

Impacts of Climate Change on Coastal Forests in the Northeast US



Photo courtesy of Jennifer Walker

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December 2020



This work was conducted for the Northeast Climate Hub under United States Department of Agriculture, United States Forest Service Agreement 19-JV-11242306-054.

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Acknowledgments

The authors are grateful for the support and guidance of the USDA-Northeast Climate Hub leadership including David Hollinger, Regional Hub Director and Erin Lane, Regional Hub Coordinator as well as additional project support from Chris Miller, USDA NRCS; Steve McNulty and Nancy Gibson, USDA Southeast Climate Hub; and Cynthia West, Executive Director Office of Sustainability and Climate, USDA Forest Service.

We wish to acknowledge all our colleagues from throughout both the Northeast region and the Southeast region, who generously participated in interviews, as well as the convening in January 2020. Report reviewers who we would like to recognize include Ken Able, Professor Emeritus, Rutgers University; Anthony Broccoli, Distinguished Professor, Rutgers University; Glen Carleton, United States Geological Survey, New Jersey Water Science Center; LeeAnn Haff, Partnership for the Delaware Estuary; Robert Kopp, Professor, Rutgers University; and Jennifer Walker, Rutgers University. Special thanks to Karrah Kwasnik, USDA-Northeast Climate Hub and Glen Carleton, United States Geological Survey, New Jersey Water Science Center for their invaluable visualization and graphics help.

Thank you to Ms. Julie Blum, Rutgers University, who assisted us with the preparation and execution of the convening. We also acknowledge the efforts and assistance of the staff at the National Agricultural Library.

Please cite as:

Sacatelli, R., Lathrop, R.G., and Kaplan, M. (2020). Impacts of Climate Change on Coastal Forests in the Northeast US. Rutgers Climate Institute, Rutgers University, New Brunswick, NJ. 48 p. DOI: <https://doi.org/doi:10.7282/t3-n4tn-ah53>

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Purpose

To better enable climate-smart decision-making, the U.S. Department of Agriculture Northeast Climate Hub engaged researchers at Rutgers University to conduct a synthesis of the current state of knowledge concerning how Northeastern U.S. coastal forests, specifically those in mid-Atlantic and southern New England states (VA, MD, DE, NJ, NY, CT, and MA), are responding to impacts from climate change. Drawing upon the scientific literature, expert interviews, and a January 2020 convening of scientists and land managers at the U.S. National Agricultural Library, Beltsville, Maryland, this synthesis identifies key knowledge gaps as well as potential management approaches.

Introduction

Sea-level rise in the Northeast and mid-Atlantic to date is higher than the global average due to the effects of both natural and anthropogenic land subsidence, and potentially also in the future due to changes in ocean circulation and gravitational effects of Antarctic ice melt (Sweet et al., 2017b; Kopp et al., 2019). The rise of global temperatures, approximately 1°C above pre-industrial levels, has caused thermal expansion of the warmer ocean water and land ice to melt, with both contributing to an acceleration in the rise of global mean sea level (Allen et al., 2018; Gregory et al., 2019; Nicholls and Cazenave, 2010). Local relative sea-level rise is projected to continue to be higher in the Northeastern U. S. than many areas around the globe (Kopp et al. 2019; Gornitz et al., 2019; Boesch et al. 2018; Sweet et al., 2017b; Oppenheimer et al., 2019). Coastal flooding from storm surge associated with tropical cyclones (hurricanes and tropical storms) and extratropical cyclones (Nor'easters) affects our coastlines; historical sea-level rise has intensified this coastal storm flooding (Gornitz et al., 2019).

Higher sea levels will increase flood baselines and increase impacts from high tides and coastal storms such as hurricanes and Nor'easters (Kopp et al., 2019). While most studies do not project an increase in the global frequency of tropical cyclones, the intensity with respect to maximum wind speeds and rate of rainfall is likely to increase (Kopp et al., 2019). Changes in tropical cyclone frequency, wind speed, and tracks remains an area of active research (Kopp et al., 2019). The scientific consensus regarding changes in the frequency of wind speed, precipitation rate, and tracks of extratropical cyclones remains an active discussion (Kopp et al., 2019).

When coupled with rising sea level, the historic and projected increase in severity of storm surge is likely to increasingly affect coastal forests, defined below, in the mid-Atlantic and southern New England states of the U. S. (USGCRP, 2018). In a recent assessment of the vulnerability of these forest ecosystems to future climate change, two specific forest communities, maritime forests and tidal swamps of the coastal plain, were rated as having high to moderate-high vulnerability (Butler-Leopold et al., 2018).

The coastal forests of the mid-Atlantic and southern New England states are commonly a mix of deciduous hardwoods and evergreen conifers with the species composition dependent upon the site level soil moisture gradient and coarser scale latitudinal gradients in species ranges (Anderson et al., 2013a; Butler-Leopold et al., 2018; Janowiak et al., 2018). Drier upland forests are dominated by a diversity of oaks (including white (*Quercus alba*), southern red (*Q. falcata*), scarlet (*Q. coccinea*), and black (*Q. velutina*)) and pines (including pitch (*Pinus rigida*), loblolly (*P. taeda*), Virginia (*P. virginiana*) and shortleaf (*P. echinata*)) (Anderson et al., 2013b). The wetter end of the gradient is dominated by red maple (*Acer rubrum*), black gum (*Nyssa sylvatica*), American Holly (*Ilex opaca*), loblolly pine (at southern end of region), pitch pine (in

the central portion of the region) and Atlantic White Cedar (*Chamaecyparis thyoides*) (Anderson et al., 2013b). The transition zone between the salt marsh and adjacent forest is often comprised of common reed (*Phragmites australis*, henceforth referred to as *Phragmites*), marsh elder (*Iva frutescens*), highbush blueberry (*Vaccinium corymbosum*), and eastern red cedar (*Juniperus virginiana*) (Anderson et al., 2013b). The forests serve as habitat to a diversity of rare plants and animals including a number of species of concern (Global Rank G1-G4) (Anderson et al., 2013b). Federally or state listed species include the swamp pink (*Helonias bullata*), rose coreopsis (*Coreopsis rosea*) and cypress swamp sedge (*Carex jooarii*) among others (Anderson et al., 2013; USDA NRCS Plants Profile). Other ecosystem services include carbon storage (McGarvey et al., 2015, Fahey et al., 2010), valuable timber resources, and, in concert with adjacent salt marshes, protective buffering of inland areas against coastal storms (Williams et al., 2003; Barbier et al., 2011; Duarte et al., 2013).

Various studies have documented that these coastal forests are showing signs of stress evidenced by trees at the forest-tidal salt marsh edge dying back and the forests transitioning into tidal salt marsh ecosystems (Kirwan and Gedan, 2019; Smith, 2013; Sacatelli, 2020). These areas have been dubbed “ghost forests” denoting the presence of standing dead trees within or fringing the edge of salt marsh ecosystems (Kirwan and Gedan, 2019; Able et al., 2018; Able, in review). While this phenomenon of coastal forest dieback and replacement with salt marshes as sea level rises has been ongoing for millennia (Clark, 1986), the concern prompting this assessment is that accelerating sea-level rise and intensifying coastal storms will further hasten this process.

Based on our review of the peer-reviewed literature and interviews with scientific experts, a conceptual model was developed identifying the key driving processes, mechanisms, and ecosystem responses and their linkages (see Figure 1). Climate change and attendant effects

on sea-level rise and storm frequency and intensity represent the ultimate driver of the system. These climate drivers initiate a chain of proximate mechanisms that are operating at both shorter term decadal time scales and longer term processes working over centuries to millennia (Able et al., 2018). Figure 2 illustrates two proximate mechanisms associated with rising sea levels that appear to be especially significant: a rising groundwater table and periodic inundation by saline water. These mechanisms change soil conditions along the upland fringe leading to accelerated tree mortality. These same proximate mechanisms also affect subsequent vegetation community dynamics following tree dieback. It is expected that an acceleration of sea-level rise rates will further intensify the effects of these mechanisms either singly or in concert. Over longer time scales, the marsh-forest ecotonal boundary or the transition zone shifts landward as sea levels steadily rise and salt marsh vegetation gradually invades the dead or dying forest. Anthropogenic factors such as ditching due to mosquito management are included as external factors that can heighten or constrain the intensity of these mechanisms.

The following review of the peer-reviewed literature explores these mechanisms and ecosystem responses along the mid-Atlantic and southern New England seaboard of the U.S. and synthesizes additional insights provided in interviews with experts in the field. Gaps in scientific understanding are highlighted based on expert interviews as well as discussions held at a January 2020 workshop of scientists and land managers. Finally, we examine several techniques for managing coastal forests to reduce the impacts of climate change.

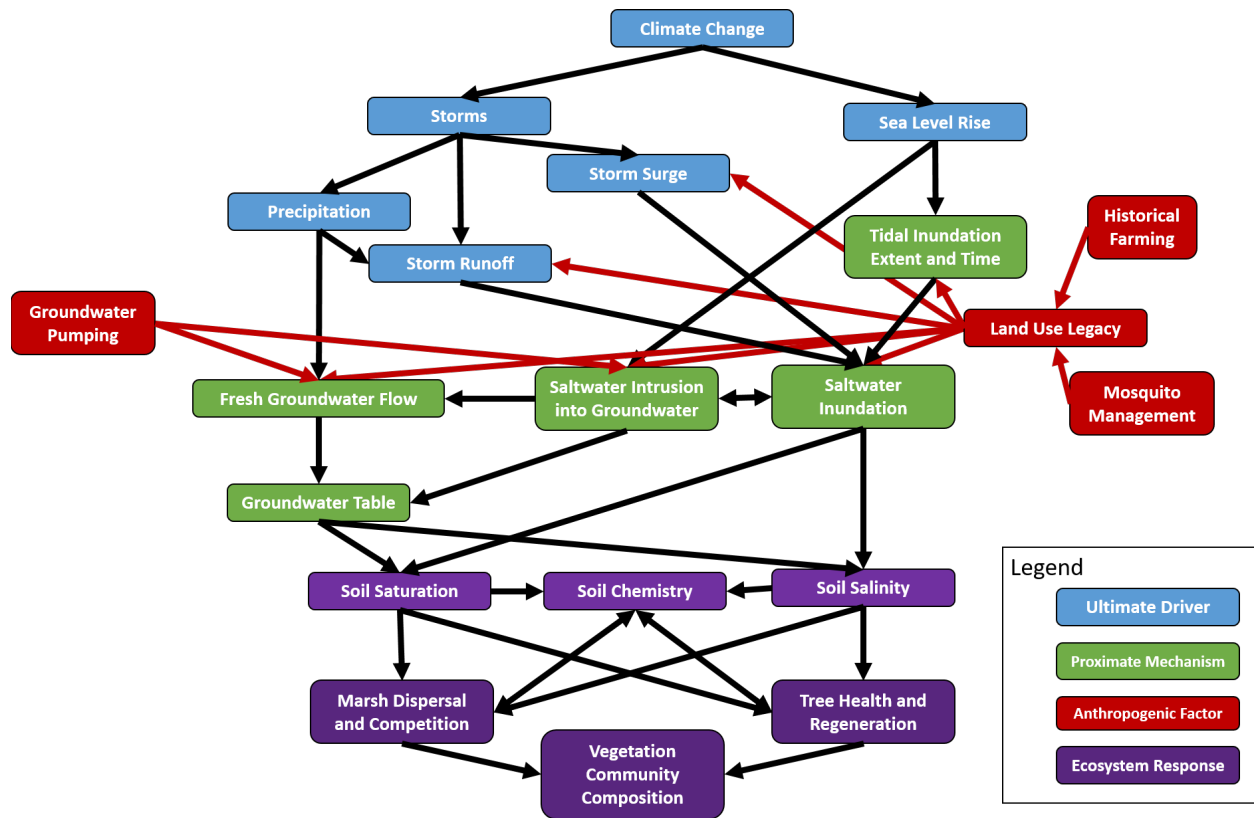


Figure 1. A concept map summary of processes controlling forest edge migration as compiled from relevant literature. The blue color denotes the ultimate drivers of change. Green denotes proximate mechanisms of change. Red denotes external anthropogenic factors that have a role in change. Purple is the ecosystem-level response that occurs due to the changes in the controlling processes.

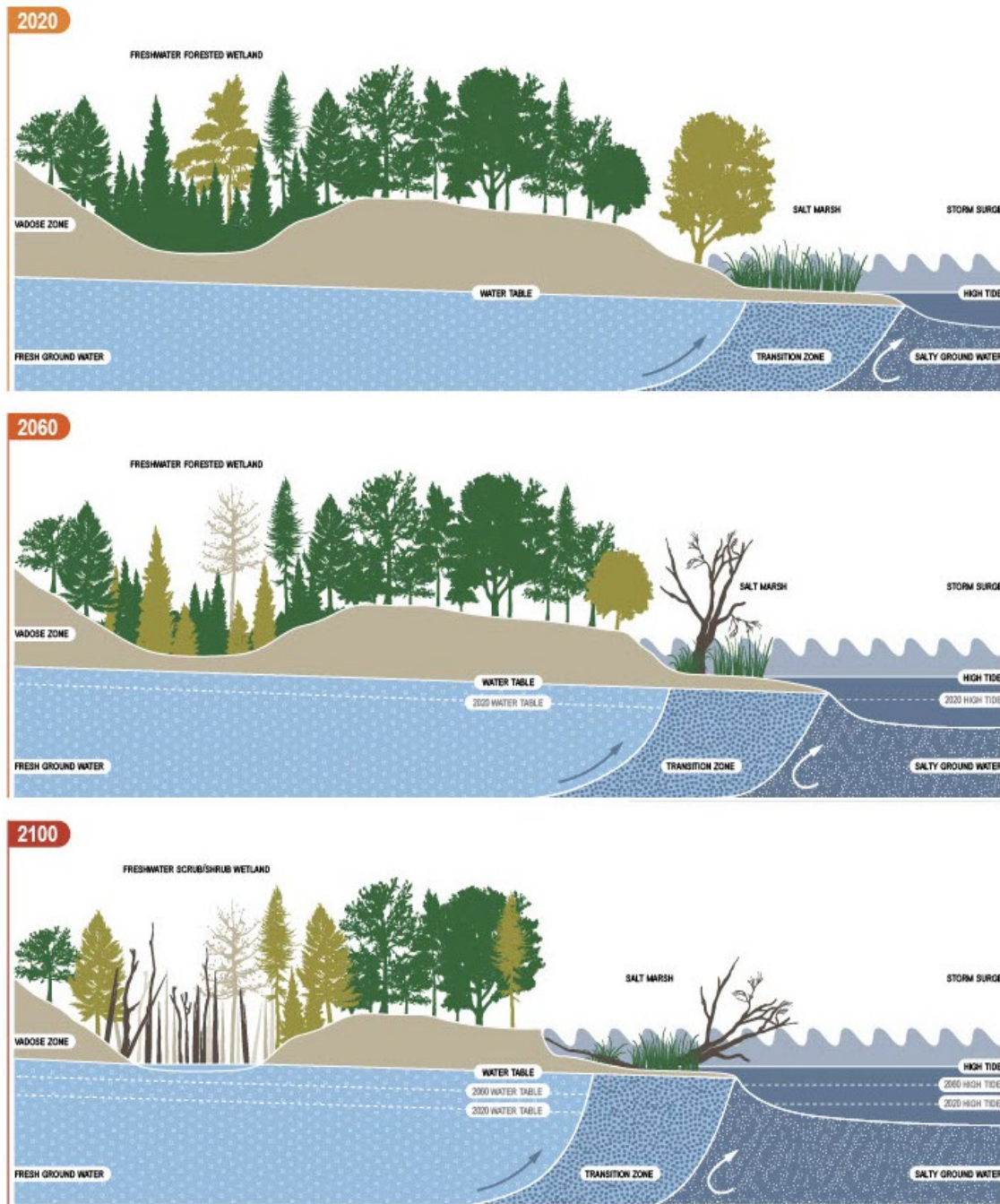


Figure 2. The baseline for coastal flooding rises as sea level rises, bringing further inland daily/monthly tidal flooding, periodic storm surges, and the fresh/saline transition zone in shallow groundwater. Over time, the further inland reach of storm surges results in coastal forest dieback (referred to as ghost forests because of still standing dead trees). Rising sea levels also raise the water table tens to hundreds of meters inland from tidal waters, resulting in a thinning vadose zone such that the water table is closer to the ground surface. The resulting saturated soils stress existing vegetation and can ultimately convert forested wetlands to standing-water wetlands with accompanying forest dieback. Not shown but also important: near-shore, low-lying freshwater wetlands become brackish as storm surges reach farther inland and the shorter interval between storm surges results in less dilution between events by precipitation and groundwater flow. Note: drawing not to scale. (Graphic credit: Karrah Kwasnik, US Department of Agriculture; Glen Carleton, US Geological Survey; Richard Lathrop, Marjorie Kaplan, and Rachael Sacatelli, Rutgers University).

Literature Review

The dieback of the forest ecosystem at the salt water tidal marsh edge (or marsh/forest ecotone) and transition to tidal salt marsh ecosystems is referred to in the literature as the migration (or transgression) of the salt water tidal marsh or coastal forest (Kirwan and Gedan, 2019, Hussein, 2009; Smith, 2013; Schieder et al., 2018; Sacatelli, 2020). The concern, mentioned above, that this migration will be hastened by accelerating sea-level rise and intensifying coastal storms is due to the link between the vegetation communities and specific physical environmental factors (Proximate Mechanisms in Figure 1). Therefore, to understand the impact that changing storm surges and rising sea level has on the forest ecosystem, it is instructive to first examine the relationship between the physical environment and vegetation zonation.

Physical Environment and Vegetation Zonation

The hydrology of the Northeastern US tidal salt water marsh and coastal forest landscape is complex. Precipitation leads to fresh water recharge of surficial aquifers that flows from inland/upland recharge areas to discharge areas in freshwater wetlands and streams, brackish estuaries, and saltwater wetlands and water bodies. In coastal areas, less dense fresh groundwater discharging to saltwater wetlands or water bodies flows over denser saline water.

The salinity of groundwater can be influenced by mixing with adjacent tidal saline water, by underlying denser saline water, and/or infiltration of saline water that inundates land surface during exceptional high tides and storm surges. In inland areas of coastal forests, freshwater recharge and inflow of fresh groundwater from upland areas result in a freshwater-only environment. In coastal areas, fresh groundwater discharges over denser saline water and there is typically a transitional mixing zone of varying salinity. Tidal salt marshes often have complex

interactions of fresh and saline water, with fresh groundwater discharging through the salt marsh at low tide and saline water inundating the marsh surface at high tide (Barlow, 2003).

The interactions of fresh groundwater recharge from precipitation, fresh groundwater discharge to tidal waters, saltwater inundation over the land surface, and fresh river flow into estuaries have important implications for soil and vegetation of the lower northeastern salt marsh and coastal forest landscape (i.e., Ecosystem Response in Figure 1). Salinity of water in the rooting zone, or pore water, is a critical factor affecting the coastal forest ecosystem. Moving from the marsh-forest boundary into the coastal forest, the pore water salinity changes and is influenced by a combination of precipitation, groundwater flow from upland areas, salt deposition from marine aerosols (especially during storms), overland saltwater inundation from extreme lunar tides and storm surges, and evapotranspiration (Wilson et al., 2015; Wells and Shunk, 1938).

The high flooding frequency in the lower elevations leads to highly saline pore water conditions and therefore are often colonized by salt-tolerant (i.e., halophytic) graminoid and herbaceous plants to form salt marshes. Further inland/upslope where tidal flooding is infrequent, the influence of precipitation and groundwater becomes the driving factor controlling pore water salinity in the unsaturated zone¹ (Barlow, 2003) and creates soil characteristics that allow trees to germinate and grow. These fringing forests may be comprised of species that have a moderate degree of salt tolerance (such as eastern red cedar, *Juniperus virginia* or the American holly, *Ilex opaca*) (USDA 2002a; USDA 2002b) and are able to tolerate occasional storm-driven salt spray

¹ The unsaturated zone is the portion of the subsurface above the ground water table. The soil and rock in this zone contains air as well as water in its pores. Hydrologically, the unsaturated zone is often the main factor controlling water movement from the land surface to the aquifer. See “USGS Groundwater Information: Unsaturated Zone” available at <http://water.usgs.gov/ogw/unsaturated.html>

(a few times per year) (Appleton et al. 2009). Where saltwater inundates the coastal forest during extreme storm or tidal events, pore water and shallow groundwater salinity increases from the pulse of saltwater and then gradually decreases as freshwater infiltration from precipitation and horizontal flux from higher-elevation freshwater-recharge areas inland serve to dilute the salinity. Farther inland, coastal wetland forests may be comprised of species that have low salt tolerance and would not survive extensive salt spray or saline soils from an inundation event despite the eventual dilution of the soil salinity (Appleton et al., 2009).

This variation in salinity of the pore water, normal tidal flooding extent, and storm surge flooding frequency influence the spatial distribution of vegetation communities in the marsh/forest ecotone (Strange et al., 2008; Barlow and Reichard, 2010). Due to variation in the salt and soil saturation tolerances of individual plant species, lateral salinity changes and flooding conditions combined with the intense competitive relationships of the species within these habitats creates well-delineated vegetation zones (Bertness, 1991; Bertness and Ellison, 1987, Strange et al., 2008). The strong links between flooding frequency, pore water salinity, and soil saturation are key factors in determining the spatial distribution of coastal vegetation communities and the location of the marsh-forest ecotone (Figure 1).

Potential Proximate Mechanisms Controlling Forest Dieback

The strong link between the soil characteristics and flooding frequency to the location of the various vegetation communities in the salt marsh/coastal forest landscape of the lower northeast makes these communities vulnerable to changes in these environmental factors. As discussed above, the vegetation communities have specific ranges of these environmental factors in which they can be successful both due to the species tolerances of these factors and competition between vegetation communities. If the soil moisture, soil salinity, or flooding

frequency changes, the vegetation communities, including the coastal forest, may no longer be able to inhabit their historical locations. In this section we will discuss how these environmental factors are currently changing due to a combination of sea-level rise and other anthropogenic factors and how these changes effect the coastal forest ecosystem.

Soil Saturation and Groundwater

In coastal locations where inland groundwater discharges directly to tidal marshes and water bodies (as opposed to non-tidal, higher-elevation streams and wetlands), groundwater level rises as sea-level rises (Bjerklie et al., 2012; Knott et al. 2019). Rising groundwater levels reduce the thickness of the unsaturated zone (reduce the depth to groundwater). With the fresh groundwater table closer to the surface there is an increasing incidence of saturated soil conditions in low-lying coastal areas (Nuttle and Portnoy 1992; Masterson et al., 2013). If the unsaturated zone decreases, the soil in the rooting zone of the coastal forest maybe become saturated. Saturated soil greatly limits the amount of oxygen that tree roots can obtain. The absence (anoxia) or near absence of oxygen in the soil (hypoxia) can also promote the growth of anaerobic bacteria that may produce conditions toxic to plants (Whitlow and Harris, 1979). Most trees can withstand a few days of fresh water flooding during the growing season but extended flooding conditions affects plant growth, development and survival (Kozlowski, 1997; Parent et al., 2008). While riparian tree species (i.e., tree species adapted to floodplains or freshwater swamp environments) tend to be more tolerant of saturated soils and the resulting anoxic conditions than upland species (Whitlow and Harris, 1979; Kozlowski, 1997; Kramer et al. 2008), very few riparian or wetland tree species can withstand extended soil inundation (Kozlowski, 2002).

Raphael (2014) documented longer term shifts in the vegetation composition of the maritime forest growing on the dune and swale topography of Fire Island, NY. The American Holly-dominated forest (*Ilex opaca*) in the swale depressions are experiencing increasing mortality in the tree canopy layer and limited seedling/sapling recruitment, which Raphael (2014) attributed to increasingly saturated soil conditions from thinning of the unsaturated zone which brings the ground water system closer to the ground surface. Similarly, in a loblolly pine-dominated coastal forest in Maryland, Kirwan et al. (2007), documented an absence of recruitment of new pines despite abundant seedlings and an open canopy, suggesting that the recruitment ability appears to be limited by saturated soils. Given that rising sea levels are leading to higher ground water tables and saturated soil conditions in low-lying areas (Figure 1), this process is likely a slow but steady contributor to coastal forest dieback (Kirwan et al., 2007; Masterson et al., 2014; Fagherazzi et al., 2019).

Soil Salinity and Severe Storms

Severe storms coupled with increased sea-level rise increase the magnitude and longevity of storms (USGCRP, 2018; Woodruff, et al., 2013, Sweet et al., 2017a). Storm surge-related surface inundation of saltwater can intensify the soil pore water salinization, (Fagherazzi et al., 2019). The impact of this influx of saline water can last for several years after the storm (Dai et al., 2011). Increases in salinity of the pore water can directly limit vegetative growth and cause other changes in soil chemistry (Figure 1). The increased salinity can stress the coastal forest vegetation causing leaves to brown (i.e., scorch) or fall and decreases both water uptake and the organism's nutrient metabolism, negatively affecting the trees' growth rates (Kozlowski, 1997; Fernandes et al., 2018). Higher soil salinity levels can also increase the solubility of minerals and other solutes, altering biogeochemical cycles (Herbert et al., 2015; Hopfensperger et al., 2014).

Increasing salinity levels affect nitrogen uptake, denitrification, and carbon mineralization rates in experimentally manipulated forest soils (Craft, 2012; Marton et al., 2012; Ardón et al., 2013; Ardón et al., 2018; Jun et al., 2013) which may also impact the health and growth of trees.

Locations that are inundated by saltwater for extended periods or several times per year may have salinity high enough/long enough to kill trees whereas locations that are briefly inundated by a storm tide once every few years may have transient salinity beneath the fatal threshold for trees (McKee et al., 2016; Holt et al., 2017).

Stalter and Heuser (2015) documented the effect of Superstorm Sandy on American Holly trees (*Ilex opaca*) on Sandy Hook, New Jersey. Hollies growing on lower dune ridges that were inundated by surge waters experienced 50-75% initial leaf loss followed by 85% leaf recovery. Hollies growing in salt water-filled depressions were killed (Stalter and Heuser, 2015). Atlantic white cedar (*Chamaecyparis thyoides*) are especially susceptible to storm surge salt water inundation with extensive diebacks of entire stands following storms (USDA Forest Service, undated). In 2012, Superstorm Sandy affected Atlantic white cedar swamps growing in the coastal margin of New Jersey (Figure 3).

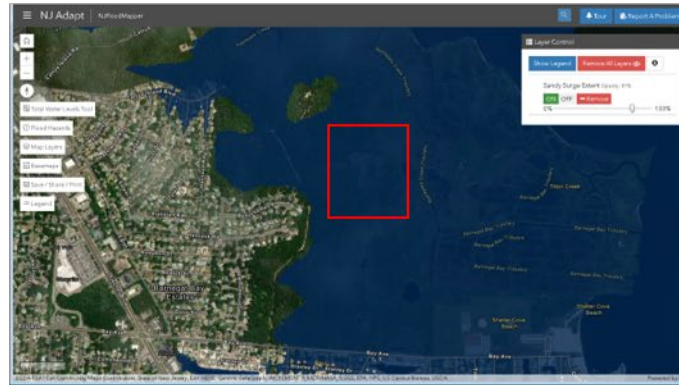
Salinity stress is especially evident in tree seedlings as seedlings have a much higher sensitivity to changes in salinity as compared to their full-grown counterparts (Kearney et al., 2019). Seedlings of common coastal tree species, such as red maple (*A. rubrum*), were found to be highly sensitive to saltwater flooding with height and diameter growth significantly reduced (Conner and Askew, 1993). Work on the west coast of Florida by Williams et al. (1998) suggested that the inability of young seedlings to resprout after storm surge-related inundation hindered subsequent tree establishment at the extreme seaward margin of the forest. This phenomenon may also apply to Northeastern coastal forests but has not been demonstrated to

Cattus Point, NJ



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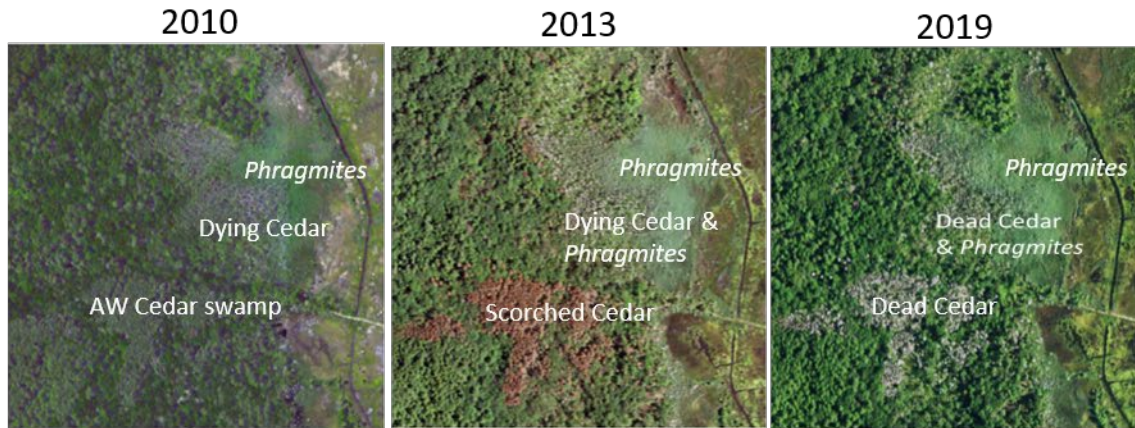
Extent of the storm surge caused by Superstorm Sandy



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Vegetation at the above area of interest

Pre-Sandy, within 1 year Post-Sandy, and 7 years Post-Sandy



USDA National Agricultural Inventory Photography (NAIP) True Color Imagery

Figure 3: Example of forest dieback near Cattus Point, Barnegat Bay, New Jersey Showing Atlantic White Cedar dominated swamps undergoing both longer term gradual dieback with replacement by Phragmites and an Extreme dieback event related to the Superstorm Sandy storm surge.

date. The net effect of higher soil salinity in the coastal forest is stressed trees with limited to no regeneration potential (i.e., Forest Health and Regeneration in Figure 1) (Fagherazzi et al., 2019; Kearney et al., 2019).

In addition to changing soil salinity, the extreme winds of severe storms can damage the coastal trees by causing breakage, defoliation, and uprooting (Merry et al., 2009). The extreme winds can also increase salt spray which can lead to leaf scorch which can cause partial or complete defoliation (Moss, 1940). Floating debris transported by waves during severe storms can come in contact with the trees and can cause damage the trees' cambium, negatively affecting nutrient transport within the tree (Stoffel et al., 2010). These damages combined with the stress caused by the increased soil salinity can lead to mortality of the stressed stand (Fernandes et al., 2018; Conner and Inabinette, 2003; Fagherazzi et al., 2019). The repercussions of these storm events increase dramatically if more than one storm occurs in successive years (Douglas et al., 2018).

The proximate mechanisms of higher groundwater tables and periodic storm surges appear to work in concert in driving coastal forest dieback. Fagherazzi et al. (2019) have posited a "ratchet" model that combines the gradual "press" disturbance of sea-level rise with the intermittent "pulse" disturbance of storms. In many respects, our conceptual model (Figure 1) shares many similarities with Fagherazzi et al.'s (2019) ratchet model. One subtle distinction is that our model places a greater emphasis on the role of rising groundwater levels in increasingly stressing the forest vegetation and decreasing regeneration potential. As in both models, episodic storm surges may then exceed the salinity or saturation tolerances of existing trees leading to a wave of mortality that leaves the site inhospitable to subsequent regeneration.

Coastal Forest Edge Migration and Location

The migration of the marsh-forest ecotone has been documented at several locations across the mid-Atlantic and southern New England coast (Hussein, 2009; Smith, 2013; Schieder et al., 2018; Field et al, 2016; Sacatelli, 2020). The rates of coastal forest dieback vary widely with respect to local conditions. Schieder et al (2018) documented an average forest dieback rate of 0.5 m/yr for the entire Chesapeake Bay shoreline over the past 100+ years but found that the local rates of dieback range from 0.1 m/yr to 2 m/yr over the same timeframe. The dieback rate for two sites near Blackwater National Wildlife Refuge on the Chesapeake Bay coast has been documented by Hussein (2009) to have average rates at over 3 m/yr and 6 m/yr. Further north, Smith (2013) documented an average of 141.2 m of movement inland of the marsh-forest ecotone over 76 years for sections of the Delaware Bayshore of New Jersey, (or an average rate of 1.8 m/yr). For a study area in southern New England, Field et al. (2016) found very little tree mortality in the marsh forest ecotone despite observing shifts in the adjacent marsh vegetation community towards an increase in low marsh and a decline in high marsh. The spatial variation in the rate of forest dieback suggests that relative influence of the proximate mechanisms and consequent ecosystem responses (in Figure 1) are highly dependent on local conditions. The impact of the increasing salinity and saturation of the soils not only may vary geographically due to differences in subsurface geology, soil type, terrain slope, and landscape configuration but also there may be additional mechanisms that play a role in marsh migration.

Knowledge Gaps

The following section reflects discussions with leading experts in this field. These experts shared preliminary research findings and opinions during interviews and the workshop convening in January 2020. The compiled knowledge gaps fall into three categories: the

intricacies in the mechanisms of change; the biological responses and tolerances to these factors; and how these mechanisms and responses vary spatially.

Understanding the Proximate Mechanisms of Coastal Forest Edge Migration

Episodic storm surge-related surface inundation of saltwater can cause soil salinization, soil oxygen depletion and changes in soil chemistry. The magnitude and duration of the salinity changes in the pore water, and the effect on common Northeastern coastal forest trees deserves further research. Given that some coastal tree species have limited tolerances to fresh water soil saturation (Parent et al., 2008), higher levels of tree mortality and/or lower regeneration potential may be the result of overly saturated soils and not the salinization of the soils. More research on the magnitude, as well as the spatial and temporal variability, of these driving processes (soil saturation vs. soil salinization), either singly or in combination, is needed.

The legacy of earlier land use alterations on either intensifying or ameliorating the proximate mechanism causing coastal forest dieback is unclear (i.e., Anthropogenic Factors in Figure 1). Ditches have been widely used along the coast to increase drainage for either farming or mosquito control. In the mid-Atlantic and southern New England, parallel ditching on 90% of the tidal marshes between Maine and Virginia was completed by 1938 in an attempt to curb the large salt marsh mosquito population to address public health concerns (Bourne and Cottam, 1950). Increasing drainage on the marsh causes less standing water, and therefore less mosquito breeding locations (Wolfe, 1996). Other areas of the marsh were both diked and ditched to promote the production of *Spartina patens* (salt hay). *Spartina patens* grows best in the higher marsh elevation zone where tidal flooding and salinity levels are reduced. To create more suitable habitat, farmers diked marshes to reduce tidal flooding and ditched them to drain the saturated soils to a moisture level optimal for *Spartina patens* growth (Hinkle and Mitsch, 2005).

The presence of dikes and ditches may play a large role in the way the present marsh and upland ecosystems react to a rising sea level. The dikes limit sediment flux into the marsh thereby lowering the marsh accretion rate and creating elevation deficits in the marsh relative to rising sea levels. Ultimately, the affected marsh sits at a lower elevation in the tidal frame than other non-diked marshes (Smith et al. 2017). This may make the diked marshes more vulnerable to sea-level rise once the dikes have been breached and saline water once again flows into the marsh unrestricted. Adjacent areas of forests may likewise be more susceptible to saline intrusion. The ditches may become pathways for saline water to more easily reach interior marsh or adjacent forests, leading to more rapid change at the marsh/forest ecotonal boundary.

Groundwater discharging into ditches locally lowers the water table: groundwater flows from higher to lower head (hydraulic pressure) and a shorter flow path requires less gradient to move the water (Harvey and Odum, 1990). Ditches near the upland edge of salt marshes might locally lower the water table and increase the rate that transient inundation events are flushed from the adjacent forested areas or increase the number and severity of inundation events by creating a pathway for surface-water flow during storm surges. Better understanding the implications of these common human alterations to the marsh may inform potential restoration approaches for previously diked or ditched marshes, and likewise, suggest the potential utility of dikes or ditches as a management tool.

The human impact on this system may extend to groundwater pumping of adjacent freshwater aquifers. Groundwater pumping for drinking water or agricultural uses close to the marsh/forest ecotone may lead to increased saltwater intrusion of the groundwater (Reilly and Goodman, 1987; Ferguson and Gleeson, 2012). If a fresh groundwater pumping well is positioned above the freshwater-saltwater interface, the pumping of fresh water out of the aquifer

can result in upward vertical intrusion of salt water, known as upconing (Reilly and Goodman, 1987; Ferguson and Gleeson, 2012). The anthropogenic saltwater intrusion occurring may, in some circumstances, affect coastal forests. Extensive groundwater pumping can also exacerbate land subsidence and subsequently increase sea-level rise rates locally (Sun et al., 1999). This increase in local sea-level rise rates could accelerate repercussions of changes in other processes that are linked to sea-level rise. The groundwater pumping regime can be modified to ameliorate these impacts.

Understanding the Physiological and Ecological Response to Changes in Proximate Mechanisms of Coastal Forest Edge Migration

A deeper understanding of the physiological and ecological responses of coastal forest vegetation to a changing physical environment such as soil salinity and saturation is needed. As mentioned above, it is unclear the extent to which tree dieback observed at the forest margin is due to salt intolerance, freshwater flooding, or a combination of both. Both mechanisms may vary in importance spatially and/or temporally. A field experiment approach might be very valuable in elucidating the individual and/or synergistic effects of the mechanisms under different conditions. Additionally, investigating whether ecological factors such as species composition and competition impact how the proximate mechanisms effect the system both in conjunction with, and independent of location. While it is generally understood that different species of woody plants have varying susceptibility to saturated or saline soils, better documentation of the range in tolerance of common Northeastern U.S. coastal tree and shrub species is needed. This information may lead to a better understanding of the mechanisms operating at a site as well as inform management.

Plant community zonation patterns in the marsh/upland ecotone have been altered with introduction of the non-native common reed, *Phragmites australis*. This non-native genotype was introduced to the mid-Atlantic in the early 1900s and now occupies the upland edge of most salt marshes in this region (Mozdzer et al., 2013). *Phragmites* reproduces both by clones and seed dispersal (Hazelton et al., 2018), readily invades any habitat within its growth tolerance range, and is known for establishing quickly and flourishing in disturbed habitats (Rice and Rooth, 2000; Bart and Hartman, 2000; Chambers et al., 1999). These characteristics make *Phragmites* a highly invasive species and can result in dense monocultures within its range that extend from marsh edge to the edge of the coastal forest occasionally intermingling with coastal forest shrub species such as marsh elder (*Iva frutescens*) before transitioning to a solely coastal forest shrub and tree community. (Chambers et al., 2003; Windham and Lathrop, 1999; Windham, 2001). *Phragmites* is also a very hardy plant (Engloner, 2009) and can likely withstand some of the changes in pore water and saturation that are occurring due to the rise in sea level as well as any episodic flooding that occurs from storm surge. These characteristics allow *Phragmites* to readily invade into areas of forest dieback at the marsh/forest ecotone (Smith, 2013; Sacatelli, 2020; Able et al. 2018). As forest trees die, *Phragmites* can quickly monopolize these canopy openings and shade out tree and shrub seedlings, thereby limiting forest regeneration, especially if an adjacent *Phragmites* stand is well established before the mortality occurs. However, *Phragmites* has lower salt-tolerance than some marsh species such as *Spartina patens* (Moore et al., 2012). Because pore water salinity increases towards the marsh shoreline edge in these coastal wetlands, *Phragmites* is only able to invade seaward until salinities reach a threshold where it is out-competed by the more salt-tolerant *S. patens* or *D. spicata*. The degree to which *Phragmites* is limited to hydric soils or sufficient light levels in an

upland environment is less clear. There is some evidence that *Phragmites* could both accelerate forest loss and hinder subsequent replacement by native marsh grass. Understanding the nuances of the *Phragmites* invasion, the inhibiting effect it might have on forest regeneration, and the eventual consequences on salt marsh expansion can lead to better management of the ecotone.

The effect of other invasive species on forest health must also be considered. For example, *Dendroctonus frontalis* (southern pine beetle) has expanded into areas of New Jersey, New York, and Connecticut (Lesk et al., 2017). *D. frontalis* is particularly attracted to *Pinus rigida* (pitch pine), *Pinus taeda* (loblolly pine), and *Pinus echinata* (shortleaf pine) which occupy many of the coastal forests in the mid-Atlantic and southern New England (Anderson and Doggett, 1993). With increasingly warmer winters that may become typical of this region, *D. frontalis* may become more and more of a concern for coastal forests. The presence of pests like *D. frontalis* may cause greater damage at the marsh-forest ecotone if the trees are already under stress from changes in groundwater, soil salinization or have sustained storm surge damage. Conversely, pests may weaken the trees making them more susceptible to subsequent storm surge flooding, and thereby leading to greater mortality than may not have occurred otherwise.

Understanding the Spatial Variation in Coastal Forest Edge Migration

While various studies documenting rates of coastal forest dieback have been conducted at several locations in the Mid-Atlantic and southern New England (Smith, 2013; Hussein, 2009; Schieder et al., 2018; Sacatelli, 2020), a more comprehensive regional-scale analysis of coastal forest dieback and marsh migration would lead to a better understanding of the scope of this phenomenon. Such regional quantification of forest productivity changes or losses would provide better estimates of the tradeoffs and loss of ecosystem services.

Additionally, depending on geographic location and landscape features such as elevation, the key mechanisms of forest dieback and marsh migration may vary from site to site. Therefore, each of the identified knowledge gaps must be explored with respect to location. The identification of key drivers in a spatial context would allow for more comprehensive modeling of future forest dieback under various sea-level rise scenarios. While models of marsh migration and forest dieback have been created (e.g., SLAMM (Warren Pinnacle, 2016)), the refined parameterization of these models based on more detailed knowledge of the causal mechanisms is needed.

Summary of Knowledge Gaps and Future Research Needs

- Intensive *in situ* measurement of the variation of groundwater depths and salinity levels across the marsh to forest ecotone in geographically varied sites: testing differences between altered (sites that are diked or ditched) vs. unaltered (or less altered) marshes, and other experimental designs to elucidate the effects of adjacent groundwater pumping.
- Response of soil pore water and soil chemistry at the marsh-forest ecotone due to the changes in salinity and depth to the groundwater and the spatial variability of those changes in geographically varied sites: altered (sites that are diked or ditched) vs. unaltered (or less altered) marshes, and in the presence of adjacent groundwater pumping.
- Salinity and saturation physiological tolerances of important coastal tree and shrub species, as well as the ecological consequences of species-specific tolerances across broader landscapes.
- Southern pine beetle and other pests' effect on the rate of marsh-forest ecotonal migration.

- Better understanding of the degree to which different proximate mechanisms operate singly or in combination under different environmental/terrain conditions and vegetation community compositions in affecting forest dieback and the rate of marsh-forest ecotonal migration.
- Controlled studies of *Phragmites* invasion (i.e., shade tolerance, salinity tolerance, competition between *Phragmites* and forest species and between *Phragmites* and high marsh species).
- Comprehensive mapping and intensive *in situ* and remotely sensed observation of the spatial extent, composition, and rate of forest dieback at geographically varied sites: altered (sites that are diked or ditched) vs. unaltered (or less altered) marshes, and in the presence of adjacent groundwater pumping.
- Comprehensive modeling and characterization of the potential dieback of coastal forests at the marsh-forest ecotone under various scenarios of sea-level rise and future time frames across the Northeastern U.S. region.

Management

The consensus of the scientists and managers at the January 2020 convening of experts was that much of current management focuses on protecting or assisting the salt marsh ecosystem and comparatively less attention has been paid to specifically managing the adjacent forest ecosystem. Maintaining eroding marsh shoreline edges through “living shorelines” restoration techniques, enhancing vertical accretion rates of the marsh platform via thin layer deposition of dredge spoil sediments, and increasing drainage in ponded marsh interiors are all examples of techniques that are focused primarily on the management of the salt marsh (Wigand

et al., 2017). These marsh management techniques may have some positive value in slowing the negative impact of sea-level rise to adjacent forest ecosystems, though these effects have not been well documented.

Mitigating forest losses as a management goal has particular merit for protecting biodiversity but being specific about the strategy for this mitigation is important. There are two possible strategies to protect the forest ecosystem: to maintain the existing upland forest in-place or to manage the forest as it responds and retreats inland in response to marsh expansion. The following discussion of possible management practices applicable to coastal forest dieback, facilitated by the contributions of scientists and land managers working within the salt marsh/coastal forest system, has been organized into three main topics: hydrological, vegetation community, and migration preparation. Depending on the management strategy, it may be possible to manipulate both the hydrology and vegetation communities to push the system in the desired direction. Many of these concepts can potentially be used to either assist or hinder forest migration.

Due to the spatially variable nature of the proximate mechanisms (Figure 1), identifying which mechanisms may be dominant at a specific site and understanding the possible synergistic effects among mechanisms helps illuminate the potential outcomes of a given management strategy. For example, a management practice might be useful in ameliorating the short-term effects of a storm surge event but may be ineffective in responding to a longer-term rise in the water table that has exceeded a given threshold. Site-specific information will ideally help create more effective management plans as well as curb the number of unintended consequences. However, adequately teasing out the site-specific proximate mechanisms may be difficult and expensive, resulting in a lack of information that makes decisions as to the most appropriate

management response challenging. A goal moving forward should be consideration of marsh and adjacent forests as an integrated system and further alignment of management objectives for both.

Hydrological Management

Manipulation of a site's hydrology to maintain optimal conditions for the existing community of tree species might be an option at a particular site. As mentioned earlier, the ditching of a salt marsh can be used to alter the hydrology of the marsh and by extension, the adjacent coastal forest ecosystem. Depending on the site conditions, ditches can be either filled to limit flooding or expanded to increase drainage. A study of marsh sites in New England by Vincent et al. (2013) found that the filling of ditches decreased sediment flux into the marsh and subsequently lowered accretion rates. Lower accretion rates create marsh instability, which could have consequences for coastal forest stability. Elsewhere, increased ditching has been used in an attempt to drain ponding of the interior marsh platform and thereby enhance revegetation (Wigand et al., 2017). The decision to fill or deepen ditches may be a question of which management goal is prioritized for the given area of concern.

The use of engineered infrastructure designed to create a local barrier to sea-level rise or protect the salt marsh/coastal forest ecosystems from storm surge are costly, require maintenance, and will need to be adjusted as the conditions continue to change, but might be applicable in select situations. Tide gates are regulated openings through which water may flow freely when the tide moves in one direction, but which close automatically and prevent the water from flowing in the other direction. Coupled with dikes and levees, tide gates have a long history of use in salt hay farming, mosquito control, and protection of assets from storm surges. Such an all-or-nothing approach may be useful in maintaining the existing marsh-forest ecotonal

boundary for some time but can lead to unintended negative consequences. In a New England marsh, the reduction of tidal flow stemming from the use of tide gates led to drying of the marsh soils, and in turn has created habitat that is ideal for the expansion of *Phragmites* (Roman et al., 1984, Roman et al., 1995). Analysis of historical aerial photography documents where dike systems have been breached with catastrophic consequences to the marsh and forest behind them (Sacatelli, 2020). Sacatelli (2020) documented that the 1970s dike breach in Delmont, NJ, resulted in marsh loss and forest dieback up to 540 meters inland by 2015.

More sophisticated tidal modification systems are widely used in Europe. Regulated Tidal Exchange (RTE) is a system of tide gates or sluices that are used to control the amount of water entering an area that is surrounded by seawalls or embankments (Masselink et al., 2017). This technique is used to restore tidal flow to mudflats and salt marshes as part of broader coastal protection strategies in the face of sea-level rise and storm surges (Environment Agency, 2003; Masselink et al., 2017). Controlled Reduced Tide (CRT) technique uses a system of inlet and outlet sluices that are designed to passively control tidal flows into an area surrounded by a sea wall or embankment (Meire et al., 2005; Maris et al., 2007). While projects using RTE and CRT systems have focused on salt marsh maintenance/restoration, their application with the express purpose of slowing the effect of rising sea-levels on coastal forests is a potential area for further exploration. Further, these tidal flow control technologies are costly as they need to be designed and implemented at a scale broad enough to be effective and require continued maintenance.

Vegetation Community Management

Regardless of the desired management goal, some form of active vegetation management would be integral to management plans. If the management goal is to maintain the coastal forest in place, then best management practices that promote the replacement of the existing vegetation

with species better adapted to the new environmental conditions may be required. For example, planting of more salt and flood tolerant tree species may be key to maintaining a forest ecosystem in light of changing salinity and saturation conditions. The control of *Phragmites* may be necessary to reduce competitive interactions and thereby promote the natural establishment and/or facilitate the growth of the planted trees/shrubs. Prescribed burning and application of herbicides together, have shown to be effective measures to control *Phragmites* (Thompson and Shay, 1989; Cross and Flemming, 1989). Attempting to minimize forest dieback and maintain a forest may be feasible in the short term (i.e., over several decades) but in the face of intensifying sea-level rise, will inevitably be a losing proposition in some locations over the long term (i.e., over 50 to 100 years). Adopting some form of adaptive management that incorporates active monitoring of forest health would be a requisite.

Planning for Marsh-Forest Ecotone Migration

If the management goal is to preserve coastal forest yet acknowledge the need for marsh ecosystems to migrate into current upland habitats, it then becomes important to protect the existing inland extent of the coastal forest and potentially facilitate the expansion of forest inland into areas that are presently non-forested (i.e., sometimes referred to as managed retreat). Rather than trying to protect the coastal forest in place, the emphasis is shifted to ensuring a “no net loss” of coastal forest at a broader regional scale.

Strategic land conservation via acquisitions or easements is one way to ensure that forest ecosystems are not being lost on the inland edge from development adding to losses on the seaward side from sea-level rise or storm surge (Maryland Department of Planning, 2019). Many states in the region have land acquisition programs and/or easement programs for different habitat types that could be used as mechanisms to facilitate management for coastal forests.

Examples include the State of New Jersey's Green Acres Program and the State of Maryland's Greenprint program. Protecting or restoring land adjacent to the coastal forest may allow for migration or expansion of coastal forest habitat. This restoration or protection would assist in maintaining coastal forests and coastal forest species closer to their historical area of habitat. Target areas for this kind of management could include undeveloped land adjacent to coastal forests or areas adjacent to already conserved properties. Conserving or actively restoring forest habitat, even a small amount, on the inland edge of the coastal forests could offset some of the losses on the seaward edge.

These acquisition or easement strategies could also assist in a separate management strategy of maintaining the habitat value of the coastal forest. Increasing the habitat connection between existing forests, both coastal and inland, can help facilitate the migration of vegetation and wildlife as the seaward edge is lost (Maryland Department of Planning, 2019). Connecting adjacent coastal forests can provide safe passage for wildlife, ensuring less of an impact on surrounding human populations as the wildlife becomes displaced due to loss of habitat, as well as ensuring the continued survival of these species. Continuous passage into the adjacent inland forest also assists in seed dispersal and other means of vegetation migration as climate change-induced changes in groundwater affect soil properties further inland in the future.

Conclusions

Our review of the scientific literature and discussion with leading experts suggests that the most important proximate mechanisms driving coastal forest edge dieback are sea-level rise induced changes in the groundwater table (G. Carleton, personal communication, May, 2020; Nuttle and Portnoy, 1992) in concert with increased saltwater inundation related to storm surges (Fernandes et al., 2018; Dai et al., 2011; Conner and Inabinette, 2003). The longer-term rise in

groundwater levels increasingly stresses the forest vegetation and decreases regeneration potential. Episodic storm surges may then exceed the salinity or saturation tolerances of existing trees leading to a wave of mortality that leaves the site inhospitable to subsequent regeneration. An acceleration of sea-level rise rates (i.e., the ultimate driver, Figure 1) is expected to further strengthen the effects of these proximate mechanisms.

It is important to take both the marsh and forest ecosystems into account as an integrated unit when determining management plans. Some of the solutions to coastal forest problems may lie in the management that takes place in the marsh such as the alteration of ditches and dikes. The possible use of engineered structures such as RTE and CRT systems requires more research but remains an option. The key to creating management plans that benefit both the marsh and the upland ecosystems is a collaboration between management entities and experts in both ecosystems. A combined management approach ensures that management effort is beneficial for both ecosystems in the long term. The salt marsh and the adjacent coastal forest are intimately linked and should be considered holistically. With a better understanding of each of the mechanisms at work in these ecosystems, managers may be better prepared for the changes ahead and facilitate proactive adaptation strategies. Finally, given the need for the marsh ecosystem to migrate inland to maintain ecosystem services, easements or buyouts are vital to ensure that there is ample space for the marsh and upland systems to migrate together. Forward thinking land use planning is needed to promote no net loss of either marsh or coastal forest ecosystems to ensure the continued provision of their vital services to society.

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Coastal Plain Pitch Pine Barrens

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North Atlantic Coastal Plain Pitch Pine Lowland

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Appendix A

January 2020 Working Meeting Participants

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Julie Blum	Rutgers University
Kate Spidalieri	Georgetown Climate Center
Kate Tully	University of Maryland
Katherine Brownson	US Forest Service
Kelly Collins	Maryland Chesapeake and Coastal Service, Maryland Department of Natural Resources
Kelsey Boyd	Natural Lands Trust
Ken Able	Rutgers University
Keryn Gedan	George Washington University
Kevin Kroeger	US Geological Survey- Woods Hole
LeeAnn Haaf	Partnership for the Delaware Estuary
Marjorie Kaplan	Rutgers University
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Soni Pradhanang	University of Rhode Island
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Stephen Smith	National Park Service
Steve McNulty	US Department of Agriculture - US Forest Service and Southeast Climate Hub
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