the proportion of eggs that hatch and does not take into account the fate of turtles after hatching (i.e., hatchlings that die in the nest are considered successfully hatched) (Mays and Shaver 1998). Emergence success measures the proportion of hatchlings that successfully emerge from each nest and would not include hatchlings that died while still in the nest. For this assessment, the project team chose to focus on emergence success.



Loggerhead hatchlings emerging from a nest (NPS photo).

Mays and Shaver (1998) documented loggerhead emergence success from CAHA and two other national seashores from 1992–1997. During this 6-year period, emergence success at CAHA ranged from 50.3–63.9% (Table 56). For comparison, emergence success at the two other national seashores (CALO, NC and Cumberland Island, GA) ranged from 45.1–85.0% (Mays and Shaver 1998).

Table 56. Reproductive success ([# hatched eggs − # dead hatchlings] / total # eggs x 100) for nesting sea turtles at CAHA and two additional National Seashores (Mays and Shaver 1998). ND = not determined.

Year	CAHA	CALO	Cumberland Island, GA
1990	63.9	71.0	ND
1991	51.5	62.0	ND
1992	58.0	73.0	45.1
1993	50.3	74.0	52.2
1994	56.2	85.0	63.3
1995	63.9	51.0	56.1
1996	51.9	75.5	67.5
1997	60.5	73.0	64.7

Since 2009, emergence success for CAHA and for North Carolina as a whole have been documented and are available through seaturtle.org. Over the past 10 years, emergence success at CAHA has ranged from a low of 28.4% (2009) to a high of 73.4% (2012), with success exceeding 50% in each of the last 4 years (Table 57). In comparison, loggerhead emergence success across the North Carolina coast as a whole ranged from 48.3% (2009) to 70.0% (2012) (Seaturtle.org 2019). CAHA emergence success was nearly always lower than success for the North Carolina coast as a whole (Figure 64) but was often similar to success rates at nearby CALO.

Table 57. Loggerhead emergence success rates at CAHA, CALO, and throughout North Carolina, 2004–2018 (NPS 2008, 2016c, Seaturtle.org 2019). Data prior to 2009 were rounded to the nearest whole number.

	Mean emergence success (%)		
Year	CAHA	CALO	North Carolina
2004	53	–	–
2005	68	–	–
2006	63	–	–
2007	58	–	–
2008	52	–	–
2009	28.4	33.0	48.3
2010	47.0	45.8	58.6
2011	37.9	42.7	48.5
2012	73.4	61.5	70.0
2013	56.4	61.5	65.6
2014	44.6	42.9	56.4
2015	48.7	53.7	60.9
2016	53.5	58.8	62.7
2017	53.1	53.2	61.7
2018	51.0	40.3	56.7
2019	50.4	41.2	54.6

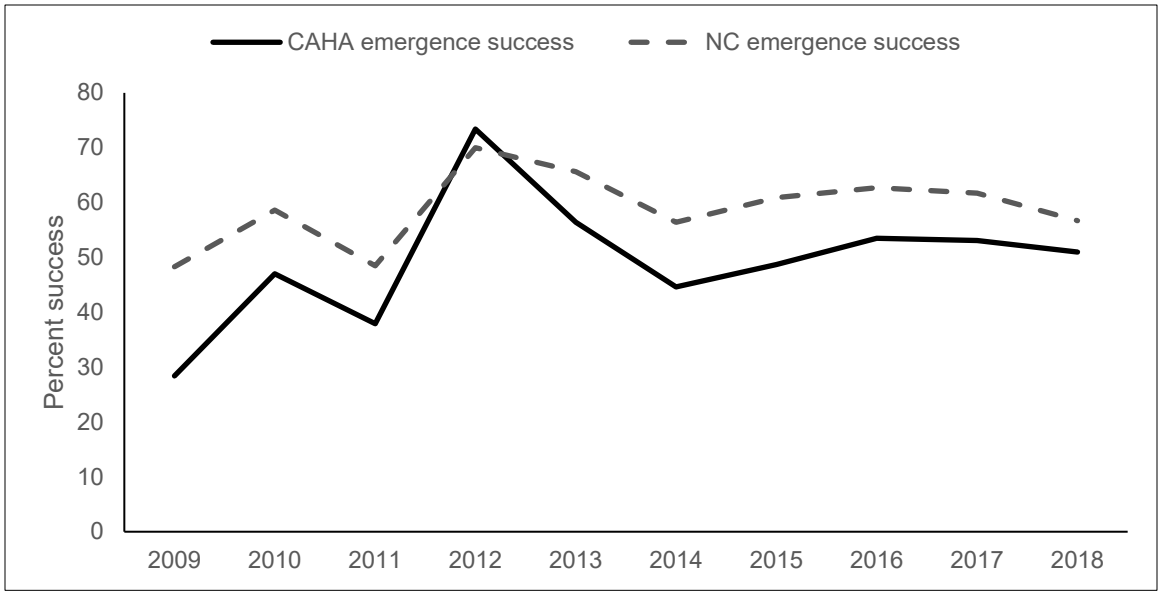


Figure 64. Loggerhead emergence success at CAHA (solid line) compared to success along the North Carolina coast as a whole (dashed line) (Seaturtle.org 2019).

Threats and Stressor Factors

Threats to CAHA's sea turtles include fisheries entanglements, marine debris, housing development and construction projects (including artificial lighting), dredging, human recreation, beach erosion, storms, habitat change, climate change, and predation. A "stranding" is a sea turtle found dead, injured, sick, or otherwise abnormal in appearance and out of the water or in very shallow water, usually along the shoreline (NOAA 2015). Strandings can have many triggers, including fisheries/boat interactions, malnourishment/illness, and cold weather. Since 2012, documented strandings at CAHA have ranged from 126 to 637 turtles annually (Table 58). Sea turtles may suffer injury or mortality as a result of boat strikes or interactions with commercial fishing gear (NMFS and USFWS 2008). Turtles are vulnerable to becoming entangled and drowning in large fishing nets, particularly those used by shrimp trawlers. Fortunately, the National Marine Fisheries Service (NMFS), in cooperation with the shrimp trawling industry, developed an effective turtle-excluder device (TED) that has been required on shrimp trawlers since the early 1990s (Figure 65). The proper use of TEDs can reduce incidental sea turtle catch by 97% (NMFS and USFWS 2008).

Table 58. Statistics related to sea turtle threats tracked by CAHA management, 2012–2017 (NPS 2013a, 2014b, 2015c, 2016c, 2018a). Protected area violation numbers include human instances only (e.g, pedestrian and ORV), not animal instances (dogs, cats, etc.).

Statistic	2012	2013	2014	2015	2016	2017
Nests lost to inundation/erosion	none detected	8	12	20	23	54
Nests depredated	127 (100% ghost crab)	27 (96% ghost crab)	19 (95% ghost crab)	19 (95% ghost crab)	62 (98% ghost crab)	21 (81% ghost crab)
Protected area violation instances	–	145	71	122	139	129
Mis- or disorientation	3	2	1	13	31	32
Strandings	126	189	219	286	637 (450 cold-stunned)	280



Figure 65. A sea turtle escaping a fishing net through a TED (NMFS photo). Shrimp and other targeted species are small enough to pass through the metal bars, but turtles are stopped and can swim out through a loose mesh opening.

Sea turtles may ingest or become entangled in marine debris, such as discarded fishing gear, rope, plastic bags, polystyrene foam pieces, tarballs, balloons, or other trash. In U.S. waters, the primary source of entanglement for loggerheads seems to be monofilament fishing line (NMFS and USFWS 2008). Ingestion of debris, especially plastics, may cause obstruction of an animal's digestive tract, reduced absorption of nutrients, or absorption of toxic byproducts (Bjorndal et al. 1994, NMFS and USFWS 2008). Debris washed up on the beach may also interfere with turtle hatchlings' progress towards the water. Identifying the source(s) of marine debris (e.g., boats, oil platforms, onshore activities) can be difficult, as it may have no distinguishing or identifying characteristics or be degraded to a point that it is unrecognizable (Cole 1998).

Housing development and construction/maintenance projects on CAHA's islands have negatively impacted both the quantity and quality of sea turtle nesting habitat. The presence of housing or other structures on a beach may deter females from nesting or cause them to select less suitable nesting sites (e.g., more vulnerable to inundation, erosion, or other disturbance) (Mays and Shaver 1998, NMFS and USFWS 2008). Beach nourishment projects, which involve the periodic replenishment of sand to maintain beach width for protection of coastal structures, may impact sea turtles if conducted during the nesting season (NMFS and USFWS 2008). In 2017, a beach nourishment project was conducted along 4.7 km (2.9 mi) of coastline in the Buxton Village area to protect the highway from ocean overwash (NPS 2018a). Because of the presence of heavy equipment and large pipes blocking ocean access, all 15 nests laid in this area were relocated by turtle monitoring staff. In addition to direct impacts, coastal development and human activity can accelerate beach erosion or disrupt natural shoreline migration, which influence turtle nesting habitat (NMFS and USFWS 2008).

The lighting from human development and construction projects, such as the multi-year Bonner Bridge replacement (2016-present), can be detrimental to nesting turtles and hatchlings. Sea turtle hatchlings emerge at night to avoid diurnal predators and lethally high sand temperatures (Camhi and Ehrenfeld 1986). Scientists believe that hatchlings find their way to the ocean by following the reflection of ambient light off the water (NMFS and USFWS 2008). Bright artificial lights in the vicinity of a nesting beach may misorient hatchlings and draw them away from the water, increasing the risk of predation, exposure, and desiccation (NMFS and USFWS 2008, NPS 2016c). Since 2005, CAHA has utilized black silt fencing around most known nests to decrease the impacts of artificial lighting (Figure 66). However, hatchling misorientation (movement in an inappropriate direction) or disorientation (lack of direct movement in an appropriate direction) was documented at 32 nests in 2017 and 31 nests in 2016 (Table 58) (NPS 2016c, 2018a). In 2019, to help reduce the potential for misorientation from park lighting, NPS staff retrofitted over 150 light fixtures at 31 park locations with new, lower impact fixtures (Crist 2019).



Figure 66. Silt fencing around a turtle nest at CAHA to shield hatchlings from artificial light sources (NPS photo).

Dredging commonly occurs in the inlets between CAHA's islands to maintain navigable channels and is sometimes used to fill unwanted channels opened during storm events (Riggs and Ames 2011, Schupp 2015). Dredging activity can degrade or destroy on and offshore sea turtle habitat and may cause incidental mortalities. The disposal of dredged material in offshore areas can impact foraging or resting grounds, and the alteration of physical features in the marine environment could influence nesting distribution (NMFS and USFWS 2008).

Human recreation at CAHA can impact sea turtles in several ways. Human presence on the beach at night, especially with lights (including campfires), may cause turtles to abandon nesting attempts. Even recreational beach items left out overnight (e.g., canopies, chairs, volleyball nets) or trash not properly disposed of can disturb or impede nesting and hatching turtles (NPS 2015c). While the effects are minimal (three mortalities in the last 10 years) another threat from human recreation is ORV or other vehicle use (D. Hallac, pers. comm., July 2020). Vehicle use on CAHA beaches has increased in recent decades due to improved access, a growing population, and the popularity of SUVs/ORVs (Figure 67) (NPS 2010). Visitors use ORVs to tour the beach and to travel to fishing, swimming, and surfing areas. ORVs are allowed to drive on the beach seaward of the primary dune line but must use designated ramps to access the beach (NPS 2010). These vehicles could not only disturb turtles on the beach but may injure or kill turtles by running over them and/or their nests. In 2016, a green turtle was euthanized on a CAHA beach after being severely injured by an ORV strike (NPS 2016c).



Figure 67. Vehicles on Bodie Island Spit during Memorial Day Weekend, 2007 (NPS photo).

Monitoring staff protect CAHA's turtle nests from human disturbance by establishing a 10x10 m (33x33 ft) signed area around each identified nest (Figure 68). Just prior to expected hatching, the protected area is expanded to a width of 30 m (98 ft) and extended to the water line (Doshkov et al. 2018a). Sites are checked daily for disturbance, and protected area intrusions are documented every year (Table 58). In 2017, 110 pedestrian intrusion instances and 18 ORV intrusion instances were recorded (Doshkov et al. 2018a), although there are no data to suggest that these intrusions resulted in any impact to the actual nests or success of the nests. Similar numbers of pedestrian intrusion instances and slightly lower ORV instances were detected in 2015 and 2016 (NPS 2015c, 2016c).

While there is no evidence that these intrusions affected nest success, continued disturbances in these areas could result in a pattern that may need to be addressed by NPS staff if nesting success rates decline in those areas.



Figure 68. A protected area around a sea turtle nest on a CAHA beach (NPS photo).

Inundation or erosion due to storm surge or excessive rainfall may cause turtle nest failure (Mays and Shaver 1998, NMFS and USFWS 2008). During development, turtle eggs require a constant supply of oxygen; high moisture content in the surrounding sand may inhibit gas exchange, causing developing eggs to "suffocate" (McGehee 1990). Unusually high tides during hurricanes and tropical storms may simply wash away nests laid close to the beach. For CAHA, the earliest published report of turtle nests washed away by storms is from Hurricane Bonnie in 1998 (Mays and Shaver 1998). In 2003, Hurricane Isabel "destroyed so many nests that losses to other sources were difficult to document" (Cohen 2009, p. 76). Since 2013, 8–54 nests have been lost to erosion or inundation annually, and additional nests experience reduced hatch success each year (Table 58). During 2017, for example, 13 nests were entirely washed away, and 41 nests completely failed due to storm/tide events (NPS 2018a). To minimize these losses, the turtle monitoring team often relocates nests laid at or below the daily high tide line or in areas susceptible to flooding/erosion. Since 2012, an average of 25% of the nests laid each year have been relocated. The risk of inundation and erosion is likely to grow as sea levels rise (see Chapter 2) and extreme weather events are projected to increase in severity with global climate change (Hawkes et al. 2009).

Although adult turtles have few terrestrial predators, juveniles and nests are especially vulnerable to predation. This predation includes digging into nests to consume eggs and preying upon hatchlings as they emerge. Known sea turtle predators at CAHA include foxes, birds, opossums, mink, and ghost

crabs (*Ocypode* sp.); raccoons, coyotes, and feral cats are potential additional predators (NPS 2016c, 2018a). The number of nests impacted by predation annually since 2012 has ranged from 19–127, the vast majority by ghost crabs (Table 58). Depredation is often only partial, impacting some but not all of the eggs/hatchlings. From 2010–2015, mammal trapping was conducted at CAHA in an effort to minimize predation (NPS 2015b). Due to limited resources and the lack of an approved predator management plan, the trapping program was inactive from 2016–2018, but resumed in cooperation with the USDA's Wildlife Services program in 2019 (USDA Wildlife Services 2019).

Warming temperatures associated with climate change may impact sea turtle sex ratios, since the temperature of the nest environment determines the sex of sea turtle hatchlings (Mrosovsky et al. 1984, Hawkes et al. 2009). Atlantic Coast loggerhead hatchling sex ratios already vary throughout the nesting season, ranging from 10% female during the cooler beginning and end of the season to 80% female during the warmer mid-season (Mrosovsky et al. 1984). Shifting temperatures may influence other aspects of sea turtle reproduction such as the timing of nesting (warmer water triggers earlier nesting and shorter intervals between clutches), the overall length of nesting season, and incubation periods (warmer sand temperatures shorten incubation) (Hawkes et al. 2009). Warmer waters could also alter the abundance and distribution of sea turtle prey species (NMFS and USFWS 2008).

Data Needs/Gaps

Park staff have consistently monitored sea turtle nesting at CAHA for decades, resulting in sufficient data for the measures selected by the project team for this NRCA. Continued monitoring and data analysis will allow park management to detect any changes or trends of concern for the park's sea turtles. Research into the potential impacts on North Carolina's sea turtles from climate change-related threats may help the park better prepare for future management.

Since 2010, CAHA has been participating in a genetic mark-recapture study of the Northern Nesting Subpopulation of loggerheads using DNA from eggs (Doshkov et al. 2018a). This data provides insight into the number of nesting females, the annual number of nests per female, and the distance between nests laid by individual females. The continuation of this study will promote a better understanding of loggerhead population dynamics at CAHA and within the nesting subpopulation. Starting in 2020, CAHA will also be participating in a pilot project placing satellite tags on nesting female turtles, to learn more about their movements and activities (Ziegler, written communication, 28 February 2020).

Overall Condition

Number of Sea Turtle Nests

The project team assigned a *Significance Level* of 3 for this measure. Sea turtle nesting numbers for the past 9 years have exceeded both the short- and long-term targets established in the ORV management plan. CAHA has also met the other management targets: the park has supported more than 10% of North Carolina's total nests annually and the percentage of nests relocated has not exceeded 30% over the past 5 years. As a result, this measure is assigned a *Condition Level* of 0, indicating no concern.

Sea Turtle Emergence Success

The emergence success measure was also assigned a *Significance Level* of 3. Emergence success rates for CAHA have varied over time, but have been relatively stable since 2013, dropping below 45% only once in the past 7 years. Therefore, this measure is currently of low concern, with a *Condition Level* of 1.

Weighted Condition Score

The Weighted Condition Score for CAHA's sea turtles is 0.17, which falls in the good condition range (Table 59). Since turtle nesting numbers have increased over the past decade and emergence success has been stable, an improving trend has been assigned.

Table 59. Current condition and trend for the Sea Turtles of CAHA.

Measures	Significance Level	Condition Level	WCS = 0.17
Number of sea turtle nests	3	0	–
Sea turtle emergence success	3	1	–
Overall	–	–	

Sources of Expertise

Tracy Ziegler, CAHA Chief of Resource Management and Science

Water Quality

Description

Water quality and quantity influence nearly all aspects of wetland and aquatic ecosystems, from vegetation and soils to wildlife, particularly sensitive species such as fish, aquatic invertebrates, and amphibians (UNEP 2008). Impaired water quality can alter plant and animal species composition, health, and reproduction (UNEP 2008, USGS 2016d). On the Outer Banks, clean water for recreation and potable drinking water is important for the tourism industry (Cole and Bratton 1994). However, the increased human development and resource use associated with tourism can negatively impact water quality (Cole and Bratton 1994, Mallin et al. 2006).

Surface water quality on barrier islands is often variable, ranging from freshwater ponds and sloughs completely isolated from the ocean to brackish and saline water bodies with intermittent connections to seawater (Cole and Bratton 1994, Bellis 1995). Water quality conditions can also be seasonal, often related to precipitation patterns (Cole and Bratton 1994). Seasonal variation may also be linked to human presence/use, as population on the Outer Banks can triple during the summer with an influx of vacationers and seasonal users (Mallin et al. 2006).



A tidal creek on Ocracoke Island (NPS photo by M. Mallin).

Measures

- pH
- Dissolved oxygen (DO)
- Specific conductance (SpC, freshwater only)
- Nutrients

- Fecal bacteria (coliform and enterococci)
- Water clarity/turbidity
- Chlorophyll a

pH

pH is a measure of the level of acidity or alkalinity of water and is measured on a scale from 0 to 14 (USGS 2016d). Water with a pH of less than 7.0 indicates acidity, whereas water with a pH greater than 7.0 indicates alkalinity, and a pH of 7 is neutral. Alkalinity and acidity are determined by the relative amount of free hydrogen (H^+) and hydroxyl (OH^-) ions in a liquid; more H^+ ions make a liquid acidic while more OH^- make it alkaline (USGS 2016d). Aquatic organisms have a preferred pH range that is ideal for growth and survival. Any chemicals that enter water can alter the pH from background levels and harm animals and plants living in the water; thus, monitoring pH can be useful for detecting natural and human-caused changes in water chemistry (USGS 2016d).

Dissolved Oxygen

Dissolved oxygen (DO) is critical for oxygen-dependent organisms that live in water. In order to survive, organisms such as fish, invertebrates, and zooplankton use DO from the water (USGS 2016d). Oxygen enters water from the air, when atmospheric oxygen mixes with water at turbulent, shallow riffles in a waterway, or when released by algae and other plants as a byproduct of photosynthesis. As the amount of DO drops, it becomes more difficult for aquatic organisms to survive (USGS 2016d). According to the EPA (2016c), waters with DO levels below 1 mg/l are typically hypoxic and devoid of life. The concentration of DO in a water body is closely related to water temperature; cold water holds more DO than warm water (USGS 2016d). Thus, DO concentrations are subject to seasonal fluctuations as low temperatures in the winter and spring allow water to hold more oxygen, and warmer temperatures in the summer and fall allow water to hold less oxygen (USGS 2016d).

Specific Conductance

Specific conductance (SpC) is a measure of the ability of water to conduct electrical current, which depends largely on the amount of dissolved ions in the water (Allan and Castillo 2007). Water with low amounts of dissolved ions (such as purified or distilled water) will have a low SpC, while water with high amounts of dissolved solids (such as sea water) will have a higher SpC (Allan and Castillo 2007). SpC is an important water quality parameter to monitor because high levels can indicate that water is unsuitable for drinking or aquatic life (USGS 2016d).

Nutrients

Nutrients, such as nitrogen and phosphorus, are crucial in supporting healthy aquatic environments. However, elevated concentrations of these nutrients can negatively impact water quality and threaten the ability of plants and aquatic organisms to thrive (USGS 2016a). Nitrogen occurs naturally in the atmosphere and in soils and is deposited into surface waters through precipitation and runoff; nitrogen deposition is increased by human inputs such as sewage, fertilizers, and livestock waste (USGS 2017a). Nitrate (NO_3) can cause a host of water quality related problems when present in

high concentrations including, but not limited to, excessive plant and algae growth, eutrophication, and depleted dissolved oxygen available to aquatic organisms. Nitrate in drinking water can be harmful to humans, particularly young children, and livestock (USGS 2017a). Phosphorus is commonly found in agricultural fertilizers, manure, organic wastes in sewage, and sometimes industrial effluent (USGS 2016b). In excess, phosphorus in water systems can increase the rate of eutrophication, encourage overgrowth of aquatic plants, deplete dissolved oxygen, and threaten fish and macroinvertebrate populations (USGS 2016b).

Fecal Bacteria

Bacteria are a common natural component of surface waterways and are mostly harmless to humans. However, certain bacteria, specifically those found in the intestinal tracts and feces of warm-blooded animals, can cause illness in humans (USGS 2011). Fecal coliform bacteria are a subgroup of coliform bacteria that, when used in monitoring water quality, can indicate if fecal contamination has occurred in a specific waterway. It is often tested by counting bacterial colonies that grow on filters placed in an incubator for 22–24 hours. High concentrations of certain fecal coliform, such as *E. coli*, can cause serious illness in humans (USGS 2011). Enterococci are another type of bacteria that indicate fecal contamination from warm-blooded animals (NCDEQ 2017).

Water Clarity/Turbidity

Water clarity is critical in order for sunlight to reach submerged aquatic vegetation, which supports a wealth of aquatic organisms, and is valued for recreational purposes (Parman et al. 2012). Turbidity assesses the amount of fine particle matter (e.g., clay, silt, plankton, microscopic organisms, or finely divided organic or inorganic matter) that is suspended in water by measuring the scattering effect they have on light that passes through water (USGS 2016d); the more light that is scattered, the higher the turbidity measurement. Turbidity often increases following rainstorms, when sediments are washed into the water from adjacent lands and stream velocity increases (USGS 2016d). High turbidity decreases light penetration, which can reduce the productivity of aquatic plants and other organisms (Parman et al. 2012, USGS 2016d).

Chlorophyll a

Chlorophyll a is a standard measure of phytoplankton biomass (e.g., algae); its concentrations can be indicative of elevated nutrients and/or eutrophication, contributing to water quality degradation (Parman et al. 2012). While phytoplankton are a natural component of aquatic ecosystems, excessive levels can lead to bad odors and unsightly scums, as well as contributing to reduced DO levels (EPA 2016b). Some phytoplankton can also produce toxins that pose a threat to wildlife and people in high concentrations (EPA 2016b).

Reference Condition/Values

Many aspects of water chemistry are influenced by salinity, and as a result, different water quality standards are typically applied to salt (e.g., estuarine) and fresh waters. Reference conditions for DO, nutrients (nitrogen and phosphorous), water clarity, and chlorophyll a in estuarine areas will be the criteria used by the SECN water quality monitoring program, which are based on standards set by the EPA (Table 60) (Gregory and Smith 2011, EPA 2016d). The DO criteria below will also apply to inland, fresh waters.

Table 60. Coastal water quality condition criteria used for SECN monitoring (Gregory and Smith 2011, EPA 2016d, Wright 2016). Water clarity was evaluated using an index (WCI) in the 2011 report and with light attenuation coefficients (k) in the 2016 report.

Rating	Bottom DO (mg/l)	TDN (mg/l) [a,b]	TDP (mg/l) [c]	Water clarity index (WCI)	Water clarity (k)	Chlorophyll a (µg/l)
Good	>5	<0.1	<0.01	<2.3	<1.61	<5
Fair	2–5	0.1–0.5	0.01–0.05	2.3–2.99	1.61–2.30	5–20
Poor	<2	>0.5	>0.05	>3.0	>2.30	>20

[a] TDN = total dissolved nitrogen (including organic nitrogen, nitrite, nitrate, ammonium).

[b] The sum of organic nitrogen, nitrite + nitrate, and ammonium in a water sample may provide a rough estimate of a minimum TDN, if TDN is not measured.

[c] TDP = total dissolved phosphorous.

Reference conditions for pH and fecal bacteria in all waters and for chlorophyll a and turbidity in freshwaters are taken from North Carolina's water quality standards for surface waters (NCDEQ 2017). These standards are presented in Table 61. The state turbidity standard for saltwater may also provide insight in cases where estuarine water clarity measurements are not available.

Table 61. North Carolina water quality standards for surface fresh and saltwaters (NCDEQ 2017). For freshwater, standards are for the protection of aquatic life (Class C); saltwater standards are for aquatic life (Class SC) or shellfish waters (Class SA).

Water type	pH	Coliform bacteria	Enterococci bacteria	Turbidity	Chlorophyll a
Freshwater	6.0–9.0	mean ≤200/100 ml	–	streams ≤50 NTU, lakes ≤25 NTU	40 µg/l
Saltwater (estuarine)	6.8–8.5	mean ≤14/100 mL, single sample ≤43/100 ml	mean ≤35/100 ml, single sample ≤104/100ml	≤25 NTU	–

North Carolina is currently in the process of developing numerical standards for nutrients, but no such standards are available at this time. The closest coastal state with nutrient standards in place for freshwater is South Carolina. These standards state that in the Middle Atlantic Coastal Plains ecoregion of the state, total dissolved nitrogen (TDN – including nitrate, nitrite, and ammonia) is not to exceed 1.5 mg/l and total dissolved phosphorous (TDP – including orthophosphates and organic phosphates) is not to exceed 0.09 mg/l (SCDHEC 2014). These numbers will serve as an informal reference point for this assessment.

State and national standards are not available for SpC. However, SpC is related to concentration of total dissolved solids (TDS), and the EPA has recommended a TDS concentration <500 mg/l for drinking water (EPA 2017). This recommended TDS concentration equates to an SpC of 325 µmhos or µS/cm. This value will be used as an informal reference point for freshwaters in this NRCA, as values above this could indicate a need for further investigation. However, given the proximity of

most CAHA freshwaters to the ocean, it is very possible that salt spray could contribute to naturally higher SpC levels in park waters and wetlands.

Data and Methods

NPS (1994) presented the results of surface-water quality data retrievals for CAHA using six EPA national databases. Although many of the sampling sites identified were either single-event or one-year intensive sampling efforts, three stations within CAHA had longer-term water quality records: Pamlico Sound near Frisco (CAHA0003), Pamlico Sound at Jack Shoal Isle near Rodanthe (CAHA 0007), and Roanoke Sound at Herring Shoal Island near Nags Head (CAHA 0008) (Figure 69). These are all estuarine sites.

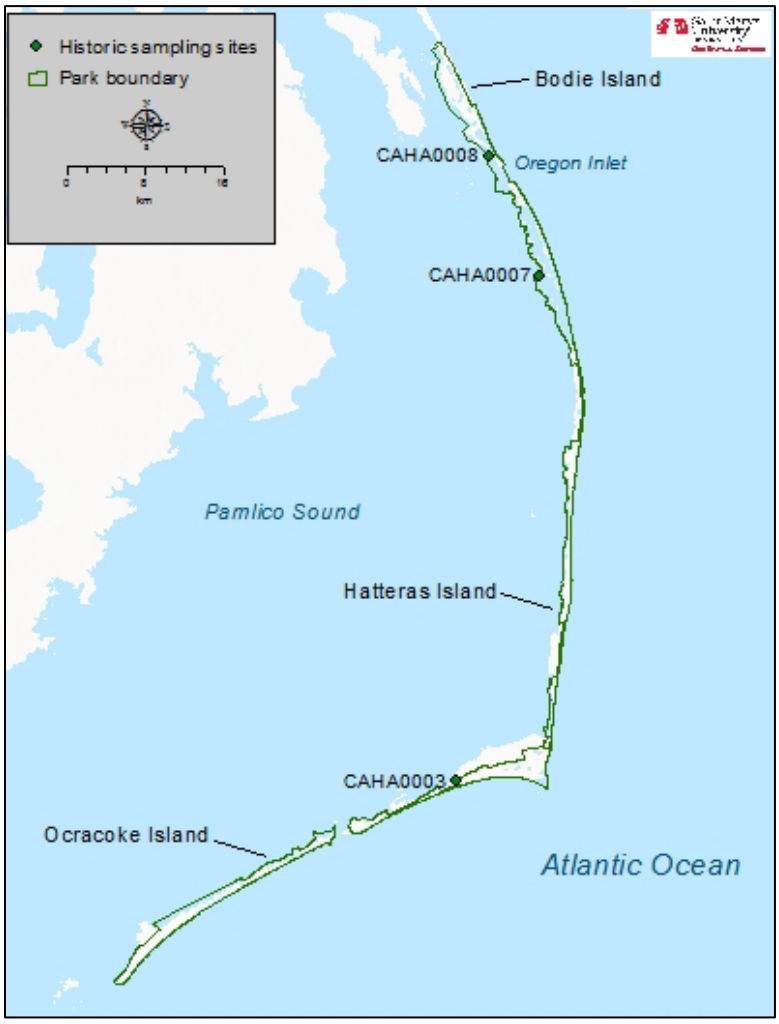


Figure 69. Historic water quality sampling locations at CAHA with longer-term water quality records.

Cole and Bratton (1994) studied water quality in freshwater marsh and ditch sites near Nags Head on Bodie Island and in the Buxton Woods area on Hatteras Island from 1988–1991. Water sampling occurred monthly at six marsh sites and seven ditch sites on Bodie Island, as well as at five wetland

sites in Buxton Woods. Measurements collected included pH, DO, salinity, SpC, selected nutrients, and fecal coliform bacteria (Cole and Bratton 1994).

Mallin et al. (2006) published an assessment of watershed conditions and coastal water resources at CAHA. The assessment incorporated a review of historic water quality studies as well as sampling for DO at several drainage ditches on lower Bodie Island and six tidal creeks on Ocracoke Island. Previous water quality monitoring efforts described by Mallin et al. (2006) included 1989 sampling of Buxton Woods swales by Ehrenfield and Oskarsson (1991) and 1995–1996 sampling of Bodie Island ditches by Evans and Houston (2000).

Mallin and McIver (2012) conducted water quality sampling at six drainage ditches (five that drain into Pamlico Sound and one into the Atlantic Ocean) and three ponds (Figure 70) between April and October 2007. One was an urban pond (UR-P) that collected surface runoff from roads during rainfall, one was a tidally-influenced pond utilized by wildlife (WW-P), and the last was a "control" pond (C-P) with no hydrologic connection to drainage ditches. Parameters sampled included pH, DO, turbidity, nutrients, chlorophyll a, and fecal bacteria (Mallin and McIver 2012).

The SECN initiated an estuarine water quality monitoring program in 2005 which included sites in CAHA (Gregory and Smith 2011, Wright and Yazdansepas 2015). The objectives of the program were to: 1) Determine diel and seasonal water quality patterns for five core parameters (DO, salinity, temperature, pH, and turbidity) using fixed-station continuous data loggers; 2) Determine monthly and seasonal patterns in nutrients (nitrogen, phosphorus, and chlorophyll a) by collecting discrete water samples; and 3) Determine status and spatial variability of water and nutrient chemistry conditions in estuarine waters every five years near SECN parks (Gregory et al. 2013). Continuous, fixed-station monitoring occurs at one site within CAHA, on a dock at the Ocracoke Village boat ramp, behind the visitor center parking lot (Figure 71) (Wright and Mockus 2015). This station collects temperature, pH, DO, salinity, conductivity, and turbidity data at 30-minute intervals. Additional monthly measurements of water clarity, nutrients, and chlorophyll a were conducted by NPS staff (Wright and Yazdansepas 2015). The continuous monitoring station was inactive in late 2012 and from April 2013 to October 2014 due to severe dock damage from Hurricane Sandy (Wright and Mockus 2015). The station was inactive again from August 2015 through May 2016 for maintenance (Hynds and Starkey 2019).

In July 2010 and 2015, the SECN conducted more spatially extensive estuarine water quality sampling within the park (Gregory and Smith 2011, Wright 2016). Seventeen random sites were visited in 2010 and 15 random sites in 2015 (Figure 72). Data gathered included DO, total nitrogen and phosphorous, chlorophyll a, and water clarity (based on light attenuation estimates and secchi depth measurements). However, water clarity index could not be calculated at many of the sampling sites due to shallow water depth (Wright 2016). Methods are described in detail in Gregory et al. (2013).

A search of the federal Water Quality Portal (WQP) database (NWQMC 2018) returned individual sampling results for several additional sites within CAHA. Between 2000 and 2002, the EPA's National Aquatic Resource Survey (NARS) program visited one Pamlico Sound site on Hatteras

Island each year (three total sites) to sample for nutrients and chlorophyll a (Table 62). In August 2012, the USGS North Carolina Water Science Center sampled one estuarine site on the north side of Oregon Inlet (Bodie Island, site USGS-0208117996) and one on the south side of the Inlet (Hatteras Island, site USGS-0208118000).

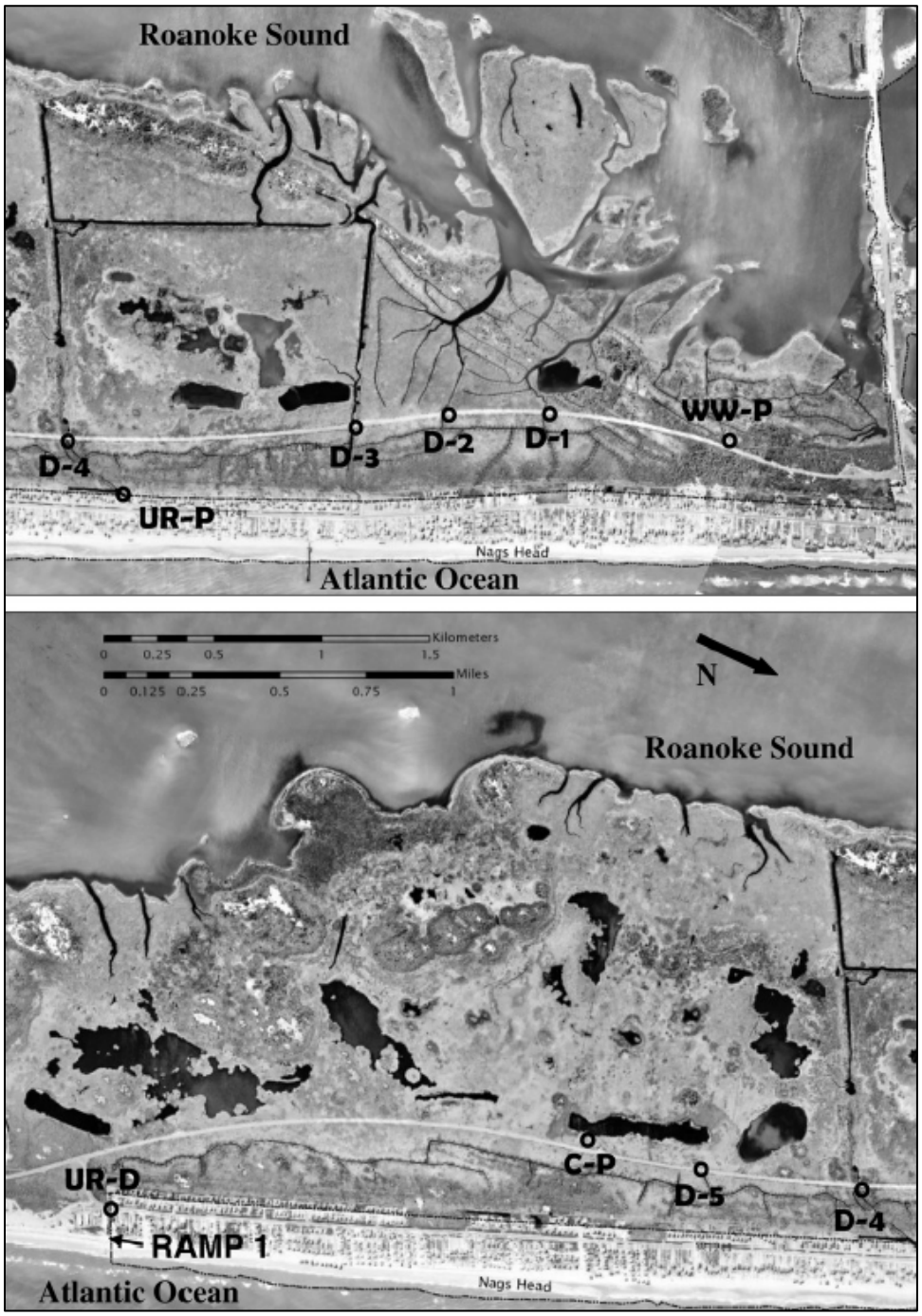


Figure 70. Ditch and pond sampling locations on south Bodie Island utilized by Mallin and McIver (2012). The six locations with “D” in the site code are ditches and the three locations with “P” are ponds. The upper image is north of the lower image.



Figure 71. The SECN continuous data logger (brown, pipe-shaped object) is attached to a dock piling at the Ocracoke Village boat ramp (NPS photo by Brian Gregory).

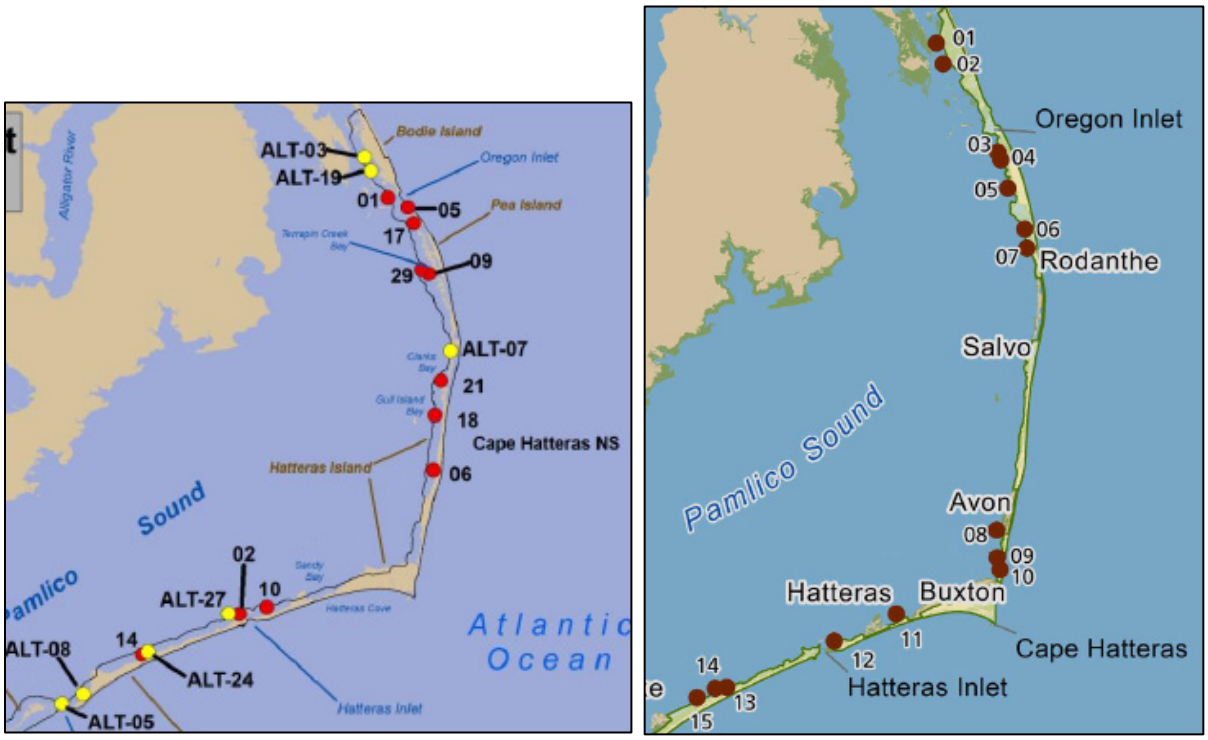


Figure 72. SECN estuarine water quality monitoring locations for 2010 (left, Gregory and Smith 2011) and 2015 (right, Wright 2016).

Table 62. NARS estuarine water quality sampling sites on Hatteras Island (NWQMC 2018).

Site	Location	Sampling date
NARS_WQX-NC02-0014	near Salvo	9/24/2002
NARS_WQX-NC01-0030	near Buxton	8/4/2001
NARS_WQX-NC00-0030	between Frisco and Hatteras	7/31/2000

The North Carolina Department of Environmental Quality's (NCDEQ) recreational water quality program currently conducts weekly sampling for enterococci bacteria from April through October at beach sites within CAHA (NCDEQ 2018). Seventeen of these sites spread across all three islands were sampled consistently from 2014–2018 (Figure 73).



Figure 73. Map of active recreational water quality monitoring sites within CAHA (NCDEQ 2018).

Current Condition and Trend

pH

During historic water quality sampling of estuarine park waters (1973–1986), pH across three locations ranged from 6.3–8.6 with means of 7.8 or 7.9 (Table 63). Several of these values fall outside of the current state standard range for pH in estuarine waters of 6.8–8.5 (NCDEQ 2017).

Table 63. Historic pH measurements (1973–1986) at estuarine sampling sites (NPS 1994). See Figure 69 for site locations.

Station	Period of record (# of observations)	Range	Mean
CAHA0003	6/1973–4/1986 (33)	6.6–8.4	7.9
CAHA0007	6/1973–4/1986 (34)	6.3–8.6	7.9
CAHA0008	6/1973–7/1984 (32)	6.3–8.4	7.8

During a sampling of waters in Buxton Woods during 1983, Schwartz (1992, as reported by Cole and Bratton 1994) found pH values between 7.9 and 8.8. All of these values fall within the state freshwater standard of 6.0–9.0 (NCDEQ 2017).

Mean pH values for Bodie Island ditches and marshes, and all pH measurements from Buxton Woods locations sampled by Cole and Bratton (1994), fell within the state freshwater standards (Table 64). Some of the samples from Bodie Island marshes fell above or below the standard range (6.0–9.0); this may be due to the natural seasonal variation on barrier islands.

Table 64. pH measurements from Bodie Island ditches, marshes, and Buxton Woods sampling sites (Cole 1990, Cole and Bratton 1994).

Metric	Bodie Isl. ditches (8/1988–7/1990) Mean	Bodie Isl. Marshes (8/1988–7/1991) Range	Bodie Isl. Marshes (8/1988–7/1991) Mean	Buxton Woods (2/1989–7/1991) Range
pH	7.3	4.1–10.5	7.8	7.1–8.4

Single samples in 2012 from USGS estuarine stations just north and south of Oregon Inlet yielded pH results of 7.6 and 8.2, respectively (NWQMC 2018). Samples taken at 15 sites during the SECN's 2015 park-wide estuarine water quality monitoring showed a pH range of 8.0–9.0, with a mean of 8.3 (Wright 2016). Readings from five locations on Bodie Island and north Hatteras Island were above the state standard.

The SECN continuous water quality monitoring site at the Ocracoke dock collected pH data from 2006–2016, with gaps for dock repair and maintenance during 2013–2014 and 2015–2016 (Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019). The majority of readings fell within the state estuarine standards of 6.8–8.5, with just a few readings slightly above

the acceptable range (Table 65). Continuous monitoring by the fixed station on the Ocracoke dock detected a small number of slight exceedances of state pH standards (Figure 74, Figure 75).

Table 65. Monthly pH ranges, from Ocracoke dock continuous monitoring (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019).

Month	2006	2007	2008	2009	2012	2013	2014	2015	2016
Jan	7.9–8.3	8.0–8.3	7.9–8.2	–	7.7–8.1	7.8–8.2	–	7.8–8.1	–
Feb	8.0–8.3	8.0–8.4	8.0–8.2	8.2–8.4	7.8–8.2	7.9–8.1	–	7.8–8.2	–
Mar	7.9–8.3	8.0–8.4	7.9–8.2	8.2–8.3	7.7–8.5	7.9–8.1	–	7.8–8.1	–
Apr	7.9–8.3	7.9–8.4	7.8–8.2	7.7–8.3	7.8–8.3	–	–	7.7–8.2	–
May	7.9–8.4	7.9–8.5	7.8–8.2	7.8–8.4	7.8–8.6 *	–	–	8.0–8.5	–
June	7.8–8.3	7.8–8.3	7.8–8.5	7.9–8.5	8.0–8.7 *	–	–	8.0–8.5	8.0–8.4
July	7.7–8.5	7.9–8.6 *	7.9–8.2	7.7–8.7 *	8.0–8.3	–	–	8.0–8.1	7.9–8.3
Aug	7.9–8.5	7.7–8.5	–	7.7–8.3	8.0–8.4	–	–	–	7.9–8.7 *
Sept	7.9–8.4	7.8–8.4	7.9–8.4	8.0–8.5	8.0–8.5	–	–	–	7.8–8.5
Oct	7.8–8.4	8.1–8.7 *	8.0–8.5	8.0–8.4	7.9–8.4	–	–	–	7.8–8.4
Nov	7.7–8.4	8.6 *	8.0–8.5	–	7.8–8.3	–	8.0–8.1	–	7.9–8.4
Dec	8.0–8.4	8.1–8.4	8.3–8.4	8.0–8.3	8.0–8.3	–	7.8–8.2	–	8.0–8.3

* Value exceeded state standards, also shown in red text.

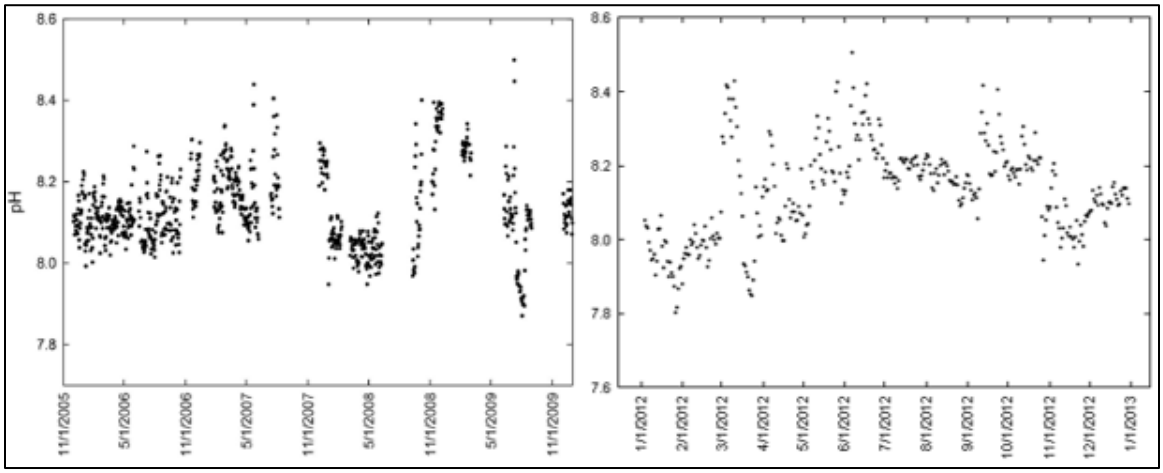


Figure 74. Mean daily pH values at Ocracoke dock, 2005–2009 (left, Wright and Yazdansepas 2015) and 2012 (right, Rinehart et al. 2013).

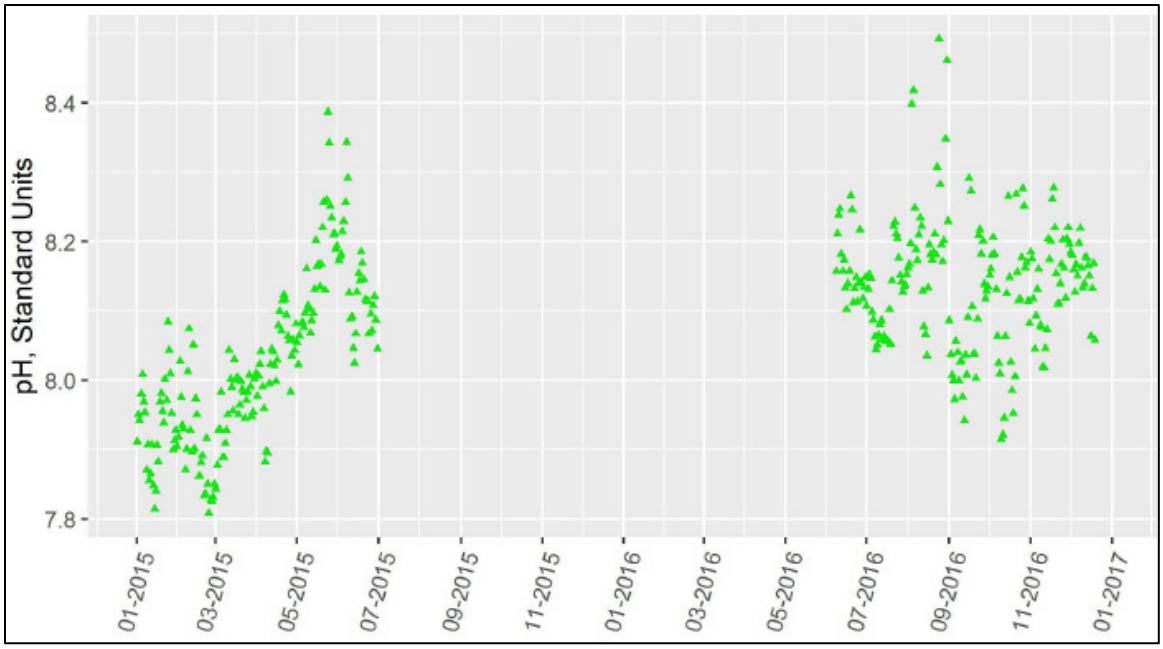


Figure 75. Mean daily pH values at Ocracoke dock during the first half of 2015 and the second half of 2016 (Hynds and Starkey 2019).

Dissolved Oxygen

Historic water quality sampling of three estuarine locations at CAHA documented DO values from 4.7–20.00 mg/l, with means of 9.3–9.5 (Table 66) (NPS 1994). Most results fell in the good condition category (>5 mg/l).

Table 66. Historic DO measurements (mg/l) at estuarine sampling sites (NPS 1994).

Station	Period of record (# of observations)	Range	Mean
CAHA0003	6/1973–7/1986 (82)	4.7–14.2	9.3
CAHA0007	6/1973–7/1986 (78)	5.8–13.5	9.4
CAHA0008	6/1973–7/1984 (75)	6.6–20.0*	9.5

* Only a single sample from 1977 exceeded 15 mg/l.

Sampling of Buxton Woods waters in 1983 documented DO levels from 6–7 mg/l (Schwartz 1992, as reported by Cole and Bratton 1994). These results meet the "good condition" criteria (see Table 52).

During sampling of Bodie Island ditches and marshes, Cole and Bratton (1994) found mean DO values of 4.6 mg/l and 6.8 mg/l, respectively (Table 67). DO levels in ditches were generally one-third lower than in marshes, sometimes falling in the fair condition range. The pH samples from Buxton Woods ranged from 3.0–7.2, with the mean values for four of five sites falling in the fair condition range (Cole and Bratton 1994).

Table 67. DO measurements (mg/l) from Bodie Island ditches, marshes, and Buxton Woods sampling sites (Cole 1990, Cole and Bratton 1994).

Metric	Bodie Isl. ditches (8/1988–7/1990) Mean	Bodie Isl. marshes (8/1988–7/1990) Mean	Buxton Woods (2/1989–7/1991) Range
DO	4.6	6.8	3.0–7.2

Mallin et al. (2006) sampled DO in three Bodie Island drainage ditches and six Ocracoke Island tidal creeks in August 2005 during high temperatures (~36.5°C [97.7°F]). Levels in the ditches ranged from 1.3–7.1 mg/l while tidal creek DO levels ranged from 2.7–5.0 mg/l (mean = 3.8 mg/l). The majority of these measurements fall in the fair condition range, with one reading (1.3 mg/l) indicating poor condition (Mallin et al. 2006). These low levels were likely related to the high temperatures at the time, as warmer waters hold less oxygen than cooler waters.

During 2007 sampling of Bodie Island ditches and ponds, Mallin and McIver (2012) found low DO levels at several of the ditch sites (Figure 76). Mean and median levels in two of the ditches (D-4, D-5) were below the state standard of 5.0 mg/l. Researchers observed one small fish kill in June at the D-1 ditch, when DO measured 1.1 mg/l (Mallin and McIver 2012).

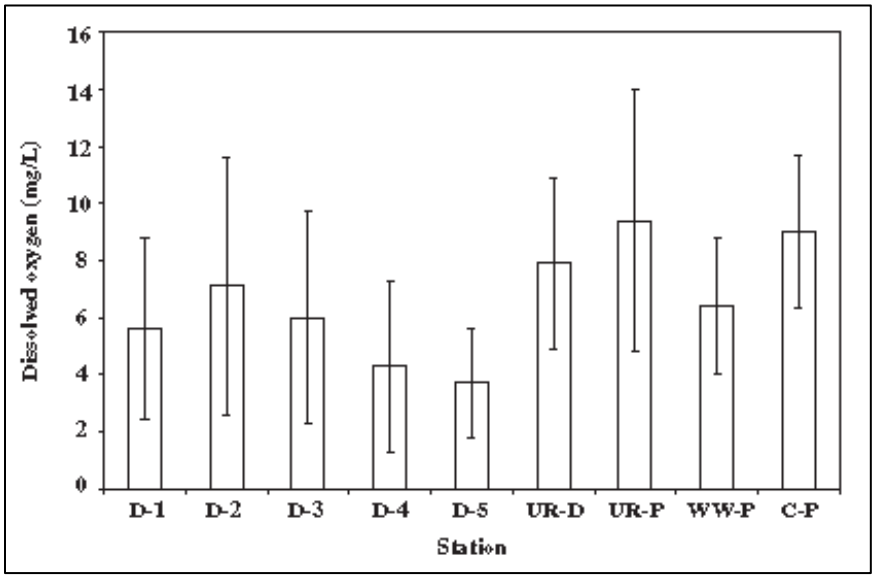


Figure 76. DO levels at Bodie Island ditch (6 sites on left) and pond (3 sites on right) sites, 2007 Mallin and McIver (2012).

In 2012, single samples from USGS stations just north and south of Oregon Inlet showed DO levels of 6.7 mg/l and 7.6 mg/l, respectively, which meet the good condition criteria (NWQMC 2018).

Monthly DO samples were taken during SECN monitoring of estuarine waters at the Ocracoke dock beginning in 2007 (Wright and Mockus 2015). Nearly all measurements were at the good condition level, with just two values (August 2008 and July 2012) in the fair condition range (Table 68).

Continuous monitoring by the fixed station on the Ocracoke dock detected only a few DO levels below 5 mg/l in 2007 (Wright and Yazdansepas 2015). From January–July of 2015 and June–December of 2016, all mean daily DO values at the Ocracoke dock were above 5 mg/l (Hynds and Starkey 2019). A graph of continuous DO observations from 2005–2009 and 2015–2016 (Figure 77, Figure 78) illustrates natural seasonal variation, as colder winter waters are capable of holding more DO than warmer summer waters.

Table 68. DO measurements (mg/l), Ocracoke dock monthly monitoring (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019).

Month	2007	2008	2009	2012	2013	2014	2015	2016
Jan	–	11.0	8.1	10.9	11.3	–	10.6	–
Feb	–	8.9	10.2	9.2	–	–	–	–
March	–	7.8	10.9	7.9	9.6	–	11.8	–
April	–	8.3	8.4	8.6	–	–	–	–
May	8.9	7.9	9.0	8.7	–	–	–	–
June	7.1	5.2	5.8	9.5	–	–	–	8.3
July	6.9	7.0	8.6	4.8 *	–	–	–	7.2
Aug	5.6	4.6 *	7.6	7.4	–	–	–	6.3
Sept	6.9	5.5	8.7	7.2	–	–	–	5.7
Oct	6.6	7.7	8.1	8.5	–	–	–	8.7
Nov	8.5	7.4	9.4	–	–	8.0	–	9.7
Dec	9.1	10.2	8.0	–	–	–	–	10.2

* Indicates measurements in fair condition (also highlighted in yellow).

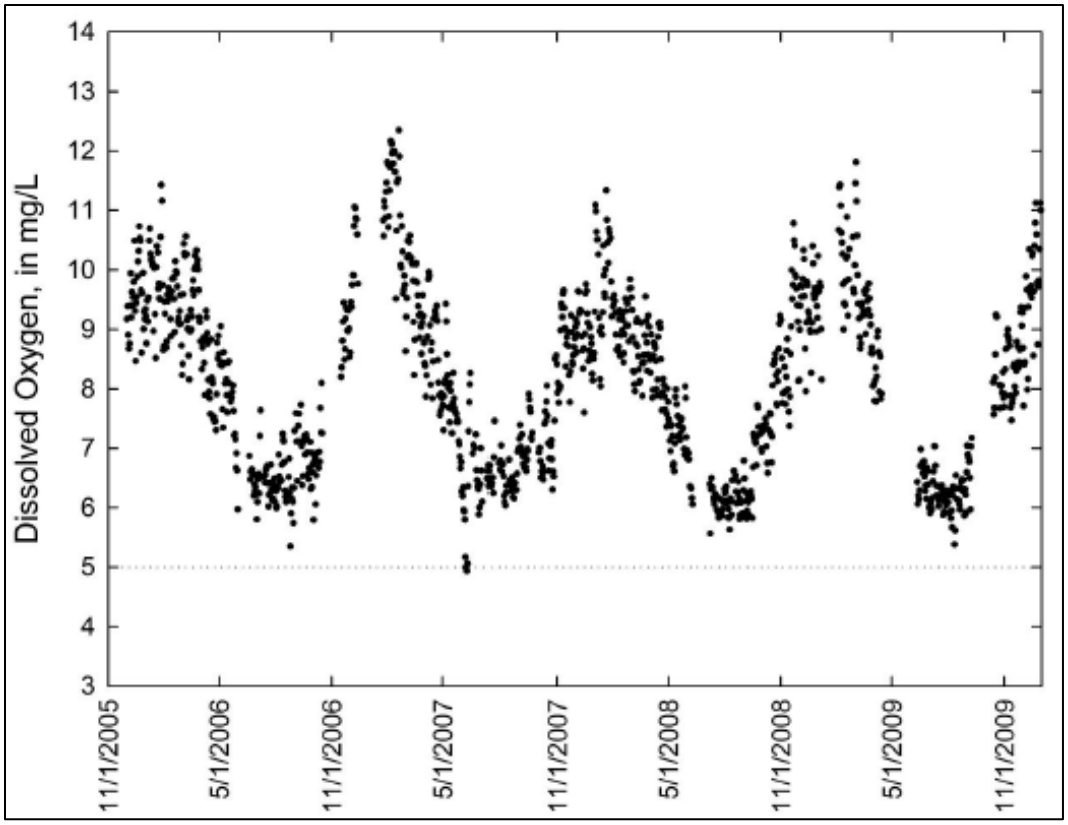


Figure 77. Mean daily DO values at Ocracoke dock, 2005–2009 (Wright and Yazdansepas 2015). The dashed line represents the "good condition" level of 5 mg/l.

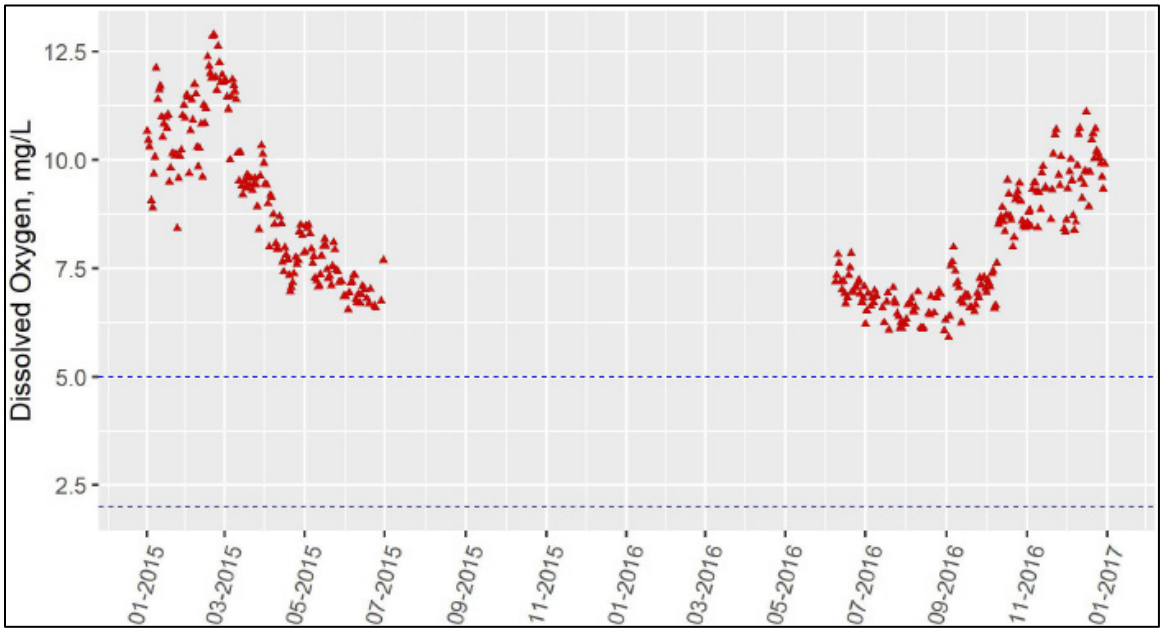


Figure 78. Mean daily DO values at Ocracoke dock, during the first half of 2015 and the second half of 2016 (Hynds and Starkey 2019).

DO measurements from more extensive SECN estuarine water quality monitoring at CAHA in 2010 and 2015 all fell in the good condition range, with no values below 5.4 mg/l (Table 69) (Gregory and Smith 2011, Wright 2016).

Table 69. Dissolved oxygen (mg/l) measurements from SECN estuarine water quality monitoring (Gregory and Smith 2011, Wright 2016). Note that sites are randomly positioned each year; as a result, the locations of sites sampled in 2010 do not correspond to the 2015 locations.

Year	Site #	DO
2010	CAHACALO-01	5.8
	CAHACALO-02	5.7
	CAHACALO-05	6.7
	CAHACALO-06	6.1
	CAHACALO-09	9.9
	CAHACALO-10	5.4
	CAHACALO-14	6.2
	CAHACALO-17	6.4
	CAHACALO-18	6.3
	CAHACALO-21	6.9
	CAHACALO-29	9.7
	CAHACALO-ALT03	6.9
	CAHACALO-ALT07	5.5
	CAHACALO-ALT08	6.6
	CAHACALO-ALT19	7.3
	CAHACALO-ALT24	8.2
	CAHACALO-ALT27	5.4
2015	01	9.7
	02	10.2
	03	7.3
	04	8.1
	05	13.2
	06	10.8
	07	10.1
	08	7.4
	09	7.9
	10	7.0
	11	6.3
	12	6.4
	13	9.7
	14	9.1
	15	7.2

Specific Conductance (freshwater only)

Bodie Island marshes sampled from 1988–1990 showed a mean SpC of 3,197 µmhos, while the mean SpC from sampled ditches was significantly higher at 5,506 µmhos (Cole 1990, Cole and Bratton 1994). During 1990 alone, all monthly samples from ditch sites exceeded 3,000 µmhos, with the highest values occurring between August and October (Figure 79). These values are well above the informal reference point of 325 µmhos based on EPA-recommended TDS concentrations (EPA 2017).

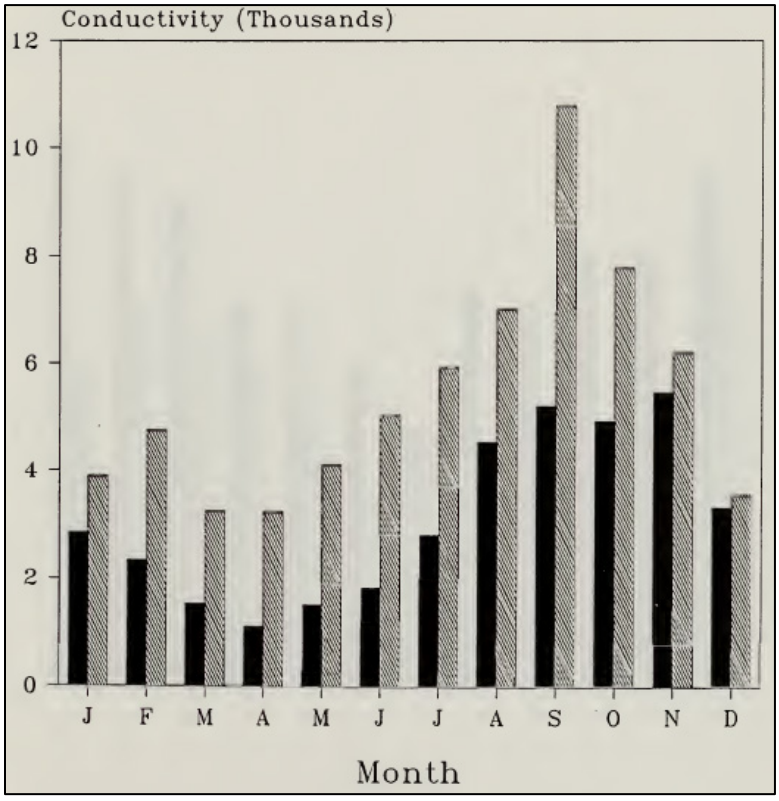


Figure 79. Monthly SpC measurements (µmhos) for Bodie Island marshes (black bars) and ditches (gray bars) during 1990 (Cole 1990).

Mean SpC measurements from Buxton Woods marshes between 1989 and 1991 ranged from approximately 270–420 µmhos (Figure 80) (Cole and Bratton 1994). The values for four of the five marshes are near the informal reference point of 325 µmhos.

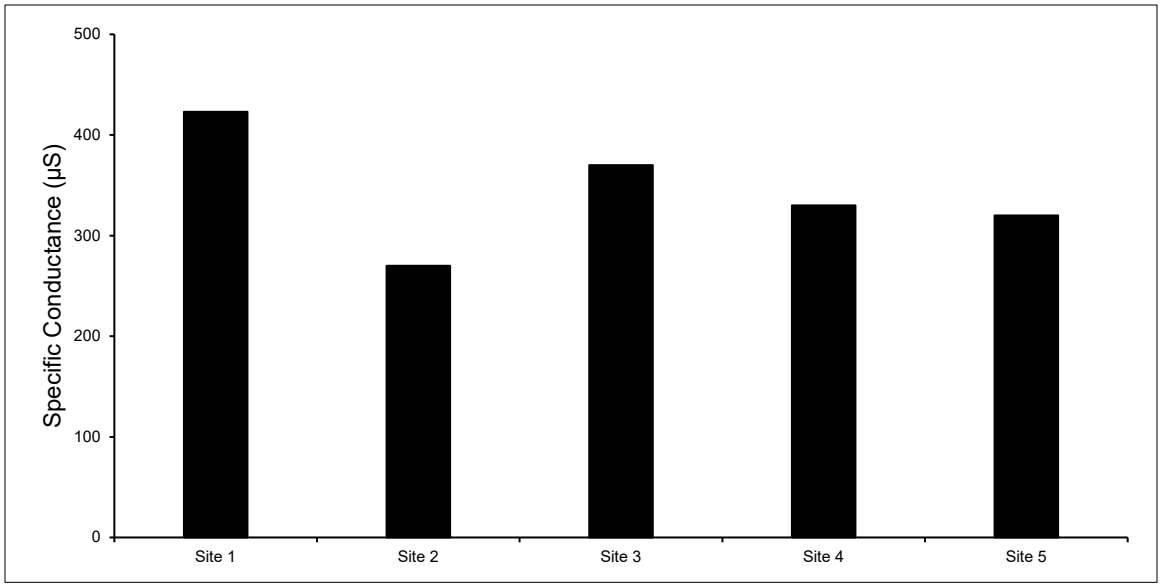


Figure 80. Specific conductance at Buxton Woods marsh sites, 1989–1991 (recreated from Cole and Bratton 1994). Note that µS (pictured on the y-axis here) are equivalent to µmhos.

Nutrients

Nitrogen

Various nitrogen measurements from historic water quality sampling of estuarine park waters are displayed in Table 70. Total organic nitrogen levels were similar at all three sites, but nitrite + nitrate and ammonia measurements were slightly higher at one site (CAHA0003) (NPS 1994). The sum of the means for nitrogen compounds from each site would meet the South Carolina TDN standard of <1.5 mg/l (SCDHEC 2014), which is being used as an informal reference point for this assessment. However, maximum values indicate that this reference point was exceeded on occasion.

Table 70. Historic nitrogen compound measurements (mg/l as N) at estuarine sampling sites (NPS 1994). See Figure 71 for site locations.

Metric	Range/Mean	CAHA0003	CAHA0007	CAHA0008
Period of record (# of observations)	–	6/1973–7/1986 (49)	6/1973–7/1986 (49)	6/1973–7/1984 (42)
Total organic (Kjeldahl) N	Range	0.1–1.4	0.05–1.3	0.3–1.8
	Mean	0.52	0.51	0.51
Nitrite + Nitrate	Range	<0.01–1.3	<0.01–1.2	<0.01–0.98
	Mean	0.11	0.07	0.08
Ammonia	Range	<0.01–3.4	<0.01–0.18	<0.01–0.27
	Mean	0.10	0.04	0.06
Total of means		**0.73**	**0.62**	**0.65**

Ehrenfield and Oskarsson (1991) compared nutrient levels in Buxton Woods swale wetlands in protected park areas and unprotected, privately owned areas. Ammonium levels were similar in protected and unprotected wetlands, but nitrate and nitrite levels were higher in unprotected areas (Table 71). The totals of these nitrogen compounds in the unprotected wetlands was more than twice as high as in the protected wetlands (Ehrenfield and Oskarsson 1991) and exceeded the informal reference point of 1.5 mg/l.

Table 71. Nitrogen compound measurements (mg/l as N) from protected and disturbed swale wetlands in Buxton Woods, 1989 (Ehrenfield and Oskarsson 1991).

Metric	Nitrate	Nitrite	Ammonium	Sum
Protected	0.008	0.001	0.790	0.799
Unprotected	1.020	0.034	0.810	1.864

During sampling of Bodie Island ditches and marshes, Cole and Bratton (1994) found similar low mean nitrite levels at both types of sites but higher mean ammonia levels at ditch sites (Table 72). When combined, the nitrite and ammonia means for marshes were below 1.5 mg/l, but ditches were slightly above this level.

Table 72. Nitrogen compound measurements (mg/l as N) from Bodie Island marshes and ditches, 1988–1991 (Cole 1990, Cole and Bratton 1994).

Metric	Bodie Island marshes (8/1988–7/1991)	Bodie Island ditches (8/1988–7/1991)
Nitrite	0.02	0.01
Ammonia	0.97	1.52

At Buxton Woods marsh sites sampled by Cole and Bratton (1994), nitrite levels ranged from 0.01–0.06 mg/l and ammonia levels from 0.5–1.6 mg/l (Figure 81). Only one of the five sites would exceed the informal reference point of 1.5 mg/l.

Evans and Houston (2000) measured nitrate and ammonium levels in Bodie Island ditches. While mean ammonium levels were similar, the mean nitrate level was higher in ocean-side ditches than in sound-side ditches (Table 73). When nitrate and ammonium means for each ditch were combined, levels fell well below 1.5 mg/l. However, the maximum values from ocean-side ditches exceeded this reference point.

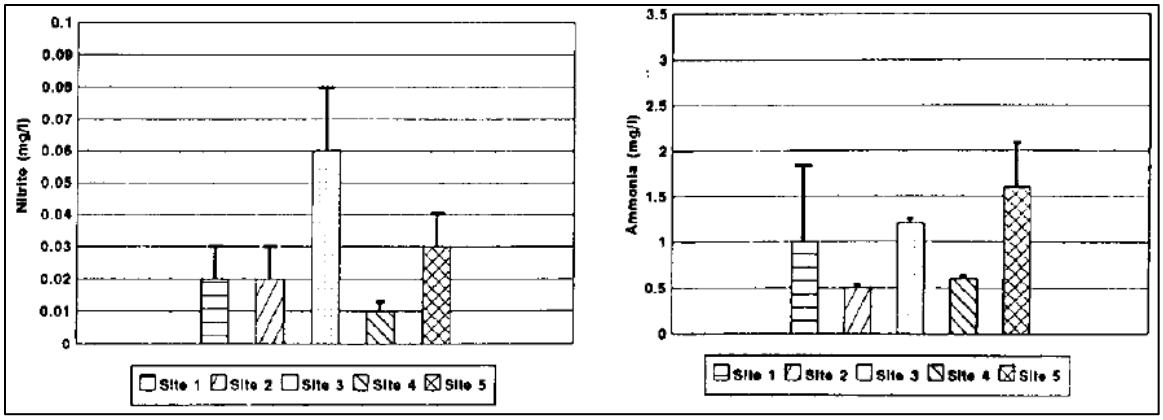


Figure 81. Nitrite (mg/l, left) and ammonia (mg/l, right) levels at Buxton Woods marsh sites, 1989–1991 (Cole and Bratton 1994).

Table 73. Nitrogen compound levels (mg/l as N) in lower Bodie Island drainage ditches, 1995–1996 (Evans and Houston 2000).

	Nitrate		Ammonium		
Sites	Range	Mean	Range	Mean	Sum of means
Sound-side ditches (4)	0.01–0.41	0.11	0.01–0.69	0.28	0.39
Ocean-side ditches (3)	0.01–0.91	0.31	0.05–1.10	0.23	0.54

Sampling by the EPA at two estuarine sites on Hatteras Island found a total nitrogen level (0.801 mg/l as N) indicating poor condition at one site between Frisco and Hatteras (Table 74). At the second site, total nitrogen was not measured, but nitrate + nitrite and ammonium were low (<0.01 mg/l as N) (NWQMC 2018).

Table 74. Nitrogen measurements (mg/l as N) from Hatteras Island estuarine sites (NWQMC 2018).

Site	Location	Sample year	Nitrate + Nitrite	Ammonium	Total nitrogen
NARS_WQX-NC02-0014	Near Salvo	Sept. 2002	0.009	0.005	–
NARS_WQX-NC00-0030	Between Frisco & Hatteras	July 2000	–	–	0.801

Mallin and McIver (2012) found high total nitrogen levels in both Bodie Island drainage ditches and ponds (Table 75). Ammonium concentrations, in particular, were relatively high and were 3–5 times higher in the summer than in the spring and fall. Mean ammonium levels at some sites were comparable to those at a southern North Carolina tidal creek that accepts sewage effluent from a wastewater treatment plant (Mallin and McIver 2012). Three of the six ditches sampled, and two of the three ponds exceeded the current South Carolina standard of <1.5 mg/l. The overall means for both the ditches and the ponds were also above this level (Table 75).

Table 75. Total nitrogen levels (mg/l) in Bodie Island drainage ditches and ponds during 2007 (Mallin and McIver 2012).

Site type (# of sites)	Overall range	Overall mean (range)
Ditches (6)	0.88–6.0	1.78 (1.23–2.99)
Ponds (3)	0.64–2.91	1.66 (1.22–1.98)

During monthly estuarine monitoring by NPS staff at the Ocracoke dock from 2007–2014, the majority of TDN measurements fell in the SECN's fair condition range, with just one reading of poor condition in 2009 (Table 76) (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019).

Table 76. Total dissolved nitrogen (mg/l as N), Ocracoke dock monthly monitoring (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019).

Month	2007	2008	2009	2012	2013	2014	2015	2016
Jan	–	0.00	0.19	–	0.29	–	0.26	–
Feb	–	0.23	0.27	–	–	–	–	–
March	–	0.28	0.00	–	–	–	0.33	–
April	–	0.24	0.34	–	–	–	–	–
May	0.35	0.29	0.31	–	–	–	–	–
June	0.29	0.30	0.34	0.37	–	–	–	0.26
July	0.22	–	0.35	0.31	–	–	–	0.33
Aug	0.25	0.24	0.27	0.30	–	–	–	0.49
Sept	0.22	0.27	0.38	0.30	–	–	–	0.34
Oct	0.31	0.46	0.53 *	0.37	–	–	–	0.36
Nov	0.21	0.29	0.23	–	–	0.17	–	0.31
Dec	0.25	0.22	0.29	–	–	–	–	0.34

* Measurement in the poor condition range (also highlighted in red).

Samples taken by the USGS in 2012 at two estuarine sites on the north and south sides of Oregon Inlet found organic nitrogen levels of 0.43 mg/l and 0.59 mg/l, respectively (NWQMC 2018). While these results were only organic nitrogen and not total nitrogen, the measurement from the site on the north side of the inlet (Bodie Island) would be in fair condition based on SECN standards, while the south side (Hatteras Island) would be in poor condition.

A majority of samples from more extensive SECN estuarine monitoring in 2010 were in the fair condition range, but six locations showed levels just into the poor condition range (Table 77) (Gregory and Smith 2011). During 2015 SECN sampling, eight of 15 locations were in fair condition and the remaining seven were in poor condition (Wright 2016). The maximum TDN value in 2015 (1.14 mg/l) was nearly twice the maximum value detected in 2010 (0.60 mg/l) (Table 77).

Table 77. Total dissolved nitrogen measurements (mg/l as N) from SECN estuarine water quality monitoring (Gregory and Smith 2011, Wright 2016). Note that sites are randomly positioned each year; as a result, the locations of sites sampled in 2010 do not correspond to the 2015 locations.

Year	Site #	TDN
2010	CAHACALO-01	0.51 *
	CAHACALO-02	0.27
	CAHACALO-05	0.15
	CAHACALO-06	0.54 *
	CAHACALO-09	0.56 *
	CAHACALO-10	0.37
	CAHACALO-14	0.46
	CAHACALO-17	0.16
	CAHACALO-18	0.60 *
	CAHACALO-21	0.52 *
	CAHACALO-29	0.51 *
	CAHACALO-ALT03	0.34
	CAHACALO-ALT07	0.48
	CAHACALO-ALT08	0.27
	CAHACALO-ALT19	0.31
	CAHACALO-ALT24	0.50
	CAHACALO-ALT27	0.29
2015	01	1.03 *
	02	1.14 *
	03	0.18
	04	0.29
	05	0.50
	06	0.89 *
	07	0.62 *
	08	0.51 *
	09	0.48
	10	0.58 *
	11	0.35
	12	0.19
	13	0.53 *
	14	0.42
	15	0.42

* Measurements in the poor condition range (also highlighted in red).

Phosphorous

Historic water quality sampling of estuarine sites at CAHA found total phosphorous levels ranging from 0.02–0.95 mg/l, with means of 0.05–0.08 mg/l (Table 78) (NPS 1994). The means for all sites met the South Carolina TDP standard of <0.09 mg/l (SCDHEC 2014), which is being used as an informal reference point for this assessment, but the maximum values exceeded this level.

Table 78. Historic total phosphorous measurements (mg/l as P) at estuarine sampling sites (NPS 1994).

Station	Period of record (# of observations)	Range	Mean
CAHA0003	6/1973–7/1986 (48)	0.02–0.14	0.06
CAHA0007	6/1973–7/1986 (49)	0.03–0.95	0.08
CAHA0008	6/1973–7/1984 (41)	0.03–0.17	0.05

Bodie Island marshes sampled from 1988–1990 showed mean phosphate levels of 0.06 mg/l, while the mean phosphate in sampled ditches was a substantially higher 0.33 mg/l (Cole 1990). In Buxton Woods wetlands, phosphate ranged from 0.2–0.5 mg/l (Figure 82). The measurements from all five Buxton Woods sites, as well as the mean for Bodie Island ditches, exceeded the reference point of 0.09 mg/l.

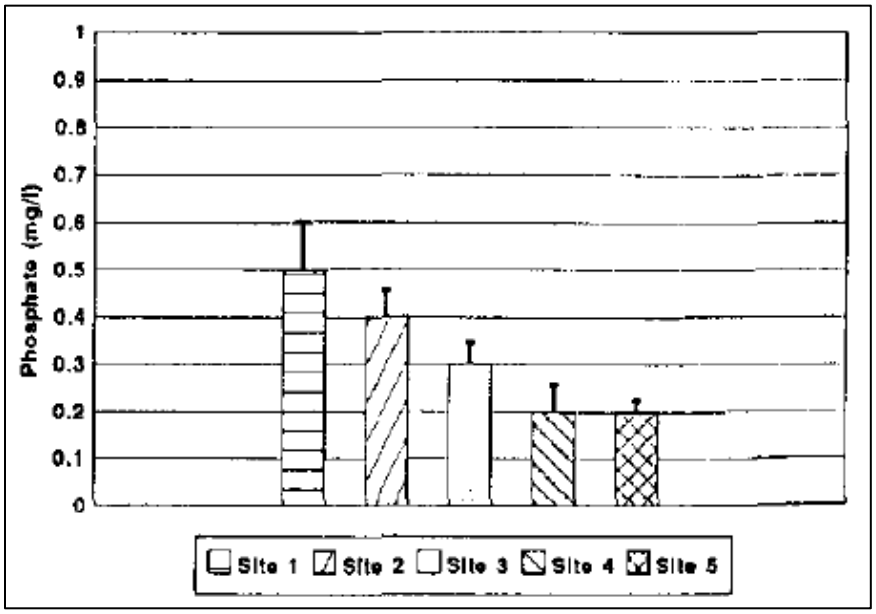


Figure 82. Phosphate levels (mg/l) at Buxton Woods marsh sites, 1989–1991 (Cole and Bratton 1994).

Ehrenfield and Oskarsson (1991) conducted sampling of five protected and five disturbed swale wetlands in Buxton Woods in 1989. Samples were tested for orthophosphate, which is just one component of total phosphorous, but yielded means of 0.122 mg/l for protected sites and 0.264 mg/l for disturbed sites. Both means exceed the informal reference point of 0.09 mg/l.

In 2007, Mallin and McIver (2012) found elevated total phosphorous levels that would be considered eutrophic at all but one of their Bodie Island ditch and pond sites (Table 79). The mean total phosphorous from just one of the ponds met the South Carolina standard of <0.09 mg/l, but the maximum value from the pond was above this level (Mallin and McIver 2012).

Monthly samples taken during SECN monitoring of estuarine waters at the Ocracoke dock showed TDP levels primarily in the fair condition range (0.01–0.05 mg/l as P) (Table 80). Three samples were in the poor condition range, all during summer or early fall (Rinehart et al. 2013, Wright and Yazdansepas 2015).

Table 79. Total phosphorous levels (mg/l) in Bodie Island drainage ditches and ponds during 2007 (Mallin and McIver 2012).

Site type (# of sites)	Overall range	Overall mean (range)
Ditches (6)	0.075–0.731	0.255 (0.156–0.368)
Ponds (3)	0.035–0.491	0.232 (0.071–0.337)

Table 80. Total dissolved phosphorous (mg/l as P), Ocracoke dock monthly monitoring (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019). Red cells indicate measurements in the poor condition range.

Month	2007	2008	2009	2012	2013	2014	2015	2016
Jan	–	0.000	0.020	–	0.034	–	0.022	–
Feb	–	0.024	0.016	–	–	–	–	–
March	–	0.020	0.000	–	–	–	0.024	–
April	–	0.015	0.020	–	–	–	–	–
May	0.016	0.015	0.023	–	–	–	–	–
June	0.012	0.034	0.043	0.027	–	–	–	0.020
July	0.015	–	0.052 *	0.052 *	–	–	–	0.020
Aug	0.023	0.020	0.038	0.044	–	–	–	0.030
Sept	0.142 *	0.036	0.040	0.046	–	–	–	0.007
Oct	0.017	0.021	0.035	0.037	–	–	–	0.013
Nov	0.013	0.020	0.023	–	–	0.039	–	0.011
Dec	0.015	0.014	0.022	–	–	–	–	0.007

* Measurements in the poor condition range (also highlighted in red).

Sampling by the USGS in 2012 at two estuarine sites north and south of Oregon Inlet documented total phosphorous of 0.094 mg/l and 0.032 mg/l, respectively (NWQMC 2018). The measurement from the site on the north side of the inlet (Bodie Island) was in poor condition while the south side (Hatteras Island) was in fair condition.

Measurements from more extensive SECN estuarine water quality monitoring at CAHA in 2010 found most sites in fair condition, with one site in poor condition and one in good condition (Table

81). During 2015 monitoring, most sites were again in the fair condition range but measurements from three sites indicated poor condition (Wright 2016).

Table 81. Total dissolved phosphorous (mg/l as P) measurements from SECN estuarine water quality monitoring (Gregory and Smith 2011, Wright 2016).

Year	Site #	TDP
2010	CAHACALO-01	0.010
	CAHACALO-02	0.017
	CAHACALO-05	0.011
	CAHACALO-06	0.233 *
	CAHACALO-09	0.011
	CAHACALO-10	0.013
	CAHACALO-14	0.010
	CAHACALO-17	0.011
	CAHACALO-18	0.013
	CAHACALO-21	0.010
	CAHACALO-29	0.011
	CAHACALO-ALT03	0.010
	CAHACALO-ALT07	0.016
	CAHACALO-ALT08	0.019
	CAHACALO-ALT19	0.013
	CAHACALO-ALT24	0.008
	CAHACALO-ALT27	0.016
2015	01	0.0388
	02	0.0513 *
	03	0.0196
	04	0.0253
	05	0.0229
	06	0.0573 *
	07	0.0297
	08	0.0366
	09	0.0284
	10	0.0521 *
	11	0.0294
	12	0.0199
	13	0.0189
	14	0.0236
	15	0.0247

* Measurements in the poor condition range (also highlighted in red).

Fecal Bacteria

Historic water quality sampling of three estuarine locations at CAHA found fecal coliform bacteria levels as high as 3,300 colonies/100 ml, with means from 19–102 colonies/100 ml (Table 82) (NPS 1994). According to NPS (1994), the three sites exceeded the bacteria standards at the time on one, two, and six occasions.

Table 82. Historic fecal coliform measurements (most probable number [MPN], colonies/100 ml) at estuarine sampling sites (NPS 1994).

Station	Period of record (# of observations)	Range	Mean	# of exceedances of WQ standards
CAHA0003	9/1976–7/1986 (55)	1–430	18.98	1
CAHA0007	8/1976–7/1986 (56)	1–3,300	101.89	6
CAHA0008	8/1976–7/1984 (50)	1–1,300	62.44	2

Cole and Bratton (1994) found significantly higher fecal coliform bacteria levels at Bodie Island ditch sites than at marsh sites. The mean MPN (most probable number) for ditches (297.6 colonies/100 ml) was over three times higher than the mean MPN for marshes (86.9 colonies/100 ml) (Table 83). The mean for ditch sites also exceeded the state freshwater standard of ≤200/100 ml (NCDEQ 2017).

Table 83. Fecal coliform bacteria measurements (MPN as colonies/ 100 ml) from Bodie Island ditch and marsh sites, August 1988-July 1991 (Cole and Bratton 1994).

	Bodie Island ditches		Bodie Island marshes	
Header	Mean MPN	Median MPN	Mean MPN	Median MPN
Bacteria	297.6	170	86.9	23

Fecal coliform MPN measurements at Buxton Woods marshes ranged from approximately 50 colonies/100 ml to over 250 colonies /100 ml (Cole and Bratton 1994). Readings from three out of five marsh sites exceeded the freshwater standard of 200 colonies /100 ml (Figure 83).

In sampling of Bodie Island drainage ditches and ponds, Mallin and McIver (2012) documented a high percentage of exceedances of North Carolina bacteria standards. Twenty-six out of 54 samples and the overall mean for ditch sites exceeded the state freshwater standard for fecal coliform bacteria of 200 colonies/100 ml (Table 84). Enterococci bacteria exceeded the state coastal water standard of 104 CFU/100 ml (CFU = colony forming units) in 44 of 54 samples, with two measurements above 20,000 CFU/100 ml from the drainage ditch along Old Oregon Inlet Road (near Ramp 1) (Mallin and McIver 2012).

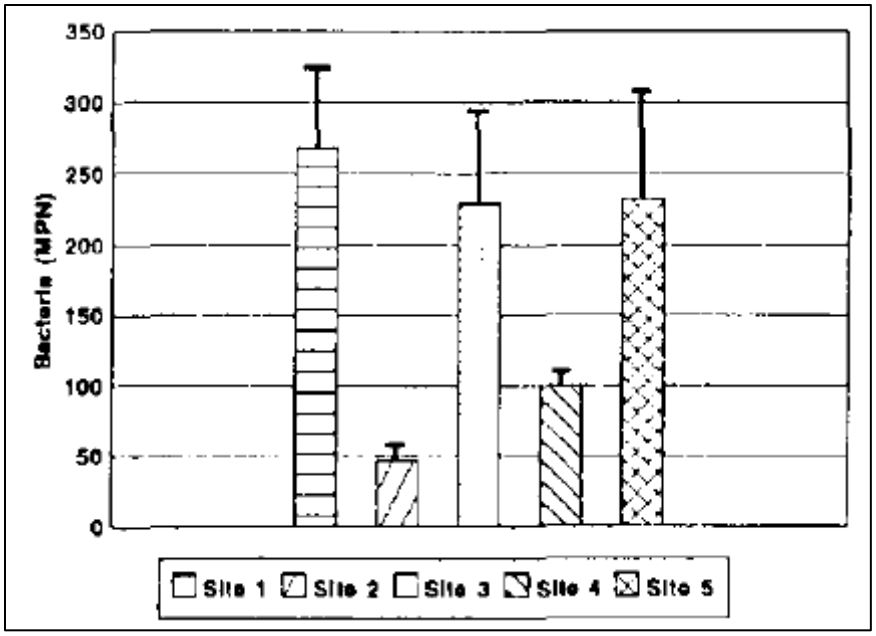


Figure 83. Fecal coliform bacteria levels (MPN, colonies /100 ml) at Buxton Woods marsh sites, 1989–1991 (Cole and Bratton 1994).

Table 84. Coliform and enterococci bacteria (CFU/100 ml) in Bodie Island drainage ditches and ponds during 2007 (Mallin and McIver 2012). CFU = colony forming units.

	Fecal coliforms		Enterococci	
Site type	Overall range	Overall mean (range)	Overall range	Overall mean (range)
Ditches	3–1,720	204.5 (95–305)	18–25,900	1,382 (272–6,267)
Ponds	1–640	130.0 (29–289)	1–2,620	292 (80–715)

In recent years, NCDEQ beach sampling for enterococci bacteria has detected several exceedances of estuarine state standards within CAHA (Table 85). From 2014–2016, the mean MPNs for 17 sites fell within state standards, but two individual samples exceeded the single sample standard of 104 colonies/100 ml (NCDEQ 2018). In 2017 alone, individual samples at three sites exceeded the state standard, with two samples from Hatteras Island exceeding 1,400 colonies/100 ml. At the sampling site on the park's northern boundary, four individual samples exceeded the single sample standard and three mean MPN measurements in late July/early August exceeded the state mean standard of 35 colonies/100 ml (Table 85). In 2018, single samples from two different sites on Hatteras Island (Ramp 34 and near Hatteras Lighthouse) exceeded the state standard (NCDEQ 2018).

Table 85. Maximum enterococci bacteria levels from oceanside sampling locations within CAHA (NCDEQ 2018). MPN = most probable number, GM = geometric mean. State standards for estuarine waters are a mean of ≤35/100 ml, and single samples ≤104/100ml (NCDEQ 2017).

Location	2014–2016		2017		2018	
	Max single MPN	Max GM MPN	Max single MPN	Max GM MPN	Max single MPN	Max GM MPN
N22 – Pipe at N park border	271 *	21.3	453 *	51.0 *	20	11.0
N23 – Oregon Inl campgrd	53	17.0	31	16.5	75	19.1
N25 – N Pea Island	53	18.6	42	14.4	42	12.8
N26 – Pea Isl Ref offices	31	17.7	42	12.5	42	14.4
N26B – Rodanthe S-turns	99	12.9	42	12.8	42	18.4
N27 – Rodanthe EMS St.	42	14.8	1,445 *	30.4	64	19.4
N29B – Ramp 30	64	13.5	2,006 *	26.5	42	12.5
N30 – Ramp 34	75	12.7	75	14.0	111 *	14.9
N32 – Ramp 38	124 *	18.1	64	13.3	42	14.7
N34 – Hatteras Light	53	14.4	87	19.7	124 *	15.2
N37 – Frisco campgrd	42	17.3	31	13.8	75	16.5
N39 – Frisco bath house	87	14.7	53	15.4	31	14.1
N40 – Ramp 55	53	17.8	75	23.0	20	10.6
N41 – 1st pub acc, Ocracoke	53	13.8	42	15.7	53	12.8
N41A – 5 mi SW of ferry	31	14.1	64	13.9	87	16.5
N42 – Ocracoke campgrd	53	17.2	20	10.8	75	16.5
N43 – Ocean ramp	64	15.6	10	9.4	53	12.8

* Measurements in the poor condition range (also highlighted in red).

Water Clarity/Turbidity

The units for turbidity measurements vary depending on the equipment used for sampling, although this distinction was not recognized until 2004 (USGS 2017b). Since 2004, measurements taken with a device using white or broadband light are presented in Nephelometric Turbidity Units (NTUs), while those taken with devices using infrared, monochromatic light are measured in Formazin Turbidity Units (FTU) (USGS 2017b). These two units are not directly comparable. Historically, turbidity was more commonly measured in FTU, but more recent measurements have been in NTU.

During historic water quality sampling of estuarine park waters (1973–1986), turbidity measurements ranged from 0.2–26.0 FTU, with means from 5.5–6.6 FTU (Table 86).

Table 86. Historical turbidity measurements (FTU) at estuarine sampling sites (NPS 1994).

Station	Period of record (# of observations)	Range	Mean
CAHA0003	6/1973–7/1986 (26)	1.2–15.0	5.5
CAHA0007	6/1973–7/1986 (26)	0.2–26.0	5.8
CAHA0008	6/1973–7/1984 (19)	2.0–16.0	6.6

In 2007 sampling of Bodie Island drainage ditches and ponds, Mallin and McIver (2012) found turbidity values ranging from 11–17 NTU in ditches and 7–12 NTU in ponds. There were no significant differences between sampling sites. These measurements met the state standards for freshwaters.

Monthly samples taken during SECN monitoring of estuarine waters at the Ocracoke dock from 2007–2014 found water clarity levels from 0.78–2.80 (Table 87). Three measurements, one each in 2007, 2008, and 2015, fell in the poor condition range (Wright and Yazdansepas 2015). From 2012–2014, samples were split nearly evenly between fair and good condition (Rinehart et al. 2013, Wright and Mockus 2015). The three measurements from 2016 were all in the good condition range (Hynds and Starkey 2019).

Table 87. Water clarity measurements (*k* – light attenuation coefficients), Ocracoke dock monthly monitoring (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019).

Month	2007	2008	2009	2012	2013	2014	2015	2016
Jan	–	2.80 [a]	1.87 [b]	–	1.87 [b]	–	1.40	–
Feb	–	–	1.40	–	–	–	–	–
March	–	1.40	0.78	–	0.80	–	2.80 [a]	–
April	–	1.12	1.40	1.56	–	–	–	–
May	0.93	0.78	1.12	1.56	–	–	–	–
June	1.12	1.87 [b]	1.40	1.40	–	–	–	1.12
July	1.40	1.40	1.40	1.12	–	–	–	1.40
Aug	1.65 [b]	1.87 [b]	1.87 [b]	1.87 [b]	–	–	–	1.12
Sept	1.12	–	1.27	1.87 [b]	–	–	–	–
Oct	0.93	0.93	–	–	–	–	–	–
Nov	2.80 [a]	0.93	1.27	–	–	1.87 [b]	–	–
Dec	1.00	1.12	–	–	–	–	–	–

[a] Measurements in the poor condition range (also highlighted in red).

[b] Measurements in the fair condition range (also highlighted in yellow).

The continuous monitoring station at Ocracoke dock recorded turbidity measurements from 2006–2016, with a gap from May 2013-October 2014 due to hurricane damage and from August 2015-May 2016 for maintenance. Mean monthly values ranged from 2.6–109.2 NTU, with six monthly means exceeding the state standard for estuarine waters (<25 NTU) (Table 88). However, no exceedances were recorded after 2012. The maximum values for nearly every month (69 out of 78) exceeded this standard (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019). Daily turbidity means for the 2015–2016 sampling period are shown in Figure 84.

Table 88. Monthly turbidity means and maximums (in parentheses) in NTU, from Ocracoke dock continuous monitoring (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019). Red cells indicate mean values that exceed the state estuarine standard.

Month	2006	2007	2008	2009	2012	2013	2014	2015	2016
Jan	8.0 (71.2)	5.6 (36.4)	4.4 (27.5)	6.7 (24.5)	6.3 (32.1)	–	–	5.6 (42.8)	–
Feb	5.5 (42.8)	3.4 (32.2)	3.6 (23.3)	4.2 (19.8)	6.7 (39.3)	9.9 (627.9)	–	18.2 (47.5)	–
March	4.4 (31.3)	3.3 (56.2)	5.1 (38.4)	3.8 (27.2)	7.2 (33.3)	10.9 (274.8)	–	12.6 (45.1)	–
April	7.8 (36.2)	10.7 (74.8)	4.9 (212.9)	6.6 (60.9)	18.9 (91.7)	7.4 (42.6)	–	7.6 (53.7)	–
May	5.7 (45.9)	60.6 (967.1)	12.3 (158.6)	6.3 (69.7)	8.0 (32.7)	–	–	7.9 (51.6)	–
June	2.7 (16.0)	12.0 (513.1)	66.2 (985.7)	6.4 (36.5)	6.0 (24.1)	–	–	6.0 (23.4)	4.8 (20.6)
July	7.9 (718.9)	5.7 (202.8)	21.7 (750.2)	8.9 (68.0)	6.3 (103.2)	–	–	7.4 (15.6)	4.7 (22.0)
Aug	78.6 (992.9)	5.5 (122.6)	15.5 (739.2)	12.4 (204.5)	5.8 (58.9)	–	–	–	4.2 (19.7)
Sept	33.5 (793.8)	4.0 (25.9)	47.4 (972.8)	109.2 (330.2)	6.5 (175.4)	–	–	–	4.9 (49.8)
Oct	6.8 (205)	–	5.5 (32.7)	4.2 (32.7)	9.4 (74.7)	–	–	–	4.6 (75.2)
Nov	8.8 (52.6)	2.6 (26.3)	7.2 (63.9)	3.7 (31.7)	7.3 (170.8)	–	8.4 (47.6)	–	4.1 (31.5)
Dec	5.5 (170.9)	5.5 (54.5)	4.6 (30.5)	6.6 (55.4)	12.1 (169.8)	–	7.3 (43.1)	–	4.7 (45.9)

* Measurements in the poor condition range (also highlighted in red).

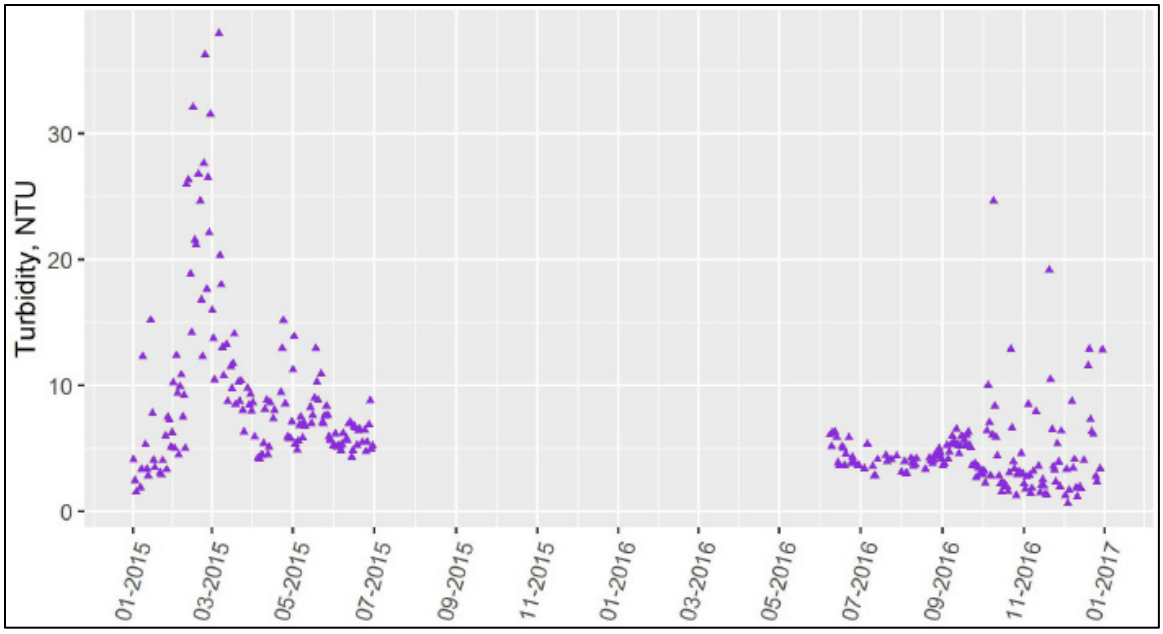


Figure 84. Mean daily turbidity values at Ocracoke dock, during the first half of 2015 and the second half of 2016 (Hynds and Starkey 2019).

Measurements from more extensive SECN estuarine water quality monitoring in 2010 documented water clarity indices (WCI) in good condition at the five sites where WCI could be calculated (Table 89) (Gregory and Smith 2011). During 2015 monitoring, WCI could only be calculated for three out of 15 sites, and two of these sites off Bodie Island were considered in poor condition (Wright 2016). Turbidity measurements were taken at all sites in 2015, and may provide some insight for locations where WCI could not be calculated. One sampling site (#06) showed turbidity readings higher than those for the two locations where WCI was in poor condition, suggesting that clarity/turbidity would also be in poor condition at this site. Turbidity readings for seven locations were below the reading for the location with a WCI in good condition (Table 89), suggesting they would be in good condition as well.

Table 89. Water clarity index (WCI) and turbidity (FNU, 2015 only) from SECN estuarine water quality monitoring (Gregory and Smith 2011, Wright 2016). Note that sites are randomly positioned each year; as a result, the locations of sites sampled in 2010 do not correspond to the 2015 locations.

Year	Site #	Turbidity	WCI
2010	CAHACALO-01	–	–
	CAHACALO-02	–	–
	CAHACALO-05	–	0.495
	CAHACALO-06	–	–
	CAHACALO-09	–	–
	CAHACALO-10	–	0.667
	CAHACALO-14	–	–
	CAHACALO-17	–	0.588
	CAHACALO-18	–	–
	CAHACALO-21	–	–
	CAHACALO-29	–	–
	CAHACALO-ALT03	–	–
	CAHACALO-ALT07	–	–
	CAHACALO-ALT08	–	0.685
	CAHACALO-ALT19	–	1.053
	CAHACALO-ALT24	–	–
	CAHACALO-ALT27	–	–
2015	01	8.39	2.33
	02	8.70	2.80
	03	2.82	–
	04	3.59	–
	05	3.26	–
	06	10.86	–
	07	6.00	–
	08	4.36	1.27
	09	4.06	–
	10	4.91	–
	11	4.01	–
	12	5.83	–
	13	3.88	–
	14	3.93	–
	15	5.93	–

* Measurements in the poor condition range (also highlighted in red).

Chlorophyll a

The first documented measurements of chlorophyll a at CAHA were taken from 2000–2002 at estuarine sites on Hatteras Island (NWQMC 2018). Samples ranged from 4.97 µg/l near Salvo in 2002 to 5.82 µg/l between Frisco and Hatteras in 2000 (Table 90). One of these sites would be considered in good condition based on SECN estuarine standards (<5 µg/l) and two would be in fair condition (5–20 µg/l).

Table 90. Chlorophyll a levels (µg/l) from Hatteras Island estuarine sites (NWQMC 2018).

Site	Location	Sample year	Chlorophyll a
NARS_WQX-NC02-0014	Near Salvo	Sept. 2002	4.97
NARS_WQX-NC01-0030	Near Buxton	August 2001	5.04
NARS_WQX-NC00-0030	Between Frisco & Hatteras	July 2000	5.82

During 2007 sampling, Mallin and McIver (2012) found chlorophyll a levels above the state freshwater standard (40 µg/l) in an urban pond on five of six occasions, and in two drainage ditches on three of six occasions. Researchers documented at least one algal bloom that elevated chlorophyll a levels above the state standard at each site during the study period (Mallin and McIver 2012). Overall ranges and means for ditch and pond study sites are shown in Table 91.

Table 91. Chlorophyll a levels (µg/l) in Bodie Island drainage ditches and ponds during 2007 (Mallin and McIver 2012).

Site type (# of sites)	Overall range	Overall mean (range)
Ditches (6)	6–275	43.2 (28–83)
Ponds (3)	5–175	42.0 (25–71)

Monthly chlorophyll a samples taken during SECN monitoring of estuarine waters at the Ocracoke dock were in good condition (30 measurements) or fair condition (19 measurements), but with no samples exceeding 10.2 µg/l (Table 92). From 2007–2012, samples were more likely to fall in the fair condition range than in good condition later in the growing season (July–September) (Rinehart et al. 2013, Wright and Yazdansepas 2015).

Table 92. Chlorophyll a measurements (µg/l), Ocracoke dock monthly monitoring (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019).

Month	2007	2008	2009	2012	2013	2014	2015	2016
Jan	–	9.36*	4.79	–	1.89	–	1.62	–
Feb	–	1.84	4.59	–	–	–	–	–
March	–	2.62	2.29	–	1.79	–	12.91*	–
April	–	2.72	5.71*	–	–	–	–	–
May	5.12*	2.99	3.92	–	–	–	–	–
June	3.85	6.02*	4.58	4.45	–	–	–	4.41
July	5.89*	6.35*	5.36*	5.47*	–	–	–	6.91*
Aug	6.83*	4.00	5.88*	6.64*	–	–	–	4.60
Sept	8.98*	5.55*	4.72	7.03*	–	–	–	4.81
Oct	3.07	3.39	2.44	1.99	–	–	–	4.26
Nov	10.20*	4.73	1.24	–	–	3.08	–	3.01
Dec	6.45*	6.53*	2.62	–	–	–	–	4.81

* Measurements in the fair condition range (also highlighted in yellow).

Measurements from more extensive SECN estuarine water quality monitoring at CAHA in 2010 were primarily in good condition (14 sites), with three sites in fair condition (Table 93) (Gregory and Smith 2011). The highest reading (18.94 µg/l) was at the very top of the fair condition range. In 2015, ten sites were in good condition and five sites were in fair condition, with one reading (20.0 µg/l) just below the poor condition range (Wright 2016).

Table 93. Chlorophyll a (µg/l) measurements from SECN estuarine water quality monitoring (Gregory and Smith 2011, Wright 2016). Note that sites are randomly positioned each year; as a result, the locations of sites sampled in 2010 do not correspond to the 2015 locations.

Year	Site #	Chlorophyll a
2010	CAHACALO-01	5.95 *
	CAHACALO-02	2.86
	CAHACALO-05	2.43
	CAHACALO-06	4.22
	CAHACALO-09	2.31
	CAHACALO-10	2.57
	CAHACALO-14	1.94
	CAHACALO-17	1.18
	CAHACALO-18	3.17
	CAHACALO-21	3.40
	CAHACALO-29	1.98
	CAHACALO-ALT03	14.49 *

* Measurements in the fair condition range (also highlighted in yellow).

Table 93 (continued). Chlorophyll a (µg/l) measurements from SECN estuarine water quality monitoring (Gregory and Smith 2011, Wright 2016). Note that sites are randomly positioned each year; as a result, the locations of sites sampled in 2010 do not correspond to the 2015 locations.

Year	Site #	Chlorophyll a
2010 (continued)	CAHACALO-ALT07	4.54
	CAHACALO-ALT08	3.57
	CAHACALO-ALT19	18.94 *
	CAHACALO-ALT24	2.57
	CAHACALO-ALT27	3.17
2015	01	17.8 *
	02	20.0 *
	03	1.5
	04	4.0
	05	1.8
	06	7.1 *
	07	2.7
	08	5.5 *
	09	4.2
	10	8.3 *
	11	3.9
	12	2.3
	13	2.4
	14	3.3
	15	3.9

* Measurements in the fair condition range (also highlighted in yellow).

Threats and Stressor Factors

Threats to park water quality identified by the project team include human development (particularly septic systems), stormwater runoff, oil/fuel spills, harmful algal blooms, and sea level rise (SLR). SLR is a threat to water quality because of the potential for saltwater intrusion into the fresh groundwater table, as well as freshwater wetlands that are seasonally fed by groundwater (Mallin et al. 2006, Werner and Simmons 2009). Changes in ground and surface water salinity can alter other water properties (DO, SpC, dissolved nutrients, density), vegetation communities, and wildlife habitat suitability (Masterson et al. 2014, VIMS 2018).

Rapid development on the Outer Banks during the 1980s and 1990s increased water use and wastewater production on the islands of CAHA (Cole and Bratton 1994, Parman et al. 2012). In the CAHA area, development occurred particularly on central Hatteras Island (Rodanthe, Avon, Buxton) and north of the park (Nags Head, Kitty Hawk). Much of the housing development at the time relied on septic systems for wastewater treatment. There have been substantial concerns that septic effluent from these developments may reach park surface and ground water, especially following heavy rains

(Bratton and Turner 1986, Cole and Bratton 1994). Septic leachate may reach groundwater, as the water table on the islands is sometimes less than 76 cm (30 in) below the ground surface (Mallin et al. 2006). On barrier islands, groundwater generally seeps from the highest points towards the shores, "passing beneath dunes and through ponds, eventually to surface in tidal wetlands or along the beach zone" (Cole and Bratton 1994, p. 137). On Bodie Island, the developed area of Nags Head is the high point, and any septic effluent or contamination that enters groundwater there can seep through and into park waters, even seemingly remote wetlands.

Cole and Bratton (1994) detected septic effluent contamination in all Bodie Island drainage ditches and marshes sampled using optical brighteners (OBs) as tracers. OBs are synthetic chemicals added to laundry detergents that are a definitive indicator of anthropogenic pollution. These chemicals were also detected at one of Cole and Bratton's (1994) Buxton Woods sampling sites. The levels of fecal coliform detected in this study were also suggestive of septic contamination. Mallin and McIver (2012) also detected likely septic contamination in Bodie Island ditches in ponds, particularly in the elevated ammonium, total phosphorous, and enterococcus bacteria levels. The positive correlation between these constituents and monthly municipal water usage for Nags Head suggests that septic leachate is significantly impacting local water bodies (Mallin and McIver 2012).

Excess nutrients from septic and other sources contributes to eutrophication and excess aquatic plant growth (Gregory and Smith 2011, Parman et al. 2012). Eutrophication is a reduction in DO levels due to increased mineral and organic nutrients (USGS 2015). If DO levels become extremely low, fish kills may occur. Eutrophic waters with algal blooms may look and smell bad (EPA 2016b), which may negatively impact park visitor experience (Figure 85).



Figure 85. A eutrophic drainage ditch found near, but outside the park along Old Oregon Inlet Road, with algal blooms and excess aquatic plant growth (NPS photo by M. Mallin).

Some algae produce toxins that can harm humans and wildlife (EPA 2018). In the CAHA area, there is a potential for toxic cyanobacterial or native dinoflagellate (*Pfiesteria* spp.) blooms, particularly near developed areas where excess nutrients are present (Mallin et al. 2006). Harmful algal blooms (HABs) can occur in estuarine or fresh waters. Potentially harmful cyanobacteria blooms have been detected near CAHA in Albemarle and Pamlico Sounds annually since at least 2012 (Clabby 2017, NCDWR 2018). In August 2012, a cyanobacteria bloom was detected near Motts Creek, just off the northern end of Hatteras Island (Figure 86). To date, however, only one toxic algal bloom has been documented at CAHA, from November 1987 through February 1988. This large bloom of the dinoflagellate *Karenia brevis* was generated off the Florida Coast and drifted into North Carolina waters on a Gulf Stream meander, where it lingered in the coastal area between Hatteras Inlet and Cape Fear (south of Wilmington, NC) (Mallin et al. 2006).

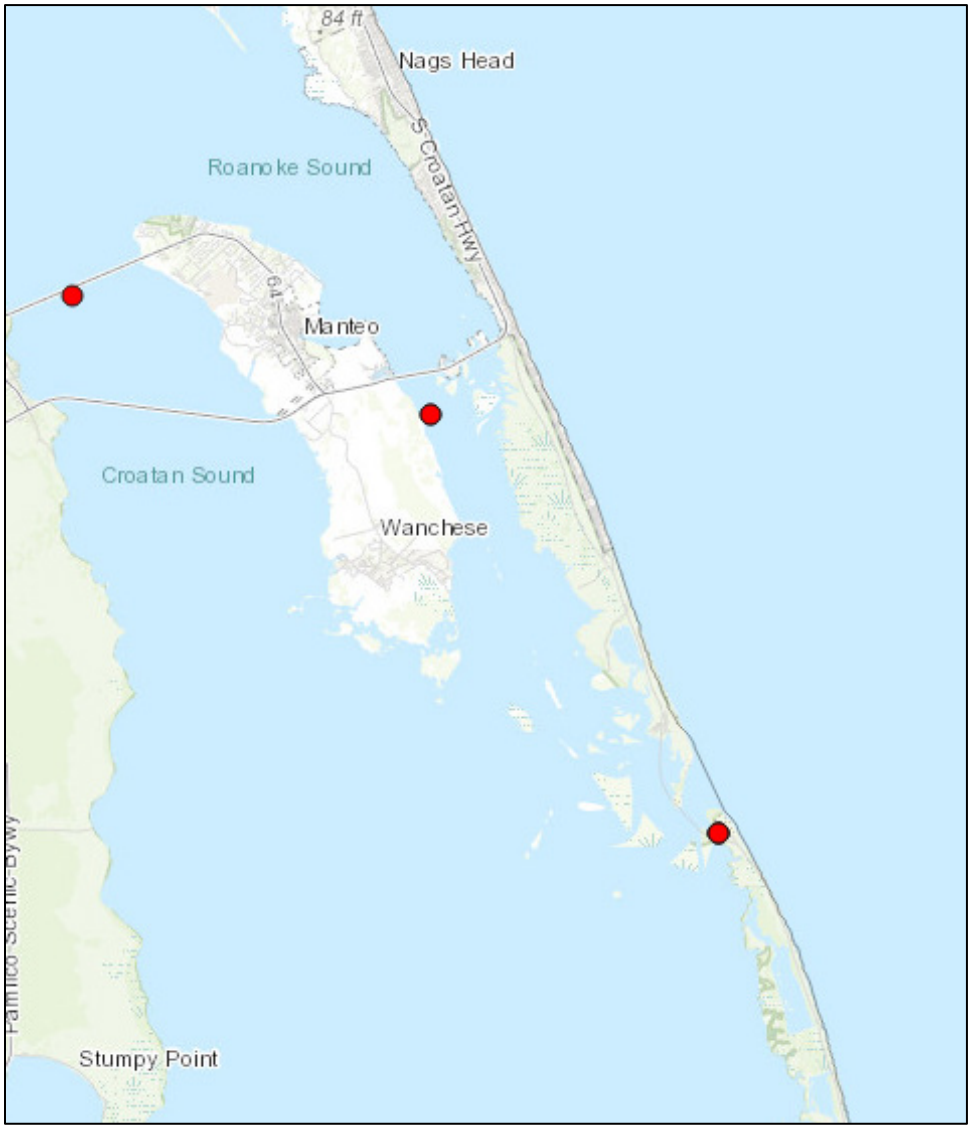


Figure 86. Locations of cyanobacterial algal blooms in or near CAHA in 2012 (NCDWR 2018). The southernmost red dot represents the bloom near Motts Creek.

Stormwater runoff from developed areas is also a potential source of water pollution for park waters (Cole 1991, Gregory and Smith 2011). The increase in impervious surfaces associated with development (e.g., roads, driveways, parking lots) has intensified storm runoff; not only is the total volume of runoff greater, but it is "flashier" (i.e., runoff increases in amount and intensity very quickly). This runoff can carry contaminants from developed areas through CAHA on its way to the sound or ocean (Bratton and Turner 1986, Gregory and Smith 2011). These contaminants can cause altered growth, reduced reproduction, and mortality in aquatic organisms (Lerberg et al. 2000).

Fuel and/or oil spills at marinas or boat docks are known to pollute coastal waters (EPA 1993, Whitfield and Becker 2014). Boats are typically fueled by diesel or a petroleum and oil-based mixture, which can inadvertently spill when filling fuel tanks (Whitfield and Becker 2014). These spills may occur directly into coastal waters or may be washed into the water later by rainfall. Pollutants such as oil and other chemicals may also be spilled during boat maintenance activities (EPA 1993).

Data Needs/Gaps

While some data are available for all of the selected measures, the most recent data are nearly all from estuarine waters. Freshwater bodies (e.g., ponds, ditches, creeks) have not been sampled since 2007 (Mallin and McIver 2012). In addition, freshwater sampling at the park has largely been limited to Bodie Island and the Buxton Woods area of Hatteras Island. Prior to brief sampling by Mallin et al. (2006) in 2005 and SECN estuarine monitoring (Wright and Yazdansepas 2015), there is no published water quality data for Ocracoke Island. Park managers would like to establish several water quality monitoring stations but have not yet found funding for this monitoring (Ziegler, written communication, March 2020).

Mallin et al. (2006) recommended resampling previously studied Bodie Island drainage ditches for standard water quality parameters (pH, DO, turbidity, bacteria, nutrients, chlorophyll a) as well as toxic compounds such as metals and polycyclic aromatic hydrocarbons (PAHs). Sampling for standard parameters at least six times per year was recommended in order to detect seasonal impacts and variations (Mallin et al. 2006). Similar water quality monitoring is recommended for freshwater sources on Hatteras and Ocracoke Islands, including wetlands in Buxton Woods. If elevated nutrients, bacteria, or toxic contaminants are found, further research would be needed to identify likely sources and reduce or eliminate the pollution. In addition, Mallin et al. (2006) recommended conducting an annual summer survey for *Pfiesteria* spp. and other potentially harmful algal species. Lastly, park managers should investigate monitoring bacteria levels at beaches where exceedances have been detected in recent years, to ensure visitor health and safety (Ziegler, written communication, March 2020).

Overall Condition

The NRCA project team assigned a *Significance Level* of 3 for all the selected measures.

pH

The majority of historic sampling in CAHA freshwaters met current state pH standards (Schwartz 1992, Cole and Bratton 1994). During more recent SECN estuarine monitoring, some small

exceedances of state pH standards occurred. At this time, pH is considered of low concern (*Condition Level* = 1).

Dissolved Oxygen

Sampling of CAHA drainage ditches and ponds just over a decade ago found DO levels at some locations that would be considered in fair condition according to SECN criteria (Mallin et al. 2006, Mallin and McIver 2012). However, no recent sampling has been conducted to determine whether conditions are currently similar. Monthly SECN monitoring at the Ocracoke dock detected only a few instances where DO levels fell just below the good condition level, and none occurred during the most recent sampling available (2015–2016). All DO measurements during park-wide SECN estuarine monitoring in 2010 and 2015 were considered in good condition (Gregory and Smith 2011, Wright 2016). Therefore, this measure is assigned a *Condition Level* of 1, indicating low concern.

Nutrients

In 2007 sampling of Bodie Island drainage ditches and ponds, Mallin and McIver (2012) found elevated total nitrogen and phosphorous levels, with particularly high ammonium concentrations (Table 75). Monthly estuarine monitoring at the Ocracoke dock from 2007–2016 documented primarily fair conditions for nitrogen and phosphorous, with just a few measurements in the poor condition range (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019). More extensive SECN monitoring in 2010 found six out of 17 locations (35%) in poor condition for nitrogen and just one location (6%) in poor condition for phosphorous (Gregory and Smith 2011). During 2015 SECN monitoring, seven out of 15 locations (47%) were in poor condition for nitrogen and three out of 15 (20%) were in poor condition for phosphorous (Wright 2016). At this time, nutrients are considered of moderate concern for park water quality (*Condition Level* = 2).

Fecal Bacteria

During 2007 sampling of Bodie Island drainage ditches and ponds, Mallin and McIver (2012) detected numerous exceedances of state bacterial standards for both fecal coliform and enterococci (Table 84). Monitoring of coastal beach waters by the NCDEQ (2018) from 2012–2018 has also documented exceedances of state enterococci standards at several CAHA locations, with two single samples in 2017 finding more than 10 times the allowable level of these bacteria (Table 85). Due to the potential human health risks posed by fecal bacteria, this measure is assigned a *Condition Level* of 2.

Specific Conductance (freshwater only)

Only one historic study (Cole and Bratton 1994) reported SpC observations from park freshwater bodies. Because of this very limited information, a *Condition Level* could not be assigned at this time.

Water Clarity/Turbidity

During the most recent years of SECN Ocracoke dock monitoring for which data are available (2012–2016), water clarity measurements were split between the good and fair condition ranges (Rinehart et al. 2013, Wright and Mockus 2015, Hynds and Starkey 2019). More extensive SECN

monitoring in 2010 found good water clarity conditions at the five sites where clarity could be measured (Gregory and Smith 2011). However, more recent park-wide SECN estuarine monitoring in 2015 found poor conditions at two of the three sites where water clarity index could be calculated (Wright 2016). As a result, this measure is assigned a *Condition Level* of 2 for moderate concern.

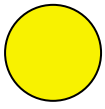
Chlorophyll a

In 2007, Mallin and McIver (2012) found at least one exceedance of the state chlorophyll a standard at each of their six ditch and three pond sites on Bodie Island, with one pond in an urban setting exceeding the standard on five of six occasions. However, no repeat sampling of park fresh waters has been completed since to determine if conditions are similar at present. Monthly chlorophyll a samples taken during SECN monitoring at the Ocracoke dock from 2007–2016 were split between good condition and fair condition, with slightly more samples in the good condition category (Rinehart et al. 2013, Wright and Mockus 2015, Wright and Yazdansepas 2015, Hynds and Starkey 2019). Park-wide SECN monitoring also found more samples in the good condition range than in the fair condition range, with three out of 17 (18%) in fair condition in 2010 and five out of 15 (33%) in fair condition in 2015 (Gregory and Smith 2011, Wright 2016). At this time, chlorophyll a is of low concern (*Condition Level* = 1) but may be bordering on moderate concern.

Weighted Condition Score

The *Weighted Condition Score* for water quality at CAHA is 0.50, indicating moderate concern (Table 94). The parameters of greatest concern currently are fecal bacteria and nutrients, especially total nitrogen. An overall trend was not assigned as trends appear to vary between measures. While some measures seem stable (pH, DO), others show potential signs of decline (nutrients) or lack enough consistent data to detect any trends (SpC, water clarity/turbidity). A medium confidence border was applied due to limited data for several measures. Confidence in this assessment is higher for park estuarine waters than for fresh waters.

Table 94. Current condition and trend for the Water Quality of CAHA.

Measures	Significance Level	Condition Level	WCS = 0.50
pH	3	1	–
Dissolved Oxygen	3	1	–
Nutrients	3	2	–
Fecal Bacteria	3	2	–
Specific Conductance	3	n/a	–
Water Clarity/Turbidity	3	2	–
Chlorophyll a	3	1	–
Overall	–	–	

Sources of Expertise

Eric Starkey, SECN Aquatic Ecologist

Tracy Ziegler, CAHA Chief of Resource Management and Science

Dark Night Skies

Description

A natural lightscape is a place or environment characterized by the natural rhythm of the sun and moon cycles, clean air, and of night skies unperturbed by artificial light (NPS NSNSD 2015). The NPS directs each of its units to preserve, to the greatest extent possible, these natural lightscapes (NPS 2006). Natural cycles of dark and light periods during the course of a day affect the evolution of species and other natural resource processes such as plant phenology (NPS 2006, Bennie et al. 2016). Several species require darkness to hunt, hide their location, navigate, or reproduce (Navara and Nelson 2007, NPS NSNSD 2015). In addition to the ecological importance of natural night skies, park visitors expect skies to be free of light pollution and allow for astronomical observation.

CAHA is located off the northeast coast of North Carolina, just south of several major tourist areas, including Nags Head, Kill Devil Hills, and Kitty Hawk (Figure 87). This area produces a substantial amount of anthropogenic light that impacts the night sky in northern portions of the park. State Highway 12 runs through CAHA, connecting many smaller towns on the islands just outside park boundaries that are also sources of anthropogenic light.

The resource of a dark night sky is important to the NPS for a variety of reasons. First, the preservation of natural lightscapes (the intensity and distribution of light on the landscape at night) will keep the nocturnal photic environment within the range of natural variability. Excursions outside this natural range may result in a modification to natural ecosystem function, especially to systems involving the behavior and survival of nocturnal animals (NPS NSNSD 2015). The natural night sky is therefore one of the physical resources under which natural ecosystems have evolved. Second, the "scenery" of national park areas is not limited to the daytime hours (NPS NSNSD 2015). Third, the history and culture of many civilizations are steeped in interpretations of night sky observations, whether for scientific, cultural, or time-keeping purposes (NPS NSNSD 2015). As such, the natural night sky may be a very important cultural resource, especially in areas where evidence of aboriginal cultures are present. Fourth, the recreational value of dark night skies is important to campers and backpackers, allowing the experience of having a campfire or "sleeping under the stars" (NPS NSNSD 2015). And lastly, night sky quality is an important wilderness value, contributing to the ability to experience a feeling of solitude in a landscape free from signs of human occupation and technology (NPS NSNSD 2015).



Figure 87. Location of CAHA with nearby communities and roads that may contribute anthropogenic light to the night sky.

Measures

The dark night sky at CAHA was assessed using the suite of measures that the NPS Natural Sounds and Night Sky Division (NSNSD) uses to define the night sky conditions in a park unit. Selection of

the standard NSNSD measures ensures that this assessment aligns with NSNSD standards. The suite of measures that the NSNSD typically uses to define the condition of dark night skies include:

- Sky luminance over the hemisphere in high resolution (thousands of measurements comprise a data set), reported in photometric luminance units (V magnitudes per square arc second [mag/arcsec^2] or milli-candela per square meter [mCd/m^2]) or relative to natural conditions, often shown as a sky brightness contour map of the entire sky. V magnitude (mags) is a broadband photometric term in astronomy, meaning the total flux from a source striking a detector after passing through a "Johnson-Cousins V" filter. It is similar to the "CIE photopic" broadband function for wavelengths of light to which the human eye is sensitive (Bessell 1990);

- Integrated measures of anthropogenic sky glow from selected areas of sky that may be attributed to individual cities or towns (known as city light domes), reported in milli-Lux of hemispheric illuminance or vertical illuminance;

- Integration of the entire sky illuminance measures, reported either in milli-Lux of total hemispheric (or horizontal) illuminance, milli-Lux of anthropogenic hemispheric (or horizontal) illuminance, V-magnitudes of the integrated hemisphere, or ratio of anthropogenic illuminance to natural illuminance;

- Vertical illuminance from individual (or groups of) outdoor lighting fixtures at a given observing location (such as the Wilderness boundary), in milli-Lux;

- Visual observations by a human observer, such as Bortle Class and Zenith limiting magnitude (ZLM);

- Integrated synthesized measure of the luminance of the sky within 50 degrees of the Zenith, as reported by the Unihedron Sky Quality Meter (SQM), in mag/arcsec^2.

The NPS NSNSD currently recommends the use of the all-sky light ratio (ALR) as a measure of the quality of the photic environment and lightscape within a park (Moore et al. 2013). The ALR measures the average anthropogenic sky luminance as a ratio of natural conditions. This measure is easily modeled using GIS and provides a robust and descriptive metric (Moore et al. 2013). The modelled ALR data can provide information on park-wide night sky condition, including areas that have not been visited by the NPS NSNSD.

Reference Condition/Values

NPS staff identified the absence of anthropogenic light as the preferred reference condition. This condition can be defined as the absence of artificial light in terms of sky luminance and illuminance at the observer's location from anthropogenic sources as follows:

> *No portion of the sky background brightness exceeds natural levels by more than 200 percent, and the sky brightness at the Zenith does not exceed natural Zenith sky brightness by more than 10 percent. The ratio of anthropogenic hemispheric illuminance to natural*

> *hemispheric illuminance from the entire night sky does not exceed 20 percent. The observed light from a single visible anthropogenic source (light trespass) is not observed as brighter than the planet Venus (0.1 milli-Lux) when viewed from within any area of the park designated the naturally dark zone* (Dan Duriscoe, NPS NSNSD, pers. comm., 2011).

Achieving this reference condition for preserving natural night skies is well summarized in the NPS Management Policies (NPS 2006, p. 7) in section 4.10 as follows:

> *The Service will preserve, to the greatest extent possible, the natural lightscapes of parks, which are natural resources and values that exist in the absence of human-caused light.*

Implementing this directive in CAHA requires that facilities within the park meet outdoor lighting standards that provide for the maximum amount of environmental protection while meeting human needs for safety, security, and convenience. This means that outdoor lights within the park:

- produce zero light trespass beyond the boundary of their intended use;
- be of an intensity that meets the minimum requirement for the task, but does not excessively exceed that requirement;
- be of a color that is toward the yellow or orange end of the spectrum to minimize sky glow;
- be controlled intelligently, preventing unnecessary dusk to dawn bright illumination of areas.

Data and Methods

The NPS NSNSD has conducted two field visits to CAHA, in 2007 and 2013. During the November 2007 visit, the team visited three sites: the boardwalk south of Frisco, Boardwalk 27 (between Salvo and Avon), and Bodie Island south of the maintenance facility (Magargal 2007). Data collected included Bortle class, zenith sky brightness, and limiting magnitude (i.e., the dimmest star that can be seen in the darkest part of the sky with averted vision). Two sites were visited by the NSNSD in November 2013: Boardwalk 27 and the Pony Pens boardwalk on Ocracoke Island (NPS NSNSD 2013a, b) (Figure 88). Data collection again included Bortle class and zenith sky brightness but also calculated light pollution ratios (artificial/natural).



Figure 88. Locations of sites visited by the NPS NSNSD in 2013: Boardwalk 27 on Hatteras Island (center) and the Pony Pens Boardwalk on Ocracoke Island (lower) (NPS NST 2016).

The NPS NSNSD has developed a geographic information system (GIS) model derived from data from the Suomi VIIRS Day/Night Band 2015 annual composite (Duriscoe et al. 2018), which depicts all-sky light pollution, including full hemispheric light sources' effects on the observers' location. A neighborhood analysis is then applied to the modelled data to determine the anthropogenic sky brightness over the entire sky. Anthropogenic light up to 200 km (124 mi) from parks can have an impact on a park's night sky quality. Finally, the modeled anthropogenic light over the entire sky is presented as a ratio (ALR) over the natural sky brightness (Duriscoe 2016). This modeled data can be used to estimate night sky conditions in areas of the park that have not been visited by the NSNSD.

Current Condition and Trend

Background for NPS Night Sky Division's Suite of Measures

Anthropogenic light in the night environment can be very significant, especially on moonless nights. Unshielded lamps mounted on tall poles have the greatest potential to cause light pollution, since light directly emitted by the lamp has the potential to follow an unobstructed path into the sky or the distant landscape. This type of light spill has been called glare, intrusive light, or light trespass (Narisada and Schreuder 2004). The dark-adapted human eye will see these individual light sources as extremely bright points in a natural environment. These sources also have the potential to illuminate the landscape, especially vertical surfaces aligned perpendicular to them, often to a level that approaches or surpasses moonlight. The brightness of such objects may be measured as the amount of light per unit area striking a "detector" or a measuring device, or entering the observer's pupil. This type of measure is called illuminance (Ryer 1997).

Illuminance is measured in lux (metric) or foot-candles (English), and is usually defined as luminous flux per unit area of a flat surface (1 lux = 1 lumen/m^2). However, different surface geometries may be employed, such as a cylindrical surface or a hemispheric surface. Integrated illuminance of a hemisphere (summed flux per unit area from all angles above the horizon) is a useful, unbiased metric for determining the brightness of the entire night sky. Horizontal and vertical illuminance are also used; horizontal illuminance weights areas near the Zenith much greater than areas near the horizon, while vertical illuminance preferentially weights areas near the horizon, and an azimuth of orientation must be specified (Ryer 1997).

Direct vertical illuminance from a nearby anthropogenic source will vary considerably with the location of the observer, since this value varies as the inverse of the square of the distance from light source to observer (Ryer 1997). Therefore, measures of light trespass are usually made in sensitive areas (such as public campgrounds).

Anthropogenic light which results in an upward component will be visible to an observer as "sky glow." This is because the atmosphere effectively scatters light passing through it. The sky is blue in daytime because of Rayleigh scattering by air molecules, which is more effective at scattering light of shorter wavelengths. For this reason, bluish light from outdoor fixtures will produce more sky glow than reddish light. Larger particles in the atmosphere (aerosols and water vapor droplets) cause Mie scattering and absorption of light, which is not as wavelength-dependent and is more directional. When the air is full of larger particles, this process gives clouds their white appearance and produces a whitish glow around bright objects (e.g., the sun and moon). The pattern of sky glow as seen by a distant observer will appear as a dome of light of decreasing intensity from the center of the city on the horizon. As the observer moves closer to the source, the dome gets larger until the entire sky appears to be luminous (Garstang 1989).

Light propagated at an angle near the horizon will be effectively scattered and the sky glow produced will be highly visible to an observer located in the direction of propagation. Predictions of the apparent light dome produced by a sky glow model demonstrate this (Luginbuhl et al. 2009). Light reflected off surfaces (e.g., a concrete road or parking area) becomes visible light pollution when it is

scattered by the atmosphere above it, even if the light fixture has a “full cutoff” design and is not visible as glare or light trespass to a distant observer. For this reason, the intensity and color of outdoor lights must be carefully considered, especially if light-colored surfaces are present near the light source.

Light domes from many cities, as they appear from a location within Joshua Tree National Park, are shown in Figure 89 and Figure 90, as a grayscale and in false color. This graphic demonstrates that the core of the light dome may be tens or hundreds of times brighter than the extremities. A logarithmic scale for sky luminance and false color are commonly used to display monochromatic images or data with a very large dynamic range, and are used extensively in reports of sky brightness by the NSNSD.



Figure 89. Grayscale representation of sky luminance from a location in Joshua Tree National Park (Figure provided by Dan Duriscoe, NPS NSNSD).

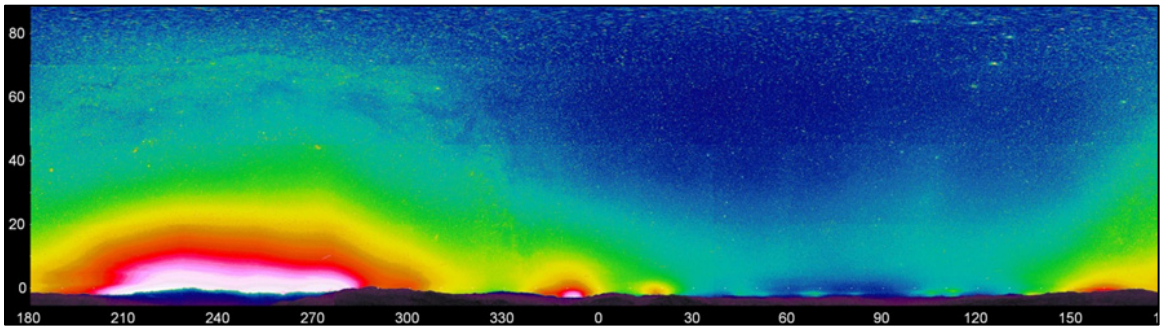


Figure 90. False color representation of Figure 91 after a logarithmic stretch of pixel values (Figure provided by Dan Duriscoe, NPS NSNSD).

The brightness (or luminance) of the sky in the region of the light domes may be measured as the number of photons per second reaching the observer for a given viewing angle, or area of the sky (such as a square degree, square arc minute, or square arc second). The NSNSD utilizes a digital camera with a large, dynamic range, monochromatic charge-coupled device (CCD) detector and an extensive system of data collection, calibration, and analysis procedures (Duriscoe et al. 2007). This system allows for the accurate measurement of both luminance and illuminance, since it is calibrated on standard stars that appear in the same images as the data and the image scale in arc seconds per pixel is accurately known. Sky luminance is reported in astronomical units of V-magnitudes per

square arc second, and in engineering units of milli-candela per square meter. High resolution imagery of the entire night sky reveals details of individual light domes that may be attributed to anthropogenic light from distant cities or nearby individual sources. These data sets may be used for both resource condition assessment and long-term monitoring.

Figure 89 and Figure 90 contain information on natural sources of light in the night sky as well as anthropogenic sources. The appearance of the natural night sky may be modeled and predicted in terms of sky luminance and illuminance over the hemisphere, given the location, date, time, and the relative brightness of the natural airglow (the so-called "permanent aurora" which varies in intensity over time) (Roach and Gordon 1973). The NSNSD has constructed such a model, and uses it in analysis of data sets to remove the natural components. This results in a more accurate measure of anthropogenic sky glow (Figure 91). Figure 90 represents "total sky brightness" while Figure 91 displays "anthropogenic sky glow" or "net light pollution." This is an important distinction, especially in areas where anthropogenic sky glow is of relatively low intensity.

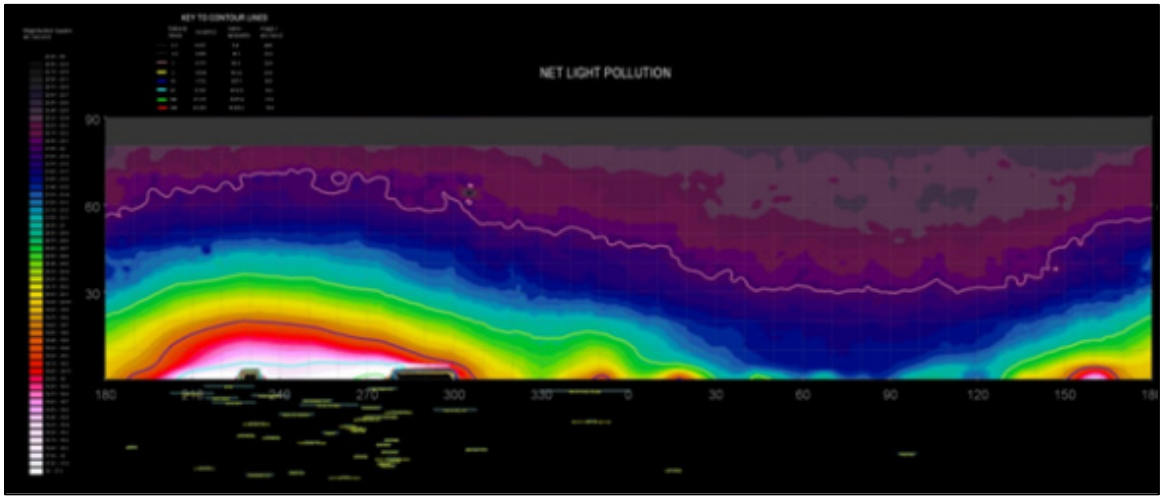


Figure 91. Contour map of anthropogenic sky glow at a location in Joshua Tree National Park, analogous to Figure 91 with natural sources of light subtracted (Figure provided by Dan Duriscoe, NPS Night Sky Division).

The accurate measurement of both anthropogenic light in the night sky and the accurate prediction of the brightness and distribution of natural sources of light allows for the use of a very intuitive metric of the resource condition—a ratio of anthropogenic to natural light, the ALR identified previously (Moore et al. 2013). Both luminance and illuminance for the entire sky or a given area of the sky may be described in this manner (Hollan 2010). This so-called "light pollution ratio" is unitless and is always referenced to the brightness of a natural moonless sky under average atmospheric conditions, or, in the case of the NSNSD data, the atmospheric conditions determined from each individual data set. The ALR is derived from ground–based measurements when available, or from a GIS model (calibrated to ground-based measurements in the park) when field-based data are measures are not available (Moore et al. 2013).

A quick and moderately accurate method of quantifying sky brightness near the Zenith is the use of a Unihedron SQM. The Unihedron SQM is a single-channeled hand-held photometric device. A single number in magnitudes per square arc second is read from the front of the device after its photodiode and associated electronics are pointed at the Zenith and the processor completes its integration of photon detection. Because the meter is relatively inexpensive and easy to use, a database of measures has grown since its introduction (see http://unihedron.com/projects/darksky/database/index.php). The NSNSD produces values from each data set as both a synthesized value derived from the high-resolution images and by handheld measures with a Unihedron SQM. The performance of the SQM has been tested and reviewed by Cinzano et al. (2001). While fairly accurate and easy to use, the value it produces is biased toward the Zenith. Therefore, the robustness of data collected in this manner is limited to areas with relatively bright sky glow near the Zenith, corresponding to severely light polluted areas. While not included in the reference condition, a value of about 21.85 would be considered "pristine," providing the Milky Way is not overhead and/or the natural airglow is not unusually bright when the reading is taken (Moore et al. 2013).

Visual observations are important in defining sky quality, especially in defining the aesthetic character of night sky features. A published attempt at a semi-quantitative method of visual observations is described in the Bortle Dark Sky Scale (Bortle 2001). Observations of several features of the night sky and anthropogenic sky glow are synthesized into a 1–9 integer interval scale, where class 1 represents a "pristine sky" filled with easily observable features and class 9 represents an "inner city sky" where anthropogenic sky glow obliterates all the features except a few bright stars. Bortle Class 1 and 2 skies possess virtually no observable anthropogenic sky glow (Bortle 2001).

NPS Night Sky Division Suite of Measures

During the NSNSD's 2007 visit to CAHA, sky brightness at the three sites ranged from nearly natural levels of darkness to significantly polluted (Magargal 2007). Measurements varied depending on the site's proximity to light sources such as towns and facilities. Bortle Class observations ranged from 3 at Boardwalk 27 to 4–5 on Bodie Island (Table 95). Similarly, all measurements of sky brightness were closest to the natural baseline at Boardwalk 27 and furthest from this baseline on Bodie Island (Magargal 2007). Panoramic false color images of the night sky at the three sites (Figure 92-Figure 94) show the influence of nearby artificial light sources.

Table 95. A summary of night sky data for three sites at CAHA visited in 2007. The astronomical magnitude scale is inverted, with negative numbers indicating brighter light flux.

Location	Bortle Class	Limiting magnitude	Zenith sky brightness (magnitudes/sq arc second)	Whole sky brightness (magnitudes)	Sky above 20° altitude (magnitudes)
Boardwalk south of Frisco	4	5.6	21.50	−7.69	−6.9
Boardwalk 27	3	NA	21.69	−6.63	−6.63
Bodie Island south of maintenance facility	4–5	NA	21.38	−8.13	−7.17
Natural baseline	**1–2**	**7.0–7.5**	**22.00–22.20**	**−6.8–7**	**6.2–6.4**

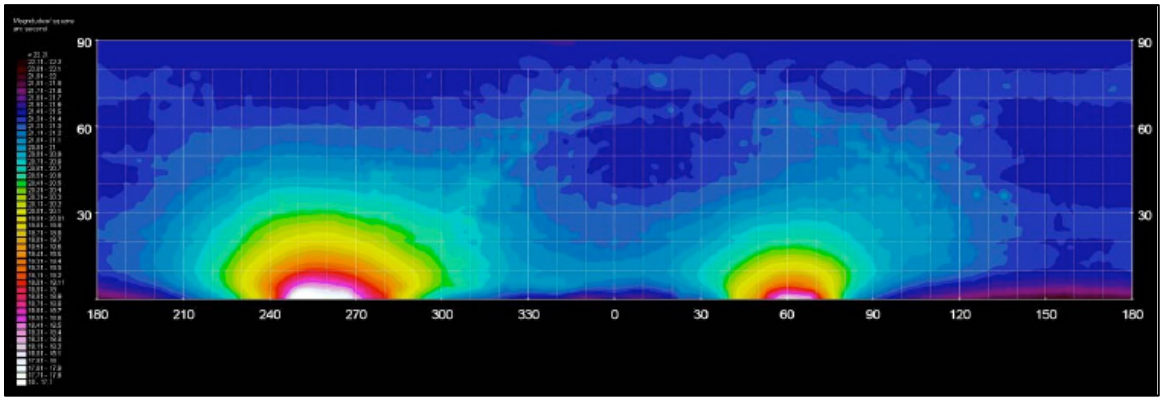


Figure 92. Panoramic false color map of the night sky from the boardwalk south of Frisco, November 2007 (reproduced from Magargal 2007). Frisco lies at around 60°azimuth and Hatteras at about 260° azimuth.

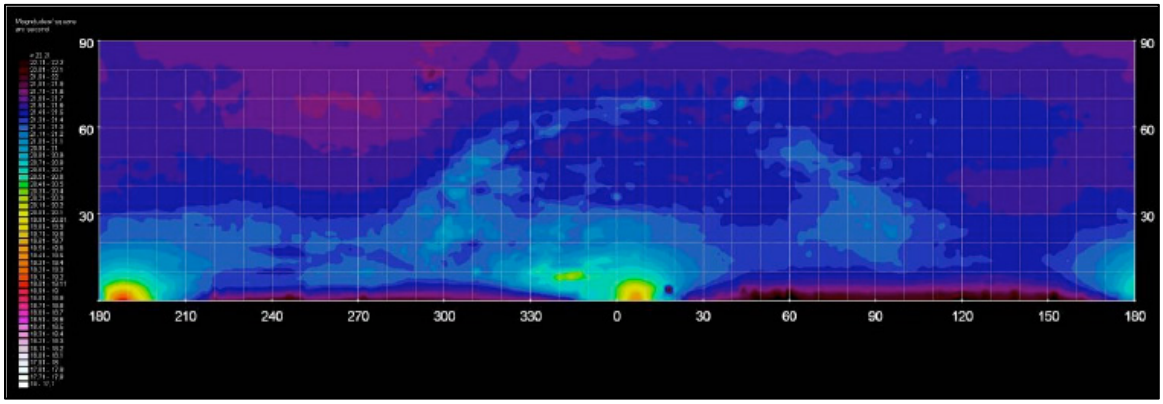


Figure 93. Panoramic false color map of the night sky from Boardwalk 27, between Salvo and Avon, November 2007 (reproduced from Magargal 2007). The combined light of Rodanthe, Salvo, and Waves is seen at about 6° and Avon at 191°.

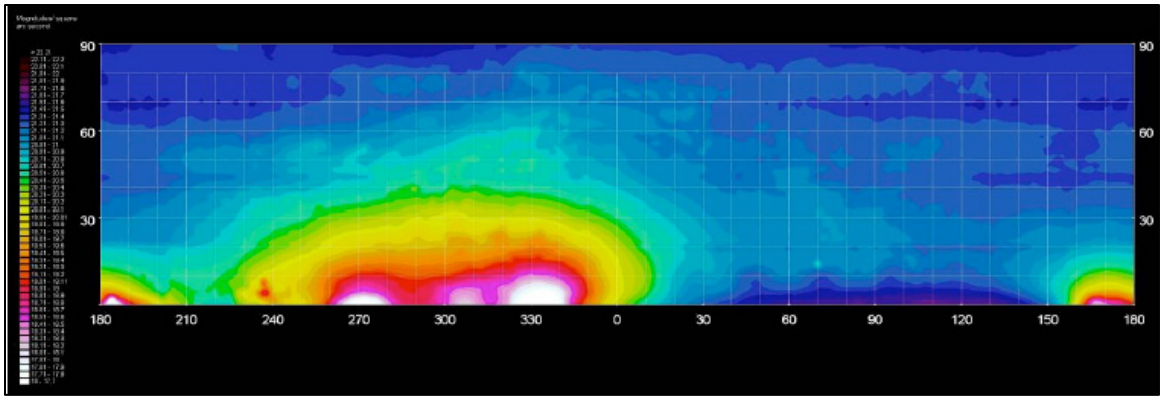


Figure 94. Panoramic false color map of the night sky from Bodie Island south of maintenance facility, November 2007 (reproduced from Magargal 2007). The combined light from Manteo, Kill Devil Hills, Nags Head, and Kitty Hawk occurs between 304°and 333°, Wanchese at 267°, and Bodie Island Lighthouse at 184°.

During the 2013 visit, the NSNSD team returned to Boardwalk 27 and sampled a new site, the Pony Pens Boardwalk on Ocracoke Island (NPS NSNSD 2013a, b). The zenith sky brightness at both sites was near the natural baseline of 22.0–22.2 magnitudes/arcsec^2 (Table 96). Mean and median light pollution ratios were slightly lower (i.e., less polluted) at the Pony Pens than at Boardwalk 27. Figure 95 and Figure 96 show all observed light sources and the estimated artificial sky glow in the night sky at the two sites.

Table 96. A summary of night sky data for the two sites at CAHA visited in 2013 (NPS NSNSD 2013a, b). All brightness measurements are in magnitudes/arcsec^2. The astronomical magnitude scale is inverted, with lower numbers indicating brighter light flux.

Measurement	Boardwalk 27	Pony Pens
Bortle Class	3	3
Zenith sky brightness – observed	21.30	21.47
Mean all-sky brightness – observed	20.91	21.08
Brightness range (brightest-darkest)	18.09–21.42	18.57–21.68
Mean all-sky light pollution ratio (Artificial/Natural)	0.32	0.18
Median light pollution ratio	0.10	0.06

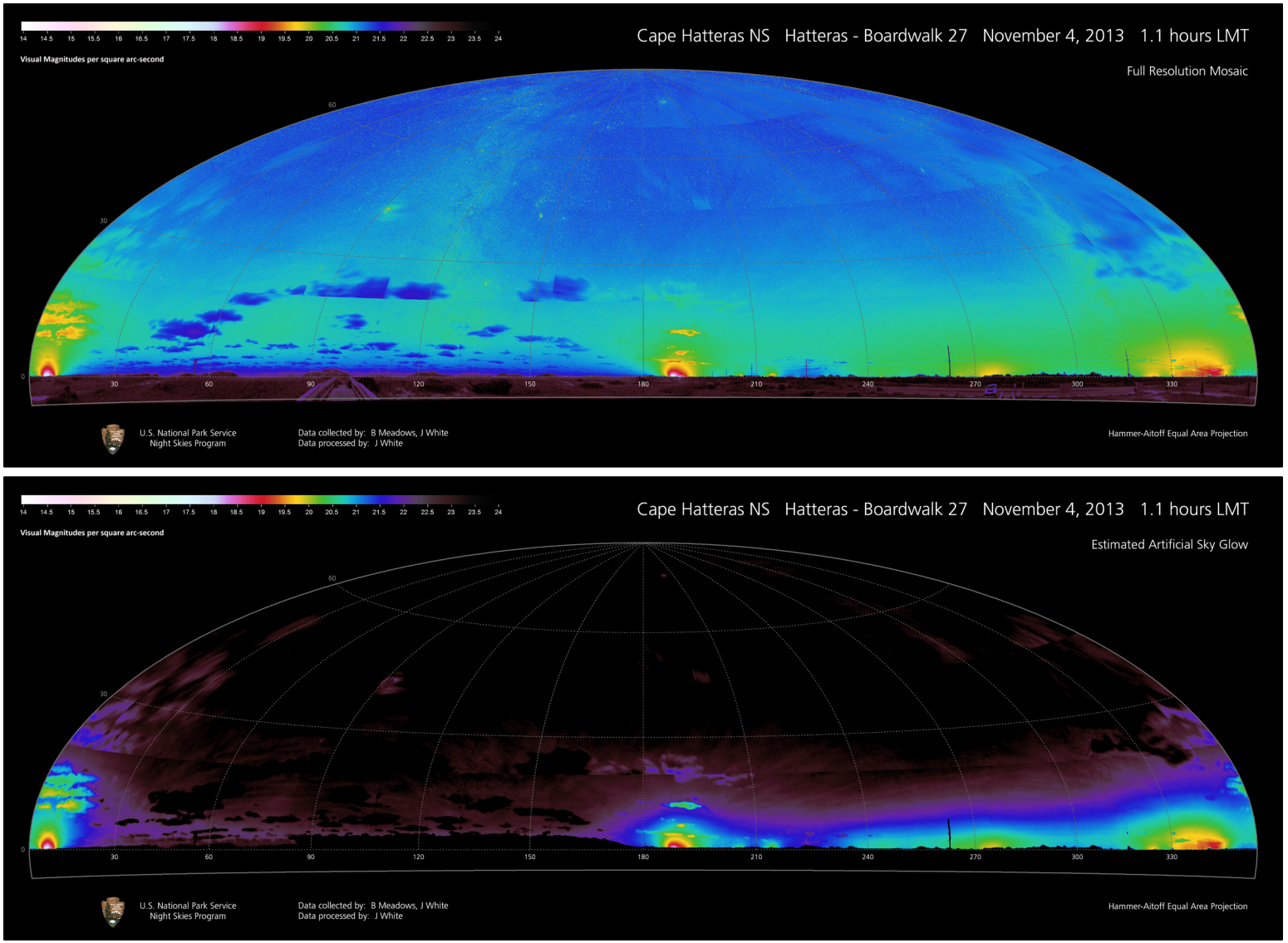


Figure 95. Panoramic image of all (natural and anthropogenic) sources of light (top) and of estimated artificial light (e.g., “sky glow”) (bottom) from Boardwalk 27 on Hatteras Island (Downloaded from NPS NST 2016).

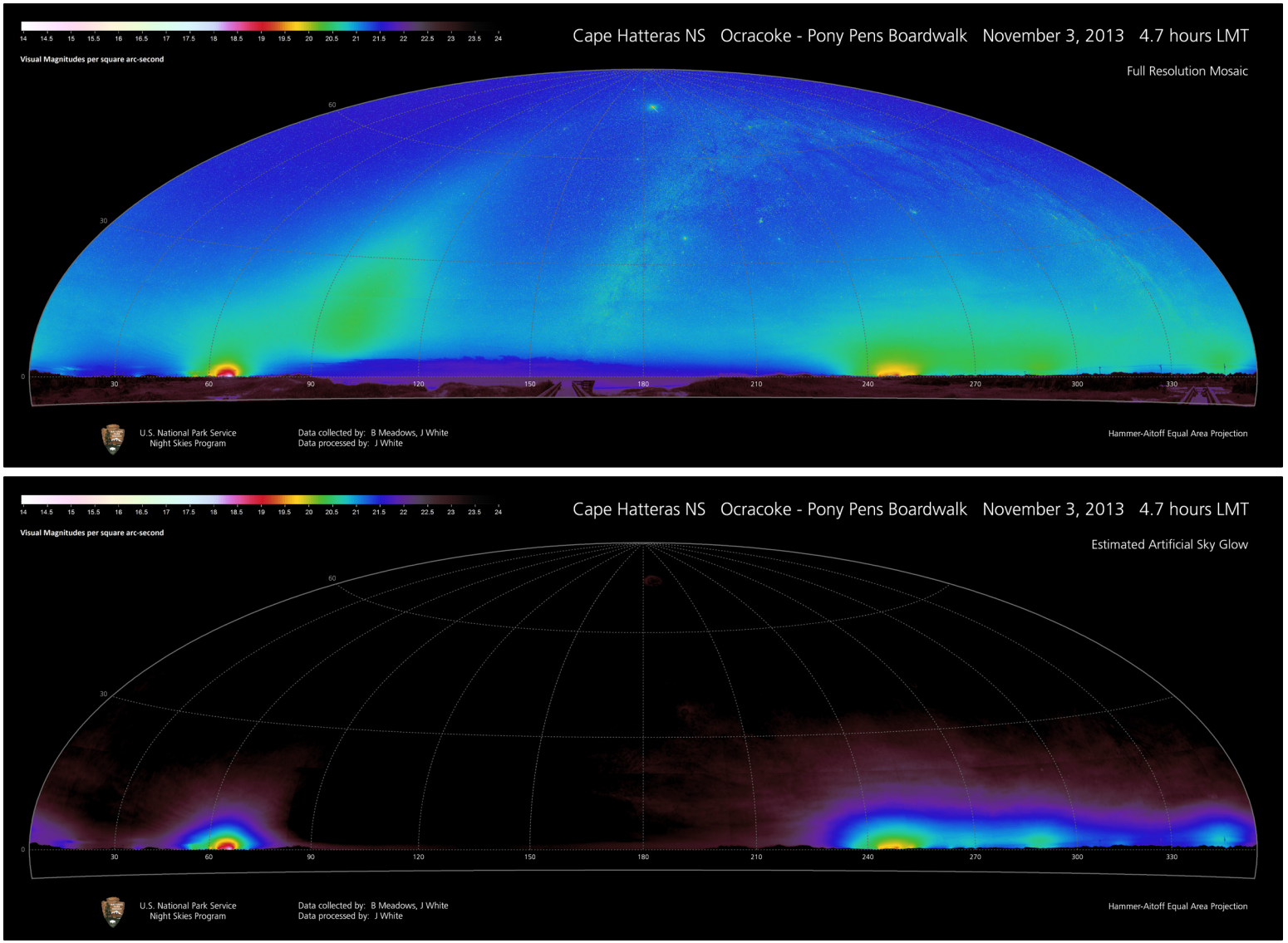


Figure 96. Panoramic image of all (natural and anthropogenic) sources of light (top) and of estimated artificial light (e.g., “sky glow”) (bottom) from the Pony Pens Boardwalk on Ocracoke Island (Downloaded from NPS NST 2016).

The NSNSD is also able to use GIS-modeling to show ALR values for areas where field data is not available. A condition level can be assigned to the modeled ALR data, based on a threshold applied spatially to the park (Moore et al. 2013). This threshold is dependent on whether the park is considered to be urban or non-urban (Moore et al. 2013). The distinction between urban (Level 2) and non-urban (Level 1) parks is based on the relative proximity of the park (and its borders) to Urban Areas as defined by the 2010 U.S. Census (Moore et al. 2013). For parks managed as wilderness, the designated condition is based on ALR level that exists in more than 90% of the wilderness area (Moore et al. 2013). According to the U.S. Census Bureau, CAHA is classified as a non-urban (Level 1) park (NPS 2016f). The modeled results for CAHA are shown in Figure 97.

When interpreting the results of the model for both urban and non-urban parks, the condition (green, amber, red) corresponds to the ALR level that represents the median condition (in at least half the park's area) for the park's landscape (Moore et al. 2013). This median condition reflects the probable night sky quality that park visitors will experience at any location within the park (Moore et al. 2013). It is also probable that the majority of wildlife and habitats within the park exist under this quality of night sky (Moore et al. 2013). The NPS NSNSD recommendations for ALR condition are given in Table 97. The median ALR value for CAHA is 0.335, which puts the park in the moderate condition category for non-urban (Level 1) parks but very near good condition (Moore et al. 2013, NPS NSNSD 2015). The mean ALR for CAHA (vs. the median) is 0.29, which would put the park in good condition; however, the area which may influence the park (the 200-km buffer) has a higher mean ALR of 1.38, which is towards the top of the moderate condition range (Sharolyn Anderson, NSNSD Scientist, written communication, March 2020).

Table 97. NPS NSNSD recommendations for condition levels for modeled ALR values (Moore et al. 2013).

Park classification	Good Condition (Green)	Moderate Condition (Amber)	Poor Condition (Red)
Non-urban (Level 1) parks	< 0.33	0.33–2.00	> 2.00
Urban (Level 2) parks	< 2.00	2.00–18.00	> 18.00
Areas Managed as Wilderness	< 0.33	0.33–2.00	> 2.00

Threats and Stressor Factors

Threats to the CAHA's night skies include park light fixtures and light from surrounding communities, communications towers, construction and beach nourishment sites, and the Oregon Inlet fishing center and boats, as well as air pollution. There are approximately 400 light fixtures within CAHA, which the park is working to retrofit with dark sky-friendly lighting (David Hallac, Outer Banks Group Superintendent, personal communication, 16 January 2018) as part of an effort to become certified as an International Dark Sky Park.

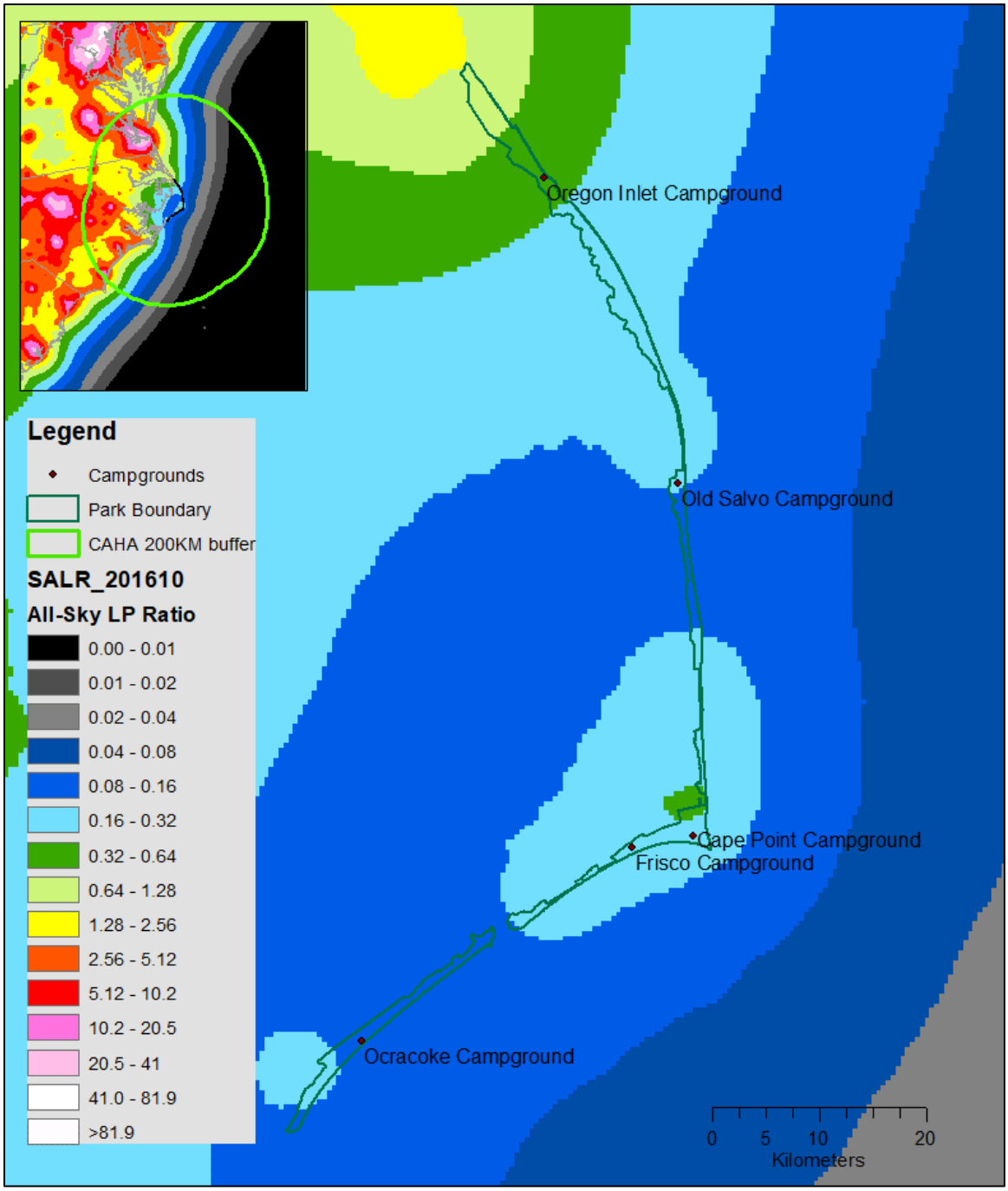


Figure 97. Modeled all-sky average sky brightness (ALR) for CAHA. Graphic provided by NPS NSNSD.

Light from surrounding communities, particularly the Nags Head-Kill Devil Hills area north of the park, contribute varying degrees of light pollution (see Figure 87 for locations). In addition to these communities, light from U.S. Coast Guard communications towers, area lighthouses, local marinas (e.g., the Oregon Inlet Fishing Center), and boats on the water also impact the park's night skies. Beach nourishment and construction projects (e.g., the new Bonner Bridge) may also be detrimental, if lighting is left on throughout the night.

Air pollution can affect night skies by reducing visibility. Haze in the sky at night dims the stars and scatters or reflects artificial light from cities and other sources (NPS 2018d). Haze has been an issue at CAHA at times, with the NPS ARD rating visibility at the park as a moderate concern in 2015 and a significant concern from 2012–2014 (see Chapter 2, Table 3) (NPS 2016a).

Data Needs/Gaps

Regular monitoring (e.g., every 5 years) at the two sites visited by the NSNSD will help to detect any changes that may impact the park's natural night skies. Over time, this periodic monitoring data collected by the park can be used to assess and track external light source impacts at CAHA. A draft plan for natural lightscape management, which documents areas where outdoor lighting is required and where the naturally dark zones occur, could benefit park managers and researchers.

Overall Condition

Anthropogenic light ratio (ALR)

The project team assigned the NPS NSNSD's suite of measures a *Significance Level* of 3 (Table 98). In 2013, the mean all-sky light pollution ratios for Boardwalk 27 and the Pony Pens were 0.32 and 0.18, respectively, which indicates good condition based on NSNSD recommendations. Based on GIS-modeled data, the median ALR value for CAHA is 0.335, which puts the park just into the moderate condition category for non-urban (Level 1) parks. Because the on-site data collected by the NSNSD and estimated ALR values in the majority of the park (see Figure 97) fall in the good condition range (< 0.33), a *Condition Level* of 1 has been assigned, indicating low concern.

Weighted Condition Score

The *Weighted Condition Score* for CAHA's dark night skies is 0.33, or in good condition with a stable trend.

Table 98. Current condition and trend of the Dark Night Skies of CAHA.

Measures	Significance Level	Condition Level	WCS = 0.33
Anthropogenic Light Ratio	3	1	

Sources of Expertise

Sharolyn Anderson, NPS NSNSD Scientist

Barrier Island Geomorphology

Description

Geomorphology refers to the arrangement of physical features on the land's surface, including their structure, origin, and development. Barrier islands, such as those that comprise CAHA, experience nearly constant geomorphological change due to natural erosion and accretion (i.e., accumulation) processes (Godfrey and Godfrey 1976, Schupp 2015). The physical structure of barrier island shores is largely shaped by wave action and tidal currents, with the retreat or advance of shorelines depending on sand/sediment availability and sea level changes (Riggs and Ames 2003, Schupp 2015). When sea levels are relatively stable, shorelines advance/accrete if sediment availability is high, and often retreat/erode when sediment supply is limited. If sea levels drop, barrier shorelines appear to advance, particularly on the ocean side; when sea levels rise, barrier shorelines retreat and appear to shift landward (e.g., towards the mainland) (Schupp 2015). Human modifications (e.g., channel dredging, shoreline stabilization, dune construction) may counteract or amplify these natural processes (Riggs and Ames 2003, Dallas et al. 2013, Schupp 2015). CAHA's islands are considered to be transgressive (i.e., migrating landward), because ocean shorelines are generally receding, although in some locations estuarine shorelines are also eroding rather than accreting/advancing landward. As a result, some barrier island segments appear to be narrowing but not migrating (Inman and Dolan 1989, Shabica et al. 1993).

The majority of CAHA's islands are considered simple barrier islands (Figure 98). These are relatively young, sediment-poor islands with narrow widths and low elevations, dominated by inlet and overwash dynamics (Ames and Riggs 2006). Small portions of CAHA, such as at Buxton Woods and Hatteras Village, are considered complex barrier islands (Schupp 2015). Complex islands are generally wider with higher elevations, often with multiple tiers of dune ridges and swales (Ames and Riggs 2006). Simple barrier islands are more vulnerable to sea level rise and inundation from storm surge than are the more developed complex barrier islands (Schupp 2015).

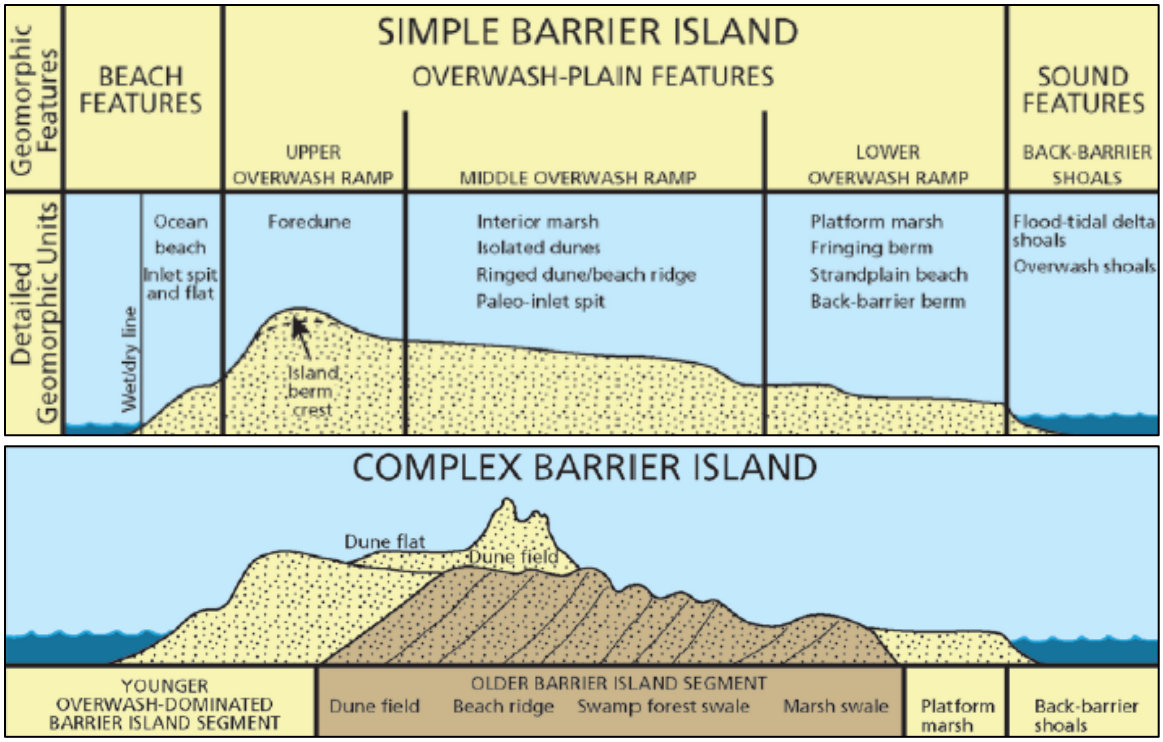


Figure 98. Cross-sectional profile showing the geomorphic components of a simple barrier island (top) vs. a complex barrier island (bottom), from the ocean beach (left) to the sound side (right) (reproduced from Schupp 2015, based on Riggs and Ames 2006).

The Outer Banks, including CAHA, are considered a wave- and storm-dominated barrier island system with low tidal ranges (<1 m [3.3 ft]) (Schupp 2015). The CAHA region experiences some of the highest wave energy along the U.S. East Coast, with mean significant wave heights of 1.2–1.3 m (3.9–4.3 ft) (Pendleton et al. 2004, Dallas et al. 2013). Currents move sediment along the shore and through inlets, while waves and storm surge bring the sediment to shore. Two major currents, one warm, north-flowing and one cold, south-flowing, meet just off Hatteras Island's Cape Point (Figure 99). Large amounts of sediment are deposited where the currents meet, forming Diamond Shoals (Schupp 2015). The rate of sediment transport along the northern Outer Banks to the south towards Cape Hatteras is particularly high, estimated to be at least 590,000 m^3/year (772,000 yd^3/year) in the late 1980s (Inman and Dolan 1989, Shabica et al. 1993).



Figure 99. This map shows the two major currents that meet in the vicinity of Cape Point, resulting in the deposition of sediment loads on Diamond Shoals (Schupp 2015).

Sediment supply plays a large role in the size and shape of barrier islands (Riggs and Ames 2006, Schupp 2015). Overwash is a key process in building island elevation and width on the estuarine side (Godfrey and Godfrey 1976, Schupp 2015). Overwash occurs when strong storms push large amounts of water over island berms/dunes and across the island towards the sound. Sediment is carried with this water and is deposited in a fan-shape, sometimes stretching all the way across the island and forming shoals in the back-barrier estuary (Figure 100) (Schupp 2015). Winds also move sediment/sand across and along barrier islands. At CAHA, winds generally blow from the south to southwest from April to August and from the north to northwest from September to February, but with the strongest winds blowing most frequently from the north and northeast (Schupp 2015). As a result, overall wind transport of sand on CAHA's islands is in a south to southwestward direction.

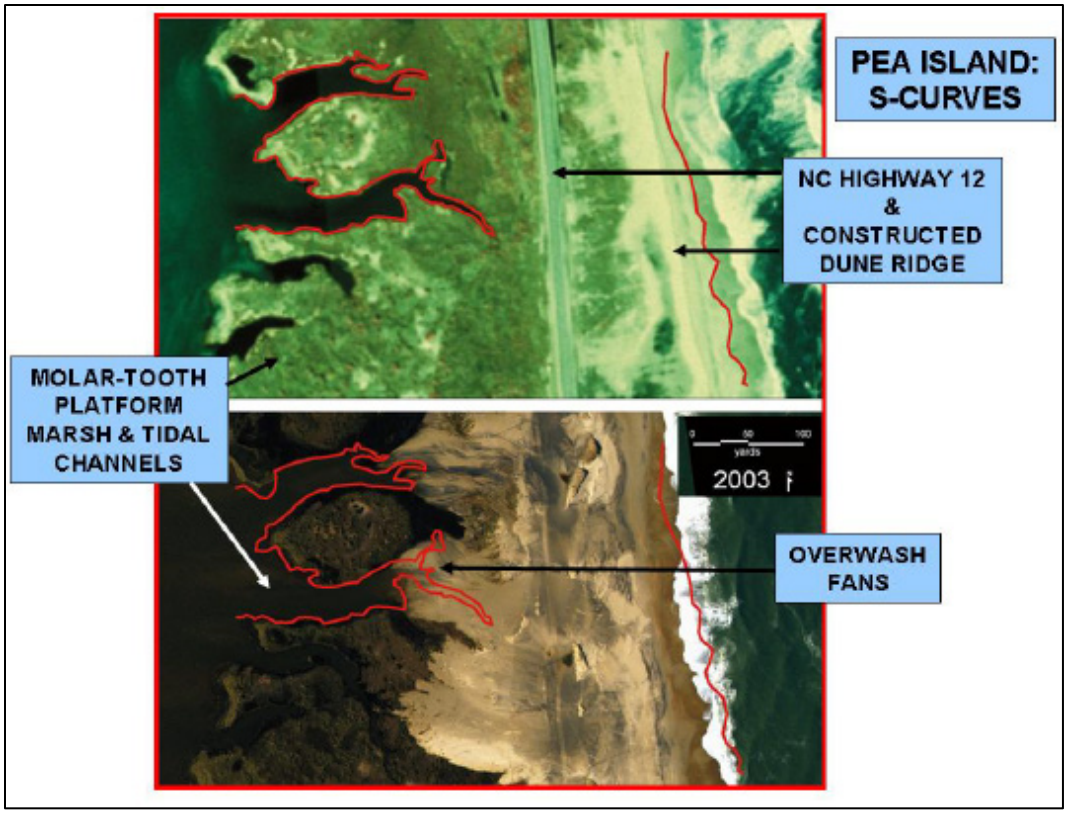


Figure 100. Aerial photos from northern Hatteras Island before (top) and after (bottom) Hurricane Isabel in 2003, showing the impacts of overwash in this portion of CAHA (Riggs and Ames 2006).

Inlet dynamics are also critical to barrier island processes and influence sediment transport in the Outer Banks system. The size and number of inlets within barrier systems is related to the volume of freshwater discharge from rivers and the volume flowing in and out of the estuary with the tides (Fenster and Dolan 1996, Schupp 2015). In northern North Carolina, where tidal range is low, there are generally fewer inlets and islands are longer than in southern North Carolina (Riggs and Ames 2006, Schupp 2015). New inlets can open during strong storms, when storm surge breaches the island; many of these inlets are temporary and fill in naturally over time. There are currently three inlets present at CAHA (Oregon, Hatteras, and Ocracoke), but as many as 10 additional inlets have formed and closed in the vicinity over the past 400 years (Figure 101).

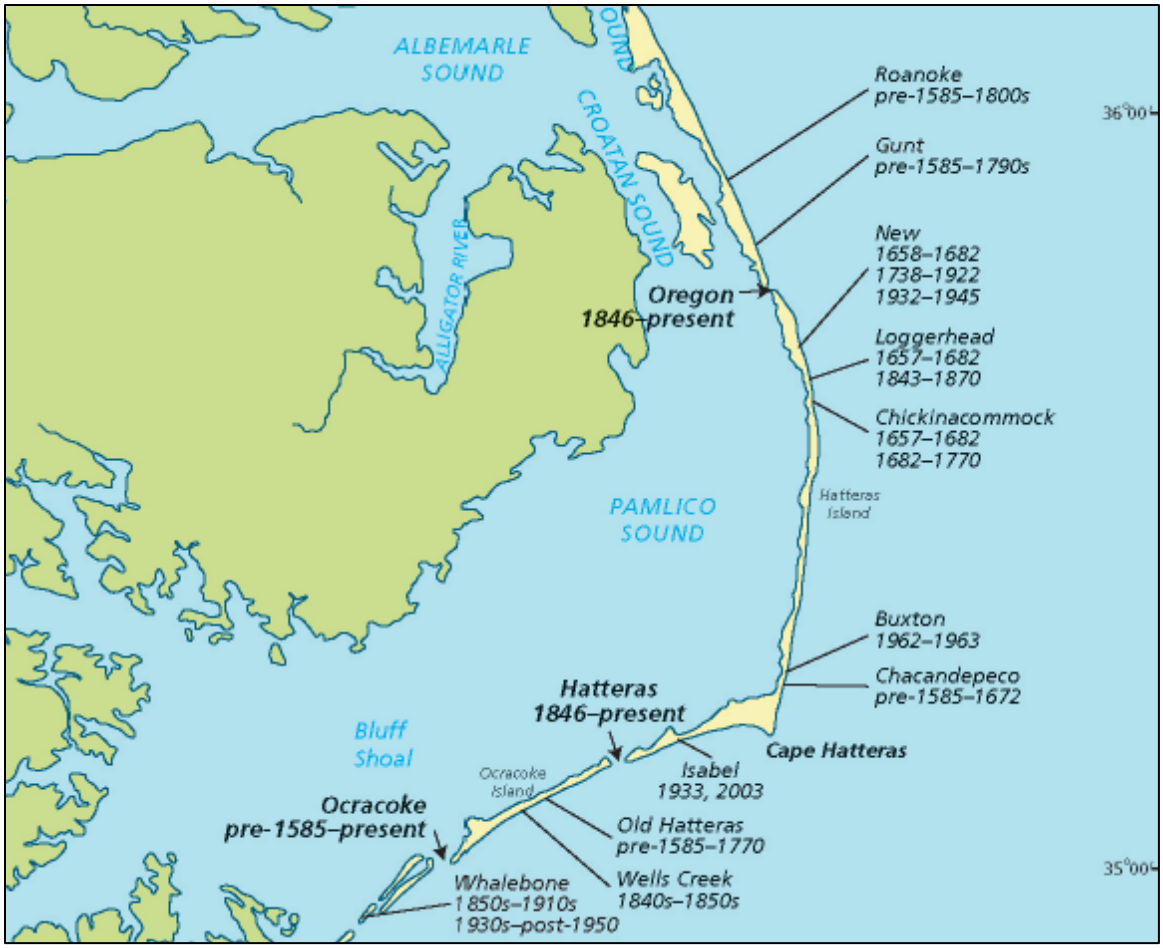


Figure 101. Location and duration of historic and modern inlets in the CAHA vicinity (Schupp 2015).

Inlets also can "migrate" over time; the island on the updrift side of the inlet typically accretes or grows, while the downdrift island erodes because inlets disrupt sediment transport. In the case of Oregon Inlet, the southern end of Bodie Island has been expanding while the northern end of Hatteras Island was eroding/retreating, until a terminal groin was installed in 1989–1991 (Figure 102) (Riggs and Ames 2011, Schupp 2015). Oregon Inlet has been called the most dynamic inlet in the southeastern region of the NPS (Shabica et al. 1993). The influence of the inlet on adjacent shoreline dynamics (e.g., accretion, erosion) extends up to 6.1 km (3.8 mi) on the updrift/north side and 13.0 km (8.1 mi) on the downdrift/south side (Fenster and Dolan 1996).



Figure 102. 2015 aerial photo showing the terminal groin (yellow arrows) on the north end of Hatteras (Pea) Island (NPS photo).

Sediment transported through inlets from the ocean to the sound side contributes to marsh building and island width expansion on the estuarine side of barrier islands. Estuarine shorelines are influenced by many factors, including size and shape of the bordering water body, offshore depth and slope, height and composition of sediment bank, wind patterns, presence of fringing vegetation, and storm frequency and intensity (Schupp 2015). At CAHA, the estuarine shore is typically broad and level, with vast tidal marshes along the wider island segments (Figure 103) (Riggs and Ames 2003).



Figure 103. A broad saltmarsh on the estuarine shore of Ocracoke Island (NPS photo).

NPS policy generally requires that natural coastal processes be allowed to continue in parks without interference (e.g., erosion, deposition, shoreline migration, overwash, inlet formation) (NPS Management Policies § 4.8.1.1) (Dallas et al. 2013). Park staff may intervene only when there is no

feasible alternative to protect natural resources, historic properties, or park facilities. Park landscapes that experience natural disturbance, including hurricanes, are allowed to recover naturally unless intervention is necessary to protect park developments and human safety or to preserve cultural and historic resources in accordance with park planning documents (NPS Management Policies § 4.1.5 and § 4.4.2.4) (Dallas et al. 2013).

Measures

- Mean rates of change in island width at locations of interest[2]
- Mean rates of change in island lengths at locations of interest (Ocracoke and Hatteras Islands)
- Change in total island area
- Change in beachfront area

Reference Condition/Values

Selecting a reference condition for barrier island geomorphology is challenging, given that barrier island shorelines shift frequently as a result of natural processes. The earliest available documentation of shoreline positions for CAHA's islands are from the mid-1800s. These sources have been used by researchers to calculate shoreline change over time, but the historic shoreline positions do not necessarily represent a "desirable" or "target" condition. For the purposes of this NRCA, geomorphology changes at CAHA could be compared to changes at portions of the Core Banks of CALO which have experienced minimal human modification and are currently managed as a "natural system" to provide some insight (Godfrey and Godfrey 1976, Ames and Riggs 2006). However, the Core Banks islands are oriented from northeast to southwest while portions of CAHA are oriented straight north to south, which influences the impacts of winds and wave energy.

Data and Methods

The barrier island processes and geomorphology of North Carolina's Outer Banks have been studied to varying degrees since the 1960s. However, not all of this research relates to the measures selected for this NRCA, and some of the selected measures have not been specifically researched at CAHA. In addition, data from recently established long-term monitoring efforts (e.g., Shoreline Change and Saltmarsh Elevation) conducted by the NPS Inventory and Monitoring Program were not yet available during this report preparation (Brian Gregory, SECN Program Manager, written communication, 28 April 2020). The sources described here are those that include information related to the four measures selected by the NRCA project team.

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[2] Locations of interest identified by CAHA park staff, from north to south, are: Coquina Beach, Bodie Island Spit/Oregon Inlet, Pea Island (across from visitor center), Rodanthe, Salvo, Little Kinnakeet, Avon (south of pier), Haulover Day Use Area, Buxton (lighthouse), Frisco Day Use Area, Pole Road/Hatteras Inlet, Ramp 55, South Point/Ocracoke Inlet.

Dallas et al. (2013) conducted an inventory and some analysis of coastal engineering projects in CAHA, including coastal structures, dune construction, beach nourishment, and dredging projects. The report briefly describes changes in beach, dune, and island width.

Schupp (2015) prepared a Geological Resources Inventory Report for CAHA that addressed many of the geomorphic processes that shape Outer Banks barrier islands. Topics included barrier island evolution, shoreline erosion, inlet dynamics, sediment transport, storm impacts, and human influence.

Change in Beachfront Area

DeKimpe et al. (1991) analyzed a 70-km (43.5-mi) stretch of CAHA from southern Bodie Island to Cape Hatteras to develop a beach-barrier dune model that predicts the timing of barrier dune demise for the Outer Banks. The authors used aerial photography from different periods to measure shoreline change, dune recession, dune and beach width, and storm surge or overwash distances at 100 m (328 ft) intervals (DeKimpe et al. 1991).

Dolan and Lins (2000) published a report analyzing the processes and hazards associated with North Carolina Outer Banks barrier islands. Topics included shoreline processes (e.g., erosion, overwash, inlet dynamics), human use and impact, and shoreline engineering efforts. The goal was to provide helpful information to coastal planners and developers for guiding future development (Dolan and Lins 2000).

Change in Island Width

Several studies have addressed changes in barrier island width over time. Everts et al. (1983) used historic maps and aerial photography assessed changes in ocean and estuarine shoreline position from 1852–1980. The study area extended from Cape Henry, VA to just west of Cape Hatteras. Smith et al. (2008a) used similar methods to assess changes in shoreline width from 1852–1998 at two Outer Banks focus areas: Pea Island and Avon-Buxton (Figure 104). Most recently, Cook (2013) evaluated changes in island width, transect area, and center line locations for Outer Banks islands from the Virginia border to the Cape Lookout area (Figure 104). Cook (2013) compared historic data from 1852–1878 maps to modern imagery from 2004, 2007 or 2009 (dates of available imagery varied by location).

Ames and Riggs (2006) published a “geomorphic framework” for North Carolina’s Outer Banks that included CAHA and portions of the urbanized areas north of the park. This effort was part of a cooperative research program between the NPS, USGS, and USFWS to develop a comprehensive understanding of “the processes that formed the coastal geologic system over the past 10,000 years and continue to affect it today and into the future, and climatic and sea-level history that produced the modern coastal system” (Ames and Riggs 2006, p. 5). The study included comparisons of topographic surveys (1852–2003) and georeferenced aerial photos (1932–2003) to explore the evolution of island geomorphic systems in response to sea level rise (SLR), storms, and human modification.

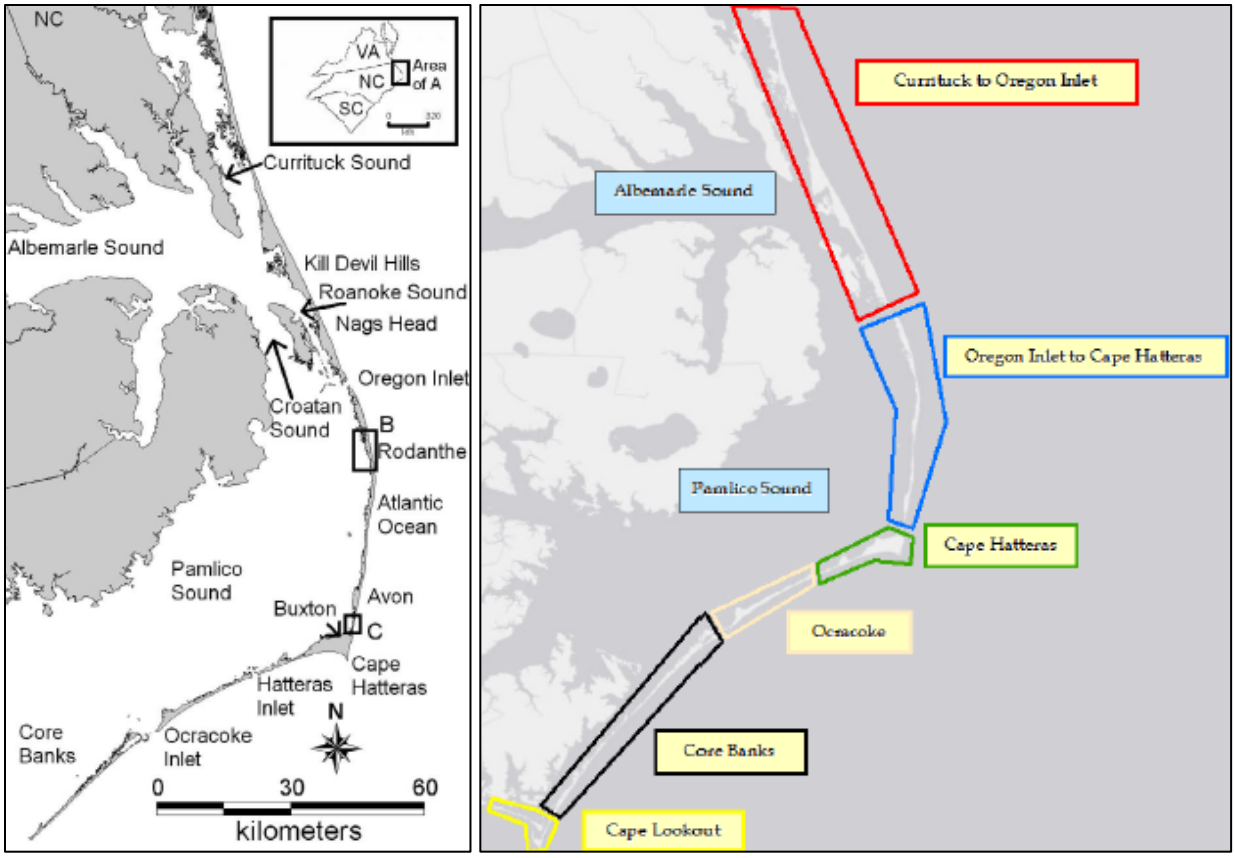


Figure 104. The Outer Banks focus areas of Smith et al. (2008a) (left, indicated by boxes B and C) and the Outer Banks study area of Cook (2013) (right).

Current Condition and Trend

Mean Rates of Change in Island Width at Locations of Interest

Island width can change due to shifts in the rates of erosion or accretion along the ocean and estuarine shorelines. If erosion on one side of the island is more rapid than accretion on the other side, or if both sides experience shoreline erosion, the island will narrow (Ames and Riggs 2006). If accretion outpaces erosion, an island will increase in width. According to Schupp (2015), most of CAHA's islands are less than 400 m (0.25 mi) across, but widths vary from 180 m (0.1 mi) near Hatteras Village to almost 5,000 m (3.1 mi) at Cape Hatteras. For comparison, Core Banks at CALO has an average width of 800 m (0.5 mi) (Schupp 2017).

Everts et al. (1983) found that from 1852–1980, more island segments narrowed on south Bodie and north Hatteras Islands than widened; this trend was more pronounced from 1946–1980 (Table 99). For the portions of the Everts et al. (1983) study area where both ocean and estuarine shoreline data were available, the islands narrowed on average by 0.9 m/yr from 1852–1980. Based on these changes in ocean and estuarine shoreline positions (Appendix P), locations of interest where island width most likely declined were Pea Island (visitor center), Rodanthe, Little Kinnakeet, and Avon. Additional locations may have narrowed, but this could not be conclusively determined from the available data.

Table 99. Number of island segments, as mapped and studied by Everts et al. (1983) that changed in width (combined ocean and estuarine shoreline change) over time.

Survey period	Change observed	Number of 1-minute latitude/longitude shoreline increments that changed		
		North of Oregon Inlet	South of Oregon Inlet	West of Cape Hatteras
1852–1980	Island widens	8	4	2
	Island narrows	16	15	2
1852–1917	Island widens	4	9	2
	Island narrows	4	7	2
1946–1980	Island widens	1	7	2
	Island narrows	9	18	3

Smith et al. (2008a) found island widening at two study segments (Pea Island 1 and 2) and narrowing at two segments (Pea Island 3 and Avon-Buxton) over the 1852–1998 period (Table 100). Narrowing was most pronounced in the Avon-Buxton area from 1917–1932 and at Pea Island segment 3 from 1932–1949. Smith et al. (2008a) noted that the estuarine shoreline of the Pea Island segment 3 area actually advanced at an average of 2–3 m/yr prior to 1932 (Figure 105), but then eroded from 1932–1949. Narrowing occurred along all study segments from 1949–1998 (Smith et al. 2008a). Pea Island segment 3 was near and likely representative of the Rodanthe location of interest, while the Avon-Buxton segment (Figure 106) includes the Haulover Day Use Area location of interest. Near the Haulover Day Use Area, as much as 76% of island width was lost between 1852 and 1998 (Riggs et al. 2008).

Table 100. Average rate of change (m/yr) in main barrier island width over various time periods, Pea Island and Avon-Buxton study areas (Smith et al. 2008a).

Study area	1852–1917	1917–1932	1932–1949	1949–1998	1852–1998
Pea Island segment 1	−2.3 (±0.2)	−9.3 (±3.0)	47.8 (±34)	−1.6 (±3.0)	**2.0 (±3.4)**
Pea Island segment 2	0 (±3.2)	18.0 (±23.5)	19.3 (±23.3)	−0.2 (±1.5)	**3.4 (±2.2)**
Pea Island seg. 1 & 2	−0.4 (±3.0)	14.5 (±23.0)	25.8 (±24.0)	−0.7 (±2.0)	**3.0 (±2.7)**
Pea Island segment 3	−2.3 (±2.7)	−2.5 (±2.1)	−8.6 (±2.0)	−3.7 (±1.2)	**−3.5 (±1.4)**
Avon-Buxton	−4.2 (±1.5)	−5.2 (±5.5)	−4.1 (±4.1)	−2.7 (±4.7)	**−4.1 (±0.1)**

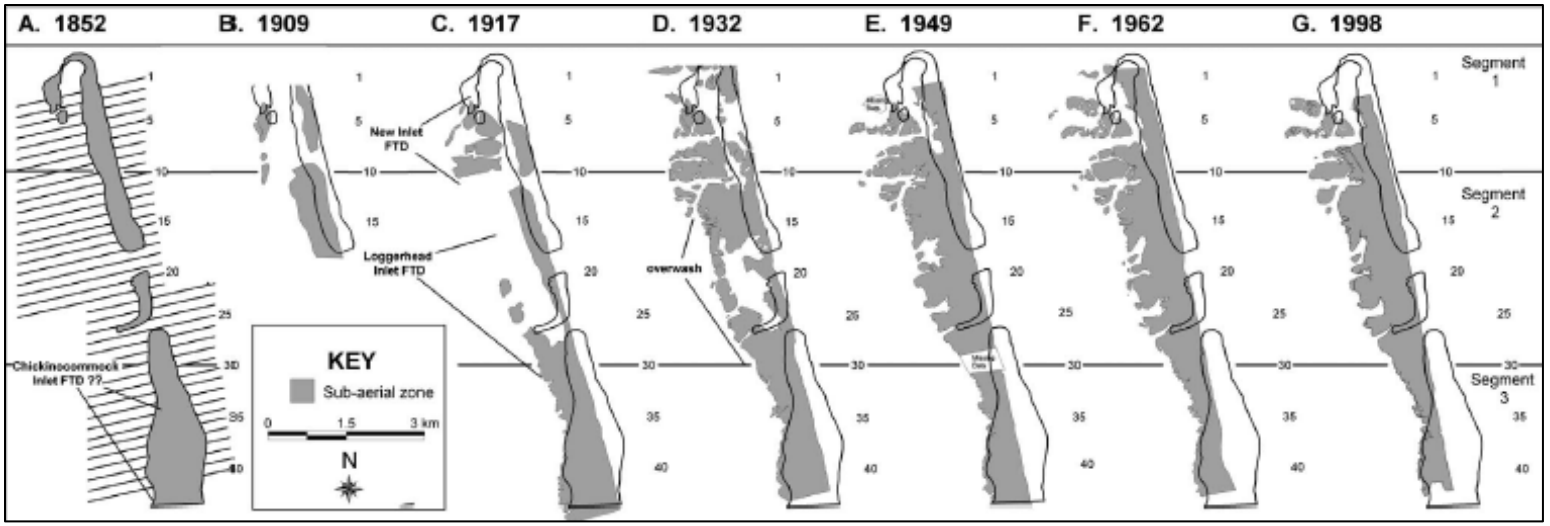


Figure 105. Changes in island width at Smith et al.'s (2008) Pea Island study segments. Gray shading shows island area in each year (1852, 1909, 1917, 1932, 1949, 1962, 1998) while the overlaid outline represents 1852 shoreline position.

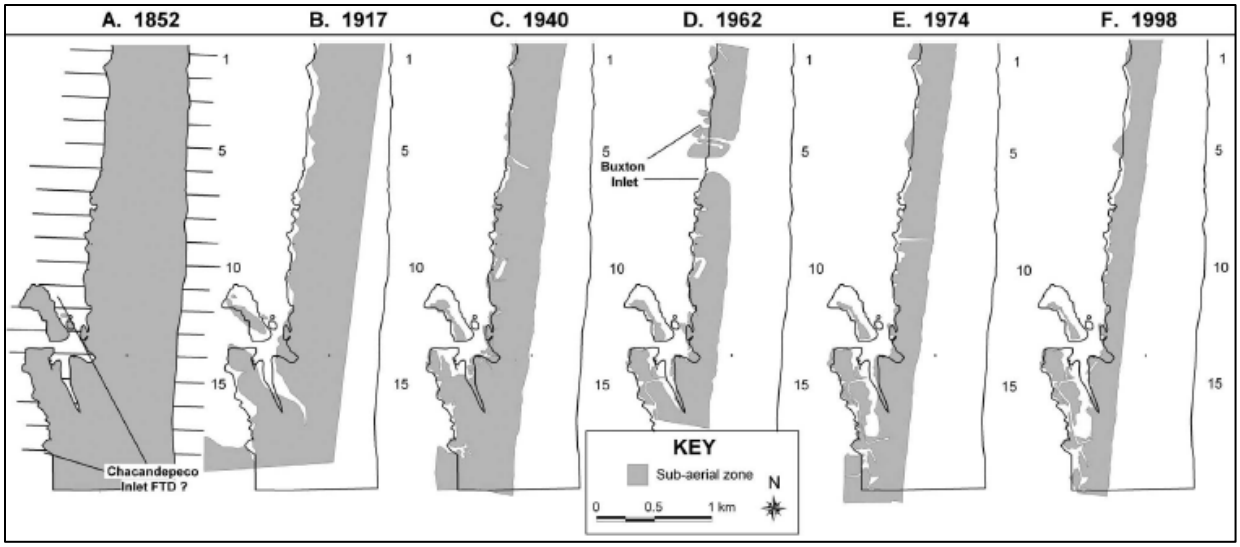


Figure 106. Changes in island width at Smith et al.'s (2008) Avon-Buxton study area. Gray shading shows island area in each year (1852, 1917, 1940, 1962, 1974, 1998) while the overlaid outline represents 1852 shoreline position.

Cook (2013) found that a majority of island width transects (75%) from Currituck Sound to Shackleford Banks experienced narrowing between the 1850s and 2000s (Table 101). Of the study zones within CAHA, the stretch from Oregon Inlet to Cape Hatteras showed the highest percentage (80%) of transects narrowing in width over time. The highest mean loss in width was from Currituck Sound to Oregon Inlet (217 m [712 ft]), although only 1/3 of the zone falls within CAHA boundaries. This northernmost zone also experienced the highest maximum narrowing and maximum widening of any zone (Table 101), suggesting it is a highly dynamic area. The smallest percentage of transects narrowing (~56%) and lowest mean loss in width were on Ocracoke Island (Cook 2013). For comparison, the Core Banks of CALO also showed a high percentage of transects narrowing (79%), but the mean narrowing for Core Banks was lower than the mean for the northern portions of CAHA. The maximum narrowing was also lower on the Core Banks than all other zones except for Ocracoke Island (Cook 2013).

Table 101. Change in island width (m) over time at sampled Outer Banks transects from Currituck Sound to Shackleford Banks (Cook 2013). Comparisons are based on historical maps from 1852–1878 and modern aerial imagery from 2004, 2007, or 2009 (availability of maps and imagery varies by location). Estimated rates of change were calculated by SMUMN GSS, based on the shortest (1878–2004) and longest (1852–2009) possible time periods.

Segment	Mean width change (m)	Estimated rates of change (m/yr)	Max narrowing/ decrease (m)	Max widening/ increase (m)	% of transects narrowing
Currituck Sound to Oregon Inlet	−216.7	−1.4 to −1.7	−4,639.6	1,894.5	73.6
Oregon Inlet to Cape Hatteras	−94.8	−0.6 to −0.8	−1,417.9	397.5	80.4
Cape Hatteras West	−32.0	−0.2 to −0.3	−494.2	816.7	69.2
Ocracoke Island	−4.6	<−0.1	−275.5	431.6	55.8
Core Banks (CALO)	−54.9	−0.3 to −0.4	−330.2	440.3	79.2
Cape Lookout to Shackleford Banks (CALO)	−65.0	−0.4 to −0.5	−402.6	689.5	~86
Entire Study Area	**−82.5**	**−0.5 to −0.7**	**–**	**–**	**75.1**

Mean Rates of Change in Island Lengths at Locations of Interest

Island lengths can change as a result of erosion or accretion at the ends of the islands or due to breaches and new inlet formation within a previously contiguous island. Barrier islands typically accrete or grow along the updrift end and erode along the downdrift end (Godfrey and Godfrey 1976). In the Oregon Inlet area, for example, Bodie Island is growing southward and Hatteras Island's northern end was eroding, until a terminal groin was installed (Figure 102) to halt this erosion (Ames and Riggs 2006, Schupp 2015). Since Oregon Inlet first opened in 1846, its location has "migrated" southward by approximately 4 km (2.5 mi) (Figure 107), due to this accretion and erosion (Schupp 2015). The rate of migration prior to the groin installation ranged from 23–165 m/yr (75–541 ft).

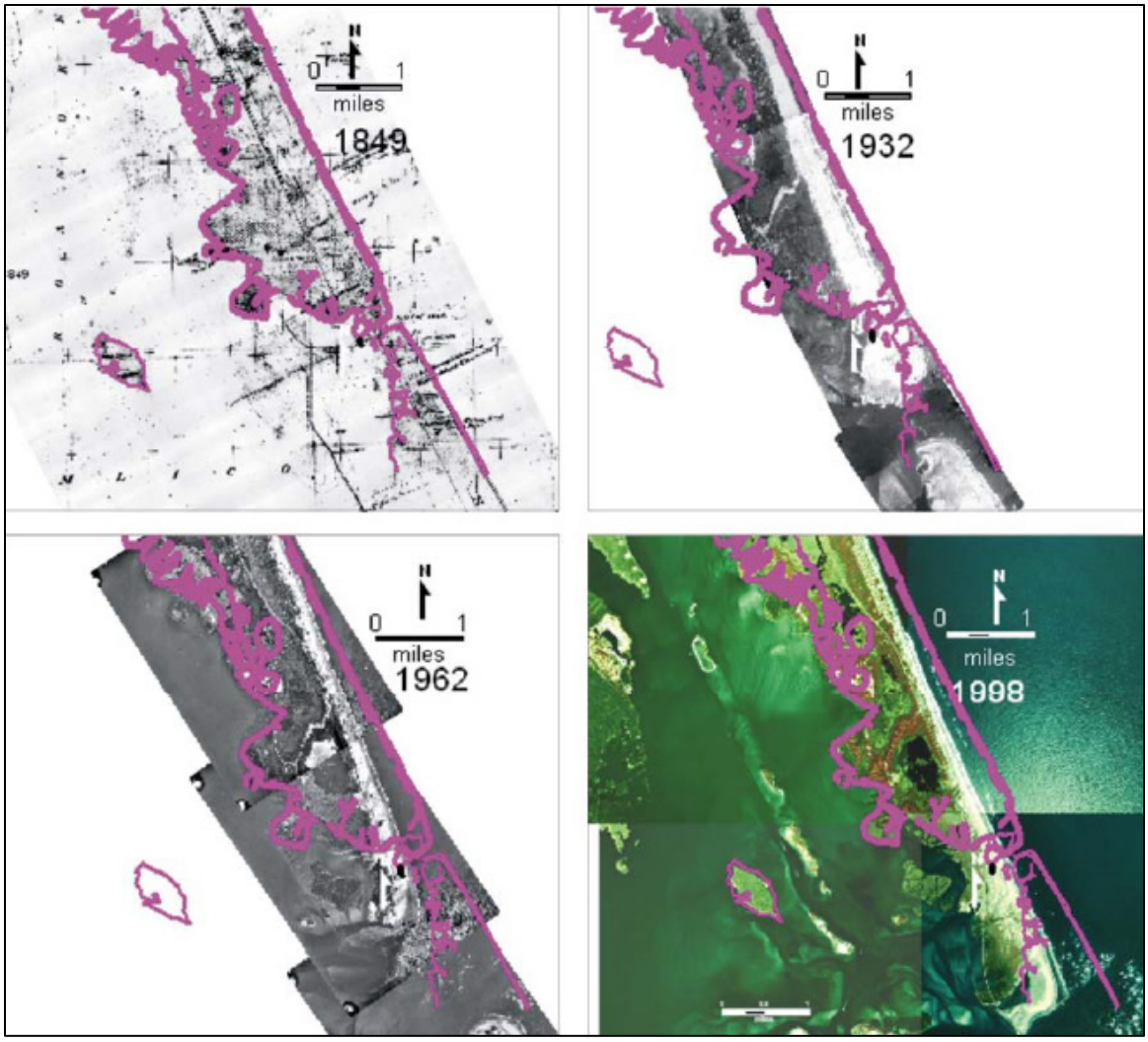


Figure 107. Changes in the location of Oregon Inlet, and thus the length of Bodie and Hatteras Islands, from 1849–1998 (Ames and Riggs 2006). A purple outline of the 1849 shoreline is shown on subsequent photos for reference.

No available published studies have officially documented changes in the lengths of Hatteras or Ocracoke Island over time. Comparisons of historic and current aerial photos can show whether these islands have retreated or advanced at their northern and southern ends. Aerial photos showing the ends of Hatteras and Ocracoke Islands between 1984 and 2016 are included in Appendix Q. Given that these aerial photos show erosion on the northern end of Hatteras Island since Oregon Inlet's formation in 1846 (Figure 107) and the substantial erosion of the island's southern end since 1984 (Appendix Q), is likely that Hatteras Island has decreased in length over the past century, and particularly since 1980. The north end of Ocracoke Island appears relatively stable on aerial imagery since 1984 (Appendix Q). The south end of the island receded between 1984 and 1991, but then accreted so that the 2016 position was similar to that in 1984. Therefore, it seems likely that the length of Ocracoke Island today is similar to the length nearly 35 years ago.

Change in Total Island Area

Total island area is influenced by changes in island width and length. If both parameters increase or decrease, then island area will also increase or decrease. However, as noted previously, changes in island width frequently are not uniform; some areas may increase while others decrease, complicating calculations of total area. No published studies could be found that officially document changes in the total area of CAHA's islands.

Change in Beachfront Area

Beachfront area along the Outer Banks is largely influenced by beach width (i.e., the distance from the wet-dry ocean shoreline to the dune field base, or to the island berm crest in the absence of dunes (Ames and Riggs 2006). Researchers have noted decreases in beach widths in portions of CAHA, as well as differences between the width of beaches on CAHA's stabilized islands and the beach width on more natural islands like the Core Banks (Dolan 1972b, Stroh 1982, Birkemeier et al. 1984, Dolan and Lins 2000). In 1932, prior to dune stabilization efforts, beach widths on southern Bodie Island were around 125 m (410 ft). By the early 1980s, beach width had declined to less than 75 m (246 ft) on average and was less than 15 m (49 ft) in some places (Birkemeier et al. 1984). Based on 1986 aerial imagery, DeKimpe et al. (1991) found beach areas in CAHA with a width of just 10 m (33 ft). Around 2000, Dolan and Lins (2000) noted that beach widths on many portions of Hatteras Island were 30 m (100 ft) or less, while Core Banks beaches ranged from 122–198 m (400–650 ft) with an average of 152 m (500 ft) (Figure 108). Ocracoke Island beach widths ranged from 49–99 m (160–325 ft), averaging 76 m (250 ft) (Dolan and Lins 2000).



Figure 108. Aerial view of beaches on Hatteras Island (left) and the Core Banks (right), illustrating the difference in beach width (Images from Dolan and Lins 2000).

Threats and Stressor Factors

Threats or stressors to CAHA's barrier island geomorphic processes include natural erosional processes (wind, waves, currents, storms), human manipulation (e.g., inlet modification/maintenance,

including dredging, shoreline stabilization), SLR, climate change, and visitor impacts (e.g., beach driving, pedestrians).

At a basic level, the factor thought to most influence coastal erosion is wave action. Waves can directly remove sediment through physical contact, or at lower water levels they may undercut banks and dunes, causing the eventual collapse of the sediment above (Riggs and Ames 2003). On barrier islands, both the ocean and back sides of the island are subject to erosion. Wave action can be magnified by natural events (e.g., storms) or by human influence (e.g., boat wakes), and can be compounded when certain factors coincide (e.g., when strong, sustained winds occur during high tide). Some areas of CAHA appear more vulnerable to erosion than others; between Cape Hatteras and Avon, 92.6% of shoreline has been eroding over the past half-century, with 63.1% eroding at a rate >1.5 m/yr (4.9 ft/yr) (Table 102) (NCDCM 2011). On the back-barrier or estuarine side of Hatteras Island, the Buxton marsh platform eroded at a mean rate of 0.79 m/yr (2.6 ft/yr) between 1962–1998 (Table 103) (Riggs and Ames 2003). As a result of continuing SLR (discussed in Chapter 2), high tide levels are expected to become even higher along the Atlantic Coast (Dahl et al. 2017), exposing additional shoreline to wave action. At the Duck, NC tidal gauge just north of CAHA, tidal flooding events are projected to increase from an average of 6.1 events/year (2001–2015) to 25.8 events/year by 2030 and 105.6 events/year by 2045 (Dahl et al. 2017).

Table 102. Shoreline change statistics for segments within CAHA, based on comparisons of historic (1933–1962) and 2009 aerial imagery (NCDCM 2011). Negative mean rates indicate erosion, while positive rates indicate accretion.

Segment	km analyzed	Mean rate (m/yr)	% eroding	% eroding >1.5 m/yr	% with increased erosion (1998–2009)
Ocracoke	26.2	−0.7	69.7	28.4	4.2
Hatteras (inlet to cape)	20.7	1.0	48.2	8.7	4.1
Cape Hatteras to Avon	11.4	−1.9	92.6	63.1	3.0
Avon	5.6	−0.4	64	0	20.2
Avon to Salvo	18.6	−0.3	70.7	0	10.2
Salvo to Rodanthe	8.7	−1.3	60	45.1	9.1
Rodanthe to Oregon Inlet	18.7	−1.3	83.8	47.1	2.7
Oregon Inlet to Nags Head	7.4	−1.4	86.6	65.1	24.2
Statewide	**494.8**	**−0.5**	**65.8**	**19.1**	**0.2**

Table 103. Estuarine shoreline erosion rates for back-barrier sites within CAHA, 1962–1998, as determined by Riggs and Ames (2003).

Site	Length analyzed (m)	Erosion rate (m/yr)	
		Mean	Range
Hatteras marsh platform	305	−0.15	−0.24–0.0
Hatteras strandplain beach	480	0.24	−0.15–0.9
Buxton marsh platform	549	−0.79	−5.67–1.42
Salvo marsh platform	457	−0.27	−0.73 to −0.06

Hurricanes and strong storms (e.g., northeasters) can have significant impacts on barrier island shorelines and dunefields, even if the storms make landfall some distance away (Gares and White 2005, Schupp 2015). The sustained winds from hurricanes can elevate tides and wave heights for at least 100 km (62 mi) from the center of the storm (Jackson 2010). For example, when Hurricane Irene made landfall south of CAHA in August 2011, it produced storm surges within the park of up to 2.4 m (8 ft) above normal tide level and created multiple breaches across Hatteras Island (Dallas et al. 2013). In September 2003, Hurricane Isabel caused a breach on southern Hatteras Island that was nearly 600 m (1,970 ft) wide and had to be mechanically closed by the Army Corps of Engineers (Figure 109) (Wamsley and Hathaway 2004, Schupp 2015). A single storm in March 1989 caused the southern shoreline of Oregon Inlet to migrate southward by approximately 350 m (1,146 ft), triggering the construction of the inlet's terminal groin, largely to protect the base of the Bonner Bridge (Riggs and Ames 2011). Storm winds and waves have frequently eroded the protective barrier dunes on Hatteras Island, flooding and damaging Highway 12 (Figure 110) (Riggs and Ames 2011, Schupp 2015). As a result of global climate change, the intensity of hurricanes is projected to increase over the next century (Knutson et al. 2010), which may in turn increase storm impacts on barrier islands such as CAHA. Areas of CAHA that are particularly vulnerable to breaching or inlet formation during storms are shown in Figure 111.

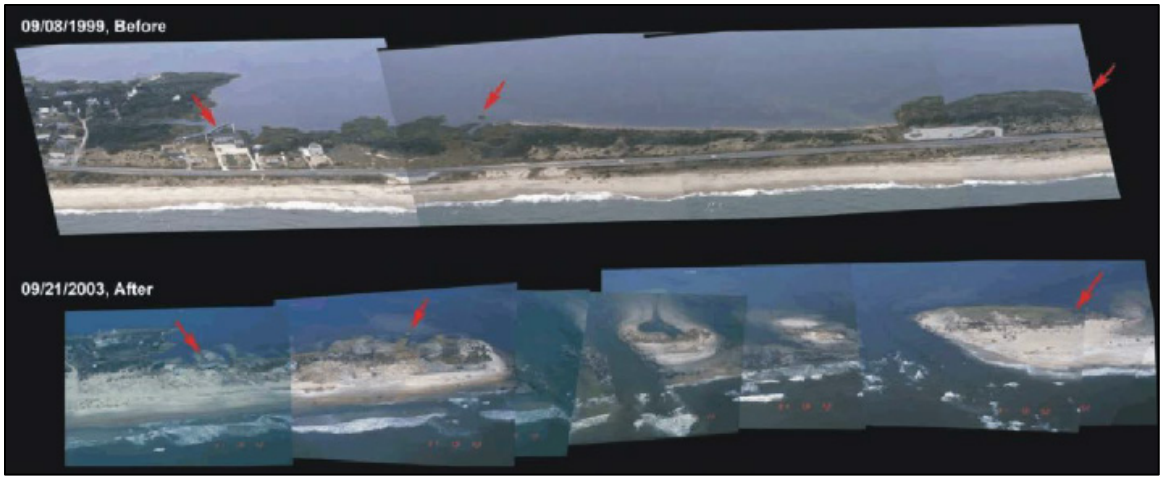


Figure 109. Composite aerial photos of breaches formed on Hatteras Island by Hurricane Isabel in 2003 (reproduced from Schupp 2015). Highway 12 (visible in the top image) was destroyed by the storm here and at several other locations on the island.



Figure 110. A dune breach on Hatteras Island just south of Oregon Inlet during a November 2019 storm allowed water and sand to flow over Highway 12 (NCDOT photo, 17 Nov 2019).

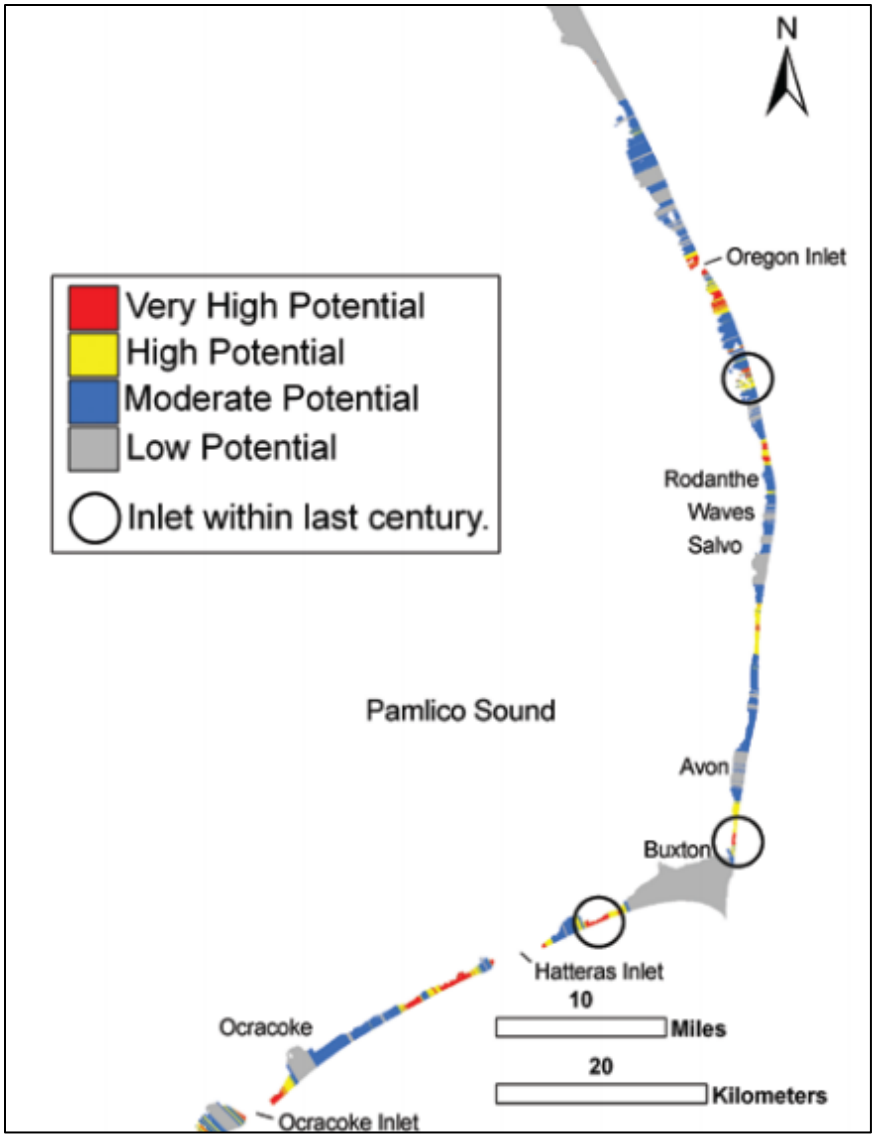


Figure 111. Inlet formation potential along CAHA's islands, as mapped by Mallinson et al. (2008).

Human manipulation of Outer Banks shorelines and inlets have had a significant impact on CAHA's island geomorphology (see Appendix R) (Dolan and Lins 2000, Dallas et al. 2013). These manipulations include barrier dune construction, inlet dredging, hardened structure installation (e.g., groins, bulkheads), and beach nourishment. Dune construction and stabilization began on the Outer Banks nearly a century ago and have disrupted natural overwash and inlet formation processes that maintain barrier island width (Smith et al. 2008a, Dallas et al. 2013). Dune stabilization has also resulted in narrower and steeper ocean beaches (Dallas et al. 2013, Schupp 2015). The NPS no longer allows dune maintenance or reconstruction on its property, but such projects continue within the right-of way along State Highway 12 (Dallas et al. 2013).

The channels between CAHA's three islands are actively maintained for navigation by dredging of the inlets (Shabica et al. 1993, Dallas et al. 2013). Dredging and deepening of these channels can

alter sediment transport processes (e.g., erosion and deposition) along the inlets and neighboring shorelines. Increased dredging of Oregon Inlet during the 1980s caused the average erosion rate on the northern end of Hatteras Island to accelerate from 3 m/yr (9.8 ft/yr) before 1980 to 5.2 m/yr (−17.1 ft/yr) from 1980–1989 (Dallas et al. 2013). In some instances, side cast dredging was used, where sediment was excavated and cast off to the sides of the inlet. Impacts to the inlet and shorelines may be lower in these cases since the sediment stays within the longshore transport system and is not entirely removed (Shabica et al. 1993). The volume of sediment dredged from CAHA's inlets through 2015 is shown in Table 104.

Table 104. Dredge activity at CAHA inlets, 1975–2015 (NCDEQ 2016). Volumes are in cubic meters (m^3) of sediment.

	1975–2015			2010–2015		
Site	Total volume	% sidecast	Mean annual volume (m^3/y)	Total volume	% sidecast	Mean annual volume (m^3/y)
Oregon Inlet	24,663,944	65	601,559	2,294,349	75	382,391
Hatteras Inlet	573,472	96	13,987	309,096	94	51,516
Ocracoke Inlet	782,412	99	19,083	280,240	100	46,707

Hardened structures such as jetties, groins, or bulkheads are sometimes used to protect inlet shorelines and other vulnerable coasts from erosion. While these structures protect shorelines in the target areas, they may accelerate erosion in other areas by disrupting sediment transport and deposition. At CAHA, the Oregon Inlet terminal groin, which was completed in 1991, stabilized the inlet shoreline but may have accelerated shoreline erosion in an area 1–10 km (0.6–6.2 mi) south of the groin (Riggs and Ames 2011, Dallas et al. 2013). The installation of hardened structures to prevent shoreline erosion was not allowed in the state of North Carolina from 1985–2013, but restrictions have since been eased to allow for several "test" terminal groins off the southern coast of North Carolina (Schupp 2015, NCCF 2020).

In areas of severe shoreline erosion, such as south of the Oregon Inlet groin, or where the island is particularly narrow, beach nourishment may be used to protect structures and infrastructure (Dolan 1972a). Nourishment projects involve the placement of sand to widen a beach, extending the shoreline out into the water. In some cases, dredged sand from nearby inlets can be used for beach nourishment. However, these projects can be complicated and expensive, and often provide only a temporary solution (Dolan and Lins 2000, Riggs et al. 2008). Major beach nourishment projects within CAHA are outlined in Table 105. Since 2000, large nourishment projects to protect human developments have occurred near Nags Head, Rodanthe, and Buxton Village (Dallas et al. 2013, NPS 2016f).

Table 105. Beach nourishment on CAHA shorelines, 1955–2015 (NCDEQ 2016). Volumes are in cubic meters (m^3) of sediment.

Site	1st year of record	1955–2015			2010–2015		
		# of times	Total volume	Mean annual volume	# of times	Total volume	Mean annual volume
Nags Head	2001	3	3,669,863	60,162	1	3,516,952	586,159
Pea Island	1990	20	7,395,713	121,242	1	444,149	74,025
Rodanthe	2014	1	1,237,113	20,281	1	1,237,113	206,186
Cape Hatteras	1966	3	1,385,373	22,711	0	–	–
South Hatteras Isl.	1974	7	678,773	11,127	0	–	–
Ocracoke Isl.	1986	5	394,558	6,468	0	–	–

Data Needs/Gaps

According to Schupp (2015, p. vii), an understanding of island geomorphic processes "is critical to park manager's ability to prepare for the island's response to coastal processes and its evolution throughout the coming decades." Smith et al. (2008a) also noted that better documentation and understanding of long-term patterns of oceanic/estuarine shoreline change and the effect on barrier island integrity is essential, given the increased population and development on the Outer Banks in recent decades. In particular, more information is needed on the processes controlling sediment flux rates in general, on sediment inputs and outputs along CAHA's islands specifically, and on the physical processes involved with barrier island breaches (Wamsley and Hathaway 2004, Gares and White 2005). Additionally, Thieler et al. (2009, p. 186) stated that, "significant opportunities exist to improve predictions of coastal response to sea-level rise." Finally, LiDAR data and digital elevation models (DEMs) from different points in time could be compared to analyze beach and dune volume changes, particularly in response to major storms (Mitasova et al. 2009).

To help address some of these data gaps and needs, the SECN Inventory and Monitoring Program has recently established two long-term monitoring efforts at CAHA that will result in annual assessments of saltmarsh elevation using surface elevation tables (SETs) (DeVivo et al. 2015) as well as annual documentation of shoreline position changes (Baron 2018). These monitoring efforts began in 2016 and 2018, respectively, and have begun to document recent geomorphic changes in these critical park areas.

Overall Condition

Mean Rates of Change in Island Width at Locations of Interest

The project team assigned this measure a *Significance Level* of 3. Over time, some portions of CAHA have narrowed while others have widened, due to changes in ocean and estuarine shoreline. In several of the park's selected locations of interest, ocean shorelines have eroded faster than estuarine shorelines have accreted, or both shorelines have experienced erosion (Everts et al. 1983, Smith et al. 2008a). Cook (2013) found that a majority of island width transects on the Outer Banks,

including CAHA, were decreasing in length, particularly on northern Hatteras Island (see Table 3). As a result, this measure is of significant concern (*Condition Level* = 3).

Mean Rates of Change in Island Lengths at Locations of Interest

This measure was also assigned a *Significance Level* of 3. While changes in island lengths have not been officially investigated or documented, aerial photo comparisons suggest that Ocracoke Island's length is relatively stable while Hatteras Island's length has likely decreased (see Appendix Q). At this time, changes in island length are of low concern (*Condition Level* = 1).

Change in Total Island Area

The island area measure was assigned a *Significance Level* of 3. At this time, no published studies could be found that officially document changes in the total area of CAHA's islands. While it seems likely that total island area is declining, particularly on Hatteras Island, due to decreasing island widths in many areas, a *Condition Level* cannot be assigned for this measure at this time due to a lack of data.

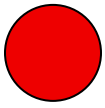
Change in Beachfront Area

A *Significance Level* of 3 was assigned for this final measure. As noted previously, researchers have observed decreases in beach widths in portions of CAHA and differences between the width of beaches on CAHA's stabilized islands and on more natural islands like the Core Banks. For example, Dolan and Lins (2000) found that beach widths on many portions of Hatteras Island were 30 m (100 ft) or less, while Core Banks beaches ranged from 122–198 m (400–650 ft). Since beaches buffer or protect the rest of the island from wave action, particularly during storms, a narrowing of their width is concerning. As a result, this measure is assigned a *Condition Level* of 2 for moderate concern.

Weighted Condition Score

The Weighted Condition Score for barrier island geomorphology at CAHA is 0.67, which is at the lower end of the significant concern range (Table 106). Because information and data are somewhat limited or absent for all of the measures except change in island width, a trend could not be assigned, and the moderate confidence border is applied.

Table 106. Current condition and trend for CAHA's Barrier Island Geomorphology.

Measures	Significance Level	Condition Level	WCS = 0.67
Mean Rates of Change – Island Width	3	3	–
Mean Rates of Change – Island Length	3	1	–
Change in Total Island Area	3	n/a	–
Change in Beachfront Area	3	2	–
Overall	–	–	

Sources of Expertise

Brian Gregory, SECN Program Manager/Aquatic Ecologist

Lisa Cowart Baron, SECN Coastal Ecologist

Tracy Ziegler, CAHA Chief of Resource Management and Science

Discussion

Chapter 5 provides an opportunity to summarize assessment findings and discuss the overarching themes or common threads that have emerged for the featured components. The data gaps and needs identified for each component are summarized and the role these play in the designation of current condition is discussed. Also addressed is how condition analysis relates to the overall natural resource management issues of the park.

Component Data Gaps

The identification of key data and information gaps is an important objective of NRCAs. Data gaps or needs are those pieces of information that are currently unavailable but are needed to help inform the status or overall condition of a key resource component in the park. Data gaps exist for most key resource components assessed in this NRCA. Table 107 provides a detailed list of the key data gaps by component. Each data gap or need is discussed in further detail in the individual component assessments (Chapter 4).

Table 107. Identified data gaps or needs for the featured components.

Component	Data gaps/needs
Backshore and Dune Communities	Continuation of SECN vegetation monitoring will help to detect any changes in plant species richness and vegetative cover. Possible study of vegetative cover using aerial photography interpretation and GIS. Develop a seabeach amaranth restoration plan for suitable sites.
Maritime Forests	A comprehensive plant survey of Buxton Woods. Additional sampling of stand structure and recruitment in park maritime forests. Obtain studies of Outer Banks maritime forests outside CAHA for comparison. Additional surveys of wildlife species within CAHA's maritime forests and other Outer Banks forests in order to assess wildlife diversity. Research to better understand the ecological processes that shape the development of maritime forests on coastal dunes.
Wetlands and Marshes	An up-to-date map showing key aquatic features such as fresh and brackish wetlands, tidal creeks, ponds, and ditches has been identified as a high priority by various studies in the park. An enhanced understanding of the islands' hydrologic dynamics would assist managers in maintaining wetlands, especially in the Buxton Woods complex. Continuation and expansion of SECN sediment elevation table monitoring is needed. A plant survey of park palustrine wetlands would allow for estimates of diversity in this community.
Birds	Continuation of annual focal shorebird monitoring is needed to fulfill ORV management plan directive, and to provide vital statistics related to shorebird nesting success. Summarization of SECN landbird monitoring is needed from 2015 and 2020 survey years, a publication is also needed for both of these survey years. Analysis of eBird citizen science data could provide additional species to the park's certified species list.

Table 107 (continued). Identified data gaps or needs for the featured components.

Component	Data gaps/needs
Mammals	Regular monitoring of mammals in CAHA is needed, especially the predator populations that are established in the park. These populations can have impacts on other communities in the park (i.e., shorebirds), and annual monitoring could help determine future impacts related to prey communities. A bat monitoring program would be beneficial to the park, as the community as a whole is understudied across the coast. Monitoring of feral hogs is needed. A census of the park's white-tailed deer population is needed to establish deer density and population trends. Studies related to deer impacts on park ecosystems (e.g., vegetative communities), and deer movement and dispersal patterns would be highly beneficial.
Sea Turtles	Continuation of annual monitoring and data analysis efforts are needed to maintain the decade's long data sets that exist for turtles in the park. Research into the potential effects of climate change on North Carolina's sea turtle may help managers prepare for future impacts. Maintaining the genetic mark-recapture study of the northern subpopulation of loggerhead sea turtles is needed to continue to provide insight into annual nesting productivity. Additionally, CAHA participation in pilot projects related to satellite tags on female turtles will allow the park and researchers to learn more about dispersal.
Water Quality	Current data are needed for the park's freshwaters (not sampled since 2007), including wetlands in Buxton Woods. Resampling previously studied Bodie Island drainage ditches for standard water quality parameters and toxic compounds; at least six times per year recommended for standard parameters in order to detect seasonal impacts and variations. Annual summer survey for *Pfiesteria* spp. and other potentially harmful algal species.
Dark Night Skies	Continuation of the park's regular monitoring schedule (approximately every 5 years) will allow park managers to detect potential changes to the park's lightscape. A draft natural lightscape management plan would allow for documentation of outdoor lighting improvement needs and also to document where naturally dark zones are in the area.
Barrier Island Geomorphology	More information is needed related to documenting and understanding long-term patterns of oceanic/estuarine shoreline changes, and their effects on barrier island integrity. Additional research is needed regarding the processes controlling sediment flux rates, sediment inputs and outputs, and on the physical processes involved with barrier island beaches. Continuation of SECN long-term monitoring (begun in 2016, repeated in 2018) is needed to document saltmarsh elevation changes, and shoreline position changes.

Table 107 (continued). Identified data gaps or needs for the featured components.

Component	Data gaps/needs
Additional Needs*	Research intertidal invertebrates, as they are an important food source for other wildlife. Study sound-side sea grass communities, an important nursery habitat Study saltwater fish communities that are actively harvested within the park by recreational and commercial fishing, as fishing is an important recreational activity on the Outer Banks. In-park air quality monitoring

* These were identified as topics of interest during project scoping but were not selected as components for the NRCA.

Many of the park's data needs involve the continuation, or summarization of data collected by current monitoring, in order to fully document and describe the vegetation and wildlife communities of CAHA. Continued monitoring will also assist researchers and managers in identifying changes to these resources. Other components would benefit from research into how environmental factors or various threats influence park resources. The establishment of additional monitoring efforts related to bats, invasive mammals, and freshwater quality, to name a few, would also benefit the park.

Component Condition Designations

Table 108 displays the conditions assigned to each resource component presented in Chapter 4 (definitions of condition graphics and examples of how symbols are applied are located in Table 109 and Table 110). It is important to remember that the graphics represented are simple symbols for the overall condition and trend assigned to each component. Because the assigned condition of a component (as represented by the symbols in Table 108) is based on a number of factors and an assessment of multiple literature and data sources, it is strongly recommended that the reader refer back to each specific component assessment in Chapter 4 for a detailed explanation and justification of the assigned condition. Condition designations for some components are supported by existing datasets and monitoring information and/or the expertise of NPS staff, while other components lack historic data, a clear understanding of reference conditions (i.e., what is considered desirable or natural), or even current information.

For featured components with available data and fewer data gaps, assigned conditions varied. Three components were considered to be in good condition: mammals, sea turtles, and dark night skies. One additional component (water quality) was of moderate concern. Barrier Island Geomorphology was the only component determined to be of significant concern. Condition could not be assigned for four of the nine components (Table 108). Trends could only be assigned for two components (sea turtles and dark night skies); the trend of the sea turtles' component was considered to be improving, while dark night skies was determined to be stable.

Table 108. Summary of current condition and condition trend for featured NRCA components.

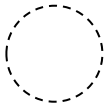
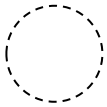
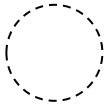
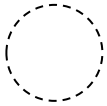
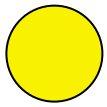
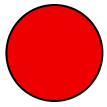
Category	Classification	Component	WCS	Condition
Biotic Composition	*Ecological Communities*	Backshore and Dune Communities	N/A	
	Ecological Communities	Maritime Forests	N/A	
	Ecological Communities	Wetlands and Marshes	N/A	
	Wildlife	Birds	N/A	
	Wildlife	Mammals	0.33	
	Wildlife	Sea Turtles	0.17	
Environmental Quality	–	Water Quality	0.50	
	–	Dark Night Skies	0.33	
Physical Characteristics	*Geologic & Hydrologic*	Barrier Island Geomorphology	0.67	

Table 109. Description of symbology used for individual component assessments.

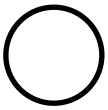
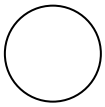
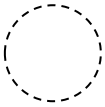
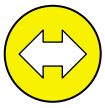
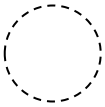
Condition Status		Trend in Condition		Confidence in Assessment	
Condition Icon	**Condition Icon Definition**	**Trend Icon**	**Trend Icon Definition**	**Confidence Icon**	**Confidence Icon Definition**
	Resource is in Good Condition		Condition is Improving		High
	Resource warrants Moderate Concern		Condition is Unchanging		Medium
	Resource warrants Significant Concern		Condition is Deteriorating		Low

Table 110. Example indicator symbols and descriptions of how to interpret them in WCS tables.

Symbol Example	Verbal Description
	Resource is in good condition; its condition is improving; high confidence in the assessment.
	Condition of resource warrants moderate concern; condition is unchanging; medium confidence in the assessment.
	Condition of resource warrants significant concern; trend in condition is unknown or not applicable; low confidence in the assessment.
	Current condition is unknown or indeterminate due to inadequate data, lack of reference value(s) for comparative purposes, and/or insufficient expert knowledge to reach a more specific condition determination; trend in condition is unknown or not applicable; low confidence in the assessment.

Park-wide Condition Observations

Despite the variety in vegetation and physical features at CAHA, and the fact that the park is spread across three very unique barrier islands, many of the resources discussed in this report are interrelated and share similar management concerns (e.g., data gaps, threats from outside the park).

Ecological Communities

The native ecological communities of CAHA are vital resources for the park, providing habitat for wildlife and performing critical ecological functions, while attracting many visitors to the area. While it is unlikely that the current condition of the backshore and dune communities in CAHA is of immediate concern, a current condition was unable to be determined due to a lack of contemporary data, particularly regarding the percent vegetative cover and acreage of the communities. Generally, the harsh environmental conditions that backshore and dune communities face result in low plant species richness compared to other communities where the environment is not as harsh. The species richness measure for the backshore and dune community component had adequate data to determine current condition, and using the results from SECN monitoring of these areas (Byrne et al. 2012a, b), it was determined that the species richness of plants in this community had no major evidence of degradation or below expected richness estimates.

The loss and fragmentation of the maritime forests due to human development on the Outer Banks has been a primary concern of the park for decades (Bourdeau and Oosting 1959, Lopazanski et al. 1988). Unfortunately, the current condition of the park's maritime forest community was unable to be determined due to a lack of contemporary data for a majority of the selected measures, as well as some degree of uncertainty regarding the reference conditions. This community represents a relatively small percentage of the park's total area (6%). Despite occupying a small area in CAHA, the park's maritime forest is still larger than any other location along the Outer Banks, including CALO (McManamay 2017, McManamay et al. 2018). There are likely several animal species dependent upon the maritime forests, but the most recent research into wildlife diversity in these areas is now decades old. Similarly, the stand structure and recruitment estimates for the trees in this community are outdated by many years. The only measure selected for CAHA's maritime forests that was able to be assigned a current condition was plant species richness, which was determined to be of low concern at present. This designation was made using SECN monitoring data from 2012 (Byrne et al. 2012a, b) and was compared to surveys from the 1950s and the most recent species richness estimates in similar areas at CALO.

Wetlands on and around the barrier islands of CAHA provide critical habitat and resources for plants and wildlife, as well as performing vital ecosystem functions (Zedler and Kercher 2005, NPS 2017d). Salt marshes, in particular, are highly productive ecosystems that provide food and shelter for fish, birds, and invertebrates, and play a key role in energy cycling (e.g., decomposition, primary productivity) (Cooper and Waits 1973, NPS 2017d). Freshwater wetlands, such as those in the Buxton Woods area, are critical areas for groundwater recharge of the aquifer that supplies fresh water for towns on Hatteras Island (Lopazanski et al. 1988). Unfortunately, a current condition was unable to be determined for this resource, as four of the seven selected measures represented data gaps. These measures were data gaps for a variety of reasons, including: a lack of a comparable environment; data that are unavailable or have yet to been summarized/published; and discrepancies in methodologies that make determining current condition problematic (i.e., McManamay et al. 2018 vs. NWI work). Given the conditions of measures that could be assessed, all of which were determined to be of low concern, combined with the threats faced by wetlands today, it seems likely that this resource is of moderate concern at present.

Other Biotics

Wildlife featured as NRCA components were birds, mammals, and sea turtles. The current condition of birds at CAHA is unknown, primarily due to a lack of contemporary data. Focal shorebird species are well-studied and have annual reproductive summaries published by the NPS, but park managers requested the assessment of birds in this NRCA not focus on reproductive parameters of these focal species. None of the five metrics that were selected for the birds component were able to be assigned condition, largely due to outdated data, or because recent surveys and inventories were yet to be summarized and published (i.e., SECN monitoring). The park has a broad assemblage of birds, but additional annual monitoring of the many groups of birds, specifically shorebirds and landbirds, is needed. There are several species of high conservation concern that utilize the park at various stages of the year, and annual monitoring would also help to identify potential trends in these species.

The park's mammal community was determined to be in good condition. Islands and coastal areas often exhibit low native mammal diversity, and the majority of terrestrial mammals that are found have broad habitat tolerances and are widely distributed throughout the southeastern U.S. (Webster 2010). Species richness estimates for both mesocarnivores and small mammals were determined to be of low concern at present. Additional information is needed to determine the current condition and density of white-tailed deer in CAHA. Some mammalian predators, such as red fox and the coyote (a species who has recently expanded its range to include CAHA), have proven to be problematic predators of native small mammal species and ground nesting avian species. The NPS has actively managed and trapped these two species to help reduce the risk of predation to native species (NPS 2015b).

Sea turtles represent a critical and charismatic group of species in CAHA, with all five species present being federally listed as either threatened (loggerhead sea turtle, green sea turtle) or endangered (leatherback turtle, hawksbill, Kemp's ridley). CAHA serves as a vital nesting area for the loggerhead sea turtle and is an important source of male hatchlings for the Northern Nesting Subpopulation (Mays and Shaver 1998). Monitoring of sea turtles has occurred annually in the park since 1987, and nest patrols help to manage the populations by isolating nests from human disturbance, relocating nests that are vulnerable to loss (predation, erosion, tidal impacts, human disturbance, etc.). This comprehensive data set allowed for a highly confident condition assessment for this resource, and the sea turtles component was determined to be in good condition with an improving trend. Sea turtle nesting numbers the past 9 years have exceeded both the short- and long-term targets established in the park's ORV management plan, and the park has supported more than 10% of North Carolina's total nests annually (Seaturtle.org 2019). Proactive management of nesting sites has resulted in a percentage of nests relocated number that has not exceeded 30% in the past 5 years.

Environmental Quality

Environmental quality is not only important for maintaining healthy functioning ecosystems, but also for maximizing visitor experience at parks. The elements of environmental quality included in this NRCA were water quality and dark night skies; while not identified as a component, air quality was also highlighted in Chapter 2 of this report and is briefly summarized below.

The current condition of water quality in CAHA was determined to be of moderate concern, with no observed overall trend at present. Of the selected measures for the component, specific conductance was the only measure unable to be assigned a condition level. Metrics exhibiting levels of moderate concern included nutrients, fecal bacteria, and water clarity/turbidity; the remaining measures were all determined to be of low concern at present. While some measures appear to be stable (pH, DO), others show potential signs of decline (nutrients) or lack enough consistent data to detect any trends (SpC, water clarity/turbidity).

With the park located just south of several major tourist areas, including Nags Head, Kill Devil Hills, and Kitty Hawk, the northern portion of CAHA is subject to a substantial amount of anthropogenic light that impacts the night sky. State Highway 12 runs through CAHA, connecting many smaller towns on the islands just outside park boundaries that are also sources of anthropogenic light. That being said, the results of NPS NSNSD visits to the park have indicated that the quality of the park's night skies are either in good condition, or in the moderate condition category for non-urban (Level 1) parks. The majority of the park fell into the good condition range for the NSNSD suite of metrics, and this component was determined to be in good condition. A stable trend was assigned to this resource, with indications that conditions may improve as park lighting is retrofitted. However, the continued growth of the surrounding communities could also further degrade the quality of this resource.

Physical Characteristics

Physical characteristics of CAHA considered in this NRCA consisted of the park's barrier island geomorphology. Barrier islands, such as those that comprise CAHA, experience nearly constant geomorphological change due to natural erosion and accretion (i.e., accumulation) processes (Godfrey and Godfrey 1976, Schupp 2015). The CAHA region experiences some of the highest wave energy along the U.S. East Coast, with mean significant wave heights of 1.2–1.3 m (3.9–4.3 ft) (Pendleton et al. 2004, Dallas et al. 2013). The rate of sediment transport to the south along CAHA's northern shores is particularly high, estimated to be at least 590,000 m^3/year (772,000 yd^3/year) in the late 1980s (Figure 101) (Inman and Dolan 1989, Shabica et al. 1993).

The barrier island geomorphology component was determined to be of significant concern, with insufficient data to determine a trend for the resource as a whole. It should be noted that the weighted condition score for this component fell at the minimum threshold value for significant concern and was very close to being assigned a moderate concern value. Over time, some portions of CAHA have narrowed while others have widened, due to changes in the ocean and estuarine shorelines. In several of the park's selected locations of interest, ocean shorelines have eroded faster than estuarine shorelines have accreted, or both shorelines have experienced erosion (Everts et al. 1983, Smith et al. 2008a). Cook (2013) found that a majority of island width transects on the Outer Banks, including CAHA, experienced narrowing, particularly on northern Hatteras Island. Researchers have observed decreases in beach widths in portions of CAHA and differences between the width of beaches on CAHA's stabilized islands and on more natural islands like the Core Banks. For example, Dolan and Lins (2000) found that beach widths on many portions of Hatteras Island were 30 m (100 ft) or less, while Core Banks beaches ranged from 122–198 m (400–650 ft). Since beaches buffer or protect the

rest of the island from wave action, particularly during storms, a narrowing of their width is concerning.

Park-wide Threats and Stressors

As highlighted in Chapter 2 of this NRCA, several threats and stressors influence the condition of multiple resources at CAHA. While not an exhaustive list, the threats spotlighted in this NRCA included human development, dune construction and landscape alteration, invasive species, and climate change. The surrounding human developments of most concern for the CAHA region include the nearby communities of Nags Head, Kill Devil Hills, and Kitty Hawk, which are found to the park's north, and Avon and Buxton on central Hatteras Island. These communities attract many tourists during the busy summer months, and the Nags Head and Kitty Hawk areas have additionally increased wastewater production on the islands (Cole and Bratton 1994). Human efforts to convert these barrier islands into stable, engineered systems are in direct conflict with the dynamic nature of the ecosystem (Riggs et al. 2008). Development impacts to date include forest clearing, wetland filling and channelization, shallow water dredging, and drainage alteration due to increased surface pavement, all of which have contributed to degraded water quality (Riggs et al. 2008). Human development was identified as a primary stressor for seven of the nine components in this report, and continued monitoring of this threat will be needed to determine the effects that it continues to have on vital CAHA communities.

As with the human development stressor, dune construction and landscape alteration projects have had, and continue to have, dramatic impacts on several of the focal communities in CAHA. Five of the nine components in this NRCA called out dune development or landscape alteration as a principle threat. The effects of this manipulation have broad consequences across many communities, and the backshore and dune communities have been particularly impacted as beach and dune stabilization efforts to protect human developments have disrupted natural barrier island processes (Riggs et al. 2008, McManamay et al. 2018; see Chapter 4.9 for further discussion). In 1982, the NPS officially ended dune maintenance on park-owned property on Bodie Island. However, active maintenance of dunes on northern Hatteras Island has continued in order to protect Highway 12 and access to and from the island (Mallinson et al. 2009, see Chapter 4.1). This road is critical to the coastal tourism industry and provides the only vehicular evacuation route in case of hurricanes (Mallinson et al. 2009).

In addition to dune construction, ditching/dredging for highway roadwork and mosquito control efforts have modified the park landscape (Stroh 1982). Mosquito control efforts on Bodie Island involved the digging of deep channels that drain west into Roanoke Sound (Stroh 1982). Extensive marsh dredging took place in the CAHA area in order to build up the roadbed elevation on Highway 12. A study by the USGS found that the Jennette Sedge ditch drained an estimated 0.01–0.1 cubic meters per second (cms) (0.4–4.5 cubic feet per second) of water from September to April in 1994 and 1995 (Rheinhardt and Faser 2001). Simulations based on this rate of drainage predicted that the water table in Jennette Sedge was about 30 cm (11.8 in) lower during wet periods than if there was no drainage (Anderson 1999, Rheinhardt and Faser 2001). The reduction in duration of flooding and/or soil saturation due to drainage here and on south Bodie Island has promoted the invasion of

shrubs into more open wetland areas (Rheinhardt and Faser 2001) and has detrimentally affected the condition of the park's wetlands and marshes. Wetlands represent a critical habitat for many avian species of concern, particularly in CAHA, and these changes in community structure likely dramatically impacted avian species in regards to abundance, richness, and density.

Beach nourishment projects, which involve the periodic replenishment of sand to maintain beach width for protection of coastal structures, may impact natural dune and backshore communities, but also the park's sea turtles if conducted during the nesting season (NMFS and USFWS 2008). In 2017, a beach nourishment project was conducted along 4.7 km (2.9 mi) of coastline in the Buxton Village area to protect the highway from ocean overwash (NPS 2018a). Because of the presence of heavy equipment and large pipes blocking ocean access, all 15 nests laid in this area were relocated by turtle monitoring staff. In addition to direct impacts, coastal development and human activity can accelerate beach erosion or disrupt natural shoreline migration, which influence turtle nesting habitat (NMFS and USFWS 2008).

Non-native invasive species pose one of the greatest threats to biodiversity and ecosystem integrity worldwide, with the potential to impact ecological community composition, structure, and function (Mooney et al. 2005, Beard and App 2013). Non-native species were identified as a primary threat to the park's maritime forests, wetlands and marshes, bird community, and mammal community, but likely affect all of the park's communities in one way or another. According to NPS (2018e), 234 non-native plant species have been documented within CAHA. Some of these are ornamental species that were intentionally brought to the islands by inhabitants and are likely not a threat to invade natural ecosystems. Forty-one of the non-native plant species confirmed at CAHA are considered invasive by the North Carolina Native Plant Society (NCNPS 2017); 10 of these species are considered a severe threat, 15 species a significant threat, and 16 species are a lesser threat to natural ecosystems in North Carolina (Appendix C). An additional 16 non-native plant species present at CAHA are on a "watch list", as they are not currently known to be invasive in the state but could become a problem in the future (NCNPS 2017).

Non-native species are not limited to the park's flora, however, as non-native mammals, birds, and insects also threaten the park's various communities. Predation from non-native species (such as feral dogs or cats) has a significant impact on nesting shorebird and priority avian species. Domestic and feral cats are one of the largest causes of bird mortality in the United States, including National Park lands (Loss et al. 2013, Dayer et al. 2019). According to Loss et al. (2013), annual global bird mortality caused by outdoor cats is estimated to be between 1.4 and 3.7 billion individuals, and almost 69% of bird mortality due to cat predation was caused by un-owned cats (i.e., strays, barn cats, and completely feral cats) (Loss et al. 2013). The findings indicate that 75–100% of the prey taken by feral cats in suburban and rural areas consist of native species, such as birds, rabbits, and native rodents (Loss et al. 2013). Feral cats are present on all three CAHA islands, and from 2010–2015, a total of 188 cats were captured and removed from the park (NPS 2015b). Feral cats also are responsible for the predation of sea turtle nests and nestlings, although these events are not as common as they are for other predators of sea turtle nestlings (i.e., ghost crabs).

As discussed in Chapters 2 and 4, temperatures are projected to increase across the southeastern United States over the next century as a result of global climate change (Carter et al. 2014). Warmer temperatures will increase evapotranspiration rates, meaning that even if annual precipitation remains constant or slightly increases, overall conditions could become drier in the future (Carter et al. 2014). Warming temperatures will likely allow invasive plants and forest pests to expand their ranges and potentially their impact, as well as altering the habitat suitability of certain areas for some tree species (Fisichelli et al. 2014). The frequency and intensity of droughts is projected to increase with higher temperatures (Karl et al. 2009, DeVivo et al. 2011).

In contrast, warming ocean temperatures due to climate change are projected to increase the intensity of Atlantic hurricanes, with more precipitation and higher wind speeds (Karl et al. 2009). For every 1°C (1.8°F) increase in ocean surface temperatures, hurricane rainfall amounts are likely to increase by 8–16%, along with wind speed increases of 1–8% (Gutowski et al. 2008).

Sea level rise driven by climate change can increase the likelihood of saltwater intrusion into freshwater wetlands, particularly wetlands close to the shoreline, and may alter coastal dynamics (shoreline erosion/accretion). Saltwater intrusion can occur over land during flooding or by encroaching into the shallow surficial water table (Ataie-Ashtiani 2013). A sudden increase in salinity from saltwater intrusion can diminish or kill off aquatic vegetation not adapted to saline or brackish conditions, altering plant community composition and reducing avian and mammalian forage habitat (McKee and Mendelssohn 1989, Riggs and Ames 2003). The areas affected by SLR are often vital nesting, staging, and foraging areas for shoreline avian species, as well as migrants passing through along the coast. If SLR accelerates, tidal saltmarshes may become permanently inundated, killing off the wetland vegetation (Feldman et al. 2009, Schupp 2015).

Overall Conclusions

CAHA is a diverse park with a variety of rare or unique resources, from protected sea turtle and shorebird species, to expansive marshes and maritime forests. This assessment serves as a review and summary of available data and literature for featured natural resources in the park. The information presented here may serve as a baseline against which any changes in condition of components in the future may be compared. Current condition could not be determined for nearly half of the components due to data gaps. For resources where condition could be assessed, the majority were in good condition and only one was of significant concern. Understanding the condition of these resources can help managers prioritize management objectives and better focus conservation strategies to maintain the health and integrity of these ecosystems.

Literature Cited

Adams, L. W. and A. D. Geis. 1983. Effects of roads on small mammals. Journal of Applied Ecology 20:403–415.

Alerstam, T. 1990. Bird Migration. Cambridge University Press, Cambridge, United Kingdom.

Allan, J. D. and M. M. Castillo. 2007. Stream ecology: Structure and function of running waters. Springer Netherlands, Dordrecht, The Netherlands.

Ament, R., A. P. Clevenger, O. Yu, and A. Hardy. 2008. An assessment of road impacts on wildlife populations in U.S. national parks. Environmental Management 42:480–496.

Ames, D. V. and S. R. Riggs. 2006. Geomophic framework of the North Carolina Outer Banks. East Carolina University, Greenville, North Carolina.

Anderson, W. P. 1999. The hydrology of Hatteras Island, North Carolina. North Carolina State University, Raleigh, North Carolina.

Asper, J. and A. C. Curtis. 2013. Salt marsh elevation monitoring. Southeast Coast Network Standard Operating Procedure NPS/SECN/SOP-1.3.6. National Park Service, Athens, Georgia.

Ataie-Ashtiani, B. 2013. How important is the impact of land-surface inundation on seawater intrusion caused by sea-level rise? Hydrogeology Journal 21(7):1673–1677.

Audubon. 2017. Important bird areas of North Carolina. http://www.audubon.org/important-bird-areas/state/north-carolina (accessed 24 March 2018).

Baron, L. C. 2018. Monitoring coastal shoreline change in Southeast Coast Network parks: Protocol implementation plan. Natural Resource Report NPS/SECN/NRR—2018/1744. National Park Service, Fort Collins, Colorado.

Beard, R. and R. App. 2013. Exotic Plant Management Team Program: 2012 annual report. Natural Resource Report NPS/NRSS/BRMD/NRR—2013/674. National Park Service, Fort Collins, Colorado.

Bekoff, M. and E. M. Gese. 2003. Coyote (*Canis latrans*). Pages 467–481 *in* G. A. Feldhammer, B. C. Thompson, and J. A. Chapman, editors. Wild mammals of North America: Biology, management and conservation (2nd ed.). John Hopkins University Press, Baltimore, Maryland.

Bellis, V. J. 1995. Ecology of maritime forests of the Southern Atlantic Coast: A community profile. Biological Report 30. National Biological Service, Southern Science Center, Lafayette, Louisiana.

Bennie, J., T. W. Davies, D. Cruse, and K. J. Gaston. 2016. Ecological effects of artificial light at night on wild plants. Journal of Ecology 104:611–620.

Berthold, P. 1993. Bird migration: a general survey. Oxford University Press, Oxford, United Kingdom.

Bessell, M. S. 1990. UBVRI Passbands. Publications of the Astronomical Society of the Pacific 102:1181–1199.

Bird Life International (BLI). 2016. *Podilymbus gigas*. The IUCN Red List of Threatened Species 2016. https://www.iucnredlist.org/species/22696577/93572322 (accessed 24 March 2018).

Birkemeier, W., R. Dolan, and N. Fisher. 1984. The evolution of a barrier island. Journal of the American Shore & Beach Preservation Association 52(2):2–12.

Bishop, L. B. 1901. The winter birds of Pea Island, North Carolina. The Auk 18(3):260–268.

Bjorndal, K. A., A. B. Bolten, and C. J. Lagueux. 1994. Ingestion of marine debris by juvenile sea turtles in coastal Florida habitats. Marine Pollution Bulletin 28(3):154–158.

Blakesley, J. A., D. C. Pavlacky, and D. Hanni. 2010. Monitoring bird populations in Wind Cave National Park. Technical report M-WICA0901. Rocky Mountain Bird Observatory, Brighton, Colorado.

Boone, J. L. 1988. Annotated list of terrestrial mammals on Bodie and Hatteras Islands, Cape Hatteras National Seashore, North Carolina. National Park Service, Manteo, North Carolina.

Bortle, J. E. 2001. Introducing the Bortle dark-sky scale. Sky & Telescope 101(2):126–129.

Bourdeau, P. F. and H. J. Oosting. 1959. The maritime live oak forest in North Carolina. Ecology 40(1):148–152.

Bratton, S. P. and K. Davison. 1985. The disturbance history of Buxton Woods, Cape Hatteras, North Carolina. National Park Service, Athens, Georgia.

Bratton, S. P. and K. Turner. 1986. Final report: Aquatics Resources Advisory Team, Cape Hatteras National Seashore, North Carolina. CPSU Technical Report 24. National Park Service, Athens, Georgia.

Bratton, S. P. and E. A. Kramer. 1989. Recovery of live oak sprouts after release from browsing on Cumberland Island National Seashore, Georgia. National Park Service, Athens, Georgia.

Burk, C. J. 1962. The North Carolina Outer Banks: A floristic interpretation. Journal of the Mitchell Society 78(1):21–28.

Butler, R. W. 2000. Stormy seas for some North American songbirds: are declines related to severe storms during migration. The Auk 117(2):518–522.

Byrne, M. W., J. M. Maxfield, J. DeVivo, C. J. Wright, and E. Thompson. 2009a. Methods for monitoring migratory and wintering shorebirds in Southeast Coast Network Parks. Natural Resource Report NPS/SECN/NRR—2009/107. National Park Service, Fort Collins, Colorado.

Byrne, M. W., J. M. Maxfield, and J. C. DeVivo. 2009b. Migratory and wintering shorebird monitoring at Cape Hatteras National Seashore, 2006–2007. Natural Resource Technical Report NPS/SECN/NRTR—2009/189. National Park Service, Fort Collins, Colorado.

Byrne, M. W., J. C. DeVivo, and B. A. Blankley. 2011a. Landbird community monitoring at Cumberland Island National Seashore, 2010. Natural Resource Data Series NPS/SECN/NRDS—2011/295. National Park Service, Fort Collins, Colorado.

Byrne, M. W., B. D. Smrekar, M. N. Moore, C. S. Harris, and B. A. Blankley. 2011b. Summary of amphibian community monitoring at Cape Hatteras National Seashore, 2010. Natural Resource Data Series NPS/SECN/NRDS—2011/153. National Park Service, Fort Collins, Colorado.

Byrne, M. W., S. L. Corbett, and J. C. DeVivo. 2012a. Vegetation community monitoring at Cape Hatteras National Seashore, 2010. Natural Resource Data Series NPS/SECN/NRDS—2012/257. National Park Service, Fort Collins, Colorado.

Byrne, M. W., S. L. Corbett, and J. C. DeVivo. 2012b. Vegetation community monitoring at Cape Lookout National Seashore, 2010. Natural Resource Data Series NPS/SECN/NRDS—2012/258. National Park Service, Fort Collins, Colorado.

Byrne, M. W., J. C. DeVivo, C. J. Wright, E. Thompson, and C. D. Jones. 2014. Protocol for monitoring landbird communities in Southeast Coast Network Parks. Natural Resource Report NPS/SECN/NRR—2014/853. National Park Service, Fort Collins, Colorado.

Cahoon, D. R., J. C. Lynch, B. C. Perez, B. Segura, R. D. Holland, C. Stelly, G. Stephenson, and P. Hensel. 2002. High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. Journal of Sedimentary Research 72(5):734–739.

Carter, L. M., J. W. Jones, L. Berry, V. Burkett, J. F. Murley, J. Obeysekera, P. J. Schramm, and D. Wear. 2014. Southeast and the Caribbean. Pages 396–417 *in* J. M. Melilo, T. C. Richmond, and G. W. Yohe, editors. Climate change impacts in the United Sates: The third national climate assessment. U.S. Global Change Research Program, Washington, D.C.

Chambers, R. M., L. A. Meyerson, and K. Saltonstall. 1999. Expansion of *Phragmites australis* into tidal wetlands of North America. Aquatic Botany 64:261–273.

Cinzano, P., F. Falchi, and C. D. Elvidge. 2001. The first world atlas of artificial sky brightness. Monthly Notices of the Royal Astronomical Society 328:689–707.

Clabby, C. 2017. Sounding the toxic algae alarm. https://www.northcarolinahealthnews.org/2017/04/20/sounding-toxic-algae-alarm/ (accessed 22 October 2018).

Cohen, J. B. 2005. Management and protection protocols for the threatened piping plover (*Charadrius melodus*) on Cape Hatteras National Seashore, North Carolina. National Park Service, Laurel, Maryland.

Cohen, J. B. 2009. Management and protection protocols for nesting sea turtles on Cape Hatteras National Seashore, North Carolina. *in* A review and synthesis of the scientific information related to the biology and management of species of special concern at Cape Hatteras National Seashore, North Carolina. U.S. Geological Survey, Reston, Virginia.

Cole, C. A. 1990. Surface water quality, Cape Hatteras National Seashore, North Carolina: Annual report, 1990. National Park Service, Raleigh, North Carolina.

Cole, C. A. 1991. Aquatic macroinvertebrate study: Final report for Cape Hatteras National Seashore. National Park Service Unpublished Report, Raleigh, North Carolina.

Cole, C. A. and S. P. Bratton. 1994. Freshwater wetlands of Cape Hatteras National Seashore: Water quality in a resort setting. Natural Areas Journal 15(2):136–147.

Cole, C. A. 1998. Final report of the National Park marine debris monitoring program. National Park Service, Washington, D.C.

Cook, E. D. 2013. Barrier island response to sea level rise in North Carolina. Thesis. Florida International University, Miami, Florida.

Cook, R. P., K. M. Boland, and T. Dolbeare. 2006. Inventory of small mammals at Cape Cod National Seashore with recommendations for long-term monitoring. Technical Report NPS/NER/NRTR--2006/047. National Park Service, Boston, Massachusetts.

Cooper, A. W. 1964. Salt marsh studies on the North Carolina Outer Banks: Vegetation types in the Bodie Island marsh. North Carolina State University, Raleigh, North Carolina.

Cooper, A. W. and E. D. Waits. 1973. Vegetation types in an irregularly flooded salt marsh on the North Carolina Outer Banks. Journal of the Mitchell Society 1973:78–91.

Cooper, S. 1986. Birds found in Buxton Woods, Cape Hatteras National Seashore, during May and June of 1986. University of North Carolina, Wilmington, North Carolina.

Côté, S. D., T. P. Rooney, J.-P. Tremblay, C. Dussault, and D. M. Waller. 2004. Ecological impacts of deer overabundance. Annual Review of Ecology, Evolution, and Systematics 35:113–147.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. La Roe. 1979. Classification of wetlands and deepwater habitats of the United States. Version 04DEC98. U.S. Fish and Wildlife Service, Washington, D.C.

Crist, J. 2019. EDITOR'S BLOG: Is our National Seashore getting closer to becoming an International Dark Sky Park? https://islandfreepress.org/blog/is-our-national-seashore-getting-closer-to-becoming-an-international-dark-sky-park/ (accessed 8 May 2020).

Curdts, T. 2011. Shoreline length and water area in the ocean, coastal and Great Lakes parks: Updated statistics for shoreline miles and water acres (rev1b). Natural Resource Report NPS/WASO/NRR—2011/464. National Park Service, Fort Collins, Colorado.

Dahl, K. A., M. F. Fitzpatrick, and E. Spanger-Siegfried. 2017. Sea level rise drives increased tidal flooding frequency at tide gauges along the U.S. East and Gulf Coasts: Projections for 2030 and 2045. PLoS ONE 12(2):e0170949.

Dahl, T. E. 1990. Wetlands losses in the United States, 1780's to 1980's. Report to Congress. U.S. Fish and Wildlife Service, Washington, D.C.

Dai, A., P. J. Lamb, K. E. Trenberth, M. Hulme, P. D. Jones, and P. P. Xie. 2004. The recent Sahel drought is real. International Journal of Climatology 24(1323–1331).

Dallas, K., M. Berry, and P. Ruggiero. 2013. Inventory of coastal engineering projects in Cape Hatteras National Seashore. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2013/713. National Park Service, Fort Collins, Colorado.

Davey, C. A., K. T. Redmond, and D. B. Simeral. 2007. Weather and climate inventory: National Park Service, Southeast Coast Network. Natural Resource Technical Report NPS/SECN/NRTR—2007/010. National Park Service, Fort Collins, Colorado.

Davison, K., S. P. Bratton, and L. Graham. 1987. Vascular plant species checklist, Bodie Island, Cape Hatteras National Seashore, North Carolina. National Park Service, Athens, Georgia.

Dayer, A. A., K. H. Redford, K. J. Campbell, C. R. Dickman, R. S. Epanchin-Niell, E. D. Grosholz, D. E. Hallac, E. F. Leslie, L. A. Richardson, and M. W. Schwartz. 2019. The unaddressed threat of invasive animals in U.S. National Parks. Biological Invasions 22:177–188.

DeKimpe, N. M., R. Dolan, and B. P. Hayden. 1991. Predicted dune recession on the Outer Banks of North Carolina, USA. Journal of Coastal Research 7(2):451–463.

DeVivo, J., C. Wright, M. Byrne, E. DiDonato, and T. Curtis. 2008. Vital Signs monitoring in the Southeast Coast Inventory & Monitoring Network. National Park Service, Southeast Coast Network, Atlanta, Georgia.

DeVivo, J. C., M. B. Gregory, T. Curtis, M. W. Byrne, and C. Wright. 2011. Southeast Coast Network climate science strategy. Natural Resource Report NPS/SECN/NRR—2011/436. National Park Service, Fort Collins, Colorado.

DeVivo, J. C. and M. B. Gregory. 2012. Assessment of benthic macroinvertebrate communities at Cape Lookout and Cape Hatteras National Seashores, 2010. Natural Resource Data Series NPS/SECN/NRDS—2011/395. National Park Service, Fort Collins, Colorado.

DeVivo, J. C., J. R. Asper, S. Eastman, N. M. Rankin, A. C. Curtis, C. J. Wright, E. Thompson, and M. W. Byrne. 2015. Protocol for Monitoring Coastal Salt Marsh Elevation and Vegetation

Communities in Southeast Coast Network Parks. Natural Resource Report NPS/SECN/NRR—2015/985. National Park Service, Fort Collins, Colorado.

DeYoung, J. 2016. Forest measurements: An applied approach. Open Oregon Educational Resources, available at https://openoregon.pressbooks.pub/forestmeasurements/.

Dinsmore, S. J., J. A. Collazo, and J. R. Walters. 1998. Seasonal numbers and distribution of shorebirds on North Carolina's Outer Banks. Wilson Bulletin 110(2):171–181.

Dolan, R. 1972a. Beach erosion and beach nourishment: Cape Hatteras, North Carolina. National Park Service, Washington, D.C.

Dolan, R. 1972b. Man's impact on the outer banks of North Carolina. National Park Service, Washington, D.C.

Dolan, R., B. P. Hayden, P. Riddel, and J. Ponton. 1973. Beach nourishment; Buxton, North Carolina post-pumping summary. National Park Service, Manteo, North Carolina.

Dolan, R. and H. Lins. 2000. The Outer Banks of North Carolina. U.S. Geological Survey, Reston, Virginia.

Doshkov, P., K. Losch, W. Thompson, J. Wright, C. Campbell, and N. Sweeney. 2018a. Sea turtle monitoring and management at Cape Hatteras National Seashore: 2017 annual report. Natural Resource Report NPS/CAHA/NRR—2018/1652. National Park Service, Manteo, North Carolina.

Doshkov, P., K. Losch, W. Thompson, J. Wright, and A. Rhodes. 2018b. Shorebird monitoring and management at Cape Hatteras National Seashore: 2017 annual report. Natural Resource Report NPS/CAHA/NRR—2018/1651. National Park Service, Fort Collins, Colorado.

Duriscoe, D. M., C. B. Luginbuhl, and C. A. Moore. 2007. Measuring night-sky brightness with a wide-field CCD camera. Publications of the Astronomical Society of the Pacific 119:192–213.

Duriscoe, D. M. 2016. Photometric indicators of visual night sky quality derived from all-sky brightness maps. Journal of Quantitative Spectroscopy and Radiative Transfer 181:33–45.

Duriscoe, D. M., S. J. Anderson, C. B. Luginbuhl, and K. E. Baugh. 2018. A simplified model of all-sky artificial sky glow derived from VIIRS Day/Night band data. Journal of Quantitative Spectroscopy & Radiative Transfer 214:133–145.

Ehrenfield, J. and H. Oskarsson. 1991. Buxton Woods freshwater wetlands: Interrelationships among vegetation, hydrology and water chemistry. Rutgers University, New Brunswick, New Jersey.

Engels, W. L. 1942. Vertebrate fauna of North Carolina coastal islands: A study in the dynamics of animal distribution, I. Ocracoke Island. The American Midland Naturalist 28(2):273–304.

Environmental Protection Agency (EPA). 1993. Management measures for marinas and recreational boating. Chapter 5 *in* Guidance specifying management measures for sources of nonpoint

pollution in coastal waters. Environmental Protection Agency, Office of Water, Washington, D.C.

Environmental Protection Agency (EPA). 2013. Primary distinguishing characteristics of Level III Ecoregions of the continental United States. National Health and Environmental Effects Research Laboratory (NHEERL), Research Triangle Park, North Carolina.

Environmental Protection Agency (EPA). 2016a. Environmental Monitoring & Assessment Program master glossary: Stressor. https://archive.epa.gov/emap/archive-emap/web/html/mglossary.html#ss (accessed 31 October 2017).

Environmental Protection Agency (EPA). 2016b. Indicators: Chlorophyll a. https://www.epa.gov/national-aquatic-resource-surveys/indicators-chlorophyll (accessed 16 October 2018).

Environmental Protection Agency (EPA). 2016c. Indicators: Dissolved oxygen. https://www.epa.gov/national-aquatic-resource-surveys/indicators-dissolved-oxygen (accessed 25 August 2017).

Environmental Protection Agency (EPA). 2016d. NCCA 2010 technical report. Environmental Protection Agency, Washington, D.C.

Environmental Protection Agency (EPA). 2017. Drinking water regulations and contaminants. https://www.epa.gov/dwregdev/drinking-water-regulations-and-contaminants#List (accessed 15 October 2018).

Environmental Protection Agency (EPA). 2018. Nutrient pollution: Harmful algal blooms. https://www.epa.gov/nutrientpollution/harmful-algal-blooms (accessed 22 October 2018).

Evans, D. G. and B. H. Houston. 2000. Assessing the impact of septic discharge on water quality on the Cape Hatteras National Seashore. National Park Service Unpublished Report, Manteo, North Carolina.

Everts, C. H., J. P. Battley, and P. N. Gibson. 1983. Shoreline movements: Cape Henry, Virginia, to Cape Hatteras, North Carolina, 1849–1980. U.S. Army Corps of Engineers and National Oceanic and Atmospheric Administration, Washington, D.C. and Rockville, Maryland.

Feely, R. A., S. C. Doney, and S. R. Cooley. 2009. Ocean acidification: Present conditions and future changes in a high-CO_2 world. Oceanography 22(4):36–47.

Feldman, R. L., J. G. Titus, B. Poulter, J. DeBlieu, and A. Shellenbarger Jones. 2009. North Carolina. Pages 229–238 *in* J. G. Titus, K. E. Anderson, D. R. Cahoon, D. B. Gesch, S. K. Gill, B. T. Gutierrez, E. R. Thieler, and S. J. Williams, editors. Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region. Environmental Protection Agency, Washington, D.C.

Fenster, M. S. and R. Dolan. 1996. Assessing the impact of tidal inlets on adjacent barrier island shorelines. Journal of Coastal Research 12(1):294–310.

Firth, I. 1987. Vegetation changes on Bodie Island, Cape Hatteras National Seashore, North Carolina. Research/Resources Management Report SER-85. National Park Service, Atlanta, Georgia.

Fisichelli, N. A., S. R. Abella, M. Peters, and F. J. Krist. 2014. Climate, trees, pests, and weeds: Change, uncertainty, and biotic stressors in Eastern U.S. national park forests. Forest Ecology and Management 327:31–39.

Fisichelli, N. A. 2015. Climate, trees, pests, and weeds: Change, uncertainty, and biotic stressors at Cumberland Island National Seashore. National Park Service, Fort Collins, Colorado.

Fraedrich, S. W., T. C. Harrington, R. J. Rabaglia, M. D. Ulyshen, A. E. Mayfield, J. L. Hanula, J. M. Eickwort, and D. R. Miller. 2008. A fungal symbiont of the redbay ambrosia beetle causes a lethal wilt in redbay and other Lauraceae in the Southeastern United States. Plant Disease 92:215–224.

Frankenberg, D. 2012. The nature of the Outer Banks: Environmental processes, field sites, and development issues, Corolla to Ocracoke. The University of North Carolina Press, Chapel Hill, North Carolina.

Gaines, K. F., A. L. Bryan, and P. M. Dixon. 2000. The effect of drought on foraging habitat selection of breeding wood storks in coastal Georgia, USA. Waterbirds 23(1):64–73.

Gardner, L. R., W. K. Michener, T. M. Williams, E. R. Blood, B. Kjerve, L. A. Smock, D. J. Lipscomb, and C. Gresham. 1992. Disturbance effects of Hurricane Hugo on a pristine coastal landscape: North Inlet, South Carolina, USA. Netherlands Journal of Sea Research 30:249–263.

Gares, P. A. and S. A. White. 2005. Volumetric analysis of overwash fans resulting from tropical storms on North Hatteras Island, North Carolina. Southeastern Geographer 45(1):1–15.

Garstang, R. H. 1989. Night-sky brightness at observatories and sites. Publications of the Astronomical Society of the Pacific 101:306–329.

Geffroy, B., D. S. M. Samia, E. Bessa, and D. T. Blumstein. 2015. How nature-based tourism might increase prey vulnerability to predators. Trends in Ecology & Evolution 30(12):755–765.

George, S. L. and K. R. Crooks. 2006. Recreation and large mammal activity in an urban nature reserve. Biological Conservation 133:107–117.

Gibson, D., K. L. Hunt, D. H. Catlin, M. J. Friedrich, C. E. Weithman, J. D. Fraser, and S. M. Karpanty. 2016. 2016 annual operations report: Winter survival of piping plovers on the Atlantic Coast through habitat changes and its relationship to multiple breeding populations. Virginia Tech Shorebird Program, Blacksburg, Virginia.

Godfrey, P. J. and M. M. Godfrey. 1976. Barrier island ecology of Cape Lookout National Seashore and vicinity, North Carolina. National Park Service, Washington, D.C.

Golder, W. 1986. Pre-burn survey: Bodie Island marsh unit. National Park Service Unpublished Report, Manteo, North Carolina.

Gordo, O. 2007. Why are bird migration dates shifting? A review of weather and climate effects on avian phenology. Climate Research 35:37–58.

Gregory, M. B. and K. A. Smith. 2011. Assessment of estuarine water and sediment quality at Cape Lookout and Cape Hatteras National Seashores, 2010. Natural Resource Data Series NPS/SECN/NRDS—2011/179. National Park Service, Fort Collins, Colorado.

Gregory, M. B., J. C. DeVivo, E. M. DiDonato, C. J. Wright, and E. Thompson. 2013. Protocol for monitoring estuarine water and sediment quality in selected Southeast Coast Network parks. Natural Resource Report NPS/SECN/NRR—2013/644. National Park Service, Fort Collins, Colorado.

Griffith, G., J. Omernik, and J. Comstock. 2002. Ecoregions of North Carolina. Environmental Protection Agency, Corvallis, Oregon.

Gutowski, W. J., G. C. Hegerl, G. J. Holland, T. R. Knutson, L. O. Mearns, R. J. Stouffer, P. J. Webster, M. F. Wehner, and F. W. Zwiers. 2008. Causes of observed changes in extremes and projections of future changes. Pages 81–116 *in* T. R. Karl, G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and W. L. Murray, editors. Weather and climate extremes in a changing climate: Regions of focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. U.S. Climate Change Science Program, Washington, D.C.

Hara, T., J. Van der Toorn, and J. H. Mook. 1993. Growth dynamics and size structure of shoots of *Phragmites australis*, a clonal plant. Journal of Ecology 81:47–60.

Hawkes, L. A., A. C. Broderick, M. H. Godfrey, and B. J. Godley. 2009. Climate change and marine turtles. Endangered Species Research 7:137–154.

Hilty, J. and A. Merenlender. 2000. Faunal indicator taxa selection for monitoring ecosystem health. Biological Conservation 92:185–197.

Hobbs, C. H., C. B. Landry, and J. E. Perry. 2008. Assessing anthropogenic and natural impacts on ghost crabs (*Ocypode quadrata*) at Cape Hatteras National Seashore, North Carolina. Journal of Coastal Research 24(6):1450–1458.

Hoegh-Guldberg, O. and J. F. Bruno. 2010. The impact of climate change on the world's marine ecosystems. Science 328:1523–1528.

Hollan, J. 2010. What is light pollution and how do we quantify it? N. Copernicus Observatory and Planetarium, Brno, Czech Republic.

Hoover, G. A. 2001. Entomological notes: Gypsy moth. Penn State University, State College, Pennsylvania.

Hutto, R. L. 1998. Using landbirds as an indicator species group. Pages 75–92 *in* Avian conservation: research and management. Island Press, Washington, D.C.

Hymel, S. N. 2009. Inventory of marine and estuarine benthic macroinvertebrates for nine Southeast Coast Network Parks. Natural Resource Report NPS/SECN/NRR—2009/121. National Park Service, Fort Collins, Colorado.

Hynds, M. and E. N. Starkey. 2019. Fixed-station water-quality monitoring at Cape Hatteras National Seashore: 2015–2016 data summary. Natural Resource Data Series NPS/SECN/NRDS—2019/1205. National Park Service, Fort Collins, Colorado.

Inman, D. L. and R. Dolan. 1989. The Outer Banks of North Carolina: Budget of sediment and inlet dynamics along a migrating barrier system. Journal of Coastal Research 5(2):193–237.

Intergovernmental Panel on Climate Change (IPCC). 2013. Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom.

Jackson, C. W. 2010. Spatio-temporal analysis of barrier island shoreline change: The Georgia Coast, U.S.A. Dissertation. University of Georgia, Athens, Georgia.

Jacobson, S. L. 2005. Mitigation Measures for Highway-caused Impacts to Birds. U. S. Forest Service, Arcata, California.

Jaeger, J. A. G., J. Bowman, J. Brennan, L. Fahrig, D. Bert, J. Bouchard, N. Charbonneau, K. Frank, B. Gruber, and K. Tluk von Toschanowitz. 2005. Predicting when animal populations are at risk from roads: an interactive model of road avoidance behavior. Ecological Modelling 185:329–348.

Jojola, S. M., G. Witmer, and D. Nolte. 2005. Nutria: An invasive rodent pest or valued resource? Pages 120–126 *in* The 11th Wildlife Damage Management Conference. The Wildlife Society, Traverse City, Michigan.

Karl, T. R., J. M. Melilo, and T. C. Peterson. 2009. Global climate change impacts in the United States. Cambridge University Press, New York, New York.

Kearney, T. H. 1900. The plant covering of Ocracoke Island; A study in the ecology of the North Carolina strand vegetation. Contributions from the United States National Herbarium 5(5):261–319.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. W. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi. 2010. Tropical cyclones and climate change. Nature Geoscience 3:157–163.

Lanly, J. P. 1982. Tropical forest resources. FAO Forestry Paper 30. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy (accessed 2 August 2016).

Lee, D. S., J. B. Funderburg, and M. K. Clark. 1982. A distributional survey of North Carolina mammals. North Carolina Biological Survey, Raleigh, North Carolina.

LeGrand, H. E., J. T. Finnegan, S. P. Hall, A. J. Leslie, and J. A. Ratcliffe. 2012. Natural heritage program list of the rare animal species of North Carolina. North Carolina Natural Heritage Program, Raleigh, North Carolina.

Lerberg, S. B., A. F. Holland, and D. M. Sanger. 2000. Responses of tidal creek macrobenthic communities to the effects of watershed development. Estuaries 23(6):838–853.

Link, W. A. and J. R. Sauer. 1998. Estimating population change from count data: Application to the North American breeding bird survey. Ecological Applications 8(2):258–268.

Lopazanski, M. J., J. P. Evans, and R. E. Shaw. 1988. An assessment of maritime forest resources on the North Carolina coast. North Carolina Department of Natural Resources and Community Development, Raleigh, North Carolina.

Lorimer, C. G. 1993. Causes of the oak regeneration problem. Pages 14–39 *in* D. Loftis and C. E. McGee, editors. Oak regeneration: Serious problems, practical recommendations. U.S. Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina.

Loss, S. R., T. Will, and P. P. Marra. 2013. The impact of free-ranging domestic cats on wildlife of the United States. Nature Communications 4:1396.

Loss, S. R., T. Will, and P. P. Marra. 2014. Estimation of Bird-Vehicle Collision Mortality on U.S. Roads. The Journal of Wildlife Management 78(5):763–771.

Luginbuhl, C. B., D. M. Duriscoe, C. W. Moore, A. Richman, G. W. Lockwood, and D. R. Davis. 2009. From the ground up II: Sky glow and near-ground artificial light propagation in Flagstaff, Arizona. Publications of the Astronomical Society of the Pacific 121:204–212.

MacArthur, R. H. 1959. On the breeding distribution pattern of North American migrant birds. Auk 76(3):318–325.

Magargal, K. 2007. Night Sky Team site visit to Cape Hatteras National Seashore. National Park Service, Night Sky Team, Fort Collins, Colorado.

Mallin, M., M. R. McIver, and V. L. Johnson. 2006. Assessment of coastal water resources and watershed conditions at Cape Hatteras National Seashore, North Carolina. Technical Report NPS/NRWRD/NRTR-2006/351. National Park Service, Water Resources Division, Fort Collins, Colorado.

Mallin, M. and M. R. McIver. 2012. Pollutant impacts to Cape Hatteras National Seashore from urban runoff and septic leachate. Marine Pollution Bulletin 64:1356–1366.

Mallinson, D. J., S. J. Culver, S. R. Riggs, J. P. Walsh, D. Ames, and C. W. Smith. 2008. Past, present and future inlets of the Outer Banks barrier islands, North Carolina. North Carolina Coastal Geology Cooperative Research Program, East Carolina University, Greenville, North Carolina.

Mallinson, D. J., S. R. Riggs, S. J. Culver, D. V. Ames, B. P. Horton, and A. C. Kemp. 2009. The North Carolina Outer Banks barrier islands: A field trip guide to the geology, geomorphology, and processes. East Carolina University, Greenville, North Carolina.

Marion, J. L. 2009. Management, monitoring, and protection protocols for seabeach amaranth at Cape Hatteras National Seashore, North Carolina. *in* A review and synthesis of the scientific information related to the biology and management of species of special concern at Cape Hatteras National Seashore, North Carolina. U.S. Geological Survey, Reston, Virginia.

Masterson, J. P., M. N. Fienen, E. R. Thieler, D. B. Gesch, B. T. Gutierrez, and N. G. Plant. 2014. Effects of sea-level rise on barrier island groundwater system dynamics – ecohydrological implications. Ecohydrology 7:1064–1071.

Mays, J. L. and D. J. Shaver. 1998. Nesting trends of sea turtles in National Seashores along Atlantic and Gulf Coast waters of the United States. National Park Service, Corpus Christi, Texas.

McGehee, M. A. 1990. Effects of moisture on eggs and hatchlings of loggerhead sea turtles (*Caretta caretta*). Herpetologica 46(3):251–258.

McKee, K. L. and I. A. Mendelssohn. 1989. Response of a freshwater marsh plant community to increased salinity and increased water level. Aquatic Botany 34(4):301–316.

McKinney, M. L. 2002. Urbanization, biodiversity, and conservation. BioScience 52(10):883–890.

McManamay, R. H. 2017. Vegetation Mapping at Cape Lookout National Seashore. Natural Resource Report NPS/SECN/NRR—2017/1561. National Park Service, Fort Collins, Colorado.

McManamay, R. H., S. C. Heath, and L. Baron. 2018. Vegetation mapping at Cape Hatteras National Seashore. Natural Resource Report NPS/SECN/NRR—2018/1630. National Park Service, Fort Collins, Colorado.

McWilliams, W. H., J. A. Westfall, P. H. Brose, D. C. Dey, M. Hatfield, K. Johnson, K. M. Laustsen, S. L. Lehman, R. S. Morin, M. D. Nelson, and others. 2015. A regeneration indicator for forest inventory and analysis: History, sampling, estimation, analytics, and potential use in the Midwest and Northeast United States. U.S. Forest Service, Northern Research Station, Newtown Square, Pennsylvania.

Merritt, J. F. 2010. The biology of small mammals. The John's Hopkins University Press, Baltimore, Maryland.

Mitasova, H., M. F. Overton, J. J. Recalde, D. J. Bernstein, and C. W. Freeman. 2009. Raster-based analysis of coastal terrain dynamics from multitemporal Lidar data. Journal of Coastal Research 25(2):207–514.

Mooney, H. A., R. Mack, J. A. McNeely, L. E. Neville, P. J. Schei, and J. K. Waage. 2005. Invasive alien species: A new synthesis. Island Press, Washington, D.C.

Moore, C. A., F. Turina, and J. White. 2013. Recommended indicators and thresholds of night sky quality for NPS State of the Parks reports. Interim Guidance – July 2013. National Park Service, Natural Sounds & Night Skies Division, WASO – Natural Resource Stewardship & Science, Lakewood, Colorado.

Moore, F. R., S. A. Gauthreaux, Jr., P. Kerlinger, and T. R. Simons. 1995. Habitat requirements during migration: Important link in conservation. *in* T. E. Martin and D. Finch, editors. Ecology and management of Neotropical migratory birds. Oxford University Press, New York, New York.

Morrison, M. L. 1986. Bird populations as indicators of environmental change. Current Ornithology 3:429–451.

Mrosovsky, N., S. R. Hopkins-Murphy, and J. I. Richardson. 1984. Sex ratio of sea turtles: Seasonal changes. Science 225(4663):739–741.

Narisada, K. and D. Schreuder. 2004. Light Pollution Handbook. Springer Publishing, Dordrecht, The Netherlands.

Nash, E. 1962. Beach and sand dune erosion control at Cape Hatteras National Seashore: A five year review (1956–1961) National Park Service, Manteo, North Carolina.

National Centers for Environmental Information (NCEI). 2018. 1981–2010 Normals for Cape Hatteras Billy Mitchell Field, NC. https://www.ncdc.noaa.gov/cdo-web/datatools/normals (accessed 2 November 2018).

National Marine Fisheries Service (NMFS) and U.S. Fish and Wildlife Service (USFWS). 2008. Recovery plan for the Northwest Atlantic population of the loggerhead sea turtle (*Caretta caretta*), second revision. National Marine Fisheries Service, Silver Spring, Maryland.

National Oceanic & Atmospheric Administration (NOAA). 2015. Reporting stranded, entangled, or injured sea turtles. https://www.pifsc.noaa.gov/marine_turtle/strandings.php (accessed 2 August 2018).

National Oceanic and Atmospheric Administration (NOAA). 2016. A primer on pH. http://pmel.noaa.gov/co2/story/A+primer+on+pH (accessed 24 February 2017).

National Oceanic & Atmospheric Administration (NOAA). 2017. Sea level trends. https://tidesandcurrents.noaa.gov/sltrends/sltrends.html (accessed 25 June 2018).

National Park Service (NPS). 1984. General management plan, Cumberland Island National Seashore, Georgia. National Park Service, St. Marys, Georgia.

National Park Service (NPS). 1994. Baseline water quality data inventory and analysis: Cape Hatteras National Seashore Technical Report NPS/NRWRD/NRTR-94/27. National Park Service, Fort Collins, Colorado.

National Park Service (NPS). 2006. Management policies 2006. National Park Service, Washington, D.C.

National Park Service (NPS). 2008. Cape Hatteras National Seashore: 2008 sea turtle annual report. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2010. Final Cape Hatteras National Seashore off-road vehicle management plan/Environmental impact statement. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2012a. Cape Hatteras National Seashore marine mammal strandings 2008–2012, a five-year summary. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2012b. Cape Hattteras National Seashore predator management: 2012 annual report. National Park Service Unpublished Report, Manteo, North Carolina.

National Park Service (NPS). 2012c. Trapping mammalian predators of protected species. National Park Service Unpublished Report, Manteo, North Carolina.

National Park Service (NPS). 2013a. Cape Hatteras National Seashore sea turtle monitoring: 2012 annual report. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2013b. Southeast Coast Exotic Plant Management Team: Cape Hatteras National Seashore. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2014a. 2014 feral hog study at Bodie Island. National Park Service Unpublished Report, Manteo, North Carolina.

National Park Service (NPS). 2014b. Cape Hatteras National Seashore sea turtle monitoring: 2013 annual report. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2015a. 2014 feral hog control work at Bodie Island. National Park Service Unpublished Report, Manteo, North Carolina.

National Park Service (NPS). 2015b. CAHA predator control trapping data, 2010–2015. National Park Service Unpublished Report, Manteo, North Carolina.

National Park Service (NPS). 2015c. Cape Hatteras National Seashore sea turtle monitoring: 2015 annual report. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2015d. Listing of acreage (summary). National Park Service, Fort Collins, Colorado.

National Park Service (NPS). 2016a. Air quality conditions & trends by park. https://www.nps.gov/subjects/air/park-conditions-trends.htm (accessed 2 November 2018).

National Park Service (NPS). 2016b. Cape Hatteras National Seashore marine mammal strandings: 2016 summary. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2016c. Cape Hatteras National Seashore natural resources: 2016 annual report. National Park Service, Manteo, North Carolina.

National Park Service (NPS). 2016d. NPS research activities. https://www.nps.gov/articles/upload/NPS-Research-Activities.pdf (accessed 2 November 2018).

National Park Service (NPS). 2016e. Padre Island birds website. https://www.nps.gov/pais/learn/nature/birds.htm (accessed 11 July 2017).

National Park Service (NPS). 2016f. State of the Park Report: Cape Hatteras National Seashore. State of the Park Series No. 33. National Park Service Washington, D.C.

National Park Service (NPS). 2017a. Cape Hatteras National Seashore: Nature & science. https://www.nps.gov/caha/learn/nature/index.htm (accessed 1 November 2018).

National Park Service (NPS). 2017b. Cape Hatteras National Seashore: Science and research. https://www.nps.gov/caha/learn/scienceresearch.htm (accessed 2 November 2018).

National Park Service (NPS). 2017c. Cape Lookout National Seashore: Beach driving. https://www.nps.gov/calo/planyourvisit/orv.htm (accessed 17 December 2018).

National Park Service (NPS). 2017d. Salt marsh monitoring program summary. National Park Service, Southeast Coast Network, Athens, Georgia.

National Park Service (NPS). 2017e. Southeast Coast Network: Salt marsh elevation monitoring. https://science.nature.nps.gov/im/units/secn/monitor/saltmarsh.cfm (accessed 7 November 2018).

National Park Service (NPS). 2018a. Annual park recreation visitation (1955 – last calendar year). https://irma.nps.gov/Stats/Reports/Park/CAHA (accessed 30 October 2018).

National Park Service (NPS). 2018b. Cape Hatteras National Seashore: Things to do. https://www.nps.gov/caha/planyourvisit/things2do.htm (accessed 30 October 2018).

National Park Service (NPS). 2018c. Effects of air pollution. https://www.nps.gov/subjects/air/effects.htm (accessed 2 November 2018).

National Park Service (NPS). 2018d. Night skies as a natural resource. https://www.nps.gov/subjects/nightskies/natural.htm (accessed 4 March 2019).

National Park Service (NPS). 2018e. NPSpecies Certified Species List. https://irma.nps.gov/NPSpecies/Search/SpeciesList/CAHA (accessed 16 February 2018).

National Park Service (NPS). 2019. Cape Hatteras Waterfowl Hunting Regulations. https://www.nps.gov/caha/planyourvisit/waterfowlhunting.htm (accessed 12 December 2019).

National Park Service (NPS). No date. Natural resource management plan: Cape Hatteras National Seashore. http://www.npshistory.com/publications/caha/nrmp.pdf (accessed 18 December 2018).

National Park Service Natural Sounds and Night Skies Division (NPS NSNSD). 2013a. Night sky quality monitoring report: Hatteras – Boardwalk 27. National Park Service, Fort Collins, Colorado.

National Park Service Natural Sounds and Night Skies Division (NPS NSNSD). 2013b. Night Sky Quality Monitoring Report: Ocracoke – pony pens boardwalk. National Park Service, Fort Collins, Colorado.

National Park Service Natural Sounds and Night Skies Division (NPS NSNSD). 2015. Night sky monitoring report metrics. http://sierranights.com/nightsky/dataPageExplain.htm (accessed 8 February 2016).

National Water Quality Monitoring Council (NWQMC). 2018. Water quality portal. https://www.waterqualitydata.us/ (accessed 11 October 2018).

Natural Resources Conservation Service (NRCS). 2018. PLANTS database. https://plants.usda.gov/java/ (accessed 30 October 2018).

Navara, K. J. and R. J. Nelson. 2007. The dark side of light at night: Physiological, epidemiological, and ecological consequences. Journal of Pineal Research 43:215–224.

NC Coastal Resources Commission (NC CRC) Science Panel. 2015. North Carolina sea level rise assessment report: 2015 update to the 2010 report and 2012 addendum. NC Coastal Resources Commission, Raleigh, North Carolina.

Niles, L. J., J. Burger, and K. E. Clark. 1996. The influence of weather, geography, and habitat on migrating raptors on Cape May Peninsula. Condor 98:382–394.

Nisley, R. G. 2012. Deer can be too many, too few, or just enough for healthy forests. Research Review No. 16:1–5.

Niven, D. K., G. S. Butcher, and G. T. Bancroft. 2009. Christmas Bird Counts and climate change: Northward shifts in early winter abundance. American Birds 82:10–15.

North American Bird Conservation Initiative (NABCI). 2009. The state of the birds, United States of America. U.S. Department of the Interior, Washington, D.C.

North Carolina Coastal Federation (NCCF). 2020. Terminal groins. https://www.nccoast.org/protect-the-coast/advocate/terminal-groins/ (accessed 20 May 2020).

North Carolina Department of Agriculture and Consumer Services (NCDACS). 2018. 2018 proposed gypsy moth treatments. http://www.ncagr.gov/PLANTINDUSTRY/Plant/entomology/ProposedGypsyMothTreatments.htm (accessed 4 October 2018).

North Carolina Department of Environmental Quality (NCDEQ). 2016. North Carolina beach and inlet management plan update. North Carolina Department of Environmental Quality, Raleigh, North Carolina.

North Carolina Department of Environmental Quality (NCDEQ). 2017. Water quality standards tables. https://deq.nc.gov/nc-stdstable-09222017. (accessed 15 October 2018).

North Carolina Department of Environmental Quality (NCDEQ). 2018. N.C. recreational water quality program: Testing sites. http://portal.ncdenr.org/web/mf/testing-sites (accessed 12 October 2018).

North Carolina Department of Transportation (NCDOT). 2019. N.C. 12 Rodanthe Bridge. https://www.ncdot.gov/projects/nc-12-rodanthe/Pages/default.aspx (accessed 4 May 2020).

North Carolina Division of Coastal Management (NCDCM). 2011. 2011 Long-term average annual erosion rate: Methods report – Summary graphs & tables. North Carolina Department of Environment & Natural Resources – Division of Coastal Management, Raleigh, North Carolina.

North Carolina Division of Water Resources (NCDWR). 2018. Algal bloom map. https://ncdenr.maps.arcgis.com/apps/webappviewer/index.html?id=58e9afca8b724b3f82cc81a8b825f83e (accessed 22 October 2018).

North Carolina Forest Service (NCFS). 2017. Laurel wilt frequently asked questions. http://www.ncforestservice.gov/forest_health/forest_health_laurelwiltfaq.htm (accessed 24 September 2018).

North Carolina Native Plant Society (NCNPS). 2017. Invasive exotic species list. https://www.ncwildflower.org/plant_galleries/invasives_list (accessed 2 November 2018).

North Carolina Wildlife Resources Commission (NCWRC). 2004. Buxton Woods game land. https://www.ncwildlife.org/Portals/0/Hunting/Game-Land-Maps/Coastal/Buxton-Woods.pdf (accessed 18 May 2020).

North Carolina Wildlife Resources Commission (NCWRC). 2018a. North Carolina inland fishing, hunting & trapping regulations digest: 2018–2019. North Carolina Wildlife Resources Commission, Raleigh, North Carolina.

North Carolina Wildlife Resources Commission (NCWRC). 2018b. White-tailed deer harvest reports. https://www.ncwildlife.org/Hunting/Seasons-Limits/Harvest-Statistics/White-tailed-Deer-Harvest-Reports (accessed 6 December 2018).

NPS Night Skies Team (NPS NST). 2016. Night sky monitoring database. Google Earth kml file. Distributed by National Park Service. Available at https://www.nps.gov/subjects/nightskies/skymap.htm (accessed 24 October 2018).

Oliver, C. J. 2018. North Carolina animal related crashes: 2015–2017 county rankings and crash data. North Carolina Department of Transportation, Traffic Safety Division, Raleigh, North Carolina.

Otte, L. J. 1981. Ocracoke Island Natural Area. Pages 300–335 *in* Natural heritage: Classification, inventory, and information. University of North Carolina Press, Chapel Hill, North Carolina.

Parman, J., J. Petrzelka, and M. Williams. 2012. Regional water quality synthesis for southeast coastal parks. Natural Resource Report NPS/NRSS/WRD/NRR—2012/518. National Park Service, Fort Collins, Colorado.

Parnell, J. F., W. D. Webster, and T. L. Quay. 1989. An evaluation of changes in the avian and mammalian faunas of the Cape Hatteras National Seashore, 1956–1989. National Park Service, Manteo, North Carolina.

Parnell, J. F., W. D. Webster, and T. L. Quay. 1992. Birds and mammals of the Cape Hatteras National Seashore: Thirty-five years of change. UNC Sea Grant UNC-SG-92-01. North Carolina Sea Grant, Raleigh, North Carolina.

Peet, R. K., M. T. Lee, M. D. Jennings, and D. Faber-Langendoen. 2013. VegBank: The vegetation plot archive of the Ecological Society of America. http://vegbank.org. (accessed 10 December 2018).

Pendleton, E. A., E. R. Thieler, and S. J. Williams. 2004. Coastal vulnerability assessment of Cape Hatteras National Seashore (CAHA) to sea-level rise. Open-file Report 2004-1064. U.S. Geological Survey, Reston, Virginia.

Peterjohn, B. G. and J. R. Sauer. 1999. Population status of North American grassland birds. Studies in Avian Biology 19:27–44.

Quay, T. L. 1959. The birds, mammals. reptiles, and amphibians of the Cape Hatteras National Seashore Recreational Area. National Park Service Unpublished Report, Manteo, North Carolina.

Radford, A. E., D. K. Otte, L. J. Otte, J. R. Massey, and P. D. Whitson. 1981. Natural heritage: Classification, inventory, and information. University of North Carolina Press, Chapel Hill, North Carolina.

Rheinhardt, R. D. and K. Faser. 2001. Relationship between hydrology and zonation of freshwater swale wetlands on lower Hatteras Island, North Carolina, USA. Wetlands 21(2):265–273.

Rich, T. D., D. J. Beardmore, H. Berlanga, P. J. Blancher, M. S. W. Bradstreet, G. S. Butcher, D. W. Demarest, E. H. Dunn, W. C. Hunter, E. E. Iñigo-Elias, and others. 2004. Partners in Flight North American landbird conservation plan. Cornell Lab of Ornithology, Ithaca, New York.

Richardson, W. J. 1976. Autumn migration over Puerto Rico and the Western Atlantic: A radar study. Ibis 118:309–332.

Riggs, S. R. and D. V. Ames. 2003. Drowning the North Carolina coast: Sea level rise and estuarine dynamics. North Carolina Sea Grant, Raleigh, North Carolina.

Riggs, S. R. and D. V. Ames. 2006. Barrier island evolution: A model for development of the geomorphic framework, North Carolina Outer Banks. East Carolina University, Greenville, North Carolina.

Riggs, S. R., S. J. Culver, D. V. Ames, D. J. Mallinson, D. R. Corbett, and J. P. Walsh. 2008. North Carolina's coasts in crisis: A vision for the future. East Carolina University, Greenville, North Carolina.

Riggs, S. R. and D. V. Ames. 2011. Consequences of human modifications of Oregon Inlet to the down-drift Pea Island, North Carolina Outer Banks. Southeastern Geology 48(3):103–128.

Rinehart, A., M. B. Gregory, and W. Wright. 2013. Fixed-station water-quality monitoring at Cape Hatteras National Seashore: 2012 data summary. Natural Resource Data Series NPS/SECN/NRDS—2013/489. National Park Service, Fort Collins, Colorado.

Roach, F. E. and J. L. Gordon. 1973. The Light of the Night Sky. D. Reidel Publishing Company, Dordrecht, Holland.

Robbins, C. S., J. R. Sauer, R. S. Greenberg, and S. Droege. 1989. Population declines in North American birds that migrate to the Neotropics. Proceedings of the National Academy of Sciences of the United States of America 86:7658–7662.

Robinson, L. G. and J. T. Finnegan. 2017. Natural Heritage Program list of rare plant species of North Carolina. North Carolina Natural Heritage Program, Raleigh, North Carolina.

Roemer, G. W., M. E. Gompper, and B. Van Valkenburgh. 2009. The ecological role of the mammalian mesocarnivore. BioScience 59:165–173.

Rosenberg, K. V., A. M. Dokter, P. J. Blancher, J. R. Sauer, A. C. Smith, P. A. Smith, J. C. Stanton, A. Panjabi, L. Helft, M. Parr, and others. 2019. Decline of the North American Avifauna. Science 366(6461):120–124.

Rowe, P. 2015. Development on the Outer Banks: A case of public perception. Inquiries Journal 7(9).

Russell, F. L., D. B. Zippin, and N. L. Fowler. 2001. Effects of white-tailed deer (*Odocoileus virginianus*) on plants, plant populations and communities: A review. The American Midland Naturalist 146(1):1–26.

Ryer, A. 1997. The Light Measurement Handbook. International Light, Inc., Newburyport, Massachusetts.

Schupp, C. A. 2015. Cape Hatteras National Seashore: Geological resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/964. National Park Service, Fort Collins, Colorado.

Schupp, C. A. 2017. Cape Lookout National Seashore: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2017/1491. National Park Service, Fort Collins, Colorado.

Schwartz, F. J. 1992. Fishes and ecology of freshwater ponds on North Carolina's Outer Banks. *in* C. A. Cole and K. Turner, editors. Barrier island ecology of the Mid-Atlantic Coast: A symposium. National Park Service, Atlanta, Georgia.

Sciaudone, E. J., L. Velasquez-Montoya, E. A. Smyre, and M. F. Overton. 2016. Spatial and temporal variability in dune field: Pea Island, North Carolina. Shore and Beach 84(2):49–58.

Seaturtle.org. 2019. Sea turtle nest monitoring system: North Carolina. http://www.seaturtle.org/nestdb/ (accessed 2 March 2020).

Settel, S. 1937. Timber survey – Hatteras Woods. National Park Service, Manteo, North Carolina.

Shabica, C. W., S. V. Cofer-Shabica, S. L. Boom, and D. E. Anderson. 1993. Inlets of the Southeast Region National Seashore Units: Effects of inlet maintenance and recommended action. National Park Service, Atlanta, Georgia.

Shearman, T. M. and G. G. Wang. 2016. Impacts of laurel wilt disease on native *Persea* ecosystems. Dissertation. Clemson University, Clemson, South Carolina.

Sherrill, B. L., A. G. Snider, and C. S. DePerno. 2010. White-tailed deer on a barrier island: Implications for preserving an ecologically important maritime forest. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 64:38–43.

Shipp-Pennock, M. A., W. D. Webster, and D. W. Freshwater. 2005. Systematics of the white-footed mouse (*Peromyscus leucopus*) in the mid-Atlantic region. Journal of Mammalogy 86(4):803–813.

Slow the Spread Foundation, I. S. (STS). 2004. 2003 accomplishments in slowing the spread of the gypsy moth. Slow the Spread Foundation, Inc., Angier, North Carolina.

Smith, C. G., S. J. Culver, S. R. Riggs, D. V. Ames, D. R. Corbett, and D. J. Mallinson. 2008a. Geospatial analysis of barrier island width of two segments of the Outer Banks, North Carolina,

USA: Anthropogenic curtailment of natural self-sustaining processes. Journal of Coastal Research 24(1):70–83.

Smith, K. G. 1982. Drought-induced changes in avian community structure along a montane sere. Ecology 63(4):952–961.

Smith, M.-L., J. Anderson, and M. Fladeland. 2008b. Forest canopy structural properties. Pages 179–196 *in* C. M. Hoover, editor. Field measurements for forest carbon monitoring. Springer Science+Business Media, New York, New York.

South Carolina Department of Health and Environmental Control (SCDHEC). 2014. R.61-68, Water classifications & standards. South Carolina Department of Health and Environmental Control, Columbia, South Carolina.

Stalter, R. and E. E. Lamont. 1997. Flora of North Carolina's Outer Banks, Ocracoke Island to Virginia. Journal of the Torrey Botanical Society 124(1):71–88.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. J. Norris. 2006. Setting expectations for the ecological condition of streams: The concept of reference condition. Ecological Applications 16(4):1267–1276.

Storm, D. J., C. K. Nielsen, E. M. Schauber, and A. Woolf. 2007. Space Use and Survival of White-Tailed Deer in an Exurban Landscape. The Journal of Wildlife Management 71(4):1170–1176.

Strickland, M. 2015. Predators and anti-predator behavior of Wilson's plover (*Charadrius wilsonia*) on Cumberland Island, Georgia. Georgia Southern University, Statesboro, Georgia.

Stroh, M. T. 1982. A study of the shrub and vegetation patterns on Bodie Island, North Carolina from 1932 to 1982. National Park Service, Manteo, North Carolina.

The H. John Heinz III Center for Science Economics and the Environment. 2008. The state of the nation's ecosystems 2008: Measuring the land, waters, and living resources of the United States. Island Press, Washington, D.C.

Thieler, E. R., K. E. Anderson, D. R. Cahoon, S. J. Williams, and B. T. Gutierrez. 2009. A science strategy for improving the understanding of sea-level rise and its impacts on U.S. coasts. Pages 185–192 *in* J. G. Titus, K. E. Anderson, D. R. Cahoon, D. B. Gesch, S. K. Gill, B. T. Gutierrez, E. R. Thieler, and S. J. Williams, editors. Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region. Environmental Protection Agency, Washington, D.C.

Turner, K. 1984. Natural resource management plan, Cape Hatteras National Seashore. National Park Service, Manteo, North Carolina.

U.S. Fish and Wildlife Service (USFWS). 2006. Comprehensive conservation plan: Pea Island National Wildlife Refuge. U.S. Fish and Wildlife Service, Atlanta, Georgia.

U.S. Fish and Wildlife Service (USFWS). 2008. Endangered and Threatened Wildlife and Plants; revised designation of critical habitat for the wintering populations of piping plovers (Charadrius melodus) in North Carolina. The Federal Register 73(204):62816–62841.

U.S. Fish and Wildlife Service (USFWS). 2018. North Carolina Coast National Wetlands Inventory data (Albemarle and Pamlico Sound watersheds). Available at https://www.fws.gov/wetlands/Data/Mapper.html (accessed 24 March 2018)

U.S. Geological Survey (USGS). 2011. Bacteria in water. http://water.usgs.gov/edu/bacteria.html (accessed 2 February 2016).

U.S. Geological Survey (USGS). 2015. Phosphorus and water. http://water.usgs.gov/edu/phosphorus.html (accessed 10 February 2016).

U.S. Geological Survey (USGS). 2016a. Effects of nutrient enrichment on stream ecosystems. http://wa.water.usgs.gov/neet/index.html (accessed 31 March 2017).

U.S. Geological Survey (USGS). 2016b. Phosphorus and water. http://water.usgs.gov/edu/phosphorus.html (accessed 31 March 2017).

U.S. Geological Survey (USGS). 2016c. Pre- and post-storm photo comparisons – Cape Lookout, NC to Oregon Inlet, NC. https://coastal.er.usgs.gov/hurricanes/irene/photo-comparisons/ (accessed 7 November 2018).

U.S. Geological Survey (USGS). 2016d. Water properties and measurements. http://water.usgs.gov/edu/characteristics.html (accessed 26 June 2018).

U.S. Geological Survey (USGS). 2017a. Nitrogen and water. http://water.usgs.gov/edu/nitrogen.html (accessed 31 March 2017).

U.S. Geological Survey (USGS). 2017b. Turbidity: Units of measurement. https://or.water.usgs.gov/grapher/fnu.html (accessed 2 October 2017).

U.S. Shorebird Conservation Plan Partnership (USSCPP). 2016. Shorebirds of conservation concern in the United States of America – 2016. http://www.shorebirdplan.org/science/assessment-conservation-status-shorebirds/ (accessed 24 March 2018).

United Nations Environment Programme (UNEP). 2008. Water quality for ecosystem and human health. United Nations Environment Programme, Global Environment Monitoring System Water Programme, Burlington, Ontario.

USDA Wildlife Services. 2019. Summary report of predator management on Bodie Island, Cape Hatteras, Ocracoke Island, and Cape Lookout: FY 2019. USDA Wildlife Services, Washington, D.C.

Van der Valk, A. G. 1974. Mineral cycling in coastal foredune plant communities in Cape Hatteras National Seashore. Ecology 55:1349–1358.

Van der Valk, A. G. 1975. The floristic composition and structure of foredune plant communities of Cape Hatteras National Seashore. Chesapeake Science 16(2):115–126.

Vickery, P. D. and J. R. Herkert. 2001. Recent advances in grassland bird research: Where do we go from here? The Auk 118:11–15.

Virginia Institute of Marine Science (VIMS). 2018. Physical characteristics: Salinity. http://web.vims.edu/bio/shallowwater/physical_characteristics/salinity.html (accessed 23 October 2018).

Wamsley, T. V. and K. K. Hathaway. 2004. Monitoring morphology and currents at the Hatteras breach. Shore and Beach 72(2):9–14.

Webster, W. D. 1988. The mammals of Nags Head Woods Ecological Preserve and surrounding area. ASB Bulletin 35:223–229.

Webster, W. D. and C. L. Reese. 1992. Mammalian zoogeography on North Carolina's barrier islands, with special reference to Cape Hatteras National Seashore. Pages 133–143 *in* C. A. Cole and K. Turner, editors. Barrier island ecology of the Mid-Atlantic Coast: A symposium. National Park Service, Atlanta, Georgia.

Webster, W. D. 2010. Mammalian diversity in nineteen Southeast Coast Network parks. Natural Resource Report NPS/SECN/NRR—2010/263. National Park Service, Fort Collins, Colorado.

Weithman, C. E., D. Gibson, K. M. Walker, S. B. Maddock, J. D. Fraser, S. M. Karpanty, and D. H. Catlin. 2018. Discovery of an important stopover location for migratory Piping Plovers. Waterbirds 41(1):56–62.

Werner, A. and C. T. Simmons. 2009. Impact of sea-level rise on sea water intrusion in coastal aquifers. Groundwater 47(2):197–204.

Whitfield, A. K. and A. Becker. 2014. Impacts of recreational motorboats on fishes: A review. Marine Pollution Bulletin 83:24–31.

Williams, T. C., J. M. Williams, L. C. Ireland, and J. M. Teal. 1977. Autumnal bird migration over the Western North Atlantic Ocean. American Birds 31:1–267.

Williams, T. C. 1985. Autumnal bird migration over the windward Caribbean Islands. Auk 102:163–167.

World Resources Institute (WRI) and International Institute for Environment and Development. 1989. World Resources 1988–89. Basic Books, New York, New York.

Wright, W. and D. Yazdansepas. 2015. Fixed-station water-quality monitoring at Cape Hatteras National Seashore: 2005–2009 data summary. Natural Resource Data Series NPS/SECN/NRDS—2015/799. National Park Service, Fort Collins, Colorado.

Wright, W. and P. Mockus. 2015. Fixed-station water-quality monitoring at Cape Hatteras National Seashore: 2013–2014 data summary. Natural Resource Data Series NPS/SECN/NRDS—2015/977. National Park Service, Fort Collins, Colorado.

Wright, W. 2016. Assessment of estuarine water quality at Cape Hatteras and Cape Lookout National Seashores: 2015 data summary. Natural Resource Data Series NPS/SECN/NRDS—2016/1056. National Park Service, Fort Collins, Colorado.

Zedler, J. B. and S. Kercher. 2005. Wetland resources: Status, trends, ecosystem services, and restorability. Annual Review of Environment and Resources 30:39–74.

Zeng, N. 2003. Drought in Sahel. Science 302:999–1000.

Zöckler, C. 2005. Migratory bird species as indicators for the state of the environment. Biodiversity 6(3):7–13.

Appendix A. Fish species confirmed present in CAHA

Table A-1. Fish species confirmed as present at CAHA (NPS 2018e).

Scientific name	Common name
Anguilla rostrata	American eel
Myrophis punctatus	speckled worm eel
Menidia beryllina	inland silverside
Menidia menidia	Atlantic silverside
Synodus foetens	inshore lizardfish
Strongylura marina	Atlantic needlefish
Hyporhamphus unifasciatus	Atlantic silverstripe halfbeak
Brevoortia tyrannus	Atlantic menhaden,
Opisthonema oglinum	Atlantic thread herring
Anchoa hepsetus	broad-striped anchovy
Anchoa mitchilli	bay anchovy
Cyprinodon variegatus	sheepshead minnow
Fundulus confluentus	marsh killifish
Fundulus diaphanus	banded killifish
Fundulus heteroclitus	mummichog
Fundulus majalis	striped killifish
Lucania parva	rainwater killifish
Gambusia holbrooki	eastern mosquitofish
Elops saurus	ladyfish
Fistularia tabacaria	bluespotted cornetfish
Syngnathus floridae	dusky pipefish
Syngnathus fuscus	northern pipefish
Syngnathus louisianae	chain pipefish
Mugil cephalus	striped mullet
Mugil curema	white mullet
Caranx hippos	crevalle jack
Chloroscombrus chrysurus	Atlantic bumper
Selene vomer	lookdown
Trachinotus carolinus	Florida pompano
Trachinotus falcatus	permit
Lepomis gibbosus	kiver, pumpkinseed
Lepomis macrochirus	bluegill
Micropterus salmoides	largemouth bass
Dormitator maculatus	fat sleeper
Chaetodipterus faber	Atlantic spadefish

Table A-1 (continued). Fish species confirmed as present at CAHA (NPS 2018e).

Scientific name	Common name
Eucinostomus argenteus	spotfin mojarra
Eucinostomus gula	silver jenny
Evorthodus lyricus	lyre goby
Haemulon sciurus	bluestriped grunt
Orthopristis chrysoptera	pigfish
Morone americana	white perch
Pomatomus saltatrix	bluefish
Bairdiella chrysoura	silver perch
Cynoscion nebulosus	spotted seatrout
Leiostomus xanthurus	spot
Menticirrhus littoralis	Gulf kingfish
Menticirrhus saxatilis	Gulf minkfish
Micropogonias undulatus	Atlantic croaker
Centropristis striata	black sea bass
Archosargus probatocephalus	sheepshead
Lagodon rhomboides	pinfish
Sphyraena barracuda	great barracuda
Trichiurus lepturus	Atlantic cutlassfish
Symphurus plagiusa	blackcheek tonguefish
Citharichthys spilopterus	bay whiff
Paralichthys albigutta	Gulf flounder
Paralichthys dentatus	fluke, summer flounder
Chilomycterus schoepfii	burrfish, porcupinefish
Diodon hystrix	porcupinefish,
Stephanolepis hispida	planehead filefish

Appendix B. Macroinvertebrate taxa in CAHA

Table B-1. Macroinvertebrate taxa documented by various surveys and studies at CAHA (Dolan et al. 1973, USFWS 2006, Hobbs et al. 2008, Hymel 2009, DeVivo and Gregory 2012, NPS 2018e).

Class	Scientific name	Common name
Bivalves	*Aequipecten irradians*	bay scallop
	Astarte nana	dwarf astarte
	Crassostrea virginica	eastern oyster
	Donax variabilis	variable coquina
	Gemma gemma	amethyst gemclam
	Lucinoma filosa	northeast lucina
	Macoma balthica	Baltic macoma
	Macoma tenta	elongate macoma
	Mercenaria mercenaria	northern quahog
	Mulinia lateralis	dwarf surfclam
	Parvilucina multilineata	many-lined lucine
	Tellina agilis	northern dwarf tellin
Crustaceans	*Acanthohaustorius millsi*	amphipod sp.
	Bowmaniella floridana	opossum shrimp sp.
	Calappa flammea	flame box crab
	Callinectes sapidus	blue crab
	Chiridotea arenicola	isopod sp.
	Edotia montosa	isopod sp.
	Emerita talpoida	Atlantic sand crab
	Farfantepenaeus aztecus	brown shrimp
	Farfantepenaeus duorarum	pink shrimp
	Gammarus palustris	amphipod sp.
	Litopenaeus setiferus	white shrimp
	Ocypode quadrata	Atlantic ghost crab
	Class Ostracoda	ostracods, seed shrimp
	Parahaustorius longimerus	amphipod sp.
	Protohaustorius wigleyi	amphipod sp.
	Sesarma reticulatum	marsh crab
	Uca minax	redjointed fiddler
	Uca pugilator	Atlantic sand fiddler
	Uca pugnax	Atlantic marsh fiddler
Phoronids	Phoronis psammophila	horseshoe worm

Table B-1 (continued). Macroinvertebrate taxa documented by various surveys and studies at CAHA (Dolan et al. 1973, USFWS 2006, Hobbs et al. 2008, Hymel 2009, DeVivo and Gregory 2012, NPS 2018e).

Class	Scientific name	Common name
Gastropods (snails)	*Acteocina canaliculata*	channeled barrel-bubble
	Haminoea solitaria	solitary glassy-bubble
	Littorina irrorata	marsh periwinkle
	Rictaxis punctostriatus	pitted baby-bubble
	Polychaetes (bristle worms)*	–
	Capitella sp.	–
	Eteone foliosa	–
	Glycinde solitaria	–
	Heteromastus filiformis	–
	Leitoscoloplos fragilis	–
	Marenzelleria viridis	–
	Mediomastus ambiseta	–
	Neanthes succinea	–
	Nephtys picta	–
	Notomastus latericeus	–
	Paraonis fulgens	–
	Prionospio heterobranchia	–
	Prionospio pygmaeus	–
	Salvatoria clavata	–
	Scolelepis texana	–
	Spiophanes bombyx	–
	Streblospio benedicti	–
Tunicates	*Aplidium* sp.	sea pork
	Molgula sp.	sea grape
	Styela sp.	sea squirt
Sea stars	*Asterias forbesi*	Forbes sea star
Cnidarians	*Stomolophus meleagris*	cannonball jellyfish
Sponges	*Microciona prolifera*	red beard sponge

* Many polychaeate species have not been given common names.

Appendix C. Non-native, invasive plant species and "watch list" species in CAHA

Table C-1. Non-native, invasive plant species and "watch list" species documented within CAHA with North Carolina invasiveness ranks. A rank of 1 indicates a severe threat, 2 is a significant threat, and 3 is a lesser threat.

Scientific name	Common name	Invasiveness rank*
Albizia julibrissin	mimosa, silktree	1
Allium vineale	wild/field garlic	3
Alternanthera philoxeroides	alligatorweed	1
Artemisia vulgaris	common wormwood	3
Arundo donax	giant reed	3
Arthraxon hispidus	hairy jointgrass	2
Bromus catharticus	rescuegrass	3
Bromus commutatus	meadow/hairy brome	3
Bromus japonicus	Japanese brome	3
Bromus secalinus	rye/chess brome	3
Broussonetia papyrifera	paper mulberry	2
Centaurea stoebe ssp. *micranthos*	spotted knapweed	2
Cichorium intybus	chicory	3
Clematis terniflora	leatherleaf clematis	2
Daucus carota	Queen Anne's lace	3
Hedera helix	English ivy	1
Kummerowia stipulacea	Korean clover	3
Kummerowia striata	Japanese clover	3
Lamium purpureum	purple deadnettle	2
Lespedeza cuneata	Chinese/sericea lespedeza	1
Ligustrum sinense	Chinese privet	1
Ligustrum vulgare	European privet	2
Lonicera japonica	Japanese honeysuckle	1
Lythrum salicaria	purple loosestrife	2
Melilotus albus	white sweetclover	3
Melilotus officinalis	yellow sweetclover	3
Microstegium vimineum	Japanese stiltgrass	1
Myriophyllum aquaticum	parrot feather	1
Myriophyllum spicatum	Eurasian watermilfoil	2

* Watch list A includes non-natives that are or could become widespread in the state, and may be a problem in the future. More information is needed to determine whether they are a threat. Watch list B includes species that cause problems in adjacent states but have not yet been reported to cause problems in North Carolina.

Table C-1 (continued). Non-native, invasive plant species and “watch list” species documented within CAHA with North Carolina invasiveness ranks. A rank of 1 indicates a severe threat, 2 is a significant threat, and 3 is a lesser threat.

Scientific name	Common name	Invasiveness rank*
Phragmites australis	common reed	1
Populus alba	white poplar	3
Pueraria montana (*P. lobata*)	kudzu	1
Senecio vulgaris	common groundsel	3
Sorghum halepense	Johnsongrass	2
Stellaria media	common chickweed	2
Vicia sativa	garden/common vetch	3
Vinca major	bigleaf periwinkle	2
Vinca minor	common periwinkle	2
Wisteria floribunda	Japanese wisteria	2
Xanthium strumarium	Canada/common cocklebur	2
Youngia japonica	oriental false hawksbeard	2
Carex kobomugi	Japanese sedge	B
Centaurea cyanus	cornflower, bachelor's button	A
Echium vulgare	blueweed, viper's bugloss	A
Elaeagnus pungens	thorny olive	A
Hibiscus syriacus	rose of Sharon	A
Hypericum perforatum	common St. John's wort	A
Melia azedarach	chinaberry	B
Verbascum thapsus	common mullein	A

* Watch list A includes non-natives that are or could become widespread in the state, and may be a problem in the future. More information is needed to determine whether they are a threat. Watch list B includes species that cause problems in adjacent states but have not yet been reported to cause problems in North Carolina.

Appendix D. Plant species reported from backshore and dune communities at CAHA

Table D-1. Plant species reported from backshore and dune communities at CAHA over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks backshore and dune communities, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study.

Scientific name	Common name	Kearney (1900)	Van der Valk (1975)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Amaranthus pumilus	seabeach amaranth	–	x	x	–	x	–	–
Ambrosia artemisiifolia	annual ragweed	–	–	–	–	–	–	x
Ammophila breviligulata	American beachgrass	–	x	x	x	/	x	–
Andropogon glomeratus	bushy bluestem	–	–	x	–	–	–	–
Andropogon virginicus	broomsedge bluestem	–	x	–	x	–	–	–
Aristida purpurea	purple threeawn	–	–	–	–	–	x	–
Atriplex mucronata	crested saltbush	–	x	–	–	–	–	–
Baccharis halimifolia	eastern baccharis	–	x	–	–	–	–	x
Bacopa monnieri	herb-of-grace	–	–	–	–	–	–	x
Borrichia frutescens	bushy seaside tansy	–	–	–	–	–	–	x
Cakile edentula	American searocket	–	x	x	x	/	x	x
Calystegia sepium	hedge false bindweed	–	–	–	–	–	x	x
Calystegia soldanella	seashore false bindweed	–	–	–	–	/	x	–
*Carex kobomugi**	Japanese sedge	–	–	–	–	–	–	x
Cenchrus sp.	sandbur sp.	–	–	–	–	–	x	–
Cenchrus tribuloides	sanddune sandbur	–	x	x	x	/	–	x
Chrysopsis gossypina ssp. *gossypina*	cottony goldenaster	–	–	–	x	/	x	–
Cirsium sp.	thistle sp.	–	–	–	–	–	–	x
Cirsium horridulum var. *horridulum*	yellow thistle	–	x	x	–	/	x	–

* Non-native species.

Table D-1 (continued). Plant species reported from backshore and dune communities at CAHA over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks backshore and dune communities, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study.

Scientific name	Common name	Kearney (1900)	Van der Valk (1975)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
*Commelina communis**	Asiatic dayflower	–	–	x	–	–	–	–
Commelina erecta	whitemouth dayflower	–	x	–	–	–	x	x
Conyza canadensis	Canadian horseweed	–	x	–	x	/	x	x
Croton punctatus	gulf croton	x	x	x	–	/	–	x
Cynodon sp.*	Bermudagrass	–	–	–	–	–	x	–
*Cynodon dactylon**	Bermudagrass	x	x	–	–	–	–	–
Cyperus sp.	sedge sp.	–	–	–	–	–	x	x
Cyperus croceus	Baldwin's flatsedge	–	–	–	x	–	–	–
*Cyperus esculentus**	yellow nutsedge	–	x	–	–	–	–	–
Cyperus strigosus	stawcolored flatsedge	–	x	–	–	–	–	–
Dichanthelium neuranthum	rosette grass	x	–	–	–	–	–	–
Diodella teres	poorjoe	–	x	x	x	–	x	x
Dysphania ambrosioides	Mexican tea	–	x	–	–	–	–	–
Eleocharis sp.	spikerush sp.	–	–	–	–	–	–	x
Elymus virginicus	Virginia wildrye	–	–	–	–	–	–	x
Eragrostis hirsuta	bigtop lovegrass	–	–	–	–	–	x	–
Eragrostis refracta	coastal lovegrass	–	–	–	x	–	–	–
Eragrostis spectabilis	purple lovegrass	–	x	x	x	–	–	–
Eupatorium capillifolium	dogfennel	–	x	–	–	–	–	–
Euphorbia polygonifolia	seaside sandmat	x	x	x	x	/	x	x
Eustachys petraea	pinewoods fingergrass	x	x	–	–	/	–	–
Euthamia sp.	goldentop sp.	–	–	–	–	–	–	x

* Non-native species.

Table D-1 (continued). Plant species reported from backshore and dune communities at CAHA over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks backshore and dune communities, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study.

Scientific name	Common name	Kearney (1900)	Van der Valk (1975)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Fimbristylis spadicea	marsh fimbry	–	–	–	–	–	x	–
Gaillardia pulchella	Indian blanket	–	–	–	–	–	–	x
Gamochaeta purpurea	spoonleaf purple everlasting	–	–	–	x	–	–	–
Heterotheca subaxillaris	camphorweed	–	–	–	–	–	x	–
Hydrocotyle bonariensis	largeleaf pennywort	–	x	x	–	/	x	x
*Hypochaeris glabra**	smooth cat's ear	–	–	–	–	–	x	–
Ilex vomitoria	yaupon	x	–	–	–	–	–	x
Ipomoea sagittata	saltmarsh morning-glory	–	x	–	–	–	–	x
Iva frutescens	Jesuit's bark	–	–	–	–	–	–	x
Iva imbricata	seacoast marsh elder	–	x	–	x	/	x	x
Juncus roemerianus	needlegrass rush	–	–	–	–	–	–	x
Juniperus virginiana	eastern redcedar	x	x	–	–	–	–	x
Juniperus virginiana var. *silicicola*	coastal redcedar	–	–	–	–	/	–	–
Kosteletzkya pentacarpos (K. virginica)	Virginia saltmarsh mallow	–	–	–	–	–	–	x
Krigia virginica	Virginia dwarfdandelion	–	–	–	x	–	x	–
Lactuca canadensis	Canada lettuce	–	x	–	x	–	–	–
Lactuca graminifolia	grass-leaf lettuce	–	–	–	–	–	x	–
Lactuca hirsuta	hairy lettuce	–	–	–	–	–	x	–
Lepidium virginicum	Virginia pepperweed	–	x	–	x	–	x	–
Mikania scandens	climbing hempvine	–	–	–	–	–	–	x

* Non-native species.

Table D-1 (continued). Plant species reported from backshore and dune communities at CAHA over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks backshore and dune communities, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study.

Scientific name	Common name	Kearney (1900)	Van der Valk (1975)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Monarda punctata	spotted beebalm	–	–	–	–	/	–	x
Monotropa uniflora	Indianpipe	–	–	–	–	–	–	–
Morella (Myrica) cerifera	wax myrtle	–	x	–	–	–	–	x
Muhlenbergia capillaris	hairawn muhly	–	–	x	x	/	–	–
Nuttallanthus canadensis	Canada toadflax	–	–	–	x	–	x	–
Oenothera humifusa	seabeach evening primrose	–	x	x	x	/	x	x
Opuntia sp.	prickly-pear sp.	x	–	–	–	–	–	–
Opuntia humifusa	devil's-tongue	–	–	–	–	–	x	x
Opuntia pusilla	cockspur pricklypear	–	–	–	x	–	x	–
Panicum amarum	bitter panicgrass	–	x	x	x	/	x	x
Parthenocissus quinquefolia	Virginia creeper	–	–	–	–	/	–	x
Persea borbonia	redbay	–	x	–	–	–	–	–
Physalis viscosa	starhair groundcherry	x	x	–	x	–	–	x
Physalis walteri	Walter's groundcherry	–	–	–	–	/	x	–
Phytolacca americana	American pokeweed	–	x	–	–	–	–	–
Plantago sp.	plantain sp.	–	–	–	–	–	–	x
Pluchea sp.	camphorweed sp.	–	–	–	–	–	–	x
Polygonum glaucum	seaside knotweed	–	–	–	–	–	–	x
Pseudognaphalium obtusifolium	rabbit-tobacco	–	x	–	x	–	x	–
Rhus copallinum	dwarf sumac	–	x	–	–	–	–	–
Rubus flagellaris	northern dewberry	–	–	–	x	–	–	–

* Non-native species.

Table D-1 (continued). Plant species reported from backshore and dune communities at CAHA over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks backshore and dune communities, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study.

Scientific name	Common name	Kearney (1900)	Van der Valk (1975)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Rubus trivialis	southern dewberry	x	–	–	–	–	–	x
*Rumex acetosella**	sheep sorrel	–	–	–	x	–	–	–
Rumex hastatulus	heartwing sorrel	–	x	–	–	–	x	–
*Salsola kali**	Russian thistle	x	x	–	–	/	–	–
Schoenoplectus americanus	chairmaker's bulrush	–	–	–	–	–	–	x
Setaria parviflora	marsh bristlegrass	–	x	–	–	–	–	–
Seutera angustifolia (Cynanchum angustifolium)	Gulf coast swallowwort	–	–	–	–	–	–	x
Smilax sp.	greenbrier sp.	–	–	–	–	–	–	x
Smilax bona-nox	saw greenbrier	x	–	–	–	–	x	–
Solanum sp.	nightshade	x	x	–	–	–	–	–
Solidago sempervirens	seaside goldenrod	–	x	x	x	/	x	x
Spartina patens	saltmeadow cordgrass	–	x	–	–	/	x	x
Strophostyles helvola	amberique-bean	–	x	x	x	/	–	x
Strophostyles umbellata	pink fuzzybean	–	–	–	x	–	x	–
Symphyotrichum subulatum	annual saltmarsh aster	–	–	x	–	–	–	–
Teucrium canadense var. *hypoleucum*	Canada germander	x	–	–	–	–	–	–
Toxicodendron radicans	poison ivy	–	–	–	–	–	–	x
Triplasis purpurea	purple sandgrass	x	x	x	x	/	–	–
Uniola paniculata	seaoats	x	x	x	x	/	x	x
Vitis sp.	grape	–	x	–	–	–	x	–

* Non-native species.

Table D-1 (continued). Plant species reported from backshore and dune communities at CAHA over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks backshore and dune communities, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study.

Scientific name	Common name	Kearney (1900)	Van der Valk (1975)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Vitis aestivalis	summer grape	–	–	–	x	/	–	–
Xanthium sp.	cocklebur sp.	x	–	–	–	–	–	–
Yucca filamentosa	Adam's needle	–	–	–	–	/	x	–
Zanthoxylum clava-herculis	Hercules-club	x	–	–	–	/	–	–

* Non-native species.

Appendix E. Plant species reported from CAHA's maritime forests

Table E-1. Plant species reported from CAHA's maritime forests over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks maritime forests, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only, and all Byrne et al. (2012a) sampling locations fell within Buxton Woods.

Scientific name	Common name	Kearney (1900)	Burk (1962)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Amelanchier canadensis	Canadian serviceberry	–	–	/	x	–
Ampelopsis arborea	peppervine	–	–	/	x	x
Andropogon sp.	bluestem sp.	–	–	–	–	x
Apios americana	groundnut	–	–	x	–	–
Aralia spinosa	devil's walkingstick	–	x	/	–	–
Aronia arbutifolia	red chokeberry	–	x	–	–	–
*Arthraxon hispidus**	small carpetgrass	–	–	–	x	–
Arundinaria tecta	switchcane	–	x	–	–	–
Asclepias sp.	milkweed sp.	–	–	–	–	x
Asplenium platyneuron	ebony spleenwort	x	x	/	x	–
Berchemia scandens	Alabama supplejack	–	–	/	x	x
Bignonia capreolata	crossvine	–	–	/	x	x
Boehmeria cylindrica	smallspike false nettle	–	–	–	–	x
Callicarpa americana	American beautyberry	–	x	/	x	x
Carex sp.	sedge sp.	–	–	–	x	x
Carpinus caroliniana	American hornbeam	–	x	/	x	x
Centella erecta	erect centella	–	–	–	–	x
Chasmanthium laxum	slender woodoats	x	x	/	x	x
Cirsium sp.	thistle sp.	–	–	–	–	x
Cirsium virginianum	Virginia thistle	–	–	–	x	–

* Non-native species.

Table E-1 (continued). Plant species reported from CAHA's maritime forests over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks maritime forests, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only, and all Byrne et al. (2012a) sampling locations fell within Buxton Woods.

Scientific name	Common name	Kearney (1900)	Burk (1962)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Cladium jamaicense	Jamaica swamp sawgrass	–	–	–	–	x
Commelina erecta	whitemouth dayflower	–	–	–	x	–
Conopholis americana	American cancer-root	–	–	x	–	–
Cornus florida	flowering dogwood	–	x	/	x	–
Cornus foemina	stiff dogwood	–	x	–	–	x
Cuscuta gronovii	scaldweed	–	–	x	–	–
Cyperus sp.	sedge sp.	–	–	–	–	x
Danthonia sericea	downy danthonia	–	–	x	–	–
Decumaria barbara	woodvamp	–	x	–	–	–
Desmodium sp.	tick trefoil sp.	–	–	–	x	x
Dichanthelium boscii	Bosc's panicgrass	–	–	–	x	–
Dichanthelium commutatum	variable panicgrass	–	–	/	x	–
Dichanthelium laxiflorum	openflower rosette grass	x	–	–	–	–
Dichanthelium portoricense (Panicum lancearium)	hemlock rosette grass	–	–	x	–	–
Diodella teres	poorjoe	x	–	–	–	–
Diodia virginiana	Virginia buttonweed	–	–	–	–	x
Diospyros virginiana	common persimmon	–	x	/	x	x
Eleocharis sp.	spikerush sp.	–	–	–	–	x
Elephantopus nudatus	smooth elephantsfoot	–	x	/	x	–
Elephantopus tomentosus	devil's grandmother	–	–	/	–	x

* Non-native species.

Table E-1 (continued). Plant species reported from CAHA's maritime forests over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks maritime forests, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only, and all Byrne et al. (2012a) sampling locations fell within Buxton Woods.

Scientific name	Common name	Kearney (1900)	Burk (1962)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Eragrostis sp.	lovegrass sp.	–	–	–	–	x
Euonymus americanus	strawberrybush	–	x	/	–	–
Eupatorium capillifolium	dogfennel	–	–	–	–	x
Eupatorium pilosum	rough boneset	–	–	x	–	–
Eustachys petraea	pinewoods fingergrass	x	–	–	–	–
Galium bermudense	coastal bedstraw	–	x	/	x	x
Gamochaeta purpurea	spoonleaf purple everlasting	–	–	–	x	–
Gaylussacia frondosa	blue huckleberry	–	–	x	x	–
Gelsemium sempervirens	evening trumpetflower	–	–	/	x	x
Helianthemum corymbosum	pinebarren frostweed	–	–	x	–	–
Hieracium gronovii	queendevil	–	–	–	x	–
Hydrocotyle bonariensis	largeleaf pennywort	–	–	–	–	x
Hydrocotyle umbellata	manyflower marshpennywort	–	–	–	–	x
Hypericum hypericoides	St. Andrew's cross	–	–	/	–	x
Ilex cassine	dahoon	–	–	x	–	–
Ilex glabra	inkberry	–	x	–	–	–
Ilex opaca	American holly	–	x	/	x	x
Ilex vomitoria	yaupon	x	x	/	x	x
Juncus sp.	rush sp.	–	–	–	–	x
Juniperus virginiana	eastern redcedar	x	x	–	x	x
Lactuca canadensis	Canada lettuce	–	–	–	–	x

* Non-native species.

Table E-1 (continued). Plant species reported from CAHA's maritime forests over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks maritime forests, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only, and all Byrne et al. (2012a) sampling locations fell within Buxton Woods.

Scientific name	Common name	Kearney (1900)	Burk (1962)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Lechea mucronata	hairy pinweed	–	–	–	x	–
Lespedeza sp.	lespedeza sp.	–	–	–	–	x
Liquidambar styraciflua	sweetgum	–	x	/	–	–
Lonicera sempervirens	trumpet honeysuckle	–	–	/	x	–
Ludwigia sp.	primrose-willow sp.	–	–	–	–	x
Lythrum lineare	wand lythrum	–	–	–	–	x
Magnolia grandiflora	southern magnolia	–	–	–	–	x
Magnolia virginiana	sweetbay	–	x	/	–	–
Melothria pendula	Guadeloupe cucumber	–	–	x	–	–
Mikania scandens	climbing hempvine	–	–	–	–	x
Mitchella repens	partridgeberry	–	x	/	x	x
Monotropa uniflora	Indianpipe	–	x	–	–	–
Morella (Myrica) cerifera	wax myrtle	x	x	/	x	x
Morus rubra	red mulberry	–	x	x	x	–
Oenothera sp.	evening primrose sp.	–	–	–	–	x
Oenothera humifusa	seabeach evening primrose	–	–	–	x	–
Oplismenus hirtellus	bristle basketgrass	x	–	–	–	x
Opuntia humifusa	devil's-tongue	–	–	–	–	x
Osmanthus americanus	devilwood	–	x	/	x	–
Osmunda regalis	royal fern	–	x	–	–	–
Panicum sp.	panicgrass sp.	–	–	–	–	x

* Non-native species.

Table E-1 (continued). Plant species reported from CAHA's maritime forests over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks maritime forests, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only, and all Byrne et al. (2012a) sampling locations fell within Buxton Woods.

Scientific name	Common name	Kearney (1900)	Burk (1962)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Parthenocissus quinquefolia	Virginia creeper	–	–	/	x	x
Paspalum sp.	crowngrass sp.	–	–	–	–	x
Persea borbonia	redbay	–	x	/	x	x
Phyla nodiflora	turkey tangle fogfruit	–	–	–	–	x
Physalis walteri	Walter's groundcherry	–	–	–	x	–
Pinus taeda	loblolly pine	–	x	–	x	x
Pityopsis graminifolia	narrowleaf silkgrass	–	x	/	x	x
Pleopeltis polypodioides	resurrection fern	–	x	/	–	–
Polygonum sp.	knotweed/smartweed sp.	–	–	–	–	x
Polypremum procumbens	juniper-leaf	–	–	–	–	x
Prunus caroliniana	Carolina laurelcherry	–	x	–	–	–
Prunus serotina	black cherry	–	x	/	–	x
Quercus hemisphaerica	Darlington oak; sand laurel oak	–	–	/	x	–
Quercus laurifolia	laurel oak	–	–	–	–	x
Quercus nigra	water oak	–	x	–	–	–
Quercus virginiana	live oak	x	x	/	x	x
Rhus copallinum	dwarf sumac	–	x	–	x	–
Rhynchospora colorata	starrush whitetop	–	–	–	–	x
Rosa palustris	swamp rose	–	–	–	–	x
Rubus cuneifolius	sand blackberry	–	–	–	–	x
Sabal minor	dwarf palmetto	–	x	x	x	x

* Non-native species.

Table E-1 (continued). Plant species reported from CAHA's maritime forests over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks maritime forests, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only, and all Byrne et al. (2012a) sampling locations fell within Buxton Woods.

Scientific name	Common name	Kearney (1900)	Burk (1962)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Sabal palmetto	cabbage palmetto	–	–	–	x	–
Salix caroliniana	coastal plain willow	–	–	–	–	x
Sanicula sp.	sanicle sp.	x	–	–	–	–
Sanicula canadensis	Canadian blacksnakeroot	–	–	/	x	x
Sassafras albidum	sassafras	–	x	/	–	–
Scleria triglomerata	whip nutrush	–	–	–	x	x
Setaria magna	giant bristlegrass	–	–	–	–	x
Smilax sp.	greenbrier sp.	–	–	–	–	x
Smilax auriculata	earleaf greenbrier	–	x	–	–	–
Smilax bona-nox	saw greenbrier	x	–	/	x	–
Smilax glauca	cat greenbrier	–	–	/	x	–
Smilax laurifolia	laurel greenbrier	–	x	/	–	–
Smilax rotundifolia	common greenbrier	–	–	/	x	–
Solidago sempervirens	seaside goldenrod	–	–	–	x	x
Spartina patens	saltmeadow cordgrass	–	–	–	x	x
Spermolepis divaricata	roughfruit scaleseed	–	–	x	–	–
Spiranthes odorata	marsh lady's tresses	–	–	–	x	–
Thelypteris sp.	maiden fern sp.	–	–	–	–	x
Tillandsia usneoides	Spanish moss	x	x	/	–	–
Toxicodendron radicans	poison ivy	x	–	/	x	x
Vaccinium corymbosum	highbush blueberry	–	x	/	–	x

* Non-native species.

Table E-1 (continued). Plant species reported from CAHA's maritime forests over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks maritime forests, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only, and all Byrne et al. (2012a) sampling locations fell within Buxton Woods.

Scientific name	Common name	Kearney (1900)	Burk (1962)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Vaccinium stamineum	deerberry	–	–	–	x	–
Vitis aestivalis	summer grape	x	–	/	x	x
Vitis rotundifolia	muscadine grape	–	–	/	x	x
Zanthoxylum clava-herculis	Hercules-club	x	x	/	–	–

* Non-native species.

Appendix F. Extent of palustrine and estuarine wetlands by type at CAHA

Table F-1. Extent of palustrine and estuarine wetlands by type at CAHA, as mapped by the NWI based on 2009–2010 imagery (USFWS 2018). For an interpretation of each code, visit https://fwsprimary.wim.usgs.gov/decoders/wetlands.aspx.

Wetland system	Wetland type/code	# of wetlands	Total area (ha)	Wetland type/code	# of wetlands	Total area (ha)
Palustrine	PEM1/SS1C	2	13.6	PSS1/4C	4	39.0
	PEM1/SS1Rd	2	20.4	PSS1/4Rd	3	13.9
	PEM1/SS3C	6	22.6	PSS1C	6	20.5
	PEM1/SS3Ch	2	3.5	PSS1Rd	22	22.5
	PEM1/SS4C	6	21.6	PSS1Sd	1	6.4
	PEM1/SS4Cd	2	3.7	PSS3/4C	1	27.0
	PEM1/SS4R	2	12.1	PSS3/EM1C	9	18.2
	PEM1/SS4Rd	1	21.0	PSS3/EM1Ch	1	1.2
	PEM1A	1	0.4	PSS3/EM1Rd	2	14.7
	PEM1C	19	19.2	PSS3A	1	0.2
	PEM1Cd	2	0.7	PSS3Ah	42	15.0
	PEM1Ch	21	23.7	PSS3C	4	3.6
	PEM1F	35	98.9	PSS3Ch	5	2.6
	PEM1Fx	1	8.2	PSS3R	3	12.5
	PEM1R	1	0.1	PSS4/1C	1	9.1
	PEM1Rd	2	4.6	PSS4/EM1C	6	27.5
	PFO1/4C	2	16.8	PSS4/EM1Rd	2	1.5
	PFO1Rd	4	5.6	PSS4C	13	42.4
	PFO3A	1	6.2	PSS4Cd	7	9.3
	PFO3Ah	4	3.0	PSS4R	1	0.9
	PFO3C	2	0.6	PSS4Rd	2	35.1
	PFO3Ch	1	0.1	PSS4Sd	2	6.8
	PFO3R	50	52.2	PUBH	8	3.6
	PFO4/1C	2	10.0	PUBHh	2	1.2
	PFO4/SS3R	2	9.6	PUBHx	3	2.5
	PFO4/SS4R	1	1.1	PUBV	1	<0.1
	PFO4C	7	17.9	PUBVx	1	0.1
	PFO4Cd	2	14.5	PUS2C	6	1.6
	PFO4R	9	26.9	PUS2Ch	3	1.3
	PFO4Sd	4	7.0	–	–	–

Table F-1 (continued). Extent of palustrine and estuarine wetlands by type at CAHA, as mapped by the NWI based on 2009–2010 imagery (USFWS 2018). For an interpretation of each code, visit https://fwsprimary.wim.usgs.gov/decoders/wetlands.aspx.

Wetland system	Wetland type/code	# of wetlands	Total area (ha)	Wetland type/code	# of wetlands	Total area (ha)
Estuarine	E1ABL	8	244.1	E2SS3/1P	1	1.6
	E1UBL	202	622,393.5	E2SS3/4P	14	63.9
	E1UBLx	24	26.8	E2SS3/EM1P	57	255.1
	E2ABM	15	229.9	E2SS3/EM1Pd	1	19.6
	E2EM1/SS3P	90	242.8	E2SS3/USP	18	22.8
	E2EM1/SS3Pd	1	9.3	E2SS3P	281	488.1
	E2EM1/SS4P	9	30.7	E2SS3Pd	2	59.0
	E2EM1/SS4Pd	1	4.1	E2SS4/1P	1	8.0
	E2EM1/USP	4	18.2	E2SS4/3P	4	23.4
	E2EM1N	200	839.4	E2SS4/EM1P	10	57.7
	E2EM1Nd	6	6. 1	E2SS4P	60	251.5
	E2EM1P	306	1,127.3	E2US2M	60	501.1
	E2EM1Pd	28	299.0	E2US2N	15	314.2
	E2EM1Px	2	0.8	E2US2P	14	62.3
	E2EM5P	34	405.7	E2USM	13	11.0
	E2EM5Pd	2	65.8	E2USN	60	102.8
	E2FO4P	5	41.1	E2USP	27	14.8

Appendix G. Plant species documented in CAHA palustrine wetlands

Table G-1. Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
*Alliaria petiolata**	garlic mustard	–	–	–	x	–
Alnus serrulata	hazel alder	–	–	x	–	–
Amaranthus cannabinus	tidalmarsh amaranth	–	x	–	–	–
Andropogon glomeratus	bushy bluestem	–	–	/	–	x
Andropogon virginicus	broomsedge bluestem	–	–	–	x	–
Aronia arbutifolia	red chokeberry	–	–	–	–	x
Asclepias sp.	milkweed sp.	–	–	–	–	x
Baccharis angustifolia	saltwater false willow	–	–	–	x	x
Baccharis halimifolia	eastern baccharis	–	–	–	x	x
Bacopa monnieri	herb-of-grace	x	–	–	x	x
Berchemia scandens	Alabama supplejack	–	–	–	x	–
Boehmeria cylindrica	smallspike false nettle	–	–	/	–	x
Bolboschoenus robustus	sturdy bulrush	–	–	–	x	x
Borrichia frutescens	bushy seaside tansy	–	–	–	x	x
Calystegia sepium	hedge false bindweed	–	–	–	–	x
Carex sp.	sedge sp.	–	–	–	–	x
Carex albolutescens	greenwhite sedge	–	–	/	x	–
Carex comosa	longhair sedge	–	–	x	–	–
Carex crinita	fringed sedge	–	–	x	–	–
Carex glaucescens	southern waxy sedge	–	–	x	–	–

* Non-native species.

Table G-1 (continued). Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Carex stipata	awlfruit sedge	–	–	x	–	–
Cenchrus tribuloides	sanddune sandbur	–	–	–	–	x
*Centella asiatica**	spadeleaf	–	–	–	x	x
Centella erecta	erect centella	x	–	/	x	x
Cephalanthus occidentalis	common buttonbush	–	–	/	–	x
Ceratophyllum sp.	hornwort sp.	–	–	–	x	–
Chasmanthium laxum	slender woodoats	–	–	–	x	–
Cirsium sp.	thistle sp.	–	–	–	–	x
Cladium jamaicense	Jamaica swamp sawgrass	–	–	/	–	x
Commelina erecta	whitemouth dayflower	–	–	–	–	x
Conyza canadensis	Canadian horseweed	–	–	–	x	–
Cornus foemina	stiff dogwood	–	–	x	–	–
Cyperus sp.	sedge sp.	–	–	–	–	x
Cyperus haspan	haspan flatsedge	–	–	x	–	–
Cyperus polystachyos	manyspike flatsedge	–	x	/	–	–
Cyperus strigosus	strawcolored flatsedge	–	–	x	–	–
Decodon verticillatus	swamp loosestrife	–	–	x	–	–
Decumaria barbara	woodvamp	–	–	x	x	–
Dichanthelium aciculare	needleleaf rosette grass	–	–	–	x	–
Dichanthelium acuminatum var. *acuminatum*	tapered rosette grass	–	–	–	x	–

* Non-native species.

Table G-1 (continued). Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Dichanthelium dichotomum var. *dichotomum*	cypress panicgrass	–	–	–	x	–
Dichanthelium laxiflorum	openflower rosette grass	–	–	–	–	–
Dichanthelium sphaerocarpon	roundseed panicgrass	–	–	–	x	–
Diodella teres	poorjoe	–	–	–	x	–
Diodia virginiana	Virginia buttonweed	x	–	/	x	–
Distichlis spicata	saltgrass	–	–	–	x	x
Eleocharis sp.	spikerush sp.	–	–	–	–	x
Eleocharis engelmannii	Engelmann's spikerush	–	–	x	–	–
Eleocharis montevidensis	sand spikerush	–	–	x	x	–
Eleocharis obtusa	blunt spikerush	–	x	–	–	–
Eleocharis parvula	dwarf spikerush	–	x	–	–	–
Eleocharis quadrangulata	squarestem spikerush	–	–	x	–	–
Elymus virginicus	Virginia wildrye	–	–	–	–	x
Eragrostis sp.	lovegrass sp.	–	–	–	–	–
Erechtites hieraciifolius	American burnweed	–	–	–	–	x
*Eremochloa ophiuroides**	centipede grass	–	–	–	x	–
Erigeron sp.	fleabane sp.	–	–	–	x	–
Eupatorium sp.	throughwort sp.	–	–	–	–	x
Eupatorium album	white thoroughwort	–	–	–	x	–
Eupatorium hyssopifolium	hyssopleaf thoroughwort	–	–	/	x	–

* Non-native species.

Table G-1 (continued). Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Euthamia sp.	goldentop sp.	–	–	–	–	x
Euthamia graminifolia	flat-top goldentop	–	–	/	x	–
Fimbristylis caroliniana	Carolina fimbry	–	–	–	–	x
Fimbristylis spadicea	marsh fimbry	–	–	/	x	–
Fuirena pumila	dwarf umbrella-sedge	–	x	x	–	–
Galium bermudense	coastal bedstraw	–	–	–	x	–
Gamochaeta purpurea	spoonleaf purple everlasting	–	–	–	x	–
Gelsemium sempervirens	evening trumpetflower	–	–	–	x	–
Gnaphalium sp.	cudweed sp.	–	–	–	x	–
Hieracium gronovii	queendevil	–	–	–	x	–
Hydrocotyle bonariensis	largeleaf pennywort	–	–	–	x	x
Hydrocotyle umbellata	manyflower marshpennywort	x	–	–	–	x
Hypericum hypericoides	St. Andrew's cross	–	–	–	x	x
Ilex glabra	inkberry	–	–	–	–	x
Ilex vomitoria	yaupon	–	–	–	x	x
Ipomoea sagittata	saltmarsh morning-glory	–	–	–	–	x
Iva frutescens	Jesuit's bark	–	–	–	–	x
Juncus bufonius	toad rush	–	–	/	x	–
Juncus dichotomus	forked rush	x	–	–	x	–
Juncus megacephalus	bighead rush	–	–	x	x	–
Juncus roemerianus	needlegrass rush	–	–	–	x	x
Juncus scirpoides	needlepod rush	x	x	/	–	–

* Non-native species.

Table G-1 (continued). Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Juniperus virginiana	eastern redcedar	–	–	–	x	x
Kosteletzkya pentacarpos (*K. virginica*)	Virginia saltmarsh mallow	–	–	–	x	x
Leersia oryzoides	rice cutgrass	–	–	x	–	–
Leersia virginica	whitegrass	–	–	x	–	–
Lepidium virginicum	Virginia pepperweed	–	–	–	x	–
Lilaeopsis carolinensis	Carolina grasswort	–	–	x	–	–
Limonium carolinianum	lavender thrift	–	–	–	–	x
Limosella australis	Welsh mudwort	–	–	–	x	–
Linum virginianum	woodland flax	–	–	–	x	–
*Lonicera japonica**	Japanese honeysuckle	–	–	–	x	–
Lonicera sempervirens	trumpet honeysuckle	–	–	–	x	–
Ludwigia sp.	primrose-willow sp.	–	–	–	–	x
Ludwigia alata	winged primrose-willow	x	–	x	–	–
Ludwigia alternifolia	bushy seedbox	–	–	/	x	–
Ludwigia maritima	seaside primrose-willow	–	–	x	–	–
Ludwigia microcarpa	smallfruit primrose-willow	x	–	x	x	–
*Lycopus europaeus**	gypsywort	–	–	x	–	–
Lythrum lineare	wand lythrum	–	–	/	x	x
Magnolia grandiflora	southern magnolia	–	–	–	–	x
Malaxis spicata	Florida adder's-mouth orchid	–	–	x	–	–
Melica mutica	twoflower melicgrass	–	–	–	x	–

* Non-native species.

Table G-1 (continued). Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Mikania scandens	climbing hempvine	x	–	/	x	x
Mitreola petiolata	lax hornpod	x	–	x	–	–
Morella (Myrica) cerifera	wax myrtle	–	–	/	x	x
Muhlenbergia capillaris	hairawn muhly	–	–	–	x	–
*Myriophyllum aquaticum**	parrot feather watermilfoil	–	–	x	–	–
Myriophyllum pinnatum	cutleaf watermilfoil	–	–	x	–	–
Nuttallanthus canadensis	Canada toadflax	–	–	/	x	–
Oenothera sp.	evening primrose sp.	–	–	–	–	x
Onoclea sensibilis	sensitive fern	–	–	–	x	–
Osmunda regalis	royal fern	–	–	/	x	x
Panicum sp.	panicgrass sp.	–	–	/	–	x
Panicum amarum	bitter panicgrass	–	–	–	x	–
Parthenocissus quinquefolia	Virginia creeper	–	–	–	x	x
Paspalum sp.	crowngrass sp.	–	–	–	–	–
Persea borbonia	redbay	–	–	–	x	x
Persea palustris	swamp bay	–	–	/	x	x
Persicaria (Polygonum) hydropiperoides	swamp smartweed	–	x	/	–	–
*Phragmites australis**	common reed	–	–	/	–	x
Phyla nodiflora	turkey tangle fogfruit	x	x	–	x	x
Physalis walteri	Walter's groundcherry	–	–	/	x	x
Pinus taeda	loblolly pine	–	–	–	x	x

* Non-native species.

Table G-1 (continued). Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Plantago virginica	Virginia plantain	–	–	–	x	–
Pluchea sp.	camphorweed sp.	–	–	/	–	x
Pluchea foetida	stinking camphorweed	–	–	/	x	–
Polygala setacea	coastal plain milkwort	–	–	–	x	–
Polygonum sp.	knotweed/smartweed sp.	–	–	–	–	x
*Polypogon monspeliensis**	annual rabbitsfoot grass	–	–	/	x	–
Potamogeton illinoensis	Illinois pondweed	–	–	x	x	–
Potamogeton perfoliatus	claspingleaf pondweed	–	x	–	–	–
Proserpinaca palustris	marsh mermaidweed	–	–	/	x	–
Prunus caroliniana	Carolina laurelcherry	–	–	–	–	x
Prunus serotina	black cherry	–	–	–	–	x
Quercus sp.	oak sp.	–	–	–	x	x
Ranunculus sceleratus	cursed buttercup	–	x	/	–	–
Rhexia nashii	maid Marian	–	–	x	–	–
Rhynchospora sp.	beaksedge sp.	–	–	–	x	–
Rhynchospora colorata	starrush whitetop	x	x	/	–	x
Rhynchospora corniculata	shortbristle horned beaksedge	–	–	x	–	–
Rhynchospora miliacea	millet beaksedge	–	–	x	–	–
Rosa palustris	swamp rose	–	x	/	–	x
Rubus cuneifolius	sand blackberry	–	–	–	–	x
Rubus flagellaris	northern dewberry	–	–	–	x	–
Rubus trivialis	southern dewberry	–	–	–	x	–

* Non-native species.

Table G-1 (continued). Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Rumex hastatulus	heartwing sorrel	–	–	/	x	–
Rumex verticillatus	swamp dock	–	–	x	–	–
Ruppia maritima	widgeongrass	–	x	–	–	–
Sabatia sp.	rose gentian sp.	–	–	/	–	x
Sabatia dodecandra	marsh rosegentian	–	–	/	x	–
Sagittaria lancifolia	bulltongue arrowhead	–	–	/	x	–
Salix nigra	black willow	–	–	/	x	–
Schoenoplectus americanus	chairmaker's bulrush	x	–	–	x	x
Schoenoplectus pungens	common threesquare	–	–	/	x	–
Scirpus cyperinus	woolgrass	–	x	–	–	–
Scleria verticillata	low nutrush	–	–	–	–	x
Setaria parviflora	marsh bristlegrass	–	–	–	–	x
Seutera angustifolia (*Cynanchum angustifolium*)	Gulf coast swallowwort	–	–	–	x	x
Smilax auriculata	earleaf greenbrier	–	–	–	x	–
Smilax bona-nox	saw greenbrier	–	–	/	x	–
Smilax glauca	cat greenbrier	–	–	–	x	–
Smilax laurifolia	laurel greenbrier	–	–	–	x	–
Smilax rotundifolia	roundleaf greenbrier	–	–	–	x	x
Solidago odora ssp. *odora*	anisescented goldenrod	–	–	–	x	–
Solidago sempervirens	seaside goldenrod	–	–	–	x	x
Spartina patens	saltmeadow cordgrass	–	–	–	x	x

* Non-native species.

Table G-1 (continued). Plant species documented in CAHA palustrine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Sphenopholis obtusata	prairie wedgescale	–	–	–	x	–
Strophostyles helvola	amberique-bean	–	–	–	x	–
Stuckenia pectinata	sago pondweed	–	x	–	–	–
Thelypteris sp.	maiden fern sp.	–	–	/	–	x
Thelypteris palustris var. *pubescens*	eastern marsh fern	–	–	–	x	–
Toxicodendron radicans	poison ivy	–	–	–	x	x
Triglochin striata	three-rib arrowgrass	x	–	–	–	–
Typha domingensis	southern cattail	–	x	–	–	–
Typha latifolia	broadleaf cattail	–	–	/	x	x
Utricularia sp.	bladderwort sp.	–	–	–	x	–
Utricularia vulgaris	common bladderwort	–	–	x	–	–
Vaccinium corymbosum	highbush blueberry	–	–	/	x	x
Vitis cinerea	graybark grape	–	–	–	x	–
Vitis rotundifolia	muscadine grape	–	–	–	x	x
Vulpia octoflora	sixweeks fescue	–	–	–	x	–
Woodwardia virginica	Virginia chainfern	–	–	/	x	–
Xyris difformis	bog yelloweyed grass	–	x	–	–	–

* Non-native species.

Appendix H. Plant species documented in CAHA estuarine wetlands

Table H-1. Plant species documented in CAHA estuarine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks estuarine wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Cooper (1963)/ Cooper & Waits (1973)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Agalinis maritima	saltmarsh false foxglove	–	–	–	x	x	–	x
Agalinis purpurea	purple false foxglove	–	–	–	x	–	x	–
Alnus serrulata	hazel alder	–	–	–	–	–	–	–
Amaranthus cannabinus	tidalmarsh amaranth	–	–	–	x	–	–	–
Ammannia latifolia	pink redstem	x	–	–	–	–	–	–
Andropogon sp.	bluestem sp.	–	x	–	–	–	–	–
Andropogon glomeratus	bushy bluestem	x	–	x	–	–	–	x
Andropogon virginicus	broomsedge bluestem	–	–	–	x	–	–	–
Atriplex patula	spear saltbush	–	–	–	x	–	–	–
Atriplex prostrata	triangle orache	x	–	–	–	–	–	–
Baccharis halimifolia	eastern baccharis	x	x	–	x	/	x	x
Bacopa monnieri	herb-of-grace	x	–	–	x	–	–	–
Bidens mitis	smallfruit beggarticks	–	–	–	–	x	–	–
Boehmeria cylindrica	smallspike false nettle	–	x	–	–	–	x	–
Bolboschoenus robustus	sturdy bulrush	–	x	–	x	–	x	–
Borrichia frutescens	bushy seaside tansy	x	x	x	x	/	x	x
Cakile edentula	American searocket	–	–	–	–	–	–	x
Calystegia sepium	hedge false bindweed	–	–	–	–	/	x	x
Carex alata	broadwing sedge	–	–	–	x	–	–	–

* Non-native species.

Table H-1 (continued). Plant species documented in CAHA estuarine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks estuarine wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Cooper (1963)/ Cooper & Waits (1973)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Chamaecrista sp.	sensitive pea sp.	–	–	–	–	–	–	x
Cladium jamaicense	Jamaica swamp sawgrass	x	–	–	–	–	–	–
Conyza canadensis	Canadian horseweed	–	–	–	x	–	–	–
Cyperus sp.	flatsedge sp.	–	–	–	–	–	–	x
Cyperus filicinus	fern flatsedge	–	x	–	x	–	–	–
Cyperus odoratus	fragrant flatsedge	–	x	–	x	–	–	–
Cyperus polystachyos	manyspike flatsedge	–	–	–	x	–	–	–
Cyperus rotundus	nutgrass	–	–	–	x	–	–	–
Cyperus strigosus	strawcolored flatsedge	–	–	–	x	–	–	–
Dichanthelium sp.	rosette grass sp.	–	–	–	–	–	–	x
Distichlis spicata	saltgrass	x	x	x	x	/	x	x
Echinochloa walteri	coast cockspur grass	x	x	–	x	–	–	–
Eleocharis sp.	spikerush sp.	x	–	–	–	–	–	x
Eleocharis albida	white spikerush	–	x	–	x	–	x	–
Eleocharis flavescens	yellow spikerush	–	x	–	–	–	–	–
Eleocharis rostellata	beaked spikerush	–	–	–	x	–	–	–
Eleocharis tuberculosa	cone-cup spikerush	–	x	–	x	–	–	–
Eleocharis uniglumis	saltmarsh spikerush	–	–	–	x	–	–	–
Elymus virginicus	Virginia wildrye	–	–	–	–	/	–	x
Festuca sp.	fescue sp.	–	x	–	–	–	–	–
Fimbristylis caroliniana	Carolina fimbry	–	–	–	–	–	–	x

* Non-native species.

Table H-1 (continued). Plant species documented in CAHA estuarine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks estuarine wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Cooper (1963)/ Cooper & Waits (1973)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Fimbristylis spadicea	marsh fimbry	–	x	x	–	–	x	–
Galactia volubilis	downy milkpea	x	–	–	–	–	–	–
Galium obtusum	bluntleaf bedstraw	–	–	–	–	–	x	–
Heliotropium curassavicum	salt heliotrope	–	–	–	–	x	–	–
Hibiscus moscheutos	crimsoneyed rosemallow	–	x	–	x	–	–	–
Hydrocotyle umbellata	manyflower marshpenny-wort	–	–	–	–	–	x	–
Hypericum gentianoides	pinweed St. Johnswort	–	–	–	–	–	–	x
Ilex vomitoria	yaupon	x	–	–	–	–	–	x
Ipomoea sagittata	saltmarsh morning-glory	x	–	–	–	/	–	x
Iresine rhizomatosa	Juda's bush	–	–	–	–	/	x	–
Iva frutescens	Jesuit's bark	x	x	x	x	/	x	x
Iva microcephala	piedmont marsh elder	–	–	–	–	–	–	x
Juncus roemerianus	needlegrass rush	x	x	x	x	/	x	x
Juniperus virginiana	eastern redcedar	–	–	–	–	–	–	x
Kosteletzkya pentacarpos	Virginia saltmarsh mallow	x	x	–	x	–	x	x
Lactuca canadensis	Canada lettuce	–	–	–	x	–	–	–
Lepidium virginicum	Virginia pepperweed	–	–	–	–	–	–	x
Leptochloa fusca ssp. *fascicularis*	bearded sprangletop	–	–	–	x	x	–	–
Lilaeopsis carolinensis	Carolina grasswort	–	–	–	x	–	–	–

* Non-native species.

Table H-1 (continued). Plant species documented in CAHA estuarine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks estuarine wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Cooper (1963)/ Cooper & Waits (1973)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Lilaeopsis chinensis	eastern grasswort	–	–	–	x	/	–	–
Limonium carolinianum	lavender thrift	–	–	x	x	/	x	x
Ludwigia sp.	seedbox sp.	–	–	–	–	–	x	–
Ludwigia alternifolia	bushy seedbox	–	–	–	x	–	–	–
Lythrum lineare	wand lythrum	–	x	–	x	–	–	–
Melothria pendula	Guadeloupe cucumber	–	–	–	–	–	–	x
Mikania scandens	climbing hempvine	–	x	x	x	–	x	x
Morella cerifera	wax myrtle	–	–	–	–	/	–	x
Oenothera laciniata	cut-leaved evening primrose	–	–	–	x	–	–	–
Opuntia humifusa	devil's-tongue	–	–	–	–	–	–	x
Panicum sp.	panic grass sp.	–	–	–	–	–	–	x
Panicum amarum	bitter panicgrass	–	–	–	–	–	x	–
Parthenocissus quinquefolia	Virginia creeper	–	–	–	–	–	–	x
Paspalum sp.	crowngrass sp.	–	x	–	–	–	–	–
Paspalum distichum	knotgrass	x	–	–	–	–	–	–
Paspalum vaginatum	seashore paspalum	–	–	–	–	–	–	x
Persea palustris	swamp bay	–	–	–	–	–	–	x
*Persicaria hydropiper**	marshpepper knotweed	–	–	–	–	–	x	–
Persicaria punctata	dotted smartweed	–	–	–	–	–	x	–
Persicaria robustior	stout smartweed	–	x	–	–	–	–	–

* Non-native species.

Table H-1 (continued). Plant species documented in CAHA estuarine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks estuarine wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Cooper (1963)/ Cooper & Waits (1973)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
*Phragmites australis**	common reed	–	–	–	x	–	–	–
Phyla nodiflora	turkey tangle fogfruit	–	–	–	x	–	–	–
Physalis walteri	Walter's groundcherry	–	–	–	–	–	–	x
Phytolacca americana	American pokeweed	–	–	–	x	–	–	x
Pluchea camphorata	camphor pluchea	x	–	–	–	–	–	–
Pluchea foetida	stinking camphorweed	–	–	–	x	–	–	–
Pluchea odorata var. *odorata*	sweetscent	–	x	x	x	–	–	–
Portulaca oleracea	little hogweed	–	x	–	–	–	–	–
Ptilimnium capillaceum	herbwilliam	–	–	–	x	–	–	–
Rhexia mariana	Maryland meadowbeauty	–	–	–	x	–	–	–
Rhynchospora sp.	beaksedge sp.	–	–	–	–	–	–	x
Rosa palustris	swamp rose	–	–	–	x	–	–	–
Rubus cuneifolius	sand blackberry	–	–	–	–	–	–	x
Rumex sp.	dock sp.	x	–	–	–	–	–	–
Ruppia maritima	widgeongrass	–	–	–	–	/	x	–
Sabatia sp.	rose gentian sp.	–	–	–	–	–	x	–
Sabatia campanulata	slender rose gentian	–	–	–	x	–	–	–
Sabatia stellaris	rose of Plymouth	–	–	x	x	/	–	–
Salicornia sp.	glasswort	–	x	–	–	–	–	–
Salicornia bigelovii	dwarf saltwort	–	–	x	x	/	x	–
Salicornia depressa	Virginia glasswort	–	–	x	x	/	x	–

* Non-native species.

Table H-1 (continued). Plant species documented in CAHA estuarine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks estuarine wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Cooper (1963)/ Cooper & Waits (1973)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Salicornia maritima	slender glasswort	x	–	–	–	/	–	–
*Salsola kali**	Russian thistle	–	–	–	–	–	–	x
Samolus valerandi	seaside brookweed	–	–	–	x	–	–	–
Sarcocornia perennis	chickenclaws	–	–	–	–	–	x	x
Schoenoplectus americanus	chairmaker's bulrush	–	x	–	x	–	x	–
Sesuvium maritimum	slender seapurslane	–	–	–	x	–	–	–
Setaria parviflora	marsh bristlegrass	x	–	x	x	–	–	x
Seutera angustifolia	Gulf coast swallowwort	x	–	–	x	/	–	x
Smilax sp.	greenbrier sp.	–	–	–	–	–	–	x
*Solanum nigrum**	black nightshade	–	–	–	x	–	–	–
Solidago sempervirens	seaside goldenrod	x	x	–	x	–	x	x
Spartina alterniflora	smooth cordgrass	–	x	x	x	/	x	x
Spartina cynosuroides	big cordgrass	–	x	–	x	–	x	–
Spartina maritima	small cordgrass	x	–	–	–	–	–	–
Spartina patens	saltmeadow cordgrass	x	x	x	x	/	x	x
Spergularia salina	salt sandspurry	–	–	–	x	/	x	–
Spiranthes praecox	greenvein lady's tresses	–	–	–	x	–	–	–
Symphyotrichum sp.	aster sp.	–	–	–	–	–	x	–
Symphyotrichum subulatum	annual saltmarsh aster	x	–	–	–	–	–	–
Symphyotrichum tenuifolium	saline aster	x	–	x	x	/	–	–

* Non-native species.

Table H-1 (continued). Plant species documented in CAHA estuarine wetlands over time. A "/" in the Stalter and Lamont (1997) column indicates a species was reported for Outer Banks estuarine wetlands, but was not specifically mentioned at a CAHA sampling location. x = species reported at CAHA in the study. The Kearney (1900) survey was on Ocracoke Island only and Davison et al. (1987) was limited to Bodie Island.

Scientific name	Common name	Kearney (1900)	Cooper (1963)/ Cooper & Waits (1973)	Otte (1981)	Davison et al. (1987)	Stalter & Lamont (1997)	Peet et al. (2013)	Byrne et al. (2012)
Teucrium canadense	Canada germander	–	x	–	x	–	–	–
Thelypteris palustris var. *pubescens*	eastern marsh fern	–	–	–	–	–	x	–
Toxicodendron radicans	poison ivy	–	x	–	–	–	x	x
Triglochin striata	three-rib arrowgrass	–	–	–	x	–	–	–
Typha sp.	cattail	–	x	–	–	–	–	–
Typha angustifolia	narrowleaf cattail	–	–	–	–	–	x	–
Typha domingensis	southern cattail	–	–	–	–	/	x	–
Typha latifolia	broadleaf cattail	x	–	–	x	–	–	–
Zostera marina	eelgrass	–	–	–	–	/	x	–

* Non-native species.

Appendix I. Wildlife species documented in the maritime forests of CAHA

Table I-1. Wildlife species documented in the maritime forests of CAHA and vicinity (Bellis 1995; adapted from Quay 1959, Webster 1988, Parnell et al. 1989). One species, the cotton mouse (*Peromyscus gossypinus*), was removed due to later evidence that specimens were misidentified (Byrne et al. 2011b).

Class	Scientific name	Common name
Amphibians	*Amphiuma means*	two-toed amphiuma
	Anaxyrus fowleri	Fowler's toad
	Hyla cinerea	green treefrog
	Hyla squirella	squirrel treefrog
	Hyla versicolor	gray treefrog
	Gastrophryne carolinensis	eastern narrow-mouthed toad
	Lithobates sphenocephala	southern leopard frog
Reptiles	*Chelydra serpentina*	snapping turtle
	Kinosternon subrubrum	eastern mud turtle
	Clemmys guttata	spotted turtle
	*Trachemys scripta scripta**	yellow-bellied slider
	Scincella lateralis	ground skink
	Eumeces inexpectatus	southeastern five-line skink
	Nerodia taxispilota	brown water snake
	Storeria dekayi	brown snake
	Thamnophis saurita	eastern ribbon snake
	Coluber constrictor	black racer
	Opheodrys aestivus	rough green snake
	Pantherophis obsoletus	black rat snake
	Lampropeltis getula	eastern kingsnake
	Agkistrodon piscivorus	cottonmouth
	Crotalus horridus	timber rattlesnake
	Crotalus adamanteus	diamondback rattlesnake
Birds	*Podilymbus podiceps*	pied-billed grebe
	Ardea herodias	great blue heron
	Butorides virescens	green heron
	Egretta caerulea	little blue heron
	Bubulcus ibis	cattle egret
	Ardea alba	common egret
	Egretta thula	snowy egret
	Egretta tricolor	tricolored heron

* Non-native species.

Table I-1 (continued). Wildlife species documented in the maritime forests of CAHA and vicinity (Bellis 1995; adapted from Quay 1959, Webster 1988, Parnell et al. 1989). One species, the cotton mouse (*Peromyscus gossypinus*), was removed due to later evidence that specimens were misidentified (Byrne et al. 2011b).

Class	Scientific name	Common name
Birds (continued)	*Nycticorax nycticorax*	black-crowned night heron
	Nyctanassa violacea	yellow-crowned night heron
	Aix sponsa	wood duck
	Aythya collaris	ring-necked duck
	Bucephala albeola	bufflehead
	Lophodytes cucullatus	hooded merganser
	Cathartes aura	turkey vulture
	Accipiter striatus	sharp-shinned hawk
	Accipiter cooperii	Cooper's hawk
	Buteo lineatus	red-shouldered hawk
	Pandion haliaetus	osprey
	*Phasianus colchicus**	ring-necked pheasant
	Rallus elegans	king rail
	Gallinula chloropus	common moorhen
	Fulica americana	American coot
	Scolopax minor	American woodcock
	Gallinago gallinago	common snipe
	Actitis macularius	spotted sandpiper
	Zenaida macroura	mourning dove
	Coccyzus americanus	yellow-billed cuckoo
	Megascops asio	eastern screech owl
	Megaceryle alcyon	belted kingfisher
	Colaptes auratus	northern flicker
	Myiarchus crinitus	great crested flycatcher
	Corvus brachyrhynchos	American crow
	Corvus ossifragus	fish crow
	Thryothorus ludovicianus	Carolina wren
	Dumetella carolinensis	gray catbird
	Toxostoma rufum	brown thrasher
	Turdus migratorius	American robin
	Catharus guttatus	hermit thrush
	Bombycilla cedrorum	cedar waxwing
	Vireo griseus	white-eyed vireo
	Protonotaria citrea	prothonotary warbler

* Non-native species.

Table I-1 (continued). Wildlife species documented in the maritime forests of CAHA and vicinity (Bellis 1995; adapted from Quay 1959, Webster 1988, Parnell et al. 1989). One species, the cotton mouse (*Peromyscus gossypinus*), was removed due to later evidence that specimens were misidentified (Byrne et al. 2011b).

Class	Scientific name	Common name
Birds (continued)	*Setophaga coronata*	yellow-rumped warbler
	Setophaga pinus	pine warbler
	Setophaga discolor	prairie warbler
	Geothlypis trichas	common yellowthroat
	Cardinalis	northern cardinal
	Pipilo erythrophthalmus	rufous-sided towhee
Mammals	*Cryptotis parva*	least shrew
	Scalopus aquaticus	eastern mole
	Sylvilagus floridanus	eastern cottontail
	Sylvilagus palustris	marsh rabbit
	Lasionycteris noctivagans	silver-haired bat
	Lasiurus borealis	red bat
	Sciurus carolinensis	gray squirrel
	Peromyscus leucopus	white-footed mouse
	Ondatra zibethicus	muskrat
	*Rattus norvegicus**	Norway rat
	Oryzomys palustris	marsh rice rat
	*Mus musculus**	house mouse
	*Myocastor coypus**	nutria
	Didelphis virginiana	Virginia opossum
	Procyon lotor	raccoon
	Mustela vison	American mink
	Lontra canadensis	river otter
	*Felis catus**	house cat
	Odocoileus virginianus	white-tailed deer

* Non-native species.

Appendix J. Bird species that have been documented in CAHA

Table J-1. Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Acadian Flycatcher	*Empidonax virescens*	X	X	–	–	X	–	–
American Avocet	*Recurvirostra americana*	X	X	–	–	–	–	X
American Bittern	*Botaurus lentiginosus*	X	X	X	X	–	–	X
American Black Duck	*Anas rubripes*	X	X	X	X	X	–	X
American Coot	*Fulica americana*	X	X	–	–	–	–	X
American Crow	*Corvus brachyrhynchos*	X	X	–	–	X	X	X
American Flamingo	*Phoenicopterus ruber*	X	–	–	–	–	–	–
American Golden-Plover	*Pluvialis dominica*	X	–	–	–	–	–	X
American Goldfinch	*Spinus tristis*	X	X	–	–	X	X	X
American Kestrel	*Falco sparverius*	X	X	–	–	–	–	X
American Oystercatcher	*Haematopus palliatus*	X	X	–	–	–	X	X
American Pipit	*Anthus rubescens*	X	X	–	–	–	–	X
American Redstart	*Setophaga ruticilla*	X	X	–	–	–	–	–
American Robin	*Turdus migratorius*	X	–	–	–	–	–	X
American Tree Sparrow	*Spizelloides arborea*	X	–	–	–	–	–	X
American White Pelican	*Pelecanus erythrorhynchos*	X	X	–	–	–	–	X
American Wigeon	*Anas americana*	X	–	–	X	–	–	X
American Woodcock	*Scolopax minor*	X	–	–	–	–	–	X
Arctic Tern	*Sterna paradisaea*	X	–	–	–	–	–	–
Ash-throated Flycatcher	*Myriartchus cinerascens*	–	–	–	–	–	–	X
Audubon's Shearwater	*Puffinus lherminieri*	X	X	–	–	–	–	–
Bachman's Sparrow	*Peucaea aestivalis*	X	–	–	–	–	–	–

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Baird's Sandpiper	*Calidris bairdii*	X	X	–	–	–	–	–
Bald Eagle	*Haliaeetus leucocephalus*	X	X	X	–	–	–	X
Baltimore Oriole	*Icterus galbula*	X	X	–	–	–	–	X
Band-rumped Storm-Petrel	*Oceanodroma castro*	X	–	–	–	–	–	–
Bank Swallow	*Riparia riparia*	X	X	–	–	–	–	–
Bar-headed Goose	*Anser indicus*	U	–	–	–	–	–	–
Barn Owl	*Tyto alba*	X	X	–	X	–	–	X
Barn Swallow	*Hirundo rustica*	X	X	–	–	X	X	X
Barnacle Goose	*Branta leucopsis*	U	–	–	–	–	–	–
Bar-tailed Godwit	*Limosa lapponica*	X	–	–	–	–	–	–
Bay-breasted Warbler	*Setophaga castanea*	X	X	–	–	–	–	–
Belted Kingfisher	*Megaceryle alcyon*	X	X	–	X	–	–	X
Bewick's Wren	*Thryomanes bewickii*	X	–	–	–	–	–	–
Black Rail	*Laterallus jamaicensis*	X	X	–	–	–	–	X
Black Scoter	*Melanitta nigra*	X	X	–	–	–	–	X
Black Skimmer	*Rynchops niger*	X	X	–	–	X	–	X
Black Tern	*Chlidonias niger*	X	X	–	–	–	–	–
Black Vulture	*Coragyps atratus*	X	–	–	–	–	–	X
Black-and-White Warbler	*Mniotilta varia*	X	X	–	–	–	–	X
Black-bellied Plover	*Pluvialis squatarola*	X	X	X	X	–	X	X
Black-bellied Whistling-Duck	*Dendrocygna autumnalis*	–	–	–	–	–	–	X
Black-billed Cuckoo	*Coccyzus erythropthalmus*	X	–	–	–	–	–	–
Black-chinned Hummingbird	*Archilochus alexandri*	–	–	–	–	–	–	X
Blackburnian Warbler	*Setophaga fusca*	X	X	–	–	–	–	–

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Black-capped Petrel	*Pterodroma hasitata*	X	–	–	–	–	–	–
Black-crowned Night-Heron	*Nycticorax nycticorax*	X	–	–	–	X	X	X
Black-headed Gull	*Chroicocephalus ridibundus*	X	X	–	–	–	–	X
Black-legged Kittiwake	*Rissa tridactyla*	X	X	–	–	–	–	X
Black-necked Stilt	*Himantopus mexicanus*	X	X	–	–	–	–	–
Blackpoll Warbler	*Setophaga striata*	X	X	–	–	–	–	–
Black-tailed Godwit	*Limosa limosa*	X	–	–	–	–	–	–
Black-tailed Gull	*Larus crassirostris*	–	–	–	–	–	–	X
Black-throated Blue Warbler	*Setophaga caerulescens*	X	X	–	–	–	–	X
Black-throated Green Warbler	*Setophaga virens*	X	X	–	–	–	–	X
Black-winged Stilt	*Himantopus himantopus*	U	–	–	–	–	–	–
Blue Grosbeak	*Passerina caerulea*	X	X	–	–	–	–	–
Blue Jay	*Cyanocitta cristata*	X	X	–	–	X	X	X
Blue-gray Gnatcatcher	*Polioptila caerulea*	X	X	–	–	–	–	X
Blue-headed Vireo	*Vireo solitarius*	X	X	–	–	–	–	X
Blue-winged Teal	*Anas discors*	X	X	–	–	–	–	X
Blue-winged Warbler	*Setophaga pinus*	X	X	–	–	–	–	–
Boat-tailed Grackle	*Quiscalus major*	X	X	X	X	–	X	X
Bobolink	*Dolichonyx oryzivorus*	X	X	–	–	–	X	–
Bonaparte's Gull	*Chroicocephalus philadelphia*	X	X	X	–	–	–	X
Brant	*Branta bernicla*	X	X	X	–	–	–	X
Brewer's Blackbird	*Euphagus cyanocephalus*	X	–	–	–	–	–	–
Bridled Tern	*Onychoprion anaethetus*	X	–	–	–	–	–	–
Broad-winged Hawk	*Buteo platypterus*	X	X	–	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Brown Booby	*Sula leucogaster*	P	–	–	–	–	–	–
Brown Creeper	*Certhia americana*	X	X	–	–	–	–	X
Brown Noddy	*Anous stolidus*	X	–	–	–	–	–	–
Brown Pelican	*Pelecanus occidentalis*	X	X	–	–	–	X	X
Brown Thrasher	*Toxostoma rufum*	X	–	–	–	X	X	X
Brown-headed Cowbird	*Molothrus ater*	X	X	–	–	X	X	X
Brown-headed Nuthatch	*Sitta pusilla*	X	X	–	–	–	X	X
Buff-breasted Sandpiper	*Tryngites subruficollis*	X	X	–	–	–	–	–
Bufflehead	*Bucephala albeola*	X	X	X	–	–	–	X
Burrowing Owl	*Athene cunicularia*	X	–	–	–	–	–	–
Cackling Goose	*Branta hutchinsii*	–	–	–	–	–	–	X
California Gull	*Larus californicus*	U	X	–	–	–	–	X
Canada Goose	*Branta canadensis*	X	X	X	–	–	X	X
Canada Warbler	*Cardellina canadensis*	X	X	–	–	–	–	–
Canvasback	*Aythya valisineria*	X	X	–	–	–	–	X
Cape May Warbler	*Setophaga tigrina*	X	X	–	–	–	–	X
Carolina Chickadee	*Poecile carolinensis*	X	X	–	–	–	–	X
Carolina Wren	*Thryothorus ludovicianus*	X	–	–	X	X	X	X
Caspian Tern	*Hydroprogne caspia*	X	X	–	–	–	X	X
Cattle Egret	*Bubulcus ibis*	X	X	–	–	–	–	X
Cave Swallow	*Petrochelidon fulva*	–	–	–	–	–	–	X
Cedar Waxwing	*Bombycilla cedrorum*	X	X	–	–	X	–	X
Cerulean Warbler	*Setophaga cerulea*	X	–	–	–	–	–	–
Chestnut-sided Warbler	*Setophaga pensylvanica*	X	X	–	–	–	–	–

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Chimney Swift	*Chaetura pelagica*	X	X	–	–	X	–	–
Chipping Sparrow	*Spizella passerina*	X	X	–	–	–	X	X
Chuck-Will's-Widow	*Antrostomus carolinensis*	X	X	–	–	X	–	X
Clapper Rail	*Rallus longirostris*	X	X	X	–	–	X	X
Clay-colored Sparrow	*Spizella pallida*	X	X	–	–	–	–	X
Cliff Swallow	*Petrochelidon pyrrhonota*	X	X	–	–	–	–	–
Common Eider	*Somateria mollissima*	X	–	–	–	–	X	X
Common Gallinule	*Gallinula galeata*	–	–	–	–	–	–	X
Common Goldeneye	*Bucephala clangula*	X	X	–	–	–	–	X
Common Grackle	*Quiscalus quiscula*	X	X	–	–	X	X	X
Common Loon	*Gavia immer*	X	X	X	–	–	X	X
Common Merganser	*Mergus merganser*	X	X	–	–	–	–	X
Common Moorhen	*Gallinula chloropus*	X	X	–	–	–	–	–
Common Murre	*Uria aalge*	U	–	–	–	–	–	–
Common Nighthawk	*Chordeiles minor*	X	X	–	–	–	–	–
Common Redpoll	*Acanthis flammea*	X	–	–	–	–	–	X
Common Snipe	*Gallinago gallinago*	X	–	–	X	–	–	–
Common Tern	*Sterna hirundo*	X	X	–	–	–	X	X
Common Yellowthroat	*Geothlypis trichas*	X	X	–	–	X	X	X
Connecticut warbler	*Oporornis agilis*	X	X	–	–	–	–	–
Cooper's Hawk	*Accipiter cooperii*	X	X	–	–	–	–	X
Cory's Shearwater	*Calonectris diomedea*	X	X	–	–	–	–	–
Curlew Sandpiper	*Calidris ferruginea*	X	X	–	–	–	–	–
Dark-eyed Junco	*Junco hyemalis*	X	X	X	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Dickcissel	*Spiza americana*	X	X	–	–	–	–	X
Double-crested Cormorant	*Phalacrocorax auritus*	X	X	–	–	–	X	X
Dovekie	*Alle alle*	X	–	–	–	–	–	X
Downy Woodpecker	*Picoides pubescens*	X	–	–	–	–	–	X
Dunlin	*Calidris alpina*	X	X	X	–	–	–	X
Eared Grebe	*Podiceps nigricollis*	X	X	–	–	–	–	X
Eastern Bluebird	*Sialia sialis*	X	X	–	–	–	–	X
Eastern Kingbird	*Tyrannus tyrannus*	X	X	–	–	X	X	X
Eastern Meadowlark	*Sturnella magna*	X	X	X	X	–	X	X
Eastern Phoebe	*Sayornis phoebe*	X	X	–	–	–	–	X
Eastern Screech Owl	*Megascops asio*	X	X	–	–	–	–	X
Eastern Towhee	*Pipilo erythrophthalmus*	X	X	–	X	–	X	X
Eastern Whip-Poor-Will	*Antrostomus vociferus*	X	–	–	–	–	X	X
Eastern Wood-Pewee	*Contopus virens*	X	X	–	–	X	–	–
Eurasian Collared Dove	*Streptopelia decaocto*	X	–	–	–	–	–	X
Eurasian Wigeon	*Anas penelope*	X	–	–	–	–	X	X
European Starling	*Sturnus vulgaris*	X	–	–	–	–	–	X
Evening Grosbeak	*Hesperiphona vespertina*	X	X	–	–	–	X	X
Field Sparrow	*Spizella pusilla*	X	X	–	–	–	X	X
Fish Crow	*Corvus ossifragus*	X	X	–	X	X	–	X
Forster's Tern	*Sterna forsteri*	X	X	–	–	X	–	X
Fox Sparrow	*Passerella iliaca*	X	X	–	–	–	–	X
Franklin's Gull	*Leucophaeus pipixcan*	X	–	–	–	–	–	–
Fulvous Whistling-Duck	*Dendrocygna bicolor*	X	–	–	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Gadwall	*Anas strepera*	X	X	–	X	–	–	X
Garganey	*Anas querquedula*	U	–	–	–	–	–	–
Glaucous Gull	*Larus hyperboreus*	X	X	–	–	–	–	X
Glossy Ibis	*Plegadis falcinellus*	X	X	–	X	X	–	X
Golden Eagle	*Aquila chrysaetos*	X	–	–	–	–	–	–
Golden-crowned Kinglet	*Regulus satrapa*	X	X	–	–	–	–	X
Golden-winged Warbler	*Vermivora chrysoptera*	X	X	–	–	–	–	–
Grasshopper Sparrow	*Ammodramus savannarum*	X	X	–	–	–	X	X
Gray Catbird	*Dumetella carolinensis*	X	–	–	X	X	–	X
Gray Kingbird	*Tyrannus dominicensis*	X	X	–	–	–	–	–
Gray-cheeked Thrush	*Catharus minimus*	X	X	–	–	–	X	–
Great Black-backed Gull	*Larus marinus*	X	X	X	–	–	–	X
Great Blue Heron	*Ardea herodias*	X	–	X	–	X	–	X
Great Cormorant	*Phalacrocorax carbo*	X	X	–	–	–	X	X
Great Crested Flycatcher	*Myiarchus crinitus*	X	X	–	–	X	X	–
Great Egret	*Ardea alba*	X	X	–	–	X	–	X
Great Grey Shrike	*Lanius excubitor*	X	–	–	–	–	–	X
Great Horned Owl	*Bubo virginianus*	X	X	–	–	–	–	X
Great Skua	*Stercorarius skua*	P	–	–	–	–	–	–
Greater Scaup	*Aythya marila*	X	X	X	–	–	–	X
Greater Shearwater	*Puffinus gravis*	X	X	–	–	–	–	–
Greater White-fronted Goose	*Anser albifrons*	X	–	–	–	–	X	X
Greater Yellowlegs	*Tringa melanoleuca*	X	–	X	–	–	X	X
Green Heron	*Butorides virescens*	X	–	–	–	X	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Green-winged Teal	*Anas crecca*	X	X	–	X	–	X	X
Gull-billed Tern	*Gelochelidon nilotica*	X	X	–	–	–	–	–
Hairy Woodpecker	*Picoides villosus*	X	–	–	–	–	–	X
Harlequin Duck	*Histrionicus histrionicus*	X	–	–	–	–	–	X
Hermit Thrush	*Catharus guttatus*	X	X	–	–	–	X	X
Herring Gull	*Larus smithsonianus*	X	X	X	–	–	–	X
Hooded Merganser	*Lophodytes cucullatus*	X	X	–	X	–	–	X
Hooded Warbler	*Setophaga citrina*	X	X	–	–	–	–	–
Horned Grebe	*Podiceps auritus*	X	X	–	–	–	–	X
Horned Lark	*Eremophila alpestris*	X	X	X	–	–	–	X
House Finch	*Haemorhous mexicanus*	X	X	–	–	–	–	X
House Sparrow	*Passer domesticus*	X	X	–	–	–	–	X
House Wren	*Troglodytes aedon*	X	–	–	X	–	–	X
Hudsonian Godwit	*Limosa haemastica*	X	X	–	–	–	–	–
Iceland Gull	*Larus glaucoides*	X	X	–	–	–	X	X
Indigo Bunting	*Passerina cyanea*	X	X	–	–	X	X	X
Kentucky Warbler	*Geothlypis formosa*	–	X	–	–	–	–	–
Killdeer	*Charadrius vociferus*	X	X	X	–	–	–	X
King Eider	*Somateria spectabilis*	X	–	–	–	–	X	X
King Rail	*Rallus elegans*	X	X	–	–	–	–	X
Lapland Longspur	*Calcarius lapponicus*	X	X	–	–	–	–	X
Lark Bunting	*Calamospiza melanocorys*	X	–	–	–	–	–	–
Lark Sparrow	*Chondestes grammacus*	X	X	–	–	–	X	X
Laughing Gull	*Leucophaeus atricilla*	X	X	–	–	X	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Le Conte's Sparrow	*Ammodramus leconteii*	X	–	–	–	–	–	X
Leach's Storm-Petrel	*Oceanodroma leucorhoa*	X	X	–	–	–	X	–
Least Bittern	*Ixobrychus exilis*	X	X	–	–	–	–	X
Least Flycatcher	*Empidonax minimus*	X	X	–	–	–	–	–
Least Sandpiper	*Calidris minutilla*	X	X	X	–	–	X	X
Least Tern	*Sternula antillarum*	X	X	–	–	–	–	–
Lesser Black-backed Gull	*Larus fuscus*	X	X	–	–	–	–	X
Lesser Scaup	*Aythya affinis*	X	X	–	–	–	X	X
Lesser Yellowlegs	*Tringa flavipes*	X	–	–	X	–	–	X
Lincoln's Sparrow	*Melospiza lincolnii*	X	X	–	–	–	X	X
Little Blue Heron	*Egretta caerulea*	X	–	–	–	X	–	X
Little Gull	*Hydrocoloeus minutus*	X	X	–	–	–	–	X
Little Stint	*Calidris minuta*	X	–	–	–	–	–	–
Loggerhead Shrike	*Lanius ludovicianus*	X	–	–	–	–	–	X
Long-billed Curlew	*Numenius americanus*	X	X	–	–	–	X	X
Long-billed Dowitcher	*Limnodromus scolopaceus*	X	X	–	–	–	–	X
Long-eared Owl	*Asio otus*	–	–	–	–	–	–	X
Long-tailed Duck	*Clangula hyemalis*	X	–	X	–	–	–	X
Long-tailed Jaeger	*Stercorarius longicaudus*	X	–	–	–	–	–	–
Louisiana Waterthrush	*Parkesia motacilla*	X	–	–	–	–	–	–
Magnificent Frigatebird	*Fregata magnificens*	P	X	–	–	–	–	–
Magnolia Warbler	*Setophaga magnolia*	X	X	–	–	–	X	–
Mallard	*Anas platyrhynchos*	X	X	–	X	X	–	X
Manx Shearwater	*Puffinus puffinus*	X	X	–	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Marbled Godwit	*Limosa fedoa*	X	X	–	–	–	–	X
Marsh Wren	*Cistothorus palustris*	X	–	X	–	–	–	X
Masked Booby	*Sula dactylatra*	X	–	–	–	–	–	–
Merlin	*Falco columbarius*	X	X	–	–	–	–	X
Mew Gull	*Larus canus*	X	–	–	–	–	–	X
Mississippi Kite	*Ictinia mississippiensis*	X	–	–	–	–	X	–
Mourning Dove	*Zenaida macroura*	X	X	–	X	X	–	X
Mourning Warbler	*Geothlypis philadelphia*	X	X	–	–	–	–	–
Mute Swan	*Cygnus olor*	X	X	–	–	–	–	X
Nashville Warbler	*Vermivora ruficapilla*	X	X	–	–	–	–	X
Nelson's Sparrow	*Ammodramus nelsoni*	U	X	X	–	–	X	X
Northern Bobwhite	*Colinus virginianus*	X	X	–	–	–	X	X
Northern Cardinal	*Cardinalis*	X	X	–	–	X	–	X
Northern Flicker	*Colaptes auratus*	X	X	–	–	X	–	X
Northern Fulmar	*Fulmarus glacialis*	X	–	–	–	–	X	–
Northern Gannet	*Morus bassanus*	X	X	–	–	–	–	X
Northern Goshawk	*Accipiter gentilis*	U	–	–	–	–	X	X
Northern Harrier	*Circus cyaneus*	X	X	X	X	–	X	X
Northern Mockingbird	*Mimus polyglottos*	X	–	–	–	–	–	X
Northern Parula	*Setophaga americana*	X	X	–	–	–	–	X
Northern Pintail	*Anas acuta*	X	X	–	–	–	–	X
Northern Rough-winged Swallow	*Stelgidopteryx serripennis*	X	X	–	–	–	–	–
Northern Saw-whet Owl	*Aegolius acadicus*	X	X	–	–	–	–	X
Northern Shoveler	*Anas clypeata*	X	X	–	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Northern Waterthrush	*Parkesia noveboracensis*	X	X	–	–	–	–	X
Northern Wheatear	*Oenanthe oenanthe*	X	–	–	–	–	–	–
Olive-sided Flycatcher	*Contopus cooperi*	X	–	–	–	–	–	–
Orange-crowned Warbler	*Leiothlypis celata*	X	X	–	–	–	–	X
Orchard Oriole	*Icterus spurius*	X	X	–	–	X	X	–
Osprey	*Pandion haliaetus*	X	X	–	–	X	–	X
Ovenbird	*Seiurus aurocapilla*	X	X	–	–	X	–	X
Pacific Loon	*Gavia pacifica*	X	–	–	–	–	X	–
Painted Bunting	*Passerina ciris*	X	X	–	–	–	–	X
Palm Warbler	*Setophaga palmarum*	X	X	–	–	–	X	X
Parasitic Jaeger	*Stercorarius parasiticus*	X	X	–	–	–	–	X
Pectoral Sandpiper	*Calidris melanotos*	X	X	–	–	–	X	–
Peregrine Falcon	*Falco peregrinus*	X	X	–	–	–	–	X
Philadelphia Vireo	*Vireo philadelphicus*	X	X	–	–	–	X	–
Pied-billed Grebe	*Podilymbus podiceps*	X	X	–	X	–	–	X
Pileated Woodpecker	*Dryocopus pileatus*	X	–	–	–	–	–	X
Pine Siskin	*Spinus pinus*	X	X	–	–	–	X	X
Pine Warbler	*Setophaga pinus*	X	X	–	–	X	X	X
Piping Plover	*Charadrius melodus*	X	X	–	–	–	–	X
Pomarine Jaeger	*Stercorarius pomarinus*	X	X	–	–	–	X	X
Prairie Warbler	*Setophaga discolor*	X	X	–	–	X	X	X
Prothonotary Warbler	*Protonotaria citrea*	X	X	–	–	X	–	–
Purple Finch	*Haemorhous purpureus*	X	X	–	–	–	–	X
Purple Gallinule	*Porphyrio martinica*	X	X	–	–	–	X	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Purple Martin	*Progne subis*	X	X	–	–	X	–	–
Purple Sandpiper	*Calidris maritima*	X	X	–	–	–	–	X
Razorbill	*Alca torda*	X	–	–	–	–	–	X
Red Crossbill	*Loxia curvirostra*	X	–	–	–	–	–	–
Red Knot	*Calidris canutus*	X	X	–	–	–	–	X
Red Phalarope	*Phalaropus fulicarius*	X	X	–	–	–	X	X
Red-bellied Woodpecker	*Melanerpes carolinus*	X	–	–	–	–	–	X
Red-billed Tropicbird	*Phaethon aethereus*	X	–	–	–	–	–	–
Red-breasted Merganser	*Mergus serrator*	X	X	X	–	–	–	X
Red-breasted Nuthatch	*Sitta canadensis*	X	X	–	–	–	–	X
Reddish Egret	*Egretta rufescens*	X	X	–	–	–	X	–
Red-eyed Vireo	*Vireo olivaceus*	X	X	–	–	X	–	–
Redhead	*Aythya americana*	X	X	X	–	–	–	X
Red-headed Woodpecker	*Melanerpes erythrocephalus*	X	–	–	–	–	–	X
Red-necked Grebe	*Podiceps grisegena*	X	X	–	–	–	–	X
Red-necked Phalarope	*Phalaropus lobatus*	X	X	–	–	–	–	X
Red-shouldered Hawk	*Buteo lineatus*	X	X	–	–	X	–	X
Red-tailed Hawk	*Buteo jamaicensis*	X	X	–	–	–	–	X
Red-throated Loon	*Gavia stellata*	X	X	–	–	–	X	X
Red-winged Blackbird	*Agelaius phoeniceus*	X	X	X	X	X	X	X
Ring-billed Gull	*Larus delawarensis*	X	X	–	–	–	–	X
Ring-necked Duck	*Aythya collaris*	X	X	–	–	–	–	X
Ring-necked Pheasant	*Phasianus colchicus*	X	X	–	–	–	–	X
Rock Dove	*Columba livia*	X	X	–	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Roseate Spoonbill	*Platalea ajaja*	X	–	–	–	–	–	–
Roseate Tern	*Sterna dougallii*	X	X	–	–	–	–	–
Rose-breasted Grosbeak	*Pheucticus ludovicianus*	X	X	–	–	–	–	X
Ross' Goose	*Chen rossii*	X	X	–	–	–	–	X
Rough-legged Hawk	*Buteo lagopus*	X	X	–	–	–	X	X
Royal Tern	*Thalasseus maximus*	X	X	–	–	–	–	X
Ruby-crowned Kinglet	*Regulus calendula*	X	X	–	–	–	–	X
Ruby-throated Hummingbird	*Archilochus colubris*	X	X	–	–	–	–	X
Ruddy Duck	*Oxyura jamaicensis*	X	X	–	–	–	X	X
Ruddy Turnstone	*Arenaria interpres*	X	X	–	–	–	–	X
Ruff	*Philomachus pugnax*	X	X	–	–	–	–	–
Rufous Hummingbird	*Selasphorus rufus*	U	–	–	–	–	–	X
Rusty Blackbird	*Euphagus carolinus*	X	X	X	–	–	–	X
Sabine's Gull	*Xema sabini*	X	–	–	–	–	–	–
Sage Thrasher	*Oreoscoptes montanus*	X	–	–	–	–	–	–
Saltmarsh Sharp-tailed Sparrow	*Ammodramus caudacutus*	X	X	X	–	–	X	X
Sanderling	*Calidris alba*	X	X	X	–	–	–	X
Sandhill Crane	*Grus canadensis*	X	–	–	–	–	X	–
Sandwich Tern	*Thalasseus sandvicensis*	X	X	–	–	–	–	X
Savannah Sparrow	*Passerculus sandwichensis*	X	X	X	–	–	–	X
Scarlet Tanager	*Piranga olivacea*	X	X	–	–	–	–	–
Scissor-tailed Flycatcher	*Tyrannus forficatus*	X	X	–	–	–	X	–
Seaside Sparrow	*Ammodramus maritimus*	X	X	–	–	–	X	X
Sedge Wren	*Cistothorus platensis*	X	–	–	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Semipalmated Plover	*Charadrius semipalmatus*	X	X	–	–	–	X	X
Semipalmated Sandpiper	*Calidris pusilla*	X	X	–	–	–	–	–
Sharp-shinned Hawk	*Accipiter striatus*	X	X	–	X	–	–	X
Short-billed Dowitcher	*Limnodromus griseus*	X	X	–	–	–	–	X
Short-eared Owl	*Asio flammeus*	X	X	–	–	–	–	X
Snow Bunting	*Plectrophenax nivalis*	X	X	X	–	–	–	X
Snow Goose	*Chen caerulescens*	X	X	X	–	–	X	X
Snowy Egret	*Egretta thula*	X	X	–	X	X	–	X
Snowy Owl	*Bubo scandiacus*	X	–	–	–	–	–	X
Snowy Plover	*Charadrius alexandrinus*	X	–	–	–	–	–	–
Solitary Sandpiper	*Tringa solitaria*	X	X	–	–	–	X	–
Song Sparrow	*Melospiza melodia*	X	X	X	–	–	–	X
Sooty Shearwater	*Puffinus griseus*	X	X	–	–	–	–	X
Sooty Tern	*Onychoprion fuscatus*	X	X	–	–	–	–	–
Sora	*Porzana carolina*	X	X	–	–	–	–	X
South Polar Skua	*Stercorarius maccormicki*	P	–	–	–	–	–	–
Spotted Redshank	*Tringa erythropus*	X	–	–	–	–	–	–
Spotted Sandpiper	*Actitis macularius*	X	X	–	–	–	–	X
Sprague's Pipit	*Anthus spragueii*	X	–	–	–	–	–	–
Stilt Sandpiper	*Calidris himantopus*	X	X	–	–	–	X	–
Summer Tanager	*Piranga rubra*	X	X	–	–	X	–	X
Surf Scoter	*Melanitta perspicillata*	X	X	–	–	–	–	X
Swainson's Hawk	*Buteo swainsoni*	X	–	–	–	–	–	–
Swainson's Thrush	*Catharus ustulatus*	X	X	–	–	–	–	–

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Swallow-tailed Kite	*Elanoides forficatus*	X	–	–	–	–	–	–
Swamp Sparrow	*Melospiza georgiana*	X	X	–	X	–	–	X
Tennessee Warbler	*Leiothlypis peregrina*	X	X	–	–	–	–	–
Thayer's Gull	*Larus thayeri*	X	X	–	–	–	–	X
Thick-billed Murre	*Uria lomvia*	X	–	–	–	–	–	X
Tree Swallow	*Tachycineta bicolor*	X	X	–	–	–	X	X
Tricolored Heron	*Egretta tricolor*	X	–	–	X	X	X	X
Tufted Titmouse	*Baeolophus bicolor*	X	X	–	–	–	–	X
Tundra Swan	*Cygnus columbianus*	X	X	–	–	–	X	X
Turkey Vulture	*Cathartes aura*	X	X	X	–	–	–	X
Upland Sandpiper	*Bartramia longicauda*	X	X	–	–	–	–	–
Veery	*Catharus fuscescens*	X	X	–	–	–	–	–
Vermilion Flycatcher	*Pyrocephalus rubinus*	X	–	–	–	–	–	–
Vesper Sparrow	*Pooecetes gramineus*	X	X	–	–	–	–	X
Virginia Rail	*Rallus limicola*	X	X	X	–	–	–	X
Warbling Vireo	*Vireo gilvus*	–	–	–	–	–	–	–
Western Grebe	*Aechmophorus occidentalis*	X	–	–	–	–	–	X
western Kingbird	*Tyrannus verticalis*	X	X	–	–	–	–	X
Western Meadowlark	*Sturnella neglecta*	X	–	–	–	–	–	–
Western Sandpiper	*Calidris mauri*	X	X	X	–	–	–	X
Western Tanager	*Piranga ludoviciana*	X	–	–	–	–	–	X
Whimbrel	*Numenius phaeopus*	X	–	–	–	–	–	X
White Ibis	*Eudocimus albus*	X	X	–	–	–	X	X
White-breasted Nuthatch	*Sitta carolinensis*	X	–	–	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
White-crowned Sparrow	*Zonotrichia leucophrys*	X	X	–	–	–	–	X
White-eyed Vireo	*Vireo griseus*	X	X	–	–	X	X	X
White-faced Storm-Petrel	*Pelagodroma marina*	X	–	–	–	–	–	–
White-rumped Sandpiper	*Calidris fuscicollis*	X	X	–	–	–	–	X
White-tailed Tropicbird	*Phaethon lepturus*	X	–	–	–	–	–	–
White-throated Sparrow	*Zonotrichia albicollis*	X	X	–	–	–	–	X
White-winged Dove	*Zenaida asiatica*	X	–	–	–	–	–	X
White-winged Scoter	*Melanitta fusca*	X	X	X	–	–	–	X
Willet	*Tringa semipalmata*	X	–	–	–	–	X	X
Willow Flycatcher	*Empidonax traillii*	X	X	–	–	–	–	–
Wilson's Phalarope	*Phalaropus tricolor*	X	X	–	–	–	–	–
Wilson's Plover	*Charadrius wilsonia*	X	X	–	–	–	–	–
Wilson's Snipe	*Gallinago delicata*	X	X	–	–	–	–	X
Wilson's Storm-Petrel	*Oceanites oceanicus*	X	X	–	–	–	–	–
Wilson's Warbler	*Cardellina pusilla*	X	X	–	–	–	–	X
Winter Wren	*Troglodytes troglodytes*	X	–	–	–	–	–	X
Wood Duck	*Aix sponsa*	X	X	–	–	X	–	X
Wood Stork	*Mycteria americana*	X	–	–	–	–	–	X
Wood Thrush	*Hylocichla mustelina*	X	X	–	–	X	–	–
Worm-eating Warbler	*Helmitheros vermivorum*	X	X	–	–	–	–	–
Yellow Rail	*Coturnicops noveboracensis*	X	X	–	–	–	–	X
Yellow Warbler	*Setophaga petechia*	X	X	–	–	X	–	X
Yellow-bellied Flycatcher	*Empidonax flaviventris*	X	X	–	–	–	–	–
Yellow-bellied Sapsucker	*Sphyrapicus varius*	X	X	–	–	–	–	X

Table J-1 (continued). Bird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b, 2011)	CBC
Yellow-billed Cuckoo	*Coccyzus americanus*	X	X	–	–	X	X	–
Yellow-breasted Chat	*Icteria virens*	X	X	–	–	X	–	X
Yellow-crowned Night-Heron	*Nyctanassa violacea*	X	–	–	–	X	–	X
Yellow-headed Blackbird	*Xanthocephalus xanthocephalus*	X	–	–	–	–	–	X
Yellow-rumped Warbler	*Setophaga coronata*	X	X	–	X	–	X	X
Yellow-throated Vireo	*Vireo flavifrons*	X	X	–	–	–	–	–
Yellow-throated Warbler	*Setophaga dominica*	X	X	–	–	–	–	X
Confirmed	–	***366***	***274***	***40***	***29***	***53***	***88***	***270***
Probably Present	–	***4***	***0***	***0***	***0***	***0***	***0***	***0***
Unconfirmed	–	***9***	***0***	***0***	***0***	***0***	***0***	***0***

Appendix K. Shorebird species that have been documented in CAHA

Table K-1. Shorebird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b)	CBC
American Golden-Plover	*Pluvialis dominica*	X	–	–	–	–	–	X
American Oystercatcher	*Haematopus palliatus*	X	X	–	–	–	X	X
American Woodcock	*Scolopax minor*	X	–	–	–	–	–	X
Arctic Tern	*Sterna paradisaea*	X	–	–	–	–	–	–
Baird's Sandpiper	*Calidris bairdii*	X	X	–	–	–	–	–
Bar-tailed Godwit	*Limosa lapponica*	X	–	–	–	–	–	–
Black Skimmer	*Rynchops niger*	X	X	–	–	X	–	X
Black Tern	*Chlidonias niger*	X	X	–	–	–	–	–
Black-bellied Plover	*Pluvialis squatarola*	X	X	X	X	–	X	X
Black-headed Gull	*Chroicocephalus ridibundus*	X	X	–	–	–	–	X
Black-legged Kittiwake	*Rissa tridactyla*	X	X	–	–	–	–	X
Black-necked Stilt	*Himantopus mexicanus*	X	X	–	–	–	–	–
Black-tailed Godwit	*Limosa*	X	–	–	–	–	–	–
Black-tailed Gull	*Larus crassirostris*	–	–	–	–	–	–	X
Black-winged Stilt	*Himantopus*	U	–	–	–	–	–	–
Bonaparte's Gull	*Chroicocephalus philadelphia*	X	X	X	–	–	–	X
Bridled Tern	*Onychoprion anaethetus*	X	–	–	–	–	–	–
Brown Noddy	*Anous stolidus*	X	–	–	–	–	–	–
Buff-breasted Sandpiper	*Tryngites subruficollis*	X	X	–	–	–	–	–
California Gull	*Larus californicus*	U	X	–	–	–	–	X
Caspian Tern	*Hydroprogne caspia*	X	X	–	–	–	X	X

Table K-1 (continued). Shorebird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b)	CBC
Common Murre	*Uria aalge*	U	–	–	–	–	–	–
Common Snipe	*Gallinago*	X	–	–	X	–	–	–
Common Tern	*Sterna hirundo*	X	X	–	–	–	X	X
Curlew Sandpiper	*Calidris ferruginea*	X	X	–	–	–	–	–
Dovekie	*Alle alle*	X	–	–	–	–	–	X
Dunlin	*Calidris alpina*	X	X	X	–	–	–	X
Forster's Tern	*Sterna forsteri*	X	X	–	–	X	–	X
Franklin's Gull	*Leucophaeus pipixcan*	X	–	–	–	–	–	–
Glaucous Gull	*Larus hyperboreus*	X	X	–	–	–	X	X
Great Black-backed Gull	*Larus marinus*	X	X	X	–	–	–	X
Great Skua	*Stercorarius skua*	P	–	–	–	–	–	–
Greater Yellowlegs	*Tringa melanoleuca*	X	–	X	–	–	X	X
Gull-billed Tern	*Gelochelidon nilotica*	X	X	–	–	–	–	–
Herring Gull	*Larus smithsonianus*	X	X	X	–	–	–	X
Hudsonian godwit	*Limosa haemastica*	X	X	–	–	–	–	–
Iceland gull	*Larus glaucoides*	X	X	–	–	–	X	X
Killdeer	*Charadrius vociferus*	X	X	X	–	–	–	X
Laughing gull	*Leucophaeus atricilla*	X	X	–	–	X	–	X
Least sandpiper	*Calidris minutilla*	X	X	X	–	–	X	X
Least tern	*Sternula antillarum*	X	X	–	–	–	–	–
Lesser Black-backed Gull	*Larus fuscus*	X	X	–	–	–	–	X
Lesser Yellowlegs	*Tringa flavipes*	X	–	–	X	–	–	X
Little Gull	*Hydrocoloeus minutus*	X	X	–	–	–	–	X
Little Stint	*Calidris minuta*	X	–	–	–	–	–	–

Table K-1 (continued). Shorebird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b)	CBC
Long-billed Curlew	*Numenius americanus*	X	X	–	–	–	X	X
Long-billed Dowitcher	*Limnodromus scolopaceus*	X	X	–	–	–	–	X
Long-tailed Jaeger	*Stercorarius longicaudus*	X	–	–	–	–	–	–
Marbled Godwit	*Limosa fedoa*	X	X	–	–	–	–	X
Mew Gull	*Larus canus*	X	–	–	–	–	–	X
Parasitic Jaeger	*Stercorarius parasiticus*	X	X	–	–	–	–	X
Pectoral Sandpiper	*Calidris melanotos*	X	X	–	–	–	X	–
Piping Plover	*Charadrius melodus*	X	X	–	–	–	–	X
Pomarine Jaeger	*Stercorarius pomarinus*	X	X	–	–	–	X	X
Purple Sandpiper	*Calidris maritima*	X	X	–	–	–	–	X
Razorbill	*Alca torda*	X	–	–	–	–	–	X
Red Knot	*Calidris canutus*	X	X	–	–	–	–	X
Red Phalarope	*Phalaropus fulicarius*	X	X	–	–	–	X	X
Red-necked Phalarope	*Phalaropus lobatus*	X	X	–	–	–	–	X
Ring-billed Gull	*Larus delawarensis*	X	X	–	–	–	–	X
Roseate Tern	*Sterna dougallii*	X	X	–	–	–	–	–
Royal Tern	*Thalasseus maximus*	X	X	–	–	–	–	X
Ruddy Turnstone	*Arenaria interpres*	X	X	–	–	–	–	X
Ruff	*Philomachus pugnax*	X	X	–	–	–	–	–
Sabine's Gull	*Xema sabini*	X	–	–	–	–	–	–
Sanderling	*Calidris alba*	X	X	X	–	–	–	X
Sandwich Tern	*Thalasseus sandvicensis*	X	X	–	–	–	–	X
Semipalmated Plover	*Charadrius semipalmatus*	X	X	–	–	–	X	X
Semipalmated Sandpiper	*Calidris pusilla*	X	X	–	–	–	–	–

Table K-1 (continued). Shorebird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	Scientific name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2009b)	CBC
Short-billed Dowitcher	*Limnodromus griseus*	X	X	–	–	–	–	X
Snowy Plover	*Charadrius alexandrinus*	X	–	–	–	–	–	–
Solitary Sandpiper	*Tringa solitaria*	X	X	–	–	–	X	–
Sooty Tern	*Onychoprion fuscatus*	X	X	–	–	–	–	–
South Polar Skua	*Stercorarius maccormicki*	P	–	–	–	–	–	–
Spotted Redshank	*Tringa erythropus*	X	–	–	–	–	–	–
Spotted Sandpiper	*Actitis macularius*	X	X	–	–	–	–	X
Stilt Sandpiper	*Calidris himantopus*	X	X	–	–	–	X	–
Thayer's Gull	*Larus thayeri*	X	X	–	–	–	–	X
Thick-billed Murre	*Uria lomvia*	X	–	–	–	–	–	X
Upland Sandpiper	*Bartramia longicauda*	X	X	–	–	–	–	–
Western Sandpiper	*Calidris mauri*	X	X	X	–	–	–	X
Whimbrel	*Numenius phaeopus*	X	–	–	–	–	–	X
White-rumped Sandpiper	*Calidris fuscicollis*	X	X	–	–	–	–	X
Willet	*Tringa semipalmata*	X	–	–	–	–	X	X
Wilson's Phalarope	*Phalaropus tricolor*	X	X	–	–	–	–	–
Wilson's Plover	*Charadrius wilsonia*	X	X	–	–	–	–	–
Wilson's Snipe	*Gallinago delicata*	X	X	–	–	–	–	X
Confirmed		**81**	**60**	**10**	**3**	**3**	**16**	**52**
Probably Present		**2**	**0**	**–**	**–**	**–**	**–**	**1**
Unconfirmed		**3**	**0**	**–**	**–**	**–**	**–**	**53**
Percent of Total Observations		**23.5%**	**22%**	**40%**	**10%**	**6%**	**18%**	**19%**

Appendix L. Landbird species that have been documented in CAHA

Table L-1. Landbird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2011)	CBC
Acadian Flycatcher	X	X	–	–	X	–	–
American Crow	X	X	–	–	X	X	X
American Goldfinch	X	X	–	–	X	X	X
American Kestrel	X	X	–	–	–	–	X
American Pipit	X	X	–	–	–	–	X
American Redstart	X	X	–	–	–	–	–
American Robin	X	–	–	–	–	–	X
American Tree Sparrow	X	–	–	–	–	–	X
Ash-throated Flycatcher	–	–	–	–	–	–	X
Bachman's Sparrow	X	–	–	–	–	–	–
Bald Eagle	X	X	X	–	–	–	X
Baltimore Oriole	X	X	–	–	–	–	X
Bank Swallow	X	X	–	–	–	–	–
Barn Owl	X	X	–	X	–	–	X
Barn Swallow	X	X	–	–	X	X	X
Bay-breasted Warbler	X	X	–	–	–	–	–
Belted Kingfisher	X	X	–	X	–	–	X
Bewick's Wren	X	–	–	–	–	–	–
Black Vulture	X	–	–	–	–	–	X
Black-and-White Warbler	X	X	–	–	–	–	X
Black-billed Cuckoo	X	–	–	–	–	–	–
Blackburnian Warbler	X	X	–	–	–	–	–
Blackpoll Warbler	X	X	–	–	–	–	–
Black-chinned Hummingbird	–	–	–	–	–	–	X
Black-throated Blue Warbler	X	X	–	–	–	–	X
Black-throated Green Warbler	X	X	–	–	–	–	X
Blue Grosbeak	X	X	–	–	–	–	–
Blue Jay	X	X	–	–	X	X	X
Blue-gray Gnatcatcher	X	X	–	–	–	–	X
Blue-headed Vireo	X	X	–	–	–	–	X
Blue-winged Warbler	X	X	–	–	–	–	–

Table L-1 (continued). Landbird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2011)	CBC
Boat-tailed Grackle	X	X	X	X	–	X	X
Bobolink	X	X	–	–	–	X	–
Brewer's Blackbird	X	–	–	–	–	–	–
Broad-winged Hawk	X	X	–	–	–	–	X
Brown Creeper	X	X	–	–	–	–	X
Brown Thrasher	X	–	–	–	X	X	X
Brown-headed Cowbird	X	X	–	–	X	X	X
Brown-headed Nuthatch	X	X	–	–	–	X	X
Burrowing Owl	X	–	–	–	–	–	–
Canada Warbler	X	X	–	–	–	–	–
Cape May Warbler	X	X	–	–	–	–	X
Carolina Chickadee	X	X	–	–	–	–	X
Carolina Wren	X	–	–	X	X	X	X
Cave Swallow	–	–	–	–	–	–	X
Cedar Waxwing	X	X	–	–	X	–	–
Cerulean Warbler	X	–	–	–	–	–	–
Chestnut-sided Warbler	X	X	–	–	–	–	–
Chimney Swift	X	X	–	–	X	–	X
Chipping Sparrow	X	X	–	–	–	X	X
Chuck-Will's-Widow	X	X	–	–	X	–	X
Clay-colored Sparrow	X	X	–	–	–	–	–
Cliff Swallow	X	X	–	–	–	–	X
Common Grackle	X	X	–	–	X	X	–
Common Nighthawk	X	X	–	–	–	–	X
Common Redpoll	X	–	–	–	–	–	X
Common Yellowthroat	X	X	–	–	X	X	–
Connecticut Warbler	X	X	–	–	–	–	X
Cooper's Hawk	X	X	–	–	–	–	X
Dark-eyed Junco	X	X	X	–	–	–	X
Dickcissel	X	X	–	–	–	–	X
Downy Woodpecker	X	–	–	–	–	–	X
Eastern Bluebird	X	X	–	–	–	–	X
Eastern Kingbird	X	X	–	–	X	X	X
Eastern Meadowlark	X	X	X	X	–	X	X
Eastern Phoebe	X	X	–	–	–	–	X

Table L-1 (continued). Landbird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2011)	CBC
Eastern Screech Owl	X	X	–	–	–	–	X
Eastern Towhee	X	X	–	X	–	X	X
Eastern Whip-Poor-Will	X	–	–	–	–	X	–
Eastern Wood-Pewee	X	X	–	–	X	–	X
Eurasian Collared Dove	X	–	–	–	–	–	X
Evening Grosbeak	X	X	–	–	–	X	X
Field Sparrow	X	X	–	–	–	X	X
Fish Crow	X	X	–	X	X	–	X
Fox Sparrow	X	X	–	–	–	–	–
Golden Eagle	X	–	–	–	–	–	X
Golden-crowned Kinglet	X	X	–	–	–	–	–
Golden-winged Warbler	X	X	–	–	–	–	X
Grasshopper Sparrow	X	X	–	–	–	X	X
Gray Catbird	X	–	–	X	X	–	–
Gray Kingbird	X	X	–	–	–	–	–
Gray-cheeked Thrush	X	X	–	–	–	X	–
Great crested Flycatcher	X	X	–	–	X	X	X
Great Grey Shrike	X	–	–	–	–	–	X
Great Horned Owl	X	X	–	–	–	–	X
Hairy Woodpecker	X	–	–	–	–	–	X
Hermit Thrush	X	X	–	–	–	X	–
Hooded Warbler	X	X	–	–	–	–	X
Horned Lark	X	X	X	–	–	–	X
House Finch	X	X	–	–	–	–	X
House Sparrow	X	X	–	–	–	–	X
House Wren	X	–	–	X	–	–	X
Indigo Bunting	X	X	–	–	X	X	X
Kentucky Warbler	–	X	–	–	–	–	–
Lapland Longspur	X	X	–	–	–	–	X
Lark Bunting	X	–	–	–	–	–	–
Lark Sparrow	X	X	–	–	–	X	X
Le Conte's Sparrow	X	–	–	–	–	–	X
Least Flycatcher	X	X	–	–	–	–	–
Lincoln's Sparrow	X	X	–	–	–	X	X
Loggerhead Shrike	X	–	–	–	–	–	X

Table L-1 (continued). Landbird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2011)	CBC
Long-eared Owl	–	–	–	–	–	–	X
Louisiana Waterthrush	X	–	–	–	–	–	–
Magnolia Warbler	X	X	–	–	–	X	–
Marsh Wren	X	–	X	–	–	–	X
Merlin	X	X	–	–	–	–	X
Mississippi Kite	X	–	–	–	–	X	–
Mourning Dove	X	X	–	X	X	–	X
Mourning Warbler	X	X	–	–	–	–	–
Nashville Warbler	X	X	–	–	–	–	X
Nelson's Sparrow	U	X	X	–	–	X	X
Northern Bobwhite	X	X	–	–	–	X	X
Northern Cardinal	X	X	–	–	X	–	X
Northern Flicker	X	X	–	–	X	–	X
Northern Goshawk	U	–	–	–	–	X	X
Northern Harrier	X	X	X	X	–	X	X
Northern Mockingbird	X	–	–	–	–	–	X
Northern Parula	X	X	–	–	–	–	X
Northern Rough-winged Swallow	X	X	–	–	–	–	–
Northern Saw-whet Owl	X	X	–	–	–	–	X
Northern Waterthrush	X	X	–	–	–	–	X
Olive-sided Flycatcher	X	–	–	–	–	–	–
Orange-crowned Warbler	X	X	–	–	–	–	X
Orchard Oriole	X	X	–	–	X	X	–
Osprey	X	X	–	–	X	–	X
Ovenbird	X	X	–	–	X	–	X
Painted Bunting	X	X	–	–	–	–	X
Palm Warbler	X	X	–	–	–	X	X
Peregrine Falcon	X	X	–	–	–	–	X
Philadelphia Vireo	X	X	–	–	–	X	–
Pileated Woodpecker	X	–	–	–	–	–	X
Pine Siskin	X	X	–	–	–	X	X
Pine Warbler	X	X	–	–	X	X	X
Prairie Warbler	X	X	–	–	X	X	X
Prothonotary Warbler	X	X	–	–	X	–	–
Purple Finch	X	X	–	–	–	–	X

Table L-1 (continued). Landbird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2011)	CBC
Purple Martin	X	X	–	–	X	–	–
Red Crossbill	X	–	–	–	–	–	–
Red-bellied Woodpecker	X	–	–	–	–	–	X
Red-breasted Nuthatch	X	X	–	–	–	–	X
Red-eyed Vireo	X	X	–	–	X	–	–
Red-headed Woodpecker	X	–	–	–	–	–	X
Red-shouldered Hawk	X	X	–	–	X	–	X
Red-tailed Hawk	X	X	–	–	–	–	X
Red-winged Blackbird	X	X	X	X	X	X	X
Ring-necked Pheasant	X	X	–	–	–	–	X
Rock Dove	X	X	–	–	–	–	X
Rose-breasted Grosbeak	X	X	–	–	–	–	X
Rough-legged Hawk	X	X	–	–	–	X	X
Ruby-crowned Kinglet	X	X	–	–	–	–	X
Ruby-throated Hummingbird	X	X	–	–	–	–	X
Rufous Hummingbird	U	–	–	–	–	–	X
Rusty Blackbird	X	X	X	–	–	–	X
Sage Thrasher	X	–	–	–	–	–	–
Saltmarsh Sharp-tailed Sparrow	X	X	X	–	–	X	X
Savannah Sparrow	X	X	X	–	–	–	X
Scarlet Tanager	X	X	–	–	–	–	–
Scissor-tailed Flycatcher	X	X	–	–	–	X	–
Seaside Sparrow	X	X	–	–	–	X	X
Sedge Wren	X	–	–	–	–	–	X
Sharp-shinned Hawk	X	X	–	X	–	–	X
Short-eared Owl	X	X	–	–	–	–	X
Snowy Owl	X	–	–	–	–	–	X
Snow Bunting	X	X	X	–	–	–	X
Song Sparrow	X	X	X	–	–	–	X
Sprague's Pipit	X	–	–	–	–	–	–
Summer Tanager	X	X	–	–	X	–	X
Swainson's Hawk	X	–	–	–	–	–	–
Swainson's Thrush	X	X	–	–	–	–	–
Swallow-tailed Kite	X	–	–	–	–	–	–
Swamp Sparrow	X	X	–	X	–	–	X

Table L-1 (continued). Landbird species that have been documented in CAHA by the various surveys and inventory efforts. X=confirmed, P=probably present, U=unconfirmed, H=historic record.

Common name	NPS (2018)	USFWS (2006)	Bishop (1901)	Golder (1986)	Cooper (1986)	SECN (Byrne et al. 2011)	CBC
Tennessee Warbler	X	X	–	–	–	–	–
Tree Swallow	X	X	–	–	–	X	X
Tufted Titmouse	X	X	–	–	–	–	X
Turkey Vulture	X	X	X	–	–	–	X
Veery	X	X	–	–	–	–	–
Vermilion Flycatcher	X	–	–	–	–	–	–
Vesper Sparrow	X	X	–	–	–	–	X
Western Kingbird	X	X	–	–	–	–	X
Western Meadowlark	X	–	–	–	–	–	–
Western Tanager	X	–	–	–	–	–	X
White-breasted Nuthatch	X	–	–	–	–	–	X
White-crowned Sparrow	X	X	–	–	–	–	X
White-eyed Vireo	X	X	–	–	X	X	X
White-throated Sparrow	X	X	–	–	–	–	X
White-winged Dove	X	–	–	–	–	–	X
Willow Flycatcher	X	X	–	–	–	–	–
Wilson's Warbler	X	X	–	–	–	–	X
Winter Wren	X	–	–	–	–	–	X
Wood Thrush	X	X	–	–	X	–	–
Worm-eating Warbler	X	X	–	–	–	–	–
Yellow Warbler	X	X	–	–	X	–	X
Yellow-bellied Flycatcher	X	X	–	–	–	–	–
Yellow-bellied Sapsucker	X	X	–	–	–	–	X
Yellow-billed Cuckoo	X	X	–	–	X	X	–
Yellow-breasted Chat	X	X	–	–	X	–	X
Yellow-headed Blackbird	X	–	–	–	–	–	X
Yellow-rumped Warbler	X	X	–	X	–	X	X
Yellow-throated Vireo	X	X	–	–	–	–	–
Yellow-throated Warbler	X	X	–	–	–	–	X
Confirmed Landbird Species	**192**	**145**	**15**	**15**	**38**	**47**	**135**
Unconfirmed Landbird Species	**3**	**0**	**0**	**0**	**0**	**0**	**0**
Percent of Total Observations	**51.6%**	**52.9%**	**35%**	**51.7%**	**72%**	**53.4%**	**50%**

Appendix M. Landbird species identified in various habitats during surveys in CAHA

Table M-1. Landbird species identified in various habitats during surveys in CAHA by Cooper (1986). Values depicted are expressed as the average number of landbirds detected in each habitat per census. Habitat codes are alphabetic and are defined as: A= Pond and Edge, B= Mixed Hardwoods, C= Mature Pine, D= Young Pine, E= Wet Thicket, F= Open Dry Thicket, G= Overhead.

Landbird species	A	B	C	D	E	F	G
Acadian Flycatcher	0	0.2	0	0.1	0	0	0
American Crow	0	1.1	1.8	2.2	1.1	0.1	1.8
American Goldfinch	0	0	0	0.1	0.2	0	0.1
Barn Swallow	0	0	0	0	0	0	1.8
Blue Jay	0	0.9	1.9	2.5	0.6	0.5	0
Brown Thrasher	0	0.1	0	0.1	0.3	0.4	0
Brown-headed Cowbird	0	0.2	0.4	0.4	0.3	0.5	3
Carolina Wren	0	3	3.6	5.6	11	1.5	0
Cedar Waxwing	0	0	0	0	0	0	0.5
Chimney Swift	0	0	0	0	0	0	0.2
Chuck-Will's-Widow	0	0	0.5	0.5	0	0.1	0
Common Grackle	0	0.6	1.1	0.5	1.5	0.8	4.9
Common Yellowthroat	0	0	0	0	1.5	0	0
Eastern Kingbird	0	0.1	0	0	0	0	0
Eastern Wood-Pewee	0	0	0	0.1	0	0	0
Fish Crow	0	1.1	0.4	0.8	0.8	0.5	0.8
Gray Catbird	0	0	0	0	0.1	0.1	0
Great-crested Flycatcher	0	0.8	0.7	2	0.1	0	0
Indigo Bunting	0	0	0	0	0.2	0	0
Mourning Dove	0	0	0.5	0	0	0	0
Northern Cardinal	0	3.6	5.5	6	13	1.6	0
Northern Flicker	0	0.1	0.7	0.3	0.2	0.3	0
Orchard Oriole	0	0.1	0.1	0.1	0.1	0	0
Osprey	0	0	0	0	0	0	0.3
Ovenbird	0	0	0	0	0	0.1	0
Pine Warbler	0	0.5	3.7	1.1	0	0	0
Prairie Warbler	0	0.5	0.6	1.7	5.3	2.6	0
Prothonotary Warbler	0	0.5	0	2.5	3	0	0
Purple Martin	0	0	0	0	0	0	2.7
Red-eyed Vireo	0	0	0.1	0.1	0	0	0
Red-shouldered Hawk	0	0.2	0.5	0.3	0	0.1	0.4

Table M-1 (continued). Landbird species identified in various habitats during surveys in CAHA by Cooper (1986). Values depicted are expressed as the average number of landbirds detected in each habitat per census. Habitat codes are alphabetic and are defined as: A= Pond and Edge, B= Mixed Hardwoods, C= Mature Pine, D= Young Pine, E= Wet Thicket, F= Open Dry Thicket, G= Overhead.

Landbird species	A	B	C	D	E	F	G
Red-winged Blackbird	1.8	0.2	0.1	0.3	0.2	0	0
Summer Tanager	0	0.1	0.1	0.6	0	0	0
White-eyed Vireo	0	0	0	0.1	0	0	0
Wood Thrush	0.1	0	0.1	0	0	0	0
Yellow Warbler	0	0	0	0	0.1	0	0
Yellow-billed Cuckoo	0	0.5	0.6	0.8	0	0.1	0
Yellow-breasted Chat	0	0	0	0	0.1	0	0

Appendix N. Proportion of sampling sites where landbird species were observed

Table N-1. Proportion of the 30 sampling sites where landbird species were observed during landbird monitoring by SECN (Byrne et al. 2011).

Species	Proportion of sites where species was observed
Boat-tailed Grackle	0.80
Carolina Wren	0.80
Red-winged Blackbird	0.77
Eastern Towhee	0.70
Common Yellowthroat	0.67
Northern Cardinal	0.57
Fish Crow	0.47
Barn Swallow	0.40
Eastern Meadowlark	0.40
Northern Mockingbird	0.37
Gray Catbird	0.33
Mourning Dove	0.33
Prairie Warbler	0.33
Brown-headed Cowbird	0.30
Great Crested Flycatcher	0.27
Brown Thrasher	0.23
Osprey	0.23
Pine Warbler	0.23
Eastern Kingbird	0.20
American Crow	0.17
Blue Jay	0.17
Sedge Wren	0.17
European Starling	0.13
Seaside Sparrow	0.13
Purple Martin	0.10
Tufted Titmouse	0.10
White-eyed Vireo	0.10
American Goldfinch	0.07
Summer Tanager	0.07
Turkey Vulture	0.07
Bobolink	0.03
Brown-headed Nuthatch	0.03

Table N-1 (continued). Proportion of the 30 sampling sites where landbird species were observed during landbird monitoring by SECN (Byrne et al. 2011).

Species	Proportion of sites where species was observed
Chipping Sparrow	0.03
Common Grackle	0.03
Eastern Wood-Pewee	0.03
Field Sparrow	0.03
Indigo Bunting	0.03
Northern Bobwhite	0.03
Northern Harrier	0.03
Painted Bunting	0.03
Peregrine Falcon	0.03
Prothonotary Warbler	0.03
Red-bellied Woodpecker	0.03
Red-eyed Vireo	0.03
Song Sparrow	0.03
Yellow-billed Cuckoo	0.03
Yellow-rumped Warbler	0.03

Appendix O. Mammal species list for CAHA

Table O-1 is a list of mammal species and Table O-2 includes additional marine mammals found stranded on CAHA beaches.

Table O-1. Mammal species list for CAHA (NPS 2018e). H = Historic, PP = Probably present, x = present at CALO. CALO species based on Webster and Reese (1992).

Scientific name	Common name	Occurrence	at CALO
Odocoileus virginianus	white-tailed deer	Present	x
*Canis familiaris**	domestic dog	Present (vagrant)	H
Urocyon cinereoargenteus	common gray fox	Present	–
Vulpes vulpes	red fox	Present	–
*Felis catus**	feral cat	Present	x
Lontra canadensis	river otter	Present	x
Mustela vison	mink	Present	x
Phoca vitulina	harbor seal	Probably Present	–
Procyon lotor	common raccoon	Present	x
Balaenoptera physalus	fin whale	Probably Present	–
Globicephala macrorhynchus	short-finned pilot whale	Probably Present	–
Pseudorca crassidens	false killer whale	Probably Present	–
Stenella frontalis	Atlantic spotted dolphin	Probably Present	–
Tursiops truncatus	bottlenose dolphin	Probably Present	–
Mesoplodon mirus	True's beaked whale	Probably Present	–
Kogia breviceps	pygmy sperm whale	Probably Present	–
Lasionycteris noctivagans	silver-haired bat	Present	PP
Lasiurus borealis	eastern red bat	Present	x
Nycticeius humeralis	evening bat	Present	PP
Didelphis virginiana	Virginia opossum	Present	H
Sylvilagus floridanus	eastern cottontail	Present	x
Sylvilagus palustris	marsh rabbit	Present	x
Microtus pennsylvanicus	meadow vole	Present	–
Ondatra zibethicus	muskrat	Present	x
Oryzomys palustris	marsh rice rat	Present	x
Peromyscus leucopus	white-footed mouse	Present	–
Sigmodon hispidus	hispid cotton rat	Unconfirmed	–
*Mus musculus**	house mouse	Present	x
*Rattus norvegicus**	Norway rat	Present	x
*Rattus rattus**	black rat	Present	–

* Non-native species.

Table O-1 (continued). Mammal species list for CAHA (NPS 2018e). H = Historic, PP = Probably present, x = present at CALO. CALO species based on Webster and Reese (1992).

Scientific name	Common name	Occurrence	at CALO
*Myocastor coypus**	nutria	Present	x
Sciurus carolinensis	eastern gray squirrel	Present	x
Blarina carolinensis	southern short-tailed shrew	Present	–
Cryptotis parva	least shrew	Present	x
Scalopus aquaticus	eastern mole	Present	x

* Non-native species.

Table O-2. Additional marine mammal species documented as strandings on CAHA beaches (NPS 2012a, 2016b).

Scientific name	Common name
Pagophilus groenlandicus	harp seal
Halichoerus grypus	grey seal
Trichechus manatus	Florida manatee
Delphinus delphis	common dolphin
Grampus griseus	Risso's dolphin
Phocoena phocoena	harbor porpoise
Kogia sima	dwarf sperm whale
Megaptera novaeangliae	humpback whale

Appendix P. Changes in island width at transect locations within CAHA

Tables P-1 and P-2 show changes in island width at transects within and west of CAHA.

Table P-1. Changes in island width (m/yr) at transect locations within CAHA, calculated from ocean and estuarine shoreline position changes given in Everts et al. (1983).

Area	Location	1849/52–1915/17	1915/17–1946/49	1946/49–1980	1946/49–1963	1963–1980	1849/52–1980*
–	35°50’	gain <2	gain <2	–	loss >2	loss >2	gain <2
–	35°49’	loss >2	loss <2	–	loss >2	–	loss >2
Oregon Inlet	35°45’	–	–	–	loss <2	–	–
	35°44’	–	–	–	loss <2	loss >2	*likely loss*
	35°43’	–	–	–	loss <2	loss >2	*likely loss*
	35°42’	–	–	–	gain <2	loss <2	–
	35°41’	–	–	–	loss <2	loss >2	–
	35°40’	–	–	–	loss >2	loss <2	*likely loss*
	35°39’	–	–	–	loss >2	gain >2	–
	35°38’	–	gain >2	–	gain <2	gain <2	*likely gain*
	35°37’	gain <2	loss >2	–	loss >2	no change	*likely loss*
	35°36’	loss <2	loss >2	–	loss >2	loss >2	*likely loss*
	35°35’	loss <2	loss <2	–	loss <2	loss >2	*likely loss*
Rodanthe	35°34’	loss <2	loss <2	–	gain <2	loss <2	*likely loss*
	35°33’	gain <2	loss <2	–	gain >2	gain <2	–
	35°32’	gain <2	loss >2	–	loss >2	gain >2	–
	35°31’	no change	loss >2	–	loss <2	gain >2	–
	35°29’	gain <2	loss <2	–	loss >2	gain <2	–
	35°28’	gain <2	loss >2	–	loss >2	gain <2	–
	35°27’	loss <2	loss <2	–	loss >2	gain <2	*likely loss*
	35°26’	no change	loss >2	–	loss >2	loss <2	*likely loss*
	35°25’	gain <2	loss >2	–	loss >2	gain <2	–
Little Kinnakeet	35°24’	gain <2	loss >2	–	loss <2	loss <2	*likely loss*
	35°23’	gain >2	loss >2	–	loss <2	gain <2	–
	35°22’	gain >2	loss >2	gain >2	–	–	–
	35°21’	no change	–	–	–	–	*likely loss*
Avon	35°20’	loss <2	loss >2	loss <2	–	–	*likely loss*
	35°19’	loss <2	loss >2	loss <2	–	–	*likely loss*
	35°17’	loss >2	loss >2	loss >2	–	–	*likely loss*

* Least-squares estimate of shoreline change rate.

Table P-2. Changes in island width (m/yr) at transect locations west of CAHA, calculated from ocean and estuarine shoreline position changes given in Everts et al. (1983).

Location	1860–1917	1917–1946	1946–1980	1860–1980*
75°32’	–	gain >2	likely gain	*likely gain*
75°33’	gain >2	gain >2	likely gain	gain >2
75°34’	gain >2	gain >2	gain	gain >2
75°35’	loss <2	gain >2	loss	loss <2
75°36’	loss >2	loss <2	likely loss	loss <2

* Least-squares estimate of shoreline change rate.

Appendix Q. Historic aerial photos of change at the ends of Hatteras and Ocracoke Islands over time

Figures Q-1 through Q-3 show aerial photos of change over time of islands at CAHA.



Figure Q-1. Aerial photos of Oregon Inlet, including the southern end of Bodie Island and the northern Hatteras Island (Pea Island) in December 1984 (left), 1989 (center), and 2016 (right). Hatteras Island receded to the south between 1984 and 1989, but advanced slightly after terminal groin installation. Images from Google Earth Pro.



Figure Q-2. Aerial photos of Hatteras Inlet, with Hatteras Island and Ocracoke Island, in December 1984 (top), 2002 (center), and 2016 (bottom). The southern end of Hatteras Island receded substantially between 1984 and 2016. The northern end of Ocracoke Island has also receded slightly, primarily between 1984 and 2002. Images from Google Earth Pro.

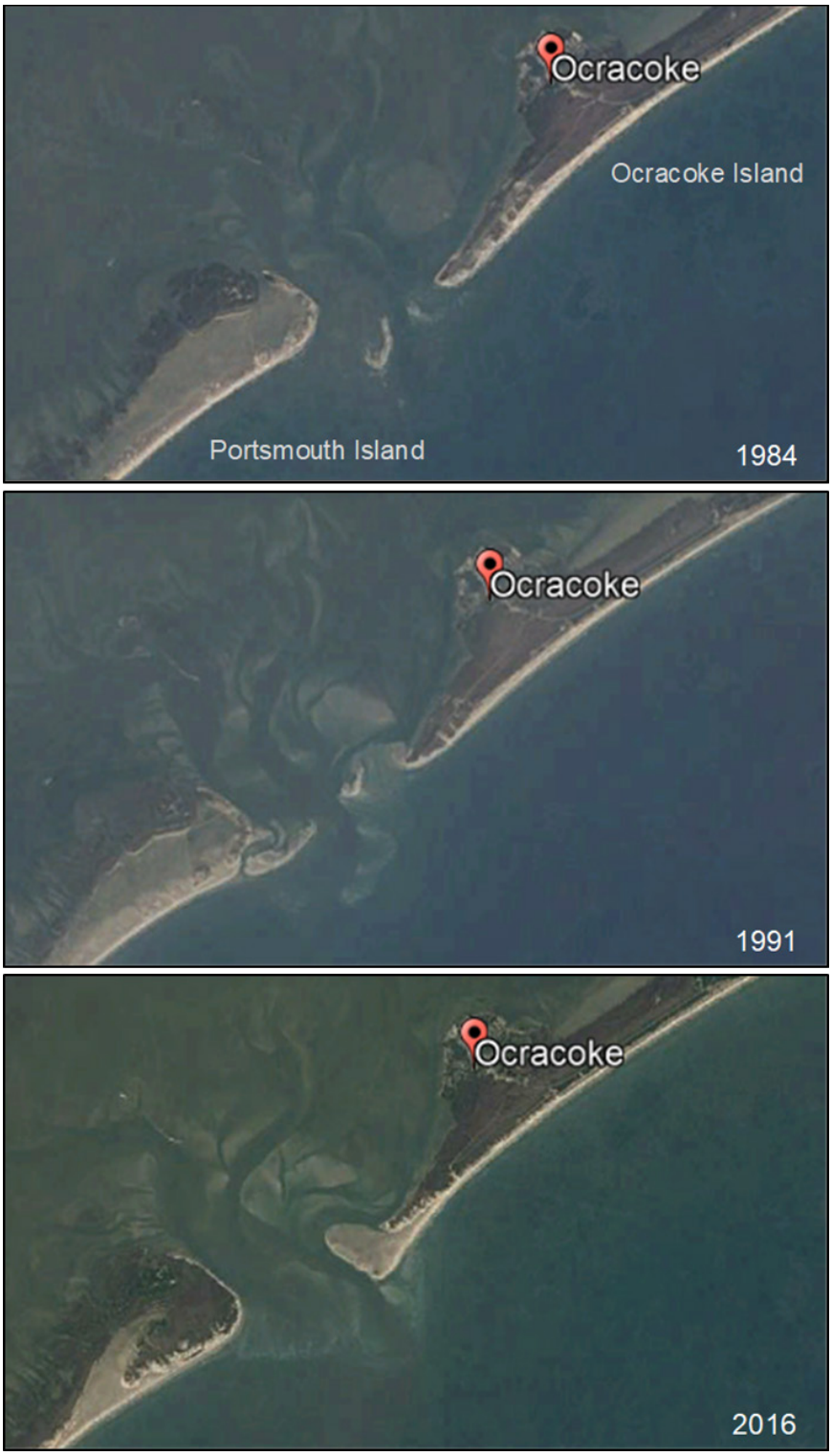


Figure Q-3. Aerial photos of south Ocracoke Island in December 1984 (top), 1991 (center), and 2016 (bottom). The south end of Ocracoke Island receded slightly between 1984 and 1991, but then accreted between 1991 and 2016, returning to a position similar to that of 1984. Images from Google Earth Pro.

Appendix R. Responses of natural and stabilized barrier islands to storms

Figure R-1 shows responses of both natural and stabilized barrier islands to storms.

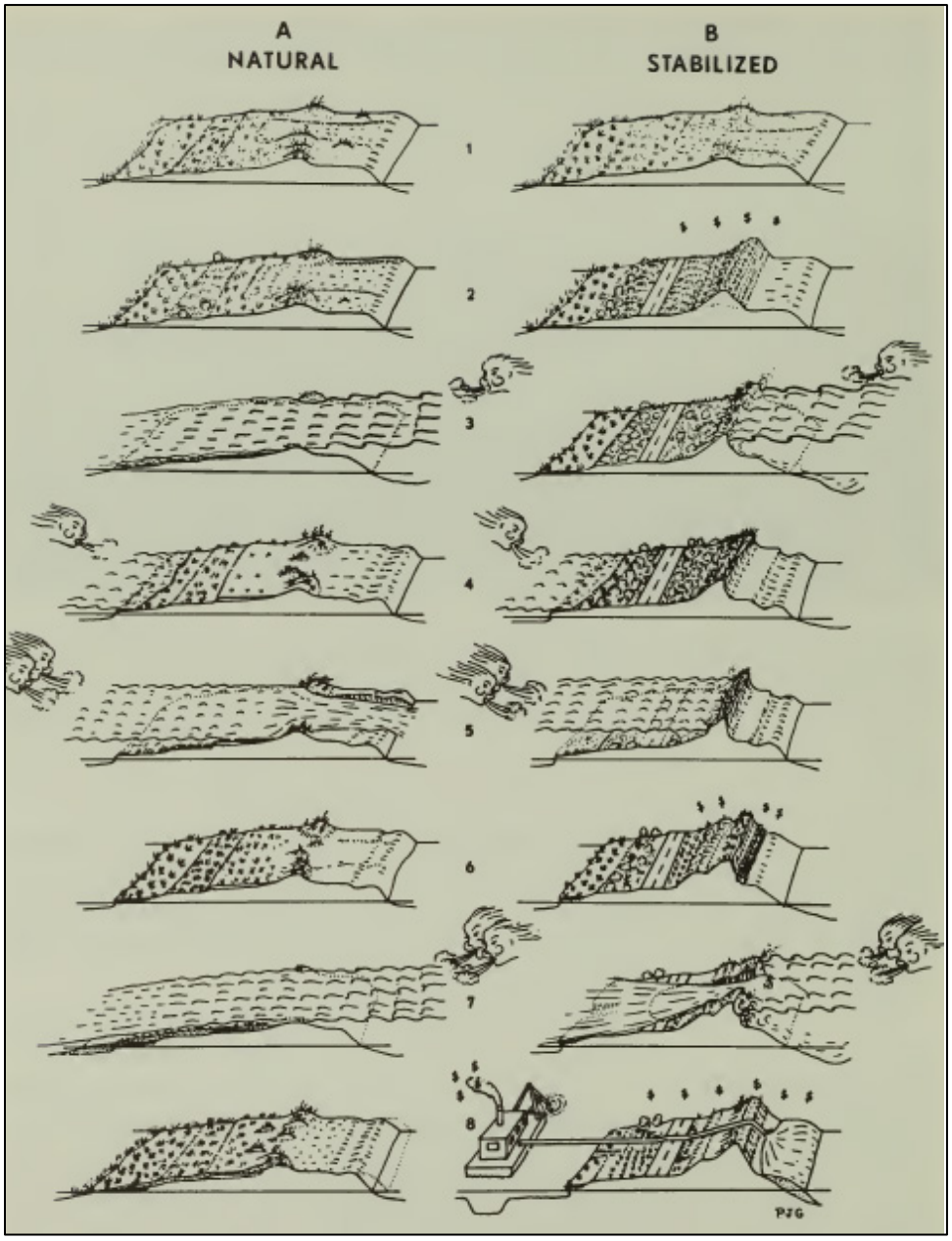


Figure R-1. Schematic diagram showing responses of natural and stabilized barrier islands to storms; see explanatory text below figure (reproduced from Godfrey and Godfrey 1976).

1. Both A and B are essentially alike at the start. Both have a wide berm, low, open dune system, grasslands, and can be overwashed.

2. In B, money has been spent to build a road and a dune to protect it; the island has been "stabilized."
3. A moderate storm strikes both islands and overwashes A. B cannot be overwashed because of the continuous dune, but there is severe erosion of both beach and dune. The erosion narrows the beach and creates deeper water nearshore, which causes more wave damage to the dune. In B there is little or no dune erosion although the beach has retreated.
4. Following the storm, the overwash terrace in A has become vegetated, and new dunes are forming. No damage can be seen. However, in B, the stabilized dune is badly eroded, and the berm markedly narrower. A new beach has been formed on both islands by gentler waves following the storm. Note that shrub vegetation has increased along the road and behind the dune in B. Strong winds from the lagoon side of the island are creating waves in the lagoon, which erode the edges of the salt marsh.
5. A severe storm with winds blowing across the lagoon has flooded the backshore of both islands. In A these flood waters can flow out to sea across the island. In B they are trapped by the man-made dune, and flood the road and other facilities. In A the flood waters remain shallow on the island and last for only a short time. In B they become deep and stand on the land for a long time. Some dune erosion may result on the backside of the dune.
6. The effects of the storm are not evident on the natural island. All vegetation zones are alive and healthy, although the edge of the salt marsh has eroded more. In B, repair work is being done to the back of the dune line. The marsh edge also has eroded. Plants not tolerant of long-term flooding have died. Further attempts to protect the main dune line have been started, with bags of sand being placed along the eroding base of the dune. The problems in B have resulted in major expenses.
7. A severe storm strikes the islands, with different effects on the two islands. In A, a sheet of water sweeps completely across the barrier, carrying sand onto the backshore and into the lagoon. A relatively uniform overwash layer has been spread over the island; the beach has retreated. In B, however, the storm resulted in massive erosion of the beach and dune line. The storm waves piled up against the dune-dike and finally broke over the top. The resulting torrent severely damaged the rear of the dune, buried the road deep in sand, and eroded the back of the island as it swept across.
8. Following the storm, the islands are very different. In A, all signs of the storm are gone. All vegetative zones have redeveloped on the overwash layer, including a new salt marsh. New dunes are forming on the beach. The main change is a slight retreat of the barrier. In B, massive projects, at great cost, are underway to rebuild the barrier in the same place. A beach nourishment project is pumping sand from behind the barrier to rebuild the beach and the dune. (Such lagoon-side dredging operations for fill are no longer carried out on National Park Service land because of the ecological damage to the lagoon and the generally poor quality of the sediment. Recent nourishment sources have been accreting spits or inlets). Once the dune has been built, it will be grassed. Even though the beach has been temporarily restored, the next storm will create difficulties again. Because of the lack of overwash sand, there has been no backshore elevation increase nor any sediment for new marshes in the

lagoon. The edge of the marshes continues to erode. More and more effort will be needed to maintain B, while A will continue its natural cycle in equilibrium with the oceanic forces.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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