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Review

Coastal Forest Dieback in the Northeast USA: Potential Mechanisms and Management Responses

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Abstract: A number of studies have documented coastal forest dieback as a historical and ongoing process across the Northeast US region. To further develop a current understanding of the state of knowledge, review adaptation and response measures available to land managers, and to identify research and management needs, we conducted a literature review, interviewed experts, and convened a workshop bringing together scientists and land managers. A synthesis of the above suggests that the most important proximate mechanisms driving coastal forest dieback in the Northeast US are sea level rise-induced changes in the groundwater table in concert with increased saltwater inundation related to storm surges. What sets our conceptual model apart from prior work is the greater emphasis placed on the role of rising fresh groundwater levels in increasingly stressing the forest vegetation and decreasing regeneration potential. Episodic storm surges often exceed the salinity or saturation tolerances of existing trees leading to a wave of mortality that leaves the site inhospitable to subsequent regeneration. Maintaining functioning coastal forests across the Northeast US will require that the marsh and forest ecosystems be considered as an integrated unit when determining an appropriate adaptation response. With a better understanding of each of the sea level rise-induced mechanisms at work in these ecosystems, managers may be better prepared for the changes ahead and facilitate proactive adaptation strategies. Easements or buyouts are vital to ensure that there is ample space for the marsh and upland systems to migrate landward together. Forward thinking land use planning is needed to promote the "no net loss" of both marsh and coastal forest ecosystems to ensure the continued provision of their vital services to society.

Keywords: ghost forest; marsh migration; climate change; sea level rise; rising groundwater table; storm surge; saltwater intrusion; no net loss of coastal wetlands; climate adaptation

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1. Introduction

Sea level rise is a physical reality that is impacting coastlines across the United States as well as around the globe [1,2], raising great concern about the implications for coastal ecosystems and human communities [2]. Much of the coastal zone of the eastern United States is fringed by low-lying barrier islands backed by shallow lagoonal estuaries and extensive tidal salt marsh [3]. The long term viability of these coastal salt marsh systems in the face of ongoing sea level rise has received increasing scrutiny [4,5]. Through the process of vertical accretion of sediment and organic matter, the tidal salt marsh surface will rise in relation to sea level, i.e., the marsh can continue to grow "up" into a rising sea [4,5]. If there is only a gradual rise in terrain elevation, tidal marshes can also "retreat" landward replacing adjacent upland ecosystems through a process known as marsh migration or transgression [6–8]. At many locations along the eastern US coast, this sea level rise-induced expansion of marshes is coming at the expense of the adjacent coastal forests [9]. Various studies have documented that 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 [10–12]. These areas have been referred to as "ghost forests" denoting the presence of standing dead trees within or fringing the edge of salt marsh ecosystems [11,13,14]. This coastal forest dieback has been documented to be occurring very broadly across the Northeast [10,12,15–17] as well as the Southeast and Gulf coastal plain of the US [18–20].

While this phenomenon of coastal forest dieback and replacement with salt marshes as sea level rises has been ongoing for millennia [21,22], there is widespread concern that accelerating sea level rise and intensifying coastal storms may be hastening this process in the Northeastern US [9]. Sea level rise in the Northeastern US to date is higher than the global average [1,23] and is projected to continue to be higher than many areas around the globe [1,2,23–26]. When coupled with rising sea level, the historic and projected increase in severity of storm surge is likely to increasingly affect coastal areas in the Northeastern US [27]. To better enable climate-smart decision-making, the US Department of Agriculture Northeast Climate Hub convened a group of scientists and land managers to conduct a synthesis of the current state of knowledge concerning how Northeastern US coastal forests, specifically those in mid-Atlantic and southern New England states (Virginia, Maryland, Delaware, New Jersey, New York, Connecticut, and Massachusetts), are responding to climate change.

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 [28–30]. The drier upland end of the gradient in these forests are dominated by a diversity of oaks (including white (*Quercus alba*), southern red (*Q. falcata*), scarlet (*Q. coccinea*), and black (*Q. velutina*)) pines (including pitch (Pinus rigida), loblolly (*P. taeda*), Virginia (*P. virginiana*), and shortleaf (*P. echinata*)) [29]. 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*) [29]. The transition zone between the salt marsh and adjacent forest is often consists of common reed (*Phragmites australis*, henceforth referred to as *Phragmites*), marsh elder (*Iva frutescens*), highbush blueberry (*Vaccinium corymbosum*), and eastern red cedar (*Juniperus virginiana*) [29]. The riparian forests towards the southern end of the region largely consist of freshwater tidal swamps (i.e., freshwater swamps that experience daily tidal swings) and dominated by bald cypress, *Taxodium distichum*, and water tupelo, *Nyssa aquatica* [31]. In addition to providing protective buffering of inland areas against coastal storms [32–34], these forests provide a range of ecosystem services including carbon storage [35,36], timber resources, and habitat for a diversity of plants and animals including a number of species of concern (Global Rank G1–G4) [37]. In a recent assessment of the vulnerability of these coastal forest ecosystems to future climate change in this mid-Atlantic region, two specific forest communities, maritime forests and tidal swamps of the coastal plain, were rated as having high to moderate-high vulnerability [28].

This paper documents this synthesis of scientific literature and inputs from scientific experts to develop a conceptual model of coastal forest dieback in the Northeast US identifying the key driving processes, mechanisms, and ecosystem responses and their linkages. We also include an assessment of potential management approaches to slow or mitigate coastal forest dieback with special relevance to the Northeastern US region. Gaps in current understanding of the underlying processes and ecosystem responses, as well as management approaches, are also highlighted. While this paper is focused on the Northeastern US, the potential mechanisms and management responses that are discussed may be applicable to other locations undergoing sea level rise-induced coastal forest dieback.

2. Methods: Literature Review and Expert Input

A search of the scientific literature was undertaken using the Web of Science (up to and including all of 2022) and the following key terms: ghost forests, coastal forest retreat or transgression, coastal forest dieback, coastal forest loss/deforestation, and sea level rise or saltwater intrusion or storm surge. The abstracts and text were scrutinized to determine the paper's relevancy to the topic and the Northeast region. Duplicates as well as citations related to mangrove forests were omitted. The geographic region (i.e., Gulf of Mexico, Southeast, Northeast USA) and year of publication were recorded. Though our focus was on the Northeast, studies from these other regions are often pertinent as the topography, landforms and plant communities share many similarities.

With the objective of uncovering knowledge gaps that exist in understanding the coastal forest ecosystem, interviews were conducted with six experts on the Northeastern US coastal forest ecotone or the adjacent salt marsh ecosystem. The experts were chosen for their contributions to key papers on diverse topics found in the literature review. Each expert was asked a series of 11 questions that, in addition to their opinion on knowledge gaps, included their personal experience with how climate change is affecting the system including the surrounding communities and any management strategies being used or that they felt warranted more investigation. More information concerning the interview questions is included in Supplementary Materials.

To further develop a current understanding of the state of knowledge, facilitate exchange among experts, review adaptation and response measures available to land managers, and to identify research and management needs, a convening of regional experts and managers was held at the USDA National Agriculture Library on 23 January 2020. The meeting consisted of 16 presentations on ecological research on coastal forests and the adjacent salt marsh ecosystems and applicable management strategies for these systems. These presentations were followed by a facilitated group discussion with a focus on identifying research gaps and developing a research agenda and management frameworks. A total of 52 professionals from State, Federal, University, non-profit, and private organizations representing all 11 coastal states from South Carolina to Massachusetts were in attendance.

3. Results and Discussion

3.1. Literature Review

A total of seventy-seven papers were found using the Web of Science and the specific search terms. Starting in 1998, there was a low level of publication until 2019 where the number of papers increased several-fold (Figure 1). Whereas interest in this topic appeared first in the Gulf and Southeast US regions, the number of papers concerning the Northeastern US region has increased dramatically over the past five years (Figure 1). This search as not all encompassing as not all papers pertinent to the topic may have employed these key words in their title or abstract. For example, seminal work from the 1980–1990's on sea level rise-induced transitions to coastal wetlands [6–8] were not included. While there was widespread interest in dieback of mangrove forests along some sections of the Gulf and Southeast coasts, those papers were not included, as our focus was on Coastal Plain forests.

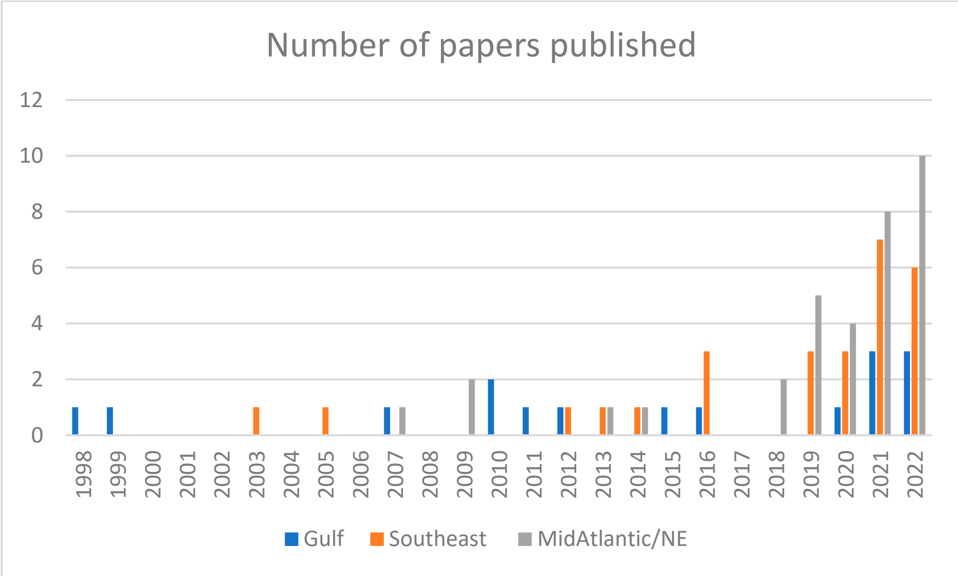

Figure 1. Results of Web of Science search on key terms: ghost forests, coastal forest retreat or transgression, coastal forest dieback, coastal forest loss/deforestation, and sea level rise or saltwater intrusion or storm surge. While the focus of the literature review was on the Northeast USA, papers from other US regions were included here for comparative purposes.

3.2. Conceptual Model

Based on a synthesis of scientific literature and as well as interviews with scientific experts and the outcome of the workshop, we developed a conceptual model of coastal forest dieback in the Northeast US that is graphically depicted in Figure 2. The model differentiates ultimate vs. proximate mechanisms of change that are affecting coastal forest ecosystem-level response. External anthropogenic factors that have a role are also included. Climate change and attendant effects on sea level rise and storm frequency and intensity represent the ultimate driver of the system (Figure 2). 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 [13]. Two of the most important proximate mechanisms associated with rising sea levels appear to be 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 (transition zone) shifts landward as sea levels rise and salt marsh vegetation invades the dead or dying forest. Areas of low-lying topography within the coastal zone in close proximity to tidal waterways are most vulnerable [9,13,38]. Anthropogenic factors such as ditching due to mosquito management or groundwater pumping are included as external factors that can increase or decrease the intensity of these mechanisms [39].

To understand the impact that changing storm surges and rising sea levels (Ultimate Drivers in Figure 2) have on the forest ecosystem, it is instructive to first examine the relationship between the physical environment and the location of the marsh–forest ecotone, then delve more into the factors driving soil salinity and soil saturation and the attendant effects on tree health and regeneration.

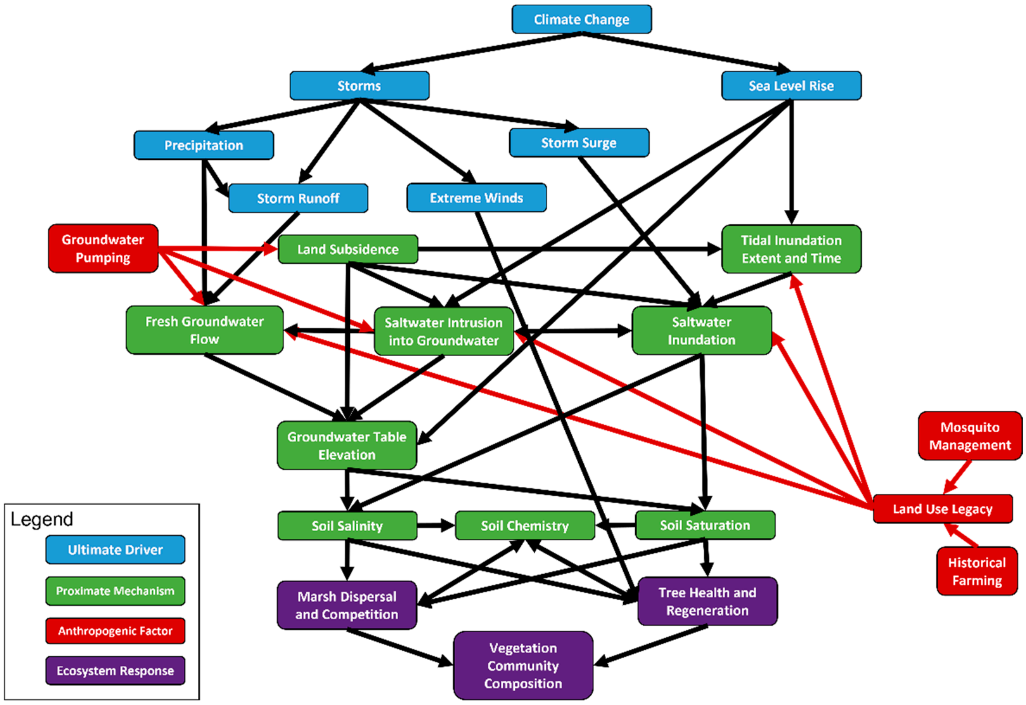

Figure 2. A concept map summary of processes controlling forest edge migration as compiled from relevant literature. The blue color denotes the ultimate drivers of change. Green denotes proximate mechanisms of change. Red denotes external anthropogenic factors that have a role in change. Purple is the ecosystem-level response that occurs due to the changes in the controlling processes.

3.3. Physical Environment and Marsh–Forest Ecotone

The strong links between flooding frequency, pore water salinity, and soil saturation are key environmental factors in determining the spatial distribution of coastal vegetation communities and the location of the marsh–forest ecotone (Figure 2) [40–42]. Variation in the salt- and soil-saturation tolerances of individual plant species, lateral salinity changes and flooding conditions, and the intense competitive relationships of the species within these habitats create well-delineated vegetation zones as one progresses across the topographic gradient from coastal marshes through the marsh–forest ecotone to adjacent coastal forests [42–44].

A review of the factors controlling groundwater flows is instructive. Precipitation recharges freshwater surficial aquifers that flow 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 [45] (p. 6). The salinity of groundwater can be influenced by mixing with adjacent tidal saline water, underlying denser saline water, and/or infiltration of saline water that inundates land surface during exceptional high tides and storm surges [45] (pp. 9–10). 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 [45] (p. 10). 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 [45] (p. 10).

Salinity of water in the rooting zone, or soil pore water, is a critical factor affecting the coastal forest ecosystem. The pore water salinity 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 [46–48]. The high tidal flooding frequency (daily to monthly) in the lower elevations leads to highly saline pore water conditions which, therefore, are often typically colonized by salt-tolerant (halophytic) graminoid and herbaceous plants to form low and high salt marshes. Further inland/upslope, where tidal flooding is infrequent (less than annual), the influence of precipitation and groundwater becomes the driving factor controlling pore water salinity in the unsaturated zone [45].

In the Northeast US, the trees at the marsh–upland ecotone often consist of species that have a moderate degree of salt tolerance (such as eastern red cedar, *Juniperus virginiana*, or the American holly, *Ilex opaca*) [49,50] and are able to tolerate occasional storm-driven salt spray (a few times per year) [51]. Where saltwater inundates the coastal forest during extreme storm or tidal events, pore water and shallow groundwater salinity increase from the pulse of saltwater and then gradually decrease as freshwater infiltration from precipitation, density-driven downward vertical flow, and horizontal flux from higher-elevation freshwater recharge areas inland serve to dilute the salinity [45]. Farther inland, coastal wetland forests may consist 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 [51].

3.4. Potential Proximate Mechanisms Controlling Forest Dieback

In this next section we discuss how these environmental factors such as soil moisture, soil salinity, or flooding frequency are currently changing due to a combination of sea level rise and other anthropogenic factors and how these changes may affect the Northeast coastal forest ecosystem.

3.4.1. Soil Saturation and Rising Groundwater Levels

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 [52–54]. Rising groundwater levels reduce the thickness of the unsaturated zone (sometimes referred to as the vadose zone), thereby reducing the depth to groundwater (i.e., groundwater table elevation in Figure 2). Recent three-dimensional groundwater-flow modeling of coastal aquifers predicts that the depth to the water table and the thickness of the unsaturated zone will decrease with rising sea levels [55–57]. The groundwater modeling was conducted on single layer aquifers of several Mid-Atlantic barrier islands. Further research on the applicability of these simulation model results to potentially more complex mainland conditions is warranted.

With the fresh groundwater table closer to the surface, there is an increasing incidence of saturated soil conditions in low-lying coastal areas [53,58]. If the unsaturated zone decreases, the soil in the rooting zone of the coastal forest may become saturated (Proximate mechanism: soil saturation in Figure 2). 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 [59]. Most trees can withstand a few days of freshwater flooding during the growing season, but extended flooding conditions affects plant growth, development, and survival [60,61]. 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 [59,60,62], very few riparian or wetland tree species can withstand extended soil inundation [63]. Extended drought can also have negative effects on tree health and regeneration. While some work on Gulf coast forests [18] has documented drought as potentially contributing to dieback, the role of drought has not been well studied in the Mid-Atlantic region to date (and thus not included in Figure 2).

Raphael [64] 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 is experiencing increasing mortality in the tree canopy layer and limited seedling/sapling recruitment. Raphael [64] attributed this decline in the holly-dominated forest to increasingly saturated soil conditions from the thinning of the unsaturated zone which brings the ground water system closer to the ground surface. Similarly, in a loblolly pine (*Pinus taeda*)-dominated coastal forest in Maryland, Kirwan et al. [65] 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, this process is likely an important contributor to coastal forest dieback [53,65,66] and will be considered in greater depth later in the paper.

3.4.2. Soil Salinity and Severe Storms

Severe storms coupled with a rising sea level increase the magnitude and longevity of storm surges [27,67,68]. As illustrated in Figure 2, storm surge-related surface inundation of saltwater can intensify soil pore water salinization [66,69]. The impact of this influx of saline water can last for several years after the storm [70]. Increases in salinity of the pore water can directly limit vegetative growth and cause other changes in soil chemistry (Figure 2). 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 [63,71]. Higher soil salinity levels can also increase the solubility of minerals and other solutes, altering biogeochemical cycles [72–74]. Increasing salinity levels affect nitrogen uptake, denitrification, and carbon mineralization rates in experimentally manipulated forest soils [75–79], which has been shown to 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 [80,81].

Stalter and Heuser [82] documented the effect of Superstorm Sandy on American Holly trees (*Ilex opaca*) at Sandy Hook, New Jersey. Hollies growing on lower dune ridges that were inundated by surge waters experienced 50–75% initial leaf loss (6 months after the storm) followed by 85% leaf recovery (20 months after the storm). Hollies growing in salt water-filled depressions were killed [82]. Atlantic white cedar (*Chamaecyparis thyoides*) are especially susceptible to storm surge saltwater inundation with extensive diebacks of entire stands following storms [83]. Fernandes et al. [71] observed declining radial growth in response to episodic storm disturbance in the coastal forests of Virginia. Ury et al. [14] documented a pulse of forested wetland dieback in the North Carolina coastal plain in the years immediately following Hurricane Irene in 2011. These NC coastal forested wetlands include significant tracts of Atlantic white cedar that serve as an important seedbank for this regionally important and imperiled species.

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 [84]. Seedlings of common coastal tree species, such as red maple (*Acer rubrum*), were found to be highly sensitive to saltwater flooding with height and diameter growth significantly reduced [85]. Work on the west coast of Florida by Williams et al. [32] 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 reported to 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 2) [66,84].

In addition to changing soil salinity, the extreme winds of severe storms can damage the coastal trees by causing breakage, defoliation, and uprooting [86]. Extreme winds can also increase salt spray which can lead to leaf scorch which can cause partial or complete defoliation [87]. Floating debris transported by wind-driven waves during severe storms can de-bark the trees, damaging the xylem and phloem tissues and negatively affecting nutrient transport within the tree [88]. These damages, combined with the stress caused by the increased soil salinity, can lead to mortality of the stressed stand [66,71,89]. The repercussions of these storm events increase dramatically if more than one storm occurs in successive years [90].

As outlined above, episodic storm surge-related surface inundation of saltwater can cause soil salinization, soil oxygen depletion, and changes in soil chemistry. There was a widespread agreement by the expert interviews and workshop participants that 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. 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 freshwater soil saturation [61], 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.

Further 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. Additionally, 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, as would investigating whether ecological factors such as species composition and competition determine how the proximate mechanisms effect the system both in conjunction with, and independent of, location.

3.4.3. Effects of Insect Pests and Invasive Species

The synergistic effects of insect pest outbreaks on tree health were also identified as an issue of concern. For example, *Dendroctonus frontalis* (southern pine beetle) has expanded into areas of New Jersey, New York, and Connecticut [91]. *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 [92]. With increasingly warmer winters, *D. frontalis* may continue to expand northward. The invasion of the Emerald Ash Borer (*Agrilus planipennis*) has affected Mid-Atlantic tidal swamps killing large numbers of ash trees (*Fraxinus* spp.) [93]. Workshop participants expressed concern that 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.

An information gap that was identified relates to the role of the invasive form of the common reed, *Phragmites australis*, in affecting plant community dynamics at the marsh–upland ecotone once a forest starts experiencing dieback. A 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 [94]. *Phragmites* reproduces both by clones and seed dispersal [95], readily invades any habitat within its growth tolerance range, and is known for establishing quickly and flourishing in disturbed habitats [96–98]. 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 [98–100]. *Phragmites* is also a very hardy plant [101] 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 populations to readily expand into areas of forest dieback at the marsh/forest ecotone [10,12,13]. 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. Understanding the nuances of the *Phragmites* invasion, the inhibiting effect it might have on forest regeneration, and the eventual consequences on salt marsh expansion may lead to better management of the ecotone.

3.5. Conceptual Model Reprise

While Tully et al. [69] suggest that saltwater intrusion is the primary mechanism driving coastal forest loss, we suggest that the proximate mechanisms of higher groundwater tables and periodic storm surges appear to work in concert in driving coastal forest dieback. Fagherazzi et al. [66] have posited a "ratchet" model that combines the gradual "press" disturbance of sea level rise with the intermittent "pulse" disturbance of storms. Our conceptual model (Figure 2) shares many similarities with Fagherazzi et al.'s [66] ratchet model. Carr et al. [102] developed a two dimensional transect model to examine the landward transgression of the marsh–forest edge. Similar to the ratchet model, Carr et al.'s [102] results suggest that the landward marsh edge is controlled by the interaction of high-water inundation events and subsequent enhanced forest mortality, resulting in punctuated transgressive (i.e., dieback) events. One subtle distinction between these studies and the present work is that our conceptual model places a greater emphasis on the role of rising fresh groundwater levels in increasingly stressing the forest vegetation and decreasing regeneration potential. The emphasis we place on rising groundwater levels is based on the critical role that fresh groundwater flow plays in the hydrology of the coastal zone [45], as well as on a recent three-dimensional groundwater-flow modeling conducted by the US Geological Survey that predicts that the depth to the freshwater table and the thickness of the unsaturated zone will decrease with rising sea levels [55–57].

Figure 3 represents a graphic illustration of our conceptual model (Figure 2) on the effects of longer term sea level rise on the proximate mechanisms driving coastal forest dieback. In inland areas of coastal forests, freshwater recharge and inflow of fresh groundwater from upland areas result in a freshwater-only environment (Figure 3a). The upland edge of the transition zone, where there is a mixing of fresh and saline water, is proximal to the marsh–forest ecotone (Figure 3a). In our conceptual model, the "press" disturbance of sea level rise is working through the proximate mechanisms of rising groundwater levels, increasing the frequency of saturated soil conditions, as well as the movement of the transition zone landward (Figure 3b,c). Given the well documented effect of saturated soils on impeding tree growth and reproduction [53,60,61,63,65], we posit that rising groundwater levels appear to contribute to coastal forest dieback. However, additional research is clearly needed to clarify the significance of rising groundwater levels in comparison to the well documented role of "pulse" disturbances [66,102].

3.6. Anthropogenic Land Use Legacies

The legacy of earlier land use alterations on either intensifying or ameliorating the proximate mechanism causing coastal forest dieback in the Northeast US 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 and address public health concerns [103]. Increasing drainage on the marsh causes less standing water, and therefore less mosquito breeding locations [104]. 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 [105].

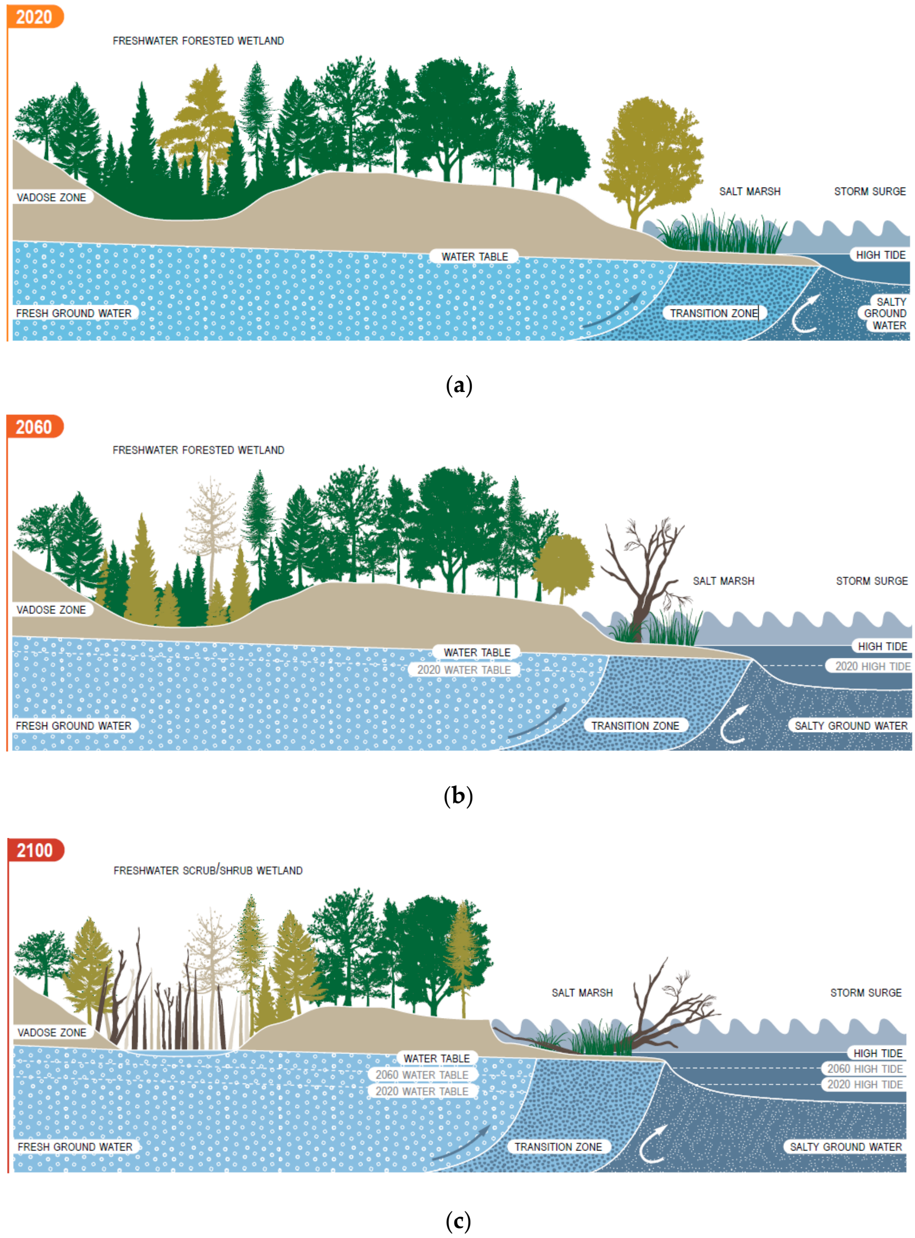

Figure 3. Graphic illustration of coastal forest dieback under rising sea levels. (**a**) Year 2020: Precipitation leads to freshwater recharge of surficial aquifers that flows from inland/upland recharge areas to discharge areas in freshwater wetlands and streams, brackish estuaries, and saltwater wetlands and water bodies. In coastal areas, less dense fresh groundwater discharging to saltwater wetlands or water bodies flows over and eventually mixes with denser saline water. (**b**) Year 2060: The likelihood of 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). (**c**) Year 2100: Rising sea levels also raise the water table tens to hundreds of meters inland from tidal waters, resulting in a thinning vadose zone (variably saturated-unsaturated zone) such that the permanent 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.

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 [106]. 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 reach interior marsh or adjacent forests more easily, 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 [107]. 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. A better understanding of 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 the 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 [108,109]. 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 up-coning [108,109]. 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 [110]. 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.

3.7. Management Responses to Coastal Forest Dieback

The consensus of the scientists and managers at the January 2020 convening of experts was that much of the current management focuses on protecting or assisting the salt marsh ecosystem and comparatively less attention has been paid to specifically managing the adjacent coastal 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 [111]. 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. 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 flood and/or salt tolerant tree species may be key to maintaining a forest ecosystem in light of changing salinity and saturation conditions [58]. 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 [10]. Adopting some form of adaptive management that incorporates active monitoring of forest health was recommended as a best management practice.

Some form of proactive water management through a combination of optimizing delivery of existing freshwater flows, enhancing recharge, and deploying engineered structures to control saltwater intrusion are possible options [29]. 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. [112] 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 [111]. 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 which, in turn, has created habitat that is ideal for the expansion of Phragmites [113,114]. For analysis of historical aerial photography that documents where dike systems have been breached with catastrophic consequences to the marsh and forest behind them, see ref. [12].

More sophisticated tidal modification systems are widely used in Europe and might be applicable in the Northeast US. The 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 [115]. 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 [115,116]. The 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 [117,118]. 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 they require continued maintenance.

Workshop participants agreed that due to the spatially varying nature of the proximate mechanisms (Figure 2), identifying which mechanisms may be dominant at a specific site, and understanding the possible synergistic effects among mechanisms is vital to determining appropriate management strategies. For example, a management practice or intervention that might be useful in ameliorating the short-term effects of a storm surge event 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.

Attempting to minimize forest dieback and maintain a vulnerable coastal forest may be feasible in the short term (i.e., over several decades) but in the face of accelerating sea level rise or intensifying storm surge, will often be a losing proposition over the long term (i.e., over 50 to 100 years). A more promising, longer-term approach may be to acknowledge that coastal marsh systems will continue to migrate into current upland habitats and shift the focus to protecting the existing inland extent of the coastal forest and facilitating the expansion of forest inland into areas that are presently non-forested (i.e., sometimes referred to as managed retreat) [11]. Rather than trying to protect the coastal forest in place, the emphasis should be shifted to ensuring a "no net loss" of coastal forest at a broader regional scale. 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 the protection or restoration of land adjacent to the coastal forest to allow for the migration or expansion of coastal forest habitat (for example, Maryland Department of Planning [119]).

4. Conclusions

Our review of the scientific literature and discussion with leading experts suggests coastal forest dieback is occurring across the entire Eastern US coast with special concern in the Northeast US region. The evidence is strong that increased saltwater inundation related to episodic storm surges [55,69,70] plays a critically important role in northeastern US coastal forest dieback. While recent hydrological modeling studies have suggested that sea level rise-induced changes in the groundwater table [55–58] may also play a critical role, the empirical evidence is less clear. Further 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. 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 US coastal tree and shrub species is needed. This information may lead to a better understanding of the mechanisms operating at a site and inform management interventions.

It is important to consider the marsh and forest ecosystems as an integrated unit when determining an appropriate adaptation response. 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 SLR-induced changes and corresponding ecosystem responses, managers may be better prepared for the changes ahead and facilitate proactive adaptation strategies. Finally, given the need for the marsh ecosystems to migrate inland if they are to keep pace with sea level rise, easements or buyouts are vital to ensure that there is ample space for the marsh and upland systems to migrate landward together. Forward thinking land use planning is needed to promote the “no net loss” of both marsh and coastal forest ecosystems to ensure the continued provision of their vital services to society.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15086346/s1, Questionnaire Adapting to Climate Risk on Working Lands: Saltwater Impact on Forests Project.

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