# Overview of the Impacts of Sea Level Rise on Coastal Forests and Wetlands in National Wildlife Refuges in the Mid-Atlantic Region

**April 23, 2019**

**Author: Elisabeth Lang**

**Mentor: Dr. Christiane Runyan, Johns Hopkins University**

**Executive Summary**

The National Wildlife Refuge System was established to assist the Fish and Wildlife Service in accomplishing their wildlife conservation goals. However, many of the refuges are located in areas susceptible to impacts from climate change, including sea level rise. Refuges in the Mid-Atlantic region of the United States are particularly vulnerable given the higher than average rate of sea level rise in the region. Therefore, this project aims to quantify the impacts of sea level rise on coastal ecosystems within the refuges of the Mid-Atlantic. Based on the findings, recommendations for adaptation and mitigation of sea level rise impacts are given. The results of this study revealed substantial loss of ecologically significant protected land, with total NWR inundation ranging from 5-100%.

Completing this research project allowed me to gain practical knowledge and further develop many skills. The data collection for this project was done through the use of ArcGIS, which gave me more technical experience with the software. I also gained more experience in conducting literature reviews and the background research necessary to develop a research topic and plan, as well as the actual process of developing and continuously revising the research plan. I also gained knowledge about the Chesapeake Bay region, including its ecological significance, the mechanisms behind sea level rise, and how sea level rise will impact its coastal ecosystems. I also now have a better understanding of where governmental management in the region is effective and where it is lacking.  While this project does not tie into what I do in my current job as a science technician in a chemistry lab, it is closely related to my ideal career, which would be research, restoration, and conservation of the Chesapeake Bay and the surrounding area, and has helped me develop skills and knowledge necessary to obtain that career.

# Table of Contents

# 1. Introduction

## *1.1 The National Wildlife Refuge System*

The National Wildlife Refuge System (NWRS) was created by the U.S. Congress and is administered by the United States Fish and Wildlife Service (FWS) to accomplish the FWS's mission of "working with others to conserve, protect, and enhance fish, wildlife, and plants and their habitats for the continuing benefit of the American people" (Czech et al. 2014). In order to achieve their conservation mission, the NWRS consists of a national network of land and water that is dedicated to wildlife conservation (Czech et al. 2014). The NWRS consists of 550 refuges, 37 wetland management districts, and 85 other units comprising over 60 million hectares (over 148 million acres) (Griffith et al. 2009). 97% of the NWRS consists of National Wildlife Refuges (NWRs) while the remaining 3% consists of waterfowl protection areas and coordination areas (Czech et al. 2014). These refuges contain habitat that has been identified as critical to conserving and protecting local and global biodiversity (Czech et al. 2014), such as migratory waterfowl and neo-tropical birds (US Fish and Wildlife Service Chesapeake Bay Field Office 2016). When authorized by congress, each NWR is established with specific goals that are aligned with the broader goals of the NWRS (Czech et al. 2014). A refuge may have been established to fulfill multiple purposes, which are defined by the legislation or executive action that resulted in the acquisition or establishment of the refuge (Czech et al. 2014). For example, almost 300 refuges have been established under the Migratory Bird Conservation Act for the purpose of conservation and protection of numerous bird species. Another 58 were established under the Endangered Species Act to protect habitat for species listed as endangered (Czech et al. 2014). Each refuge is created in areas of significance to the species they aim to protect, and the methods they each use to ensure the protection and conservation of the species varies depending on the legislation surrounding their creation (Czech et al. 2014). Once established, a refuge is legally obligated to fulfill its defined purpose and to contribute to the overall conservation mission of the NWRS (Czech et al. 2014). However, the NWRS faces many threats to its ability to protect and conserve wildlife.

Contemporary threats to the NWRS include habitat loss and fragmentation, invasive species, urbanization, natural disasters, and pollution (Griffith et al. 2009). These threats are likely to be further exacerbated by climate change, which the FWS has identified as a threat to the ability of established refuges to fulfill their purposes that must be accounted for in governmental planning and decision making (Griffith et al. 2009; Czech et al. 2014). For example, climate change impacts are likely to cause northward biome shifts by the year 2100 (Griffith et al. 2009). These changes constitute a regime shift which are large and persistent changes in the structure and function of an ecosystem (Griffith et al. 2009). Regime shifts may make it impossible for each NWR to meet its specific purposes and highlight the importance of planning for future climate change impacts (Griffith et al. 2009). Of the 562 NWRs in the country, 173 of them are located in marine coastal areas, and are thus susceptible to the impacts of sea level rise (SLR) associated with climate change. These changes are a significant threat not only to the ability of the refuges to fulfill their goals of establishment, but also to the ability of the NWRS to accomplish its overall mission (Czech et al. 2014). For example, marshes within Blackwater NWR in Maryland have been experiencing inundation for the past 60 years with complete inundation projected to occur by 2060 (Larsen et al. 2004).Similarly, Forsythe NWR in New Jersey is losing 27% of its marsh to inundation annually (Griffith et al. 2009).

### *1.2 Global Sea Level Rise*

SLR has been occurring globally at accelerating rates due to climate change and will have many socioeconomic and ecological impacts (Czech et al. 2014). During the twentieth century, global sea level has risen approximately 0.17 meters, and the rate of SLR may double during the next century (Li et al. 2009). SLR will disrupt physical processes, economy, and social and natural systems located in coastal regions (Li et al. 2009). Many ecosystems that provide important ecosystem services are located within coastal areas. These ecosystems, including different types of wetlands, forests, grasslands, and shrub lands, and provide important services such as nutrient cycling, biological productivity, and disturbance regulation, which are important processes for not only wildlife, but also for society (Craft et al. 2009). By 2100, global sea level is predicted to rise by 0.2-2.0 meters (0.7-6.5ft) (Parris et al. 2012). There are several factors that contribute to global SLR, including increased ocean water volume from melting ice sheets and thermal expansion due to increasing water temperatures (Czech et al. 2014).

Global and local rates of SLR are often unequal. Local rates may vary from global rates due to geological factors such as land subsidence and lifting, with areas experiencing land subsidence having higher rates of SLR (Eggleston & Pope 2013). For example, due to land subsidence, the entire Mid-Atlantic region of the United States north of Cape Hatteras, NC and south of Boston, MA is considered a "hotspot" of accelerated sea level rise (Exer et al. 2014), where SLR is occurring at a rate 3 to 4 times faster than the global average (Allen et al. 2016). More specifically, the Chesapeake Bay region is experiencing the highest rates of SLR on the Atlantic Coast of the United States due to the effect of land subsidence and glacial isostatic rebound on SLR (Eggleston & Pope 2013). Since the 1940s, land subsidence in the Chesapeake Bay region has been observed at rates of 1.1 to 4.8 mm/yr (Eggleston & Pope 2013). Excessive groundwater pumping has been identified as contributing to 1.5 to 3.7 mm/yr, with the remaining subsidence occurring due to glacial isostatic rebound (Eggleston & Pope 2013). SLR in the region has been accelerating, with SLR rates in 2011 calculated as 4-10 mm/yr, which corresponds to an acceleration of 0.05-0.1 mm/yr from historical rates (Ezer & Corlett 2012). Along with increasing rates of SLR and land subsidence, the shallow slope of the coast in the Mid-Atlantic region makes it especially vulnerable to impacts from SLR (Kleinosky et al. 2007). As examined in this study, the higher rates of SLR seen locally throughout this region constitute a significant threat to its coastal ecosystems.

### *1.2.1 Sea Level Rise and the NWRS*

As discussed, the ecosystems within the NWRs are ecologically significant and important to achieving the goals of the NWRS, and the Mid-Atlantic region is expected to experience comparatively significant amounts of sea level rise. Therefore, this study focuses on impacts of SLR on coastal ecosystems within NWRs of Delaware, Maryland, and Virginia, and in particular forest and wetland since they are common ecosystems to all NWRs in the study. The ecosystems within the NWRs provide critical habitat and numerous ecosystem services that support the wildlife that the NWRs were established to protect, yet will likely experience some level of inundation from SLR (Craft et al. 2009; Griffith et al. 2009). Inundation is the main threat that coastal ecosystems face from SLR, but salinization accompanying SLR also impacts the ability of an ecosystem to persist (Czech et al. 2014). Salinization of surface and groundwater can lead to fragmentation and reduced extent of coastal ecosystems (Glick et al. 2008). These expected impacts from SLR on ecosystems within the NWRS in the Chesapeake Bay region will likely affect the overall ability of the individual NWRs to achieve their goals, which will limit the capacity of the NWRS to fulfill its mission. In particular, each of the refuges in this study contain coastal forest and wetland that are necessary for conservation goals to be met.

### *1.2.2 Sea Level Rise and Coastal Forests*

Coastal forests have high vulnerability to SLR due to inundation, erosion, flooding, and salinization (Swanston et al. 2018). For example, forests along the Gulf Coast have been retreating due to SLR (Friar 2017). Increased salinization results in a lack of seedling regeneration, and increased inundation, even with salt-tolerant species, places more stress on trees because of frequent flooding. Forests nearest to the coast have therefore been dying (Czech et al. 2014). Forests along the east coast of the United States, commonly referred to as “ghost forests”, have also experienced a similar phenomenon. The trees in many of these coastal forests have died as a result of increased salinization accompanying SLR, leaving stands of dead trees in newly formed marsh or open water (Friar 2017). While many species of trees found within coastal forests are salt tolerant, such as the bald cypress and the Atlantic white cedar, SLR has increased salinity levels enough that even these more tolerant species are unable to survive (Friar 2017).

In the Mid-Atlantic, coastal forests are responsible for providing habitat for many species, including endangered and migrating species. For example, the red-cockaded woodpecker, an endangered species, and the Delmarva fox squirrel, which was recently taken off of the endangered species list, rely on these forests (Maryland Department of Natural Resources, Maryland Mammals; Friar 2017). Neo-tropical birds from across the Americas migrate along a corridor known as the Atlantic Flyway, which brings them directly over the Mid-Atlantic region (Glick et al. 2008). Some of these birds, such as songbirds like the wood thrush, black-throated green warbler, and scarlet tanager, use coastal forests for roosting during migration, and are therefore threatened by the potential impacts of SLR on forests within the Mid-Atlantic (Glick et al. 2008; Friar 2017).

While forests do migrate when faced with a stressor and have new available habitat within their niche, migration does not happen fast enough to make up for forest lost to SLR. There is often a significant lag between changes seen in the climate and observable forest migration (Zhu et al. 2014). If coastal forests do not migrate quick enough or are unable to migrate inland due to development or unsuitable habitat, the overall area of these ecosystems will decrease with SLR, resulting in the loss of several ecosystem services as well as important habitat that supports biodiversity.

### *1.2.3 Sea Level Rise and Coastal Wetlands*

Wetlands, including different types of marshes such as saltwater, tidal freshwater, and brackish marshes, are some of the most vulnerable ecosystems to SLR given their location at the interface of land and water, and are often converted to open water as a result of SLR (Craft et al. 2009; Friar 2017). Wetlands provide flood protection, carbon and nutrient sequestration, water quality maintenance, and essential habitat for fish, shellfish, and other wildlife, including species that may be threatened or endangered (Wigand et al. 2017).  In the Mid-Atlantic, wetlands are of significant importance due to their location along the Atlantic Flyway and use as a stopover site for many migratory waterfowl including canvasback, mallard ducks, and Canada geese (Glick et al 2008). Wetlands in the Mid-Atlantic are also essential for the persistence of notable species such as the diamondback terrapin (Glick et al. 2008). The ability of wetlands to provide ecosystem services depends largely on their size, which makes ensuring that a large enough area of wetland remain protected a priority (Kirwan et al. 2016a).

While tidal freshwater and salt marshes will be the most impacted by SLR, all coastal wetlands have the potential to be affected (Craft et al. 2009). Wetland conversion to open water as a result of SLR has already resulted in an estimated 20-45% loss of total coastal wetlands in the Mid-Atlantic region of the United States (Kirwan & Megonigal 2013). Many wetlands, including marshes, build vertically at rates that surpass those of SLR, allowing the ecosystem to persist (Kirwan & Megonigal 2013). However, given that SLR is occurring at faster rates in the Mid-Atlantic due to land subsidence and glacial isostatic rebound, wetlands in the region have not been able to keep up, resulting in the transition from marsh to open water (Kirwan & Megonigal 2013). While SLR is expected to impact coastal wetlands, these ecosystems also have the ability to migrate inland, assuming no constraints; however, increased development in the Chesapeake Bay region has made this increasingly difficult and unlikely (Kirwan et al. 2016b; Glick et al. 2008). Available habitat for colonization is the main factor that results in successful migration of marshes, along with similar levels of elevation and proximity to the shoreline resulting in the same exposure to tidal cycles (Enwright et al. 2016). However, the death of trees within coastal forests will provide potential habitat for marshes to migrate to, which would provide further nesting ground and breeding habitat for birds and aquatic species, greater flood protection, and increased carbon sequestration (Friar 2017).

## 2. Research Statement and Objectives

Given the presence and importance of coastal forests and marshes within NWRs of Delaware, Maryland, and Virginia, this study aims to quantify the potential impacts of future SLR on forest and wetland within coastal NWRs in the Mid-Atlantic region at SLR predictions for three different carbon-emission scenarios: (1) Increased emissions (high), (2) Stabilized emissions (medium), and (3) Emissions Meeting Paris Climate Agreement standards (low). The quantification of impacts of SLR was accomplished by calculating the total area of inundation for each NWR, as well as area of inundation for wetland and forest ecosystems for each NWR in a GIS-based analysis. Recommendations are then provided for the conservation of these ecosystems, including the mitigation or reduction of future SLR impacts. It is hypothesized that SLR amounts associated with higher carbon emission scenarios will have greater impacts on the NWRs and that wetland and forest within the NWRs, while not equally impacted, will experience inundation at levels likely to impact their ability to support the wildlife they were established to protect.

## 3. Methods

### 3.1 Study Area Background Information

This study assesses SLR in 18 NWRs in Delaware, Maryland, and Virginia. Two are located in Delaware (Figure 1), three in Maryland (Figure 2), and 13 in Virginia (Figure 3). Of the 18 refuges in the study, ten have special designations. For example, seven refuges are listed as Ramsar Wetlands of International Importance, of which there are only 17 sites in the United States (United States Fish and Wildlife Service 2019a). Eight refuges are listed as Important Bird Areas by different organizations such as the Audubon Society and the American Bird Conservancy (United States Fish and Wildlife Service 2009, 2012, 2014a, 2016, 2018c, 2018d, 2019a, 2019c, 2019d, 2019e). Each refuge, with the exception of Featherstone NWR, was established with the specific goal of conserving habitat for migratory birds along the Atlantic Flyway given the Mid-Atlantic's use as an important stopover site for migratory birds (United States Fish and Wildlife Service 27-44). Several were also established with the purpose of conserving species listed as threatened or endangered and providing opportunities for wildlife dependent education and recreation. Mason Neck NWR was established solely for the protection of the bald eagle (United States Fish and Wildlife Service 2018b). These refuges contain many habitat types, but common to all refuges in the study are coastal forest and wetland (United States Fish and Wildlife Service 27-44). Other habitat types include grassland, shrub land, cropland, and beach/dune. Cropland within the NWRs is often created for the purpose of a food source for migratory birds (United States Fish and Wildlife Service 2009). The diversity of ecosystems in the study area NWRs provide habitat for many species, including waterfowl, diamondback terrapin, migratory neo-tropical birds, beaver, red fox, bald eagles, the Delmarva fox squirrel, as well as many other reptiles, amphibians, birds, marine species, and mammals (United States Fish and Wildlife Service 27-44).

The NWRS has a system in place that establishes Approved Acquisition Boundaries (AABs), which are areas where the FWS has been authorized to acquire land to expand an NWR (Czech et al. 2104). Of the 18 NWRs in this study, ten of them have AABs. Of these ten, six have AABs larger than 1000 acres, three have AABs between 50 and 1000 acres, and one has an AAB less than one acre. Table 1 lists the study area refuges, important refuge designations, the refuge size in acres, important habitat, their purpose as specified at establishment, and specifies the area of the AABs for the refuges that have them.


Figure 1. The figure above shows the locations of the NWRs in the study in Delaware.

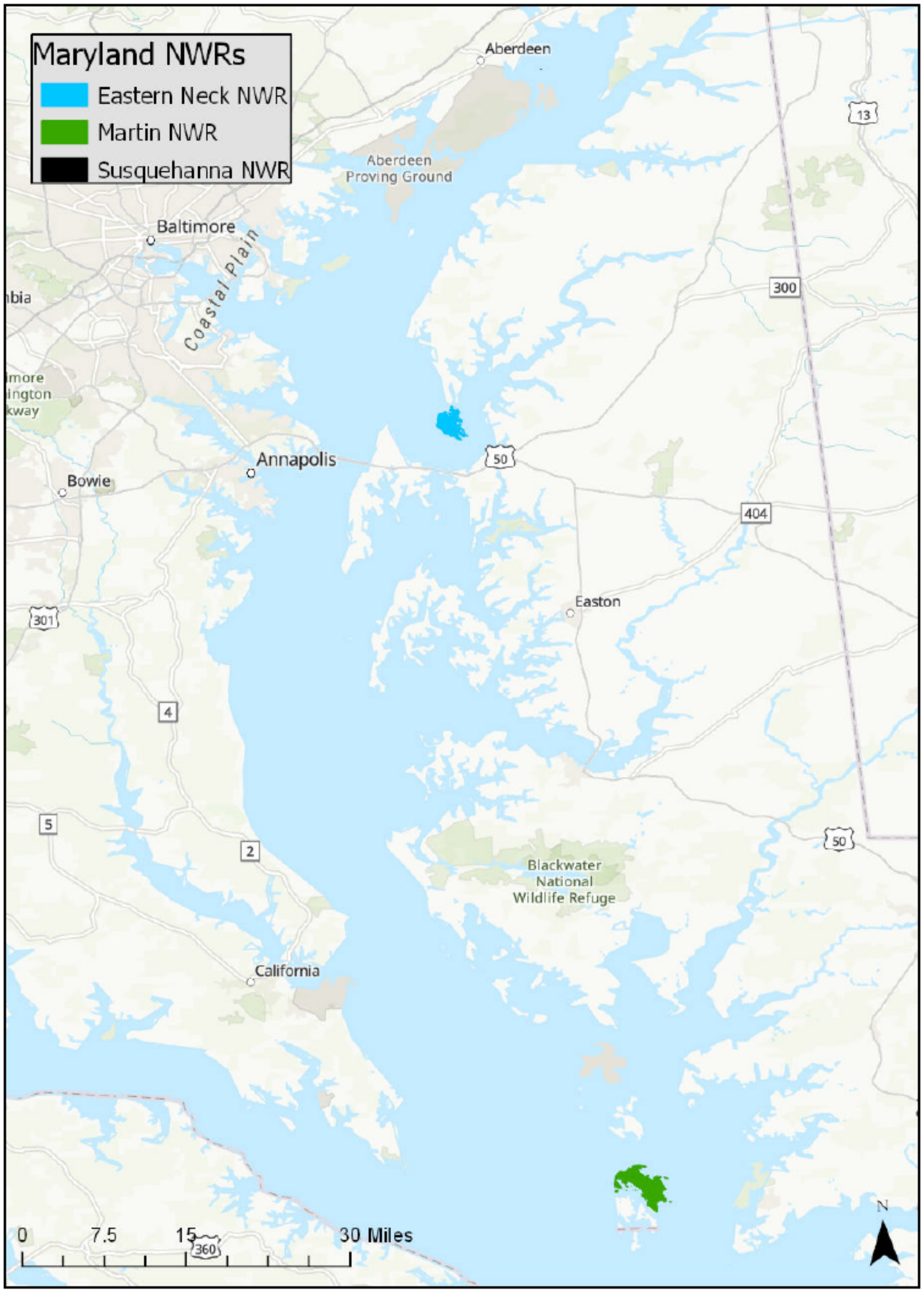



Figure 2. The figure above shows the location of the NWRs in Maryland. Susquehanna NWR is not visible on the map due to its small size, but is located to the south of the word "Aberdeen" on the map.

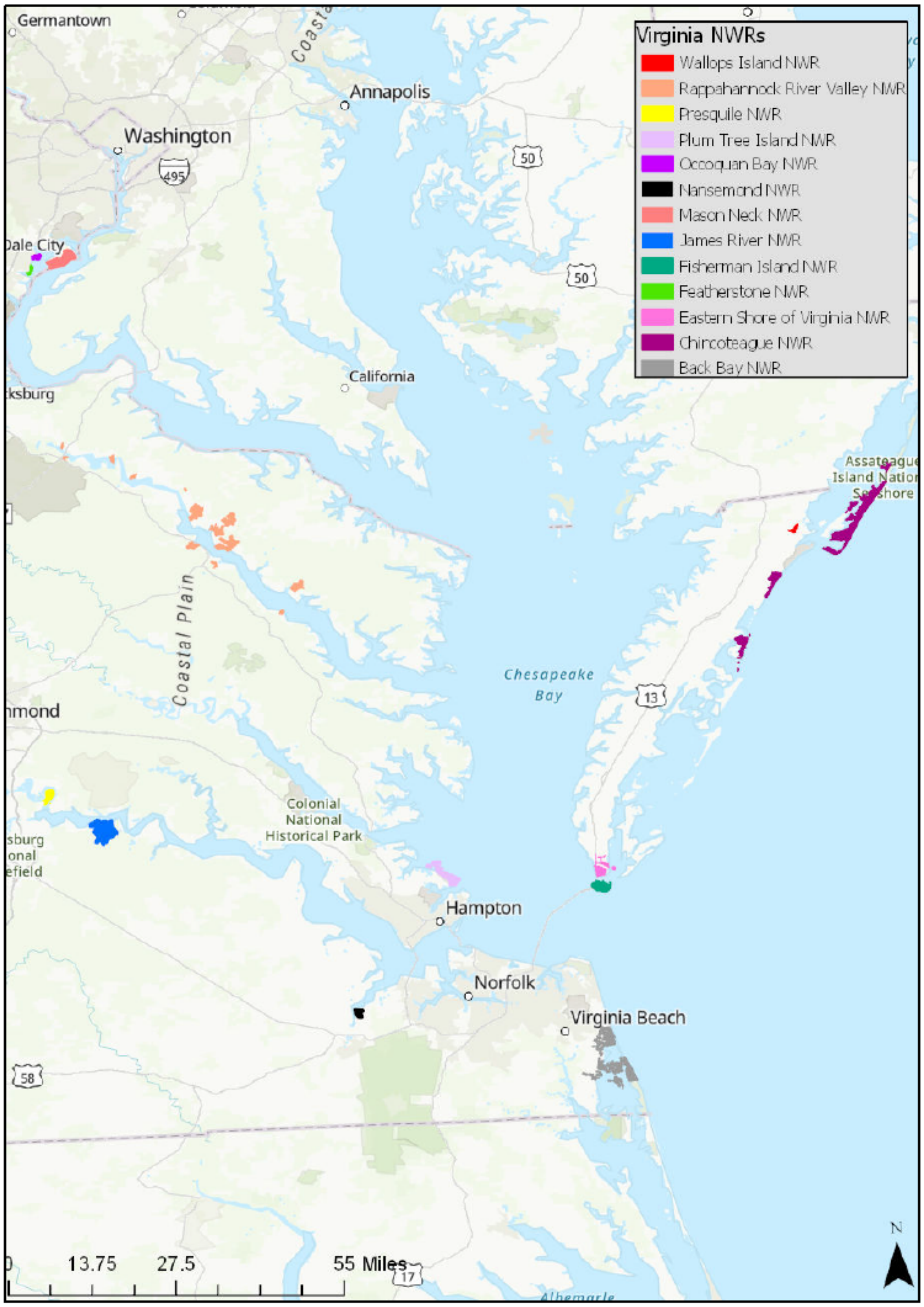



Figure 3. The figure above shows the location of the NWRs in Virginia.

Table 1. The table below indicates important information for each NWR in the study. Next to the refuge name, the letters indicate the following designations: (A) Important Bird Area by the Audubon Society, (B) Ramsar Wetland of International Importance, (C) Globally Important Bird Area, (D) Western Hemisphere Shorebird Reserve Network site, and (E) Important Bird Area designation by the American Bird Conservancy. Refuge purpose is indicated as follows: (1) Migratory bird/habitat protection/conservation, (2) wildlife dependent recreation and education,

(3) protection of the bald eagle, (4) conservation of species listed as threatened/endangered, (5) protection of natural resources, and (6) protection of features of contiguous wetland area. For habitat, the numbers indicate the following: (1) forest, (2) wetland, (3) grassland and shrub land, (4) cropland, and (5) beach/dune.

| National Wildlife Refuge | Area (Acres) | Purpose | Habitat | AAB Area (Acres) |
|---|---|---|---|---|
| **Delaware** | | | | |
| Bombay Hook NWR (B, C) | 15,374 | 1, 4 | 1, 2, 3 | 5,376 |
| Prime Hook NWR (B, D, E) | 10,133 | 1 | 1, 2, 3 | 122 |
| **Maryland** | | | | |
| Eastern Neck NWR (A) | 2,285 | 1 | 1, 2, 3, 4 | 0.1 |
| Martin NWR | 4,276 | 1 | 1, 2, 3 | 60 |
| Susquehanna NWR | 1.37 | 1 | 1, 2, 3 | - |
| **Virginia** | | | | |
| Nansemond NWR | 424 | 1 | 1, 2, 3 | - |
| James River NWR (A,B) | 4,325 | 4 | 1, 2 | 213 |
| Presquile NWR (A,B) | 1,297 | 1, 4 | 1, 2, 3 | - |
| Plum Tree Island NWR (A,B) | 3,063 | 1 | 1, 2, 5 | 1,910 |
| Occoquan Bay NWR (A) | 634 | 1, 2 | 1, 2, 3 | - |
| Featherstone NWR | 338 | 6 | 1, 2 | - |
| Rappahannock River Valley NWR (A) | 9,492 | 1, 6 | 1, 2, 3 | - |
| Mason Neck NWR | 2,272 | 1, 2, 3, 4, 5 | 1, 2 | - |
| Chincoteague Island NWR | 13,189 | 1 | 1, 2, 5 | 4,935 |
| Wallops Island NWR | 372 | 1 | 1, 2 | 4,288 |
| Eastern Shore of Virginia NWR (A,B) | 1,341 | 1, 2, 4 | 1, 2, 3, 5 | 5,810 |
| Fisherman Island NWR (A,B) | 2,175 | 1, 2, 4 | 1, 2, 3, 5 | - |
| Back Bay NWR | 8,658 | 1 | 1, 2, 3, 4, 5 | 7,585 |

### *3.2 Inundation Analysis*

In order to quantify the impacts of SLR on the NWRs and the forest and wetland within them, a GIS-based analysis was conducted to determine total area of inundation for each NWR and their forests and wetlands for the year 2050 and for the year 2100 at each carbon emission scenario. Based on research conducted by a working group at the University of Maryland Center for Environmental Science, a SLR scenario of 1-2 feet was chosen for the year 2050 (Boesch et al., 2018). For the year 2100, three carbon-emission scenarios were used to inform sea level rise predictions. Boesch et al. (2009) found that under an Increasing Carbon Emission scenario (High), 2-5 feet of SLR are expected in the Mid-Atlantic by 2100. Under Stabilized Carbon Emissions (Medium), 2-4 feet is expected, and under Emissions that Comply with the Paris Climate Agreement (Low), 1-3 feet is expected (Boesch et al. 2009).

### *3.2.1 Total NWR Inundation*

NWR boundary shapefiles were obtained from the Fish and Wildlife Service's Geospatial Data and Services program and include boundaries for acquired land as well as approved acquisition boundaries for all coastal NWRs within Delaware, Maryland, and Virginia with the exception of Blackwater NWR and Patuxent Research NWR (Geospatial Data and Services 2018). These two NWRs have had a significant amount of research already conducted regarding SLR and climate change impacts and were therefore excluded from the study. Sea level rise inundation shapefiles were acquired from NOAA's Sea Level Rise Viewer project for 1 to 5 feet of sea level rise in 1 foot increments, which covers each of the predicted ranges of SLR for 2050 and for 2100 at the different carbon emission scenarios (Office for Coastal Management 2019). The inundation shape files were then used in conjunction with the NWR boundaries to calculate total area inundated at each amount of sea level rise. An accuracy assessment conducted by NOAA resulted in the SLR data having an 18.5 cm RMSE (NOAA Office for Coastal Management 2017).

### *3.2.2 Total Coastal Forest and Wetland Inundation*

Land cover data for 2013 at 1m resolution was obtained from the Chesapeake Conservancy's Land Cover Data Project for Delaware, Maryland, and Virginia (Chesapeake Conservancy 2016; Virginia Geographic Information Network 2017). The land cover data was clipped to the boundaries of each of the coastal NWRs in the study. Initial area of forest and wetland in the year 2013 was calculated with this data. The inundation shapefiles were then used in conjunction with the clipped land cover data to remove land cover that would be inundated, allowing area inundated for forest and wetland to be calculated. An accuracy assessment of the land cover data conducted by the Chesapeake Conservancy and the Virginia Information Technologies Agency resulted in greater than 91% accuracy for the Delaware and Maryland dataset and 85-95% accuracy for the Virginia dataset depending on the land cover classification in question (Pallai, C. and Wesson, K. n.d.; WorldView Solutions Inc. 2016).

#### *3.2.3 Approved Acquisition Boundary (AAB) Inundation*

Acquiring land within the AABs for the refuges that have them may help to compensate for inundation within the current NWR boundaries since the acquisition of this land would expand the refuge. Therefore, the second part of this analysis involved calculating the area of inundation for each refuge that has AABs with the AABs included to see if adding that area would help to make up for area lost by SLR. For each SLR scenario, the area of the NWR including the AAB that was not inundated was calculated. This value was then compared to the current area of the NWR to determine if adding the AAB to the NWR would compensate for land lost to SLR. Based on these analyses, the overall expected state of the ecosystems within the NWRs with SLR can be better understood and management actions regarding restoration, conservation, and the acquisition of land can be recommended.

## 4. Results

### *4.1 Land Cover in 2013*

All of the NWRs within the study area, with the exception of Susquehanna NWR which is an island less than 2 acres in size, are comprised mostly of wetlands and forest, with grass and shrub land making up smaller areas proportionally for most NWRs. The following tables (2 and

3) indicate starting conditions in the year 2013 for each NWR in the study in terms of acres of each ecosystem of interest and the total percent of the NWR that those ecosystems comprise. The remaining area of each refuge is composed of other vegetation types, including grassland and shrub land.

Tables 2 and 3. The tables below list the total area in acres and total percent of wetland and forest within the coastal NWRs studied in Delaware, Maryland, and Virginia.

**2013 Wetland and Forest Cover (DE and MD)**

| | Bombay Hook | Prime Hook | Martin | Eastern Neck | Susquehanna |
|---|---|---|---|---|---|
| **Wetlands (Acres)** | 10,657 (69%) | 4,042 (40%) | 3,131 (73%) | 624 (27%) | 0.01 (0.83%) |
| **Forest (Acres)** | 1,227 (8%) | 1,716 (17%) | 7 (0.2%) | 609 (27%) | 0.02 (1.6%) |

**2013 Wetland and Forest Cover (VA)**

| | Nansemond | James River | Presquile | Plum Tree Island | Occoquan Bay | Mason Neck | Featherstone |
|---|---|---|---|---|---|---|---|
| **Wetlands (Acres)** | 217(51%) | 816 (19%) | 914 (70%) | 2,455 (80%) | 223 (35%) | 407 (18%) | 225(67% |
| **Forest (Acres)** | 31 (7%) | 3,421 (79%) | 41 (3%) | 2 (0.1%) | 125 (20%) | 1,786 (79%) | 61 (18%) |
| | **Rappahannock River Valley** | **Chincoteague Island** | **Wallops Island** | **Eastern Shore of Virginia** | **Fisherman Island** | **Back Bay** | |
| **Wetlands (Acres)** | 2,496 (26%) | 6,526 (49%) | 203 (55%) | 566 (42%) | 1,113 (51%) | 5,934 (69%) | |
| **Forest (Acres)** | 4,562 (48%) | 1,153 (9%) | 148 (40%) | 393 (29%) | 5 (0.2%) | 253 (3%) | |

### *4.2 Total NWR Inundation in 2050 and 2100*

By 2050, the expected amount of one to two feet of SLR will result in the average inundation of 52-63% of each NWRs in the study area. The total area of each NWR inundated varied between individual NWRs. At one foot, the total percent of each NWR inundated ranged from 5-100%, and at two feet, it ranged from 6-100% (Table 4). At one foot of SLR, three NWRs experience at least 90% inundation while two experience less than 10%, and at two feet of SLR, four experience at least 90% inundation while only one experiences less than 10% (Table 4). At the High carbon emissions scenario and the associated two to five feet of SLR, the NWRs in the study experience an average of 63-71% inundation (Table 5). For the individual NWRs, the percent inundated ranges from 6-100% at two feet of SLR and 7-100% at five feet of

SLR (Table 5). For five feet of SLR, only one NWR experiences below 10% inundation, while eight NWRs experience at least 90% inundation (Table 5). The Medium carbon emission scenario is associated with two to four feet of SLR. At this amount of SLR, the NWRs are expected to experience an average of 63-70% inundation (Table 6). Four feet of SLR results in 1% less inundation than five feet, at 70% rather than 71%. In terms of the individual NWRs, the range of percent inundation is the same as the previous carbon emission scenario. At four feet of SLR, six NWRs experience at least 90% inundation and only one experiences less than 10% (Table 6). At the Low emission scenario, approximately one to three feet of SLR is expected in the area. This would result in an average of 52-66% of each NWR being inundated (Table 7). At one foot of SLR, as in the 2050 SLR scenario, percent inundation ranges from 5-100%, and at three feet of SLR, it ranges from 7-100% (Table 7). At three feet of SLR, five NWRs experience at least 90% inundation and only one experiences less than 10% inundation (Table 7). The amount of inundation experienced by each NWR is smaller at the low carbon emission scenario and largest at the high emissions scenario.

Two NWRs in the study, James River NWR and Susquehanna NWR, are responsible for the similar ranges of inundation seen for each SLR scenario. Susquehanna NWR will be 100% inundated at only one foot of SLR, and therefore all other amounts of SLR greater than one foot. Each SLR scenario thus has one NWR that is completely inundated. For the remaining NWRs, percent inundation has greater variability. For example, excluding Susquehanna and James River NWRs, one foot of SLR produces inundation ranging from 12-91% and five feet of SLR produces inundation ranging from 17-100%.

Tables 4, 5, 6, and 7. The tables below indicate the area in acres and the percent of each NWR that will be inundated by 2050 and at each carbon emission scenario by 2100.

**Table 4. NWR Inundation (Acres) – SLR by 2050**

| NWR | Area Inundated - 1 foot SLR | Area Inundated - 2 feet SLR |
|---|---|---|
| Bombay Hook | 14061 (91%) | 14703 (92%) |
| Prime Hook | 8159 (81%) | 8874 (88%) |
| Eastern Neck | 191 (8%) | 806 (35%) |
| Martin | 3622 (85%) | 4151 (97%) |
| Susquehanna | 1.37 (100%) | 1.37 (100%) |
| Rappahannock River Valley | 7954 (16%) | 1817 (19%) |
| Mason Neck | 277 (12%) | 303 (13%) |
| Chincoteague Island | 6212 (47%) | 7615 (58%) |
| Wallops Island | 121 (33%) | 211 (57%) |
| Eastern Shore of Virginia | 517 (39%) | 596 (44%) |
| Fisherman Island | 1473 (68%) | 1668 (77%) |
| Back Bay | 3443 (40%) | 6250 (72%) |
| Nansemond | 276 (65%) | 285 (67%) |
| James River | 227 (5%) | 265 (6%) |
| Presquile | 969 (75%) | 1020 (79%) |
| Plum Tree Island | 2757 (90%) | 3026 (99%) |
| Occoquan Bay | 506 (20%) | 270 (43%) |
| Featherstone | 218 (65%) | 267 (79%) |
| Average (Percent) | 52.2% | 62.5% |

**Table 5. NWR Inundation (Acres) – SLR by 2100, High Emissions**

| NWR | Area Inundated - 2 feet | Area Inundated - 5 feet |
|---|---|---|
| Bombay Hook | 14703 (92%) | 15003 (98%) |
| Prime Hook | 8874 (88%) | 9845 (97%) |
| Eastern Neck | 806 (35%) | 1150 (50%) |
| Martin | 4151 (97%) | 4160 (97%) |
| Susquehanna | 1.37 (100%) | 1.37 (100%) |
| Rappahannock River Valley | 1817 (19%) | 2028 (21%) |
| Mason Neck | 303 (13%) | 393 (17%) |
| Chincoteague Island | 7615 (58%) | 12023 (91%) |
| Wallops Island | 211 (57%) | 236 (64%) |
| Eastern Shore of Virginia | 596 (44%) | 732 (55%) |
| Fisherman Island | 1668 (77%) | 2026 (93%) |
| Back Bay | 6250 (72%) | 8216 (95%) |
| Nansemond | 285 (67%) | 294 (69%) |
| James River | 265 (6%) | 315 (7%) |
| Presquile | 1020 (79%) | 1058 (82%) |
| Plum Tree Island | 3026 (99%) | 3061 (100%) |
| Occoquan Bay | 270 (43%) | 384 (61%) |
| Featherstone | 267 (79%) | 292 (86%) |
| Average (Percent) | 62.5% | 71.3% |

**Table 6. NWR Inundation (Acres) - SLR by 2100, Medium Emissions**

| NWR | Area Inundated - 2 feet SLR | Area Inundated - 4 feet SLR |
|---|---|---|
| Bombay Hook | 14703 (92%) | 14876 (97%) |
| Prime Hook | 8874 (88%) | 9626 (95%) |
| Eastern Neck | 806 (35%) | 1083 (47%) |
| Martin | 4151 (97%) | 4160 (97%) |
| Susquehanna | 1.37 (100%) | 1.37 (100%) |
| Rappahannock River Valley | 1817 (19%) | 1957 (21%) |
| Mason Neck | 303 (13%) | 381 (17%) |
| Chincoteague Island | 7615 (58%) | 11606 (88%) |
| Wallops Island | 211 (57%) | 229 (62%) |
| Eastern Shore of Virginia | 596 (44%) | 712 (53%) |
| Fisherman Island | 1668 (77%) | 1939 (89%) |
| Back Bay | 6250 (72%) | 8040 (93%) |
| Nansemond | 285 (67%) | 291 (69%) |
| James River | 265 (6%) | 315 (7%) |
| Presquile | 1020 (79%) | 1048 (81%) |
| Plum Tree Island | 3026 (99%) | 3056 (100%) |
| Occoquan Bay | 270 (43%) | 364 (57%) |
| Featherstone | 267 (79%) | 286 (85%) |
| Average (Percent) | 62.5% | 69.9% |

**Table 7. NWR Inundation (Acres) - SLR by 2100, Low Emissions**

| NWR | Area Inundated - 1 foot SLR | Area Inundated - 3 feet SLR |
|---|---|---|
| Bombay Hook | 14061 (91%) | 14141 (96%) |
| Prime Hook | 8159 (81%) | 9325 (92%) |
| Eastern Neck | 191 (8%) | 985 (43%) |
| Martin | 3622 (85%) | 4158 (97%) |
| Susquehanna | 1.37 (100%) | 1.37 (100%) |
| Rappahannock River Valley | 7954 (16%) | 7595 (20%) |
| Mason Neck | 277 (12%) | 311 (14%) |
| Chincoteague Island | 6212 (47%) | 8754 (66%) |
| Wallops Island | 121 (33%) | 221 (59%) |
| Eastern Shore of Virginia | 517 (39%) | 667 (50%) |
| Fisherman Island | 1473 (68%) | 1816 (83%) |
| Back Bay | 3443 (40%) | 7415 (86%) |
| Nansemond | 276 (65%) | 288 (68%) |
| James River | 227 (5%) | 297 (7%) |
| Presquile | 969 (75%) | 1036 (80%) |
| Plum Tree Island | 2757 (90%) | 3046 (99%) |
| Occoquan Bay | 506 (20%) | 333 (53%) |
| Featherstone | 218 (65%) | 278 (82%) |
| Average (Percent) | 52.2 | 66.4 |

### *4.3 Coastal Forest and Wetland Inundation*

By the year 2050, the one to two feet of expected SLR will result in an average 15-25% forest inundation and 65-85% wetland inundation (Figure 4). However, there is variation between the individual refuges regarding percentages of each ecosystem inundated. Forest inundation ranges from 0-100% for one foot of SLR and 1-100% for two feet of SLR, while wetland inundation ranges from 15-100% for one foot of SLR and 25-100% for two feet of SLR (Appendix 1). By 2100 with increasing carbon emissions, two to five feet of SLR is expected. Many of the NWRs in the study area are expected to more severely impacted by inundation. An average of about 25-50% of forest will be inundated and an average of about 85-95% of wetlands will be inundated (Figure 5). As before, a wider range of inundation is found between the individual refuges. Forest inundation ranges from 1% to 100% at both one and five feet of SLR and wetland inundation ranges from 25-100% at one foot of SLR and from 32-100% at five feet of SLR (Appendix 6). Under a stabilized carbon emissions scenario, two to four feet of SLR by 2100 are expected in the Chesapeake Bay region. This would result in an average inundation of about 25-45% of forest and about 85-90% of wetlands (Figure 6). On the high end, this scenario would have about 5% less forest and wetland inundation than the increasing carbon emissions scenario. Looking at the refuges individually, forest inundation ranges from 1-100% at both two and four feet of SLR, and wetland inundation ranges from 25-100% for two feet of SLR and from 30-100% for four feet of SLR (Appendix 3). At a carbon emission scenario that meets the standards set forth by the Paris Climate Agreement, one to three feet of SLR are expected in the Chesapeake Bay region. With this amount of SLR, an average of 15-35% of forest within the NWRs will be inundated and an average of about 65-85% of wetland will be inundated (Figure 7). For the refuges individually, forest inundation ranges from 0-100% at one foot of SLR and from 1-100% at three feet of SLR, while wetland inundation ranges from 15-100% at one foot of SLR and from 29-100% at three feet of SLR (Appendix 4). This scenario would result in about 10% less forest inundation and could result in 20% less wetland inundation than a stabilized carbon emission scenario would result in.

Figure 4

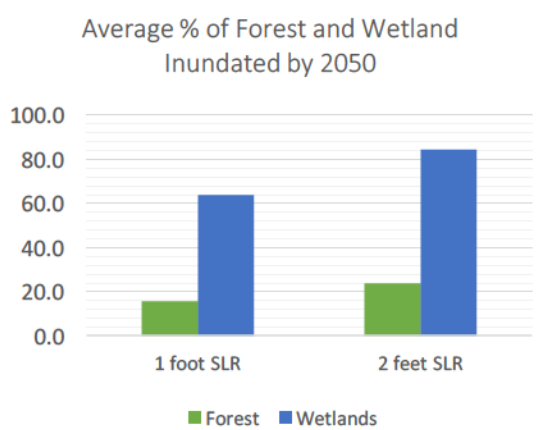



Figure 5

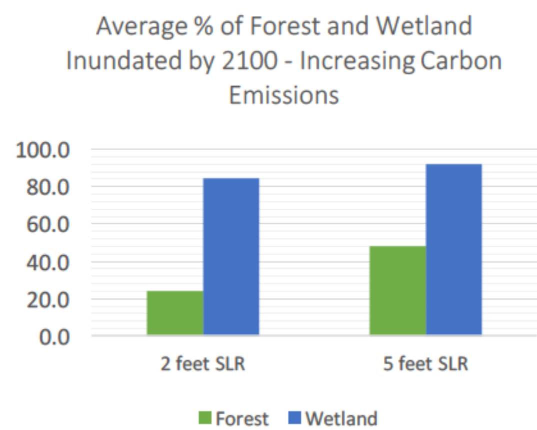



Figure 6

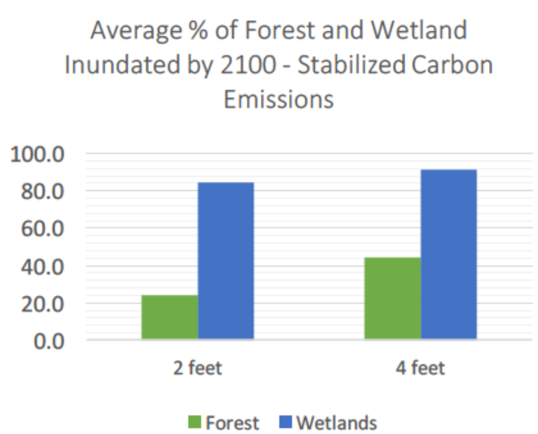
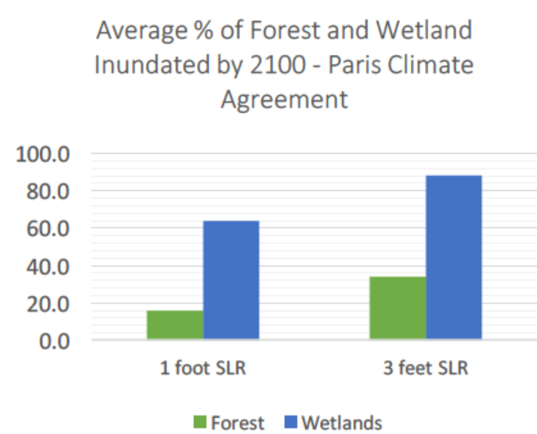



Figure 7




Figures 4, 5, 6, and 7. The figures above show the average percent of forest and wetland ecosystems inundated by 2050 and by 2100 at each carbon emission scenario.

### *4.4 Approved Acquisition Boundary Inundation*

Of the 18 NWRs in this study, ten have AABs that would add to the current area of the NWR if they were to be obtained. Of the ten that have AABs, only 2 NWRs have AABs that would add enough area or are located in areas that won't be as impacted by SLR at all scenarios that, with their acquisition, would result in increased area of the NWRs with SLR factored in. The other eight NWRs that have AABs would be smaller than their current size at each SLR scenario even if the AABs were to be acquired. Tables 8, 9, 10, and 11 below show a comparison of the deficit between current NWR area and NWR area including AABs for each SLR scenario.

Tables 8, 9, 10, and 11. The tables below indicate the difference in the amount of land between the current NWR boundaries and the current boundaries plus the AABs at each SLR scenario. Positive numbers indicate a deficit, meaning that the area of the NWR including the AABs is smaller than the current area of the NWR when SLR is factored in. Negative numbers indicate that the area of the NWR plus the AABs will be greater than the current area with SLR factored in.

**Sea Level Rise by 2050 (Table 8)**

| Difference Between Current NWR Area and Area of NWR + Approved Acquisition Boundaries (acres) | | |
|---|---|---|
| **NWR** | **1 foot SLR** | **2 feet SLR** |
| Bombay Hook | 9053 | 10589 |
| Prime Hook | 9960 | 9965 |
| Eastern Neck | 191 | 806 |
| Martin | 3612 | 4149 |
| James River | 24 | 63 |
| Plum Tree Island | 1916 | 2923 |
| Chincoteague Island | 5591 | 7148 |
| Wallops Island | -1014 | -607 |
| Eastern Shore of Virginia | -4524 | -4207 |
| Back Bay | 1471 | 5498 |

**Sea Level Rise by 2100 – High Carbon Emissions (Table 9)**

| Difference Between Current NWR Area and Area of NWR + Approved Acquisition Boundaries (acres) | | |
|---|---|---|
| **NWR** | **2 feet SLR** | **5 feet SLR** |
| Bombay Hook | 10589 | 13249 |
| Prime Hook | 9965 | 10033 |
| Eastern Neck | 806 | 1150 |
| Martin | 4149 | 4159 |
| James River | 63 | 134 |
| Plum Tree Island | 2923 | 3061 |
| Chincoteague Island | 7148 | 11974 |
| Wallops Island | -607 | -15 |
| Eastern Shore of Virginia | -4207 | -3674 |
| Back Bay | 5498 | 8122 |

**Sea Level Rise by 2100 – Medium Carbon Emissions (Table 10)**

| Difference Between Current NWR Area and Area of NWR + Approved Acquisition Boundaries (acres) | | |
|---|---|---|
| **NWR** | **2 feet of SLR** | **4 feet of SLR** |
| Bombay Hook | 10589 | 12903 |
| Prime Hook | 9965 | 10013 |
| Eastern Neck | 806 | 1083 |
| Martin | 4149 | 4159 |
| James River | 63 | 115 |
| Plum Tree Island | 2923 | 3056 |
| Chincoteague Island | 7148 | 11470 |
| Wallops Island | -607 | -289 |
| Eastern Shore of Virginia | -4207 | -3783 |
| Back Bay | 5498 | 7803 |

**Sea Level Rise by 2100 – Low Carbon Emissions (Table 11)**

| Difference Between Current NWR Area and Area of NWR + Approved Acquisition Boundaries (acres) | | |
|---|---|---|
| **NWR** | **1 foot SLR** | **3 feet SLR** |
| Bombay Hook | 9053 | 11231 |
| Prime Hook | 9960 | 10002 |
| Eastern Neck | 191 | 985 |
| Martin | 3612 | 4157 |
| James River | 24 | 96 |
| Plum Tree Island | 1916 | 3041 |
| Chincoteague Island | 5591 | 8461 |
| Wallops Island | -1014 | -405 |
| Eastern Shore of Virginia | -4524 | -3935 |
| Back Bay | 1471 | 7035 |

## 5. Discussion

### *5.1 Comparison of Carbon Emission Scenarios*

As expected, the amount of SLR associated with each carbon emission scenario produces different results in terms of total NWR and forest and wetland inundation, with higher carbon emission scenarios leading to increasing levels of inundation. By 2050, it can be expected that regardless of carbon emissions, on average of 52-63% of each NWR may be inundated by 2050, with 15-25% of forest and 65-85% of wetland inundated on average. In order to keep the amount of inundation from surpassing 2050 levels, future carbon emissions would have to meet or exceed the standards set forth by the Paris Climate Agreement. Under this scenario, an expected 15-35% of forest and 65-88% of wetlands will be inundated. An average of 52-66% of each NWR can be expected to experience inundation. If the low end of inundation occurs with this scenario, little additional inundation past what is expected by 2050 will occur. While there is little that can be done to prevent the SLR that will occur by 2050 since it is locked in, these results highlight the importance of reducing carbon emissions, since a reduced emissions scenario is what is required to prevent further inundation.

### *5.2 Impacts of Inundation*

As shown through the results of this study, the coastal NWRs of Delaware, Maryland, and Virginia are susceptible to inundation at all levels of predicted SLR for 2050 and 2100. The major impact that this inundation will have on the NWRS system is a loss of land within the protected boundaries of each NWR. Figures 8 and 9 depict cumulative inundation from SLR for Eastern Neck NWR, which experienced relatively lower inundation compared to other refuges (8%-50%), and for Back Bay NWR, which experienced relatively higher inundation (40%-95%). The loss of protected land in the NWRs in the study could impact the ability of the NWRS to achieve its mission of conservation, protection, and enhancement of species and their habitats since the overall area of land under their protection will decrease. All of the NWRs in this study have wetland and forest ecosystems, and most have other ecosystems such as grass and shrub land. The extent of inundation of wetland and forest along with the extent of overall NWR inundation can be used as an indicator of the level of inundation that the other ecosystem types, which are also important to the species, such as the migratory birds, that inhabit the NWRs and the overall ability of the NWRS to accomplish its mission.

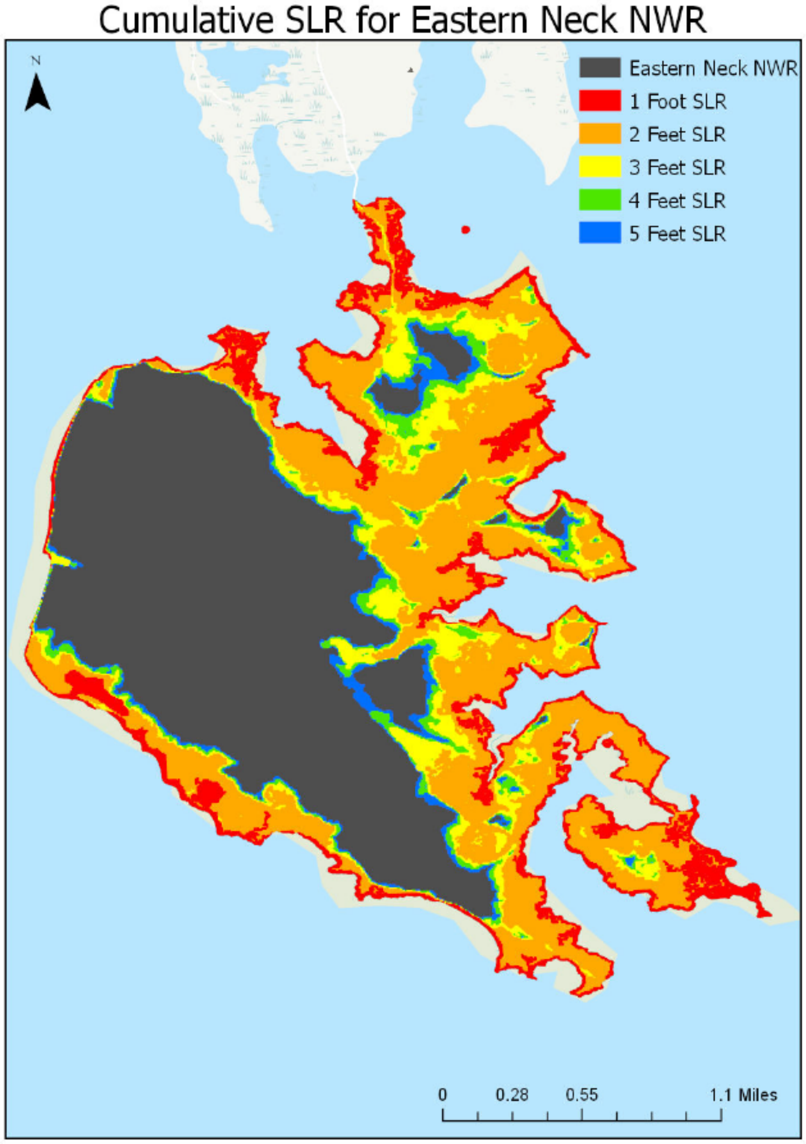



Figure 7. The above figure shows cumulative inundation from SLR for Eastern Neck NWR. Grey indicates area of the refuge remaining after SLR.

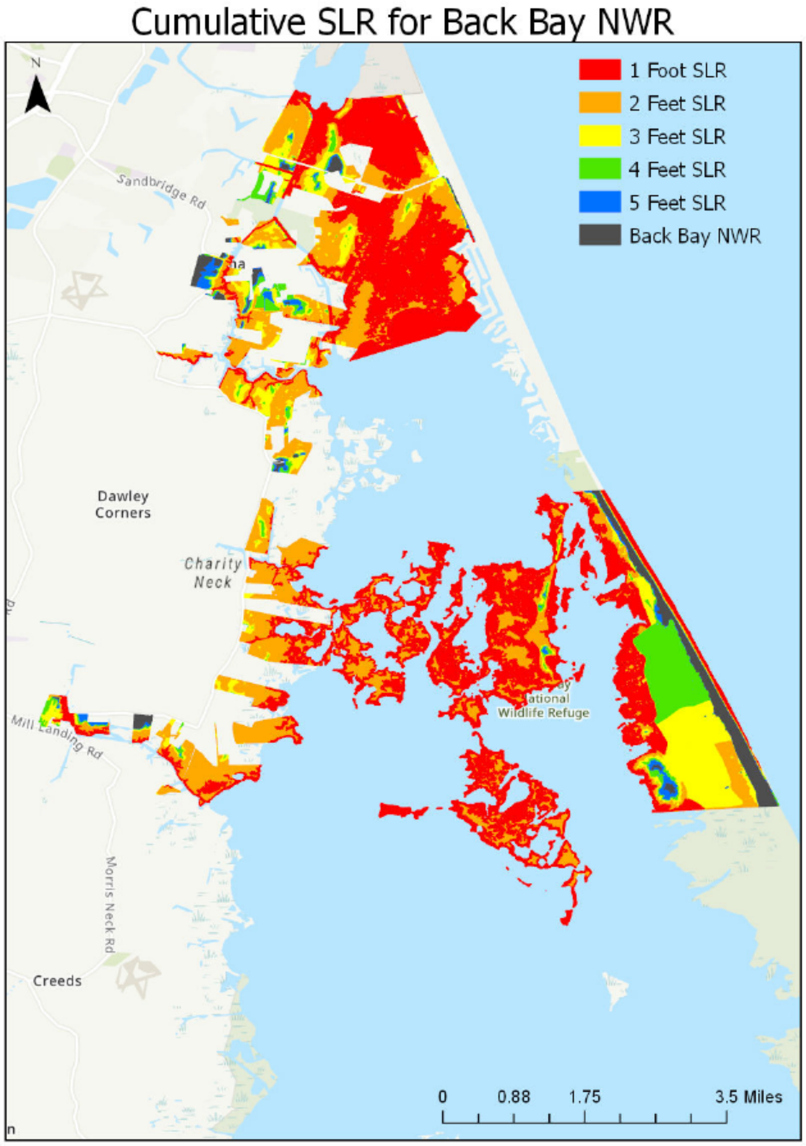



Figure 8. The above figure shows cumulative inundation from SLR for Back Bay NWR. Grey indicates area of the refuge remaining after SLR.

### *5.2.1 Impacts of Inundation on Coastal Forests*

Forests, which are generally further from the water and protected from flooding by wetlands, are shown to experience less overall inundation than wetlands, which generally make up a larger proportion of the NWRs (Craft et al. 2009). However, even with relatively less inundation, the inundation that is experienced by forests of 15%-48% on average will still impact the species that the NWR was designed to protect. One of the main goals of the majority of the

NWRs in this study is to provide protected habitat for several species of birds, both migratory and non-migratory, who rely on the forests within the NWR for roosting and breeding. The availability of habitat for these birds has led to the designation of several refuges as Important Bird Areas. The forests of these NWRs are also home to several mammal species, one of which includes the Delmarva fox squirrel, which was recently removed from the endangered species list (Maryland Department of Natural Resources, Maryland Mammals). The overall loss of forest will reduce the habitat available to these species and therefore the capacity of the NWR to fulfill its purpose of protecting forest-dependent wildlife. While forests can migrate, with the high levels of inundation that most NWRs are expected to experience, there will be less land available for forests to migrate to or for forest restoration or conservation efforts to occur (Zhu et al. 2014). Additionally, forest migration is a slow event. For example, Dyer (1994) found that, with a generation time of 10 years, coastal plain forests could take 50 to 130 generations to fully migrate and be established in a similar condition as it was before migration. Migration may not occur quickly enough within the time period that SLR will occur to make up for forest inundated.

#### *5.2.2 Impacts of Inundation on Coastal Wetlands*

Wetlands within the NWRs, being closer to the shoreline and more susceptible to flooding, are expected to experience a greater proportion of inundation than forests. Wetlands within seven of the refuges in this study are designated as Ramsar Wetlands of International Importance, which means that the loss of protected wetland within those NWRs can have international consequences. Many species of birds, and particularly waterfowl such as swans, geese, and ducks, as well as other birds such as songbirds, migrating along the Atlantic Flyway use the wetlands within the NWRs for stopovers or to overwinter (US Fish and Wildlife Service Chesapeake Bay Field Office 2016). A reduction in the amount of protected wetland available would result in the loss of important stopover sites for these birds during their migration. The wetlands also provide habitat for amphibians and reptiles, including the diamondback terrapin, and a reduction in available habitat could threaten or lead to extinction for many of these species (United States Fish and Wildlife Service 2018a). It is likely that forests, shrub land, and grasslands that are inundated will convert to wetlands in some circumstances (Friar 2017). This indicates that while a large proportion of wetland will become inundated at the presented SLR scenarios, there is the opportunity for wetland to migrate inland and become established in areas that were once other ecosystem types. However, while this means that the total loss of wetland may not be equal to what has been inundated, the remaining area of many of the refuges after SLR do not make up for the area of wetland inundation experienced, meaning that the area of protected wetland will still be smaller than it currently is in most cases. For example, with one foot of SLR, Bombay Hook NWR would be about 9000 acres smaller than it currently is even if the AABs are acquired. Comparing the amount of wetland lost to the amount of each refuge remaining, six of the 18 NWRs (Eastern Neck NWR, James River NWR, Occoquan Bay NWR, Rappahannock River Valley NWR, Eastern Shore of Virginia NWR, and Mason Neck NWR) have enough total land left at each SLR scenario that, if wetlands were able to migrate and establish, would be enough area to make up for the total acreage of wetland inundated. Chincoteague NWR would have enough total land left at one and two feet of SLR to make up for the amount of wetland inundated and Back Bay NWR would have enough at one foot of SLR. The remaining NWRs lose too much land at each SLR scenario to compensate for the amount of wetland lost. As wetlands are one of the most relied on ecosystems for migratory birds, the overall reduction in size of protected wetlands that is likely to occur at higher amounts of SLR will reduce the capacity of the NWRs to accomplish their established goals and to help the NWRS as a whole achieve its mission.

### *5.3 Acquisition of Land within AABs*

As previously mentioned, 10 of the 18 refuges in the study have AABs to potentially expand the refuge, which means that their total area could be increased by the acquisition of that land. However, the AABs are often adjacent to or in the general proximity of the current boundaries of the NWRs, meaning that they will also be impacted by SLR. The AABs vary greatly in total acreage. Eastern Neck NWR has an AAB that adds only 0.1 acres to the refuge size, while Back Bay NWR has AABs that add over 7000 acres. Of the 10 refuges that have AABs, only the Eastern Shore of Virginia NWR and Wallops Island NWR, both of which have over 4000 additional acres in AABs, would have an area greater than their current area at each SLR scenario if the land was to be acquired. Interestingly, Back Bay NWR, which has the largest AAB area, still faces a land deficit at each SLR scenario. This shows that the location of the AAB, along with the size, plays an important role in determining if adding that land to the NWR will compensate for land lost due to SLR. Acquiring land within the AABs could be helpful in terms of compensating for the amount of wetland lost within the NWRs. For example, without the AAB, Wallops Island NWR would not have enough land left at any SLR scenario to compensate for the amount of wetland lost. With the AAB, there is enough land at each SLR scenario that, if wetland can migrate to and establish within it, would be able to make up for the amount of wetland lost, allowing for the same amount of protected wetland to be present within the NWR. This result demonstrated the potential ability of AABs to compensate for land lost to inundation, but they need to be expanded to provide further compensation for expected losses. The location of expansion must be carefully considered for them to be as effective as possible.

### *5.4 Adaptation and Mitigation of SLR Impacts*

The most direct way to prevent the loss of land within the NWRS would be a global reduction in carbon emissions that meet or exceed the standards set by the Paris Climate Agreement. This would result in little inundation beyond what is already expected by 2050. However, given that climate change impacts, such as SLR, are currently being seen in many NWRs and that some unavoidable warming is predicted throughout the next century because we are 'locked-in' to some warming from past emissions (Glick et al. 2008), the NWRS as a whole must adapt for a changing future and mitigate the change that has already occurred. For example, one adaptation method could include increasing the resiliency of each NWR to climate change through increasing connectivity and total area of each NWR. Mitigation efforts could include habitat restoration, especially in areas that are known to be less likely to be impacted by SLR or other effects of climate change, to offset habitat that will be inundated.

#### *5.4.1 Current NWRS Strategies for Adaptation and Mitigation of SLR Impacts*

The FWS has a strategic plan that lists objectives for adaptation, mitigation, and community involvement that will help the system as a whole remain effective with climate change (US Fish and Wildlife Service 2010). Among these objectives is the inclusion of current and future climate change impacts in the Comprehensive Conservation Plans (CCPs) that are required for each refuge (US Fish and Wildlife Service 2010). The strategic plan recognizes the threat that SLR poses and states that the FWS will use the SLAMM (Sea Level Affecting Marshes Model) model system-wide to focus land acquisition efforts (US Fish and Wildlife Service 2010). While using the SLAMM model to focus land acquisition efforts will assist in the acquisition of land best suited for wetland and marsh, it does not help in the acquisition process for land best suited for forest, which, as shown in this study, will also experience inundation.

The FWS completes CCPs for each refuge within the NWRS. These plans are 15-year management plans designed to help the NWR fulfill its purpose (United States Fish and Wildlife Service 2012). The CCPs, for the most part, recognize that climate change and SLR are an issue for the NWRs in the Mid-Atlantic region (United States Fish and Wildlife Service 27-44). The exception to this is the CCP for Occoquan Bay NWR, which was last completed in 1997 and does not address climate change or SLR (United States Fish and Wildlife Service 2019c). While most CCPs recognize the importance of SLR in making management decisions, the CCPs do not appear to be specific in how the NWRS will mitigate or adapt to SLR in each specific refuge outside of broad, general management steps and goals. Proposed actions in the CCPs include recognizing that climate change and SLR need to be taken into consideration in management decisions, monitoring the situation, and implementing geoengineering projects to attempt to prevent inundation (United States Fish and Wildlife Service 27-44). Monitoring and recognizing the importance of SLR in making management decisions are important, but they are broad, general management steps. Many geoengineering projects, such as the creation of freshwater impoundments and beach nourishment, have ultimately failed due to continued and increasing SLR (United States Fish and Wildlife Service 2012). Looking beyond efforts to physically prevent inundation to mitigate the impacts of SLR on the ecosystems within the NWRs is necessary given that they often fail. The CCPs that recognize climate change and SLR as a threat to the NWRs focus mainly on the impact that SLR will have on wetlands; very few mention SLR with respect to forested habitat and how forested habitat will be managed with respect to SLR. Thus, major gaps in adaptation and management plans include a lack of site-specific proposed plans and the exclusion of impacts of SLR on forest ecosystems. The following recommendations aim to fill these gaps and offer solutions to mitigate SLR in the NWRS.

### *5.4.2 Multi-Scale NWR Governance*

There are three scales at which the NWRS makes management decisions: (1) system-wide, (2) regional, and (3) individual NWR. As highlighted by this study, all three of these scales should be used in management decisions. Having an overall, system-wide goal allows for more specific goals aligned with the mission of the NWRS to be created at the regional and individual NWR level. At the regional level, NWRs may face similar threats, such as the coastal NWRs in the Mid-Atlantic region facing potentially severe impacts from SLR. Regionally, many NWRs were established with similar purposes and protect the same species, such as the NWRs in the Mid-Atlantic being established for migratory bird conservation. Considering all refuges in the region together if they have similar purposes and face similar threats can help to direct management decisions. As seen in this study, while all NWRs in the region will be impacted, they are impacted at varying degrees. For example, some NWRs will experience more inundation than others and the proportions of forest and wetland inundated varies for each NWR. Understanding how each individual NWR will be impacted ecologically and how its ability to accomplish its purpose will be impacted is essential to creating a management plan that will successfully reduce or mitigate those impacts, and will allow the NWRS to achieve its mission (Griffith et al. 2009).

Recommendations for mitigation and adaptation presented below are focused on the regional and individual NWR scales and include (1) increasing refuge size through land acquisition; (2) the informed selection of land to be acquired for expansion and establishment of new refuges; (3) taking action quickly in regards to ecosystem restoration and conservation, particularly for forest ecosystems, and (4) community outreach and incentives to encourage conservation.

### *5.4.3 Refuge Expansion*

Increasing the size of the NWRs in the region will help to mitigate some of the expected loss from inundation, which is demonstrated by the Eastern Shore of Virginia NWR and Wallops Island NWR. These two NWRs have enough land with the inclusion of the AABs that, if the AABs were acquired, the refuge would be larger than it otherwise would be at each SLR scenario, showing that expanding the refuges, even within a region likely to be severely impacted by SLR, has the potential to offset the land inundated. On the individual NWR scale, refuges in the study should have AABs created or expanded that would add beneficial land to the NWRs, even as SLR occurs. On the regional scale, there are several NWRs in the study that are less likely to be impacted by SLR than others, which may make them ideal NWRs to consider expanding. For examples, James River NWR is expected to experience only 5-7% inundation by 2100 at all SLR scenarios. These refuges are more likely to retain a higher amount of habitat and have greater connectivity, as well as be located in an area that may be less likely to be impacted by SLR than other areas in the region. Expanding these refuges may help compensate for land inundated in other NWRs, especially since many of the NWRs in the region have very similar habitat types and were established to protect the same species. Creating expansion plans with specific actions to be taken for each refuge would help to fill the gap in the current management plans created by a lack of specific plans for each refuge that consider SLR.

### *5.4.4 Establishment of New Refuges and Informed Selection of Land for Expansion*

Along with individual refuge expansion, new refuges should be established, but informed selection of the land chosen for expansion or establishment is necessary. The fact that ten NWRs have AABs but only two would actually experience an increase in area as SLR occurs shows that, along with the total area, the placement of the AABs is critical. On the individual refuge scale, AABs should be established in areas that have high quality habitat, are less likely to be impacted by SLR, and are over contiguous habitat that would increase the connectivity of the NWR. This would allow for adaptation in the form of increasing resilience to occur while SLR impacts are being mitigated by the availability of more protected land. On a regional scale, land selection for expansion or new refuge establishment should be made to increase the connectivity between refuges since they contain similar habitat and serve similar purposes. The FWS has a system called the Land Acquisition Priority System (LAPS), which could be altered so that climate change based selection criteria are used to select parcels of land for acquisition (Griffith et al. 2009). Using this system with altered selection criteria, optimal land parcels could be selected or added to each NWR that would lead to mitigation and adaptation outcomes. For example, with the likelihood that wetland will migrate further inland throughout the entire region, land parcels that are likely to convert to or remain wetland as SLR occurs can be selected for expansion or establishment. Another consideration for future wetland site selection is that with SLR, many shoreline armoring projects will likely be implemented to prevent the loss of infrastructure. Shoreline armoring will impact where wetlands are able to develop, and should therefore be considered in planning processes and site selection (Glick et al. 2008). For forests, site selection should be prioritized to areas that will not experience inundation with SLR. In particular, James River, Mason Neck, and Rappahannock River Valley NWRs contain more forest than wetland and experience relatively lower amounts of SLR. These refuges could be ideal candidates to reprioritize for forest conservation and help make up for forest lost in other refuges throughout the region.

### *5.4.5 Coastal Forest and Wetland Restoration and Conservation*

Apart from new refuge establishment and expansion, restoration and conservation efforts that take SLR into consideration should be enacted now in NWRs since current actions can help prevent future loss (Griffith et al. 2009; Glick et al. 2008). The six refuges (Eastern Neck NWR, James River NWR, Occoquan Bay NWR, Rappahannock River Valley NWR, Eastern Shore of Virginia NWR, and Mason Neck NWR) that would retain more total area than wetland lost would be ideal candidates for restoration and conservation efforts for all ecosystem types present. This would allow for those refuges to maintain high quality habitat as SLR occurs, which would help them accomplish their goals of protecting and conserving wildlife.

Further highlighting the need for action to be taken as soon as possible is the loss of forest that will be experienced with SLR. Since forests consist of slower growing species and regeneration and migration takes considerably longer then wetland regeneration, proactive planning and efforts to mitigate the impacts of forest loss are especially important to ensure that forest cover within the refuges remains at a level that will allow the refuge to accomplish its purpose (Dyer 1994). Considering that there is likely to be impacts on forest from inundation in each of the NWRs in this study by the year 2050, and then potentially even more impact by 2100, efforts to restore and protect forest in and around each NWR should be prioritized. This prioritization would fill a gap in many of the CCPs since forest loss from SLR and climate change is not always specifically addressed. As with expanding the refuges in general, adaptation can occur along with mitigation via restoration and conservation efforts. Land that is chosen for forest restoration and conservation efforts should be located in areas that will not only be able to support a forest ecosystem with climate change, but also increase the size and connectivity of current forest ecosystems within the refuges. This will increase the resilience of the ecosystem and NWR as a whole, as well as improve the ability of the NWRS to adapt to climate change.

#### *5.4.6 Community Outreach and Incentives*

Community outreach and incentives may also be important in mitigating and adapting to SLR. Acquisition of land to expand the NWRS may prove difficult since it would require that the FWS acquire land that is most likely not federally owned, but rather privately owned. Convincing landowners to sell or give their land up is unlikely to occur at the amount required to provide all of the land that the FWS would need to maintain the function to the NWRS given the expected loss. Therefore, other approaches, such as partnerships and coordination with landowners should be implemented as well (Griffith et al. 2009). Through these methods, landowners could understand how important their land is to wildlife and society. They could also be taught how to conserve and protect their land with specific species in mind, and could learn how conservation may be possible without losing the ability to use their land. The FWS could also implement incentive programs to encourage landowners to engage in restoration and conservation projects, which could add more habitat to the land already protected within the NWRS (Griffith et al. 2009). While these recommendations are focused more NWRS-wide, they could be implemented on a regional level within the Mid-Atlantic to allow the goals of the NWRS and individual NWRs to be met even with climate change.

## 6. Conclusion

The coastal NWRs within the Mid-Atlantic region are expected to experience significant impacts from future climate change, including SLR (Griffith et al. 2009). These NWRs provide essential habitat for the conservation of many species and support global conservation efforts given the Mid-Atlantic region’s position in the Atlantic Flyway and the designation of several refuges as Ramsar Wetlands of International Importance. Forest and wetland ecosystems will experience some level of inundation at each SLR scenario, and even if AABs are acquired, the remaining area of the NWR is often not large enough to compensate for land inundated. Current management strategies contain gaps such as a lack of specific plans for each refuge and the exclusion of forests in climate change mitigation plans. Therefore, the FWS should develop plans that are specific to each NWR focused on strategically acquiring land for refuge expansion and restoring and conserving important ecosystems, with a focus on forests, through community outreach and incentives. These plans should be specific to each NWR while considering the broader role that each NWR plays within the region relative to one another so that the refuges in the region can work both independently of each other and as a regional system. While this study quantifies the inundation of wetland and forest in each NWR, further research must be done in order to effectively create the type of plans listed above. The exact locations that would be suitable for ecosystem restoration and conservation need to be identified so that the FWS acquires land that will effectively aid in the conservation of the specific species that the refuges were established to protect. Furthermore, this study looks solely at SLR. There are many other impacts associated with climate change that may play a role in which ecosystems are able to persist in a specific location, which, when taken into account, would result in optimal land acquisition (Griffith et al 2009). Through the creation of site-specific management plans accounting for climate change and SLR adaptation for each NWR, the purpose of the individual NWR can be met, which will contribute to the success of the NWRS as a whole and contribute to the success of global conservation efforts.

**References**

1. Allen, J.L., and Lendemer, J.C. "Quantifying the impacts of sea-level rise on coastal biodiversity: A case study on lichens in the mid-Atlantic Coast of eastern North America." *Biological Conservation* 202 (2016): 119-126.

2. Boesch, D.F., W.C. Boicourt, R.I. Cullather, T. Ezer, G.E. Galloway, Jr., Z.P. Johnson, K.H. Kilbourne, M.L. Kirwan, R.E. Kopp, S. Land, M. Li, W. Nardin, C.K. Sommerfield, W.V. Sweet. 2018. Sea-level Rise: Projections for Maryland 2018, 27 pp. University of Maryland Center for Environmental Science, Cambridge, MD.

3. Chesapeake Conservancy. (2016). Land Cover Data Project. Retrieved from https://chesapeakeconservancy.org/conservation-innovation-center/high-resolution-data/land-cover-data-project/

4. Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H., and Machmuller, M. (2009). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. *Frontiers in Ecology and the Environment*, *7*(2), 73-78.

5. Czech, B., S. Covington, T.M. Crimmins, J.A. Ericson, C. Flather, M. Gale, K. Gerst, M. Higgins, M. Kaib, E. Marino, T. Moran, J. Morton, N. Niemuth, H. Peckett, D. Savignano, L. Saperstein, S. Skorupa, E. Wagener, B. Wilen, and B. Wolfe. 2014. *Planning for Climate Change on the National Wildlife Refuge System.* U.S. Fish and Wildlife Service, National Wildlife Refuge System, Washington, DC.

6. Dyer, J. M. (1994). Land use pattern, forest migration, and global warming. *Landscape and Urban Planning*, *29*(2-3), 77-83.

7. Eggleston, J. and Pope, J. "Land subsidence and relative sea-level rise in the southern Chesapeake Bay region." *US Geological Survey Circular* 1392 (2013): 30.

8. Enwright, N.M., Griffith, K.T., and Osland, M.J. "Barriers to and opportunities for landward migration of coastal wetlands with sea-level rise." *Frontiers in Ecology and the Environment* 14, no. 6 (2016): 307-316.

9. Ezer, T, and Atkinson, L.P. "Accelerated flooding along the US East Coast: on the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic oscillations." *Earth's Future* 2, no. 8 (2014): 362-382.

10. Ezer, T. and Corlett, W.B. "Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data." *Geophysical Research Letters* 39, no. 19 (2012).

11. Friar, Greta. "Ghost Forests of the Mid-Atlantic: how sea-level rise is killing our coastlines." PhD diss., Massachusetts Institute of Technology, 2017.

12. Geospatial Data and Services. (2018). U.S. Fish and Wildlife National Cadastral. U.S Fish and Wildlife Service. Retrieved from https://www.fws.gov/gis/data/CadastralDB /links_cadastral.html

13. Glick, P., Clough, J., and Nunley, B. (2008). Sea level rise and coastal habitats in the Chesapeake Bay region. Technical Report. National Wildlife Federation, Washington, DC. 121 pp.

14. Griffith, B., Scott, J. M., Adamcik, R., Ashe, D., Czech, B., Fischman, R., Gonzalez, P., Lawler, J., McGuire, A.D., and Pidgorna, A. (2009). Climate change adaptation for the US national wildlife refuge system. *Environmental Management*, *44*(6), 1043-1052.

15. Kirwan, M.L. and Megonigal, J.P. "Tidal wetland stability in the face of human impacts and sea-level rise." *Nature* 504, no. 7478 (2013): 53.

16. Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R., & Fagherazzi, S. (2016a). Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change*, *6*(3), 253.

17. Kirwan, M. L., Walters, D. C., Reay, W. G., and Carr, J. A. (2016b). Sea level driven marsh expansion in a coupled model of marsh erosion and migration. *Geophysical Research Letters*, *43*(9), 4366-4373.

18. Kleinosky, L. R., Yarnal, B., & Fisher, A. (2007). Vulnerability of Hampton Roads, Virginia to storm-surge flooding and sea-level rise. *Natural Hazards*, *40*(1), 43-70.

19. Larsen, C., Clark, I. E., Guntenspergen, G., Cahoon, D., Caruso, V., Hupp, C., & Yanosky, T. (2004). *The Blackwater NWR Inundation Model. Rising sea level on a low-lying coast: land use planning for wetlands* (No. 2004-1302).

20. Li, X., Rowley, R. J., Kostelnick, J. C., Braaten, D., Meisel, J., and Hulbutta, K. (2009). GIS analysis of global impacts from sea level rise. *Photogrammetric Engineering & Remote Sensing*, *75*(7), 807-818.

21. Maryland Department of Natural Resources. (n.d.). Maryland Mammals. Retrieved from http://dnr.maryland.gov/wildlife/Pages/plants_wildlife/Delmarva_FoxSquirrel.aspx

22. NOAA Office for Coastal Management. (2017). Frequent Questions Digital Coast Sea Level Rise Viewer. Retrieved from https://coast.noaa.gov/data/digitalcoast/pdf/slr-faq.pdf

23. Office for Coastal Management. (2019) NOAA Office for Coastal Management Sea Level Rise Data: 1-6 ft Sea Level Rise Inundation Extent. Retrieved from https://coast.noaa.gov/slrdata/

24. Pallai, C. and Wesson, K. (n.d.). Chesapeake Bay Program Partnership High-Resolution Land Cover Classification Accuracy Assessment Methodology. Retrieved from https://chesapeakeconservancy.org/wp-content/uploads/2017/01/Chesapeake_Conservancy_Accuracy_Assessment_Methodology.pdf

25. Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Ballenger, and J. Weiss. 2012. Global sea level rise scenarios for the US National Climate Assessment. NOAA Technical Memo OAR CP0-1. National Oceanic and Atmospheric Administration, Washington, DC. 37 pp.

26. Swanston, C., Brandt, L. A., Janowiak, M. K., Handler, S. D., Butler-Leopold, P., Iverson, L., Thompson, F.R., Ontl, T.A., and Shannon, P. D. (2018). Vulnerability of forests of the Midwest and Northeast United States to climate change. *Climatic change*, *146*(1-2), 103-116.

27. United States Fish and Wildlife Service. (2009). Eastern Neck National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/eastern_neck/

28. United States Fish and Wildlife Service. (2011). Back Bay National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/back_bay/

29. United States Fish and Wildlife Service. (2012). Prime Hook National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/prime_hook/

30. United States Fish and Wildlife Service. (2013a). Nansemond National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/Nansemond/

31. United States Fish and Wildlife Service. (2013b). Susquehanna National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/Susquehanna/

32. United States Fish and Wildlife Service. (2014a). Bombay Hook National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/bombay_hook/

33. United States Fish and Wildlife Service. (2014b). Wallops Island National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/wallops_island/

34. United States Fish and Wildlife Service. (2015). Glenn Martin National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/martin/

35. United States Fish and Wildlife Service. (2016). Fisherman Island National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/fisherman_island/

36. United States Fish and Wildlife Service. (2018a). Chincoteague National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/chincoteague/

37. United States Fish and Wildlife Service. (2018b). Elizabeth Hartwell Mason Neck National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/mason_neck/

38. United States Fish and Wildlife Service. (2018c). James River National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/James_River/

39. United States Fish and Wildlife Service. (2018d). Rappahannock River Valley National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/rappahannock_river_valley/

40. United States Fish and Wildlife Service. (2019a). Eastern Shore of Virginia National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/eastern_shore_of_virginia/

41. United States Fish and Wildlife Service. (2019b). Featherstone National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/featherstone/

42. United States Fish and Wildlife Service. (2019c). Occoquan Bay National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/occoquan_bay/

43. United States Fish and Wildlife Service. (2019d). Plum Tree Island National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/plum_tree_island/

44. United States Fish and Wildlife Service. (2019e). Presquile National Wildlife Refuge. Retrieved from https://www.fws.gov/refuge/presquile/

45. US Fish and Wildlife Service. (2010). Rising to the Urgent Challenge: Strategic Plan for Responding to Accelerating Climate Change Technical Report

46. US Fish and Wildlife Service Chesapeake Bay Field Office. (2016). Migratory Birds. Retrieved from https://www.fws.gov/chesapeakebay/migbird.html

47. Virginia Geographic Information Network. (2017). Virginia Land Cover Dataset. Retrieved from https://vgin.maps.arcgis.com/home/item.html?id=d3d51bb5431a4d26a313f586c7c2c848

48. Wigand, C., Ardito, T., Chaffee, C., Ferguson, W., Paton, S., Raposa, K., Vandemoer, C., and Watson, E. "A climate change adaptation strategy for management of coastal marsh systems." *Estuaries and Coasts* 40, no. 3 (2017): 682-693.

49. WorldView Solutions Inc. (2016) Technical Plan of Operations Virginia Statewide Land Cover Data Development. Retrieved from https://www.vita.virginia.gov/media/vitavirginiagov/integratedservices/pdf/LandCover_TechnicalPlanOfOperations_v7_20160506.pdf

50. Zhu, K., Woodall, C. W., Ghosh, S., Gelfand, A. E., and Clark, J. S. (2014). Dual impacts of climate change: forest migration and turnover through life history. *Global change biology*, *20*(1), 251-264.

## Appendix 1

| Percent of Wetlands and Forest Lost by 2050 (DE and MD) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bombay Hook | | Prime Hook | | Martin | | Eastern Neck | | Susquehanna | |
| | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet |
| Forest | 3 | 10 | 31 | 55 | 0 | 14 | 3 | 9 | 100 | 100 |
| Wetlands | 84 | 96 | 95 | 99 | 78 | 100 | 15 | 96 | 100 | 100 |

| Percent of Wetlands and Forest Lost by 2050 (VA) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rappahannock River Valley | | Mason Neck | | Chincoteague | | Wallops Island | | Eastern Shore of Virginia | | Fisherman Island | | Back Bay | |
| | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet |
| Forest | 0 | 1 | 1 | 1 | 3 | 16 | 0 | 4 | 2 | 4 | 20 | 40 | 1 | 16 |
| Wetlands | 30 | 61 | 50 | 56 | 62 | 74 | 55 | 96 | 75 | 86 | 71 | 82 | 28 | 75 |
| | Nansemond | | James River | | Presquile | | Plum Tree Island | | Occoquan Bay | | Featherstone | | | |
| | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | 1 foot | 2 feet | | |
| Forest | 6 | 6 | 0 | 1 | 5 | 7 | 100 | 100 | 6 | 35 | 3 | 11 | | |
| Wetlands | 95 | 99 | 22 | 25 | 88 | 96 | 87 | 99 | 43 | 86 | 70 | 92 | | |

The above tables show the percent of forest and wetlands expected to be inundated at one and two feet of SLR by the year 2050 for each NWR in the study broken up by states.

## Appendix 2

| Percent of Wetlands and Forest Lost by 2100 (DE and MD) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bombay Hook | | Prime Hook | | Martin | | Eastern Neck | | Susquehanna | |
| | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet |
| Forest | 10 | 76 | 55 | 86 | 14 | 43 | 9 | 49 | 100 | 100 |
| Wetlands | 96 | 100 | 99 | 100 | 100 | 100 | 96 | 100 | 100 | 100 |

| Percent of Wetlands and Forest Lost by 2100 (VA) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rappahannock River Valley | | Mason Neck | | Chincoteague | | Wallops Island | | Eastern Shore of Virginia | | Fisherman Island | | Back Bay | |
| | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet |
| Forest | 1 | 3 | 1 | 2 | 16 | 85 | 4 | 16 | 4 | 19 | 40 | 80 | 16 | 70 |
| Wetlands | 61 | 64 | 56 | 72 | 74 | 99 | 96 | 100 | 86 | 97 | 82 | 95 | 75 | 99 |
| | Nansemond | | James River | | Presquile | | Plum Tree Island | | Occoquan Bay | | Featherstone | | | |
| | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | 2 feet | 5 feet | | |
| Forest | 6 | 19 | 1 | 1 | 7 | 17 | 100 | 100 | 35 | 67 | 11 | 31 | | |
| Wetlands | 99 | 100 | 25 | 32 | 96 | 98 | 99 | 100 | 86 | 96 | 92 | 99 | | |

The above tables show the percent of forest and wetlands expected to be inundated with High carbon emissions at two and five feet of SLR by the year 2100 for each NWR in the study broken up by state.

## Appendix 3

| Percent of Wetlands and Forest Lost by 2100 (DE and MD) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bombay Hook | | Prime Hook | | Martin | | Eastern Neck | | Susquehanna | |
| | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet |
| Forest | 10 | 67 | 55 | 80 | 14 | 43 | 9 | 41 | 100 | 100 |
| Wetlands | 96 | 100 | 99 | 100 | 100 | 100 | 96 | 100 | 100 | 100 |

| Percent of Wetlands and Forest Lost by 2100 (VA) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rappahannock River Valley | | Mason Neck | | Chincoteague | | Wallops Island | | Eastern Shore of Virginia | | Fisherman Island | | Back Bay | |
| | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet |
| Forest | 1 | 2 | 1 | 2 | 16 | 74 | 4 | 11 | 4 | 18 | 40 | 80 | 16 | 62 |
| Wetlands | 61 | 64 | 56 | 71 | 74 | 98 | 96 | 100 | 86 | 95 | 82 | 94 | 75 | 97 |
| | Nansemond | | James River | | Presquile | | Plum Tree Island | | Occoquan Bay | | Featherstone | | | |
| | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | 2 feet | 4 feet | | |
| Forest | 6 | 16 | 1 | 1 | 7 | 15 | 100 | 100 | 35 | 61 | 11 | 25 | | |
| Wetlands | 99 | 100 | 25 | 30 | 96 | 97 | 99 | 100 | 86 | 96 | 92 | 97 | | |

The above tables show the percent of forest and wetlands expected to be inundated with Medium carbon emissions at two and four feet of SLR by the year 2100 for each NWR in the study broken up by state.

## Appendix 4

| Percent of Wetlands and Forest Lost by 2100 (DE and MD) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bombay Hook | | Prime Hook | | Martin | | Eastern Neck | | Susquehanna | |
| | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet |
| Forest | 3 | 19 | 31 | 70 | 0 | 43 | 3 | 29 | 100 | 100 |
| Wetlands | 84 | 96 | 95 | 100 | 78 | 100 | 15 | 100 | 100 | 100 |

| Percent of Wetlands and Forest Lost by 2100 (VA) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rappahannock River Valley | | Mason Neck | | Chincoteague | | Wallops Island | | Eastern Shore of Virginia | | Fisherman Island | | Back Bay | |
| | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet |
| Forest | 0 | 2 | 1 | 1 | 3 | 36 | 0 | 8 | 2 | 11 | 20 | 60 | 1 | 42 |
| Wetlands | 30 | 62 | 50 | 57 | 62 | 82 | 55 | 99 | 75 | 92 | 71 | 89 | 28 | 91 |
| | Nansemond | | James River | | Presquile | | Plum Tree Island | | Occoquan Bay | | Featherstone | | | |
| | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | 1 foot | 3 feet | | |
| Forest | 6 | 10 | 0 | 1 | 5 | 10 | 100 | 100 | 6 | 51 | 3 | 18 | | |
| Wetlands | 95 | 99 | 22 | 29 | 88 | 97 | 87 | 100 | 43 | 94 | 70 | 96 | | |

Tables 9 and 10. The above tables show the percent of forest and wetlands expected to be inundated with Low carbon at one to three feet of SLR by the year 2100 for each NWR in the study broken up by state.